



# Potential vorticity modification by turbulence in the upper troposphere and lower stratosphere – Part 2: Coherent upscale effect in a warm conveyor belt outflow

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**Abstract.** While the effect of turbulence on potential vorticity (PV) modification in the upper troposphere and lower stratosphere (UTLS) has long been identified, previous studies mainly focused on the situation of an upper-level jet and the associated frontal zones. In this study, a more complex flow situation is investigated, which is a case with turbulence-induced PV changes in a warm conveyor belt (WCB) outflow. A numerical simulation of the case is performed with the Integrated Forecasting System (IFS) model from the European Centre for Medium-Range Weather Forecasts, with additional outputs allowing a direct examination of the instantaneous PV tendencies generated by individual non-conservative processes parametrised in the model. Arc-shaped tripolar PV tendency bands due to turbulence are simulated in the UTLS region, which align with the WCB outflow boundary. A detailed analysis of vertical cross sections illustrates that the divergent outflow of the WCB is the key to the emergence of these banded structures. The tripolar pattern of the bands is the result of divergent non-advective PV fluxes associated with turbulent mixing, which is explainable by the analytical framework developed in Part 1 of this study, validating its applicability to complex flows. When accumulated over time, systematic material PV changes along air parcel trajectories occur in the UTLS. Turbulence is the most relevant among the non-conservative processes in causing these PV changes, with a major band of PV decrease identified in the WCB outflow region. The examination of individual air parcel trajectories shows a surprisingly steady accumulation of PV changes despite the local flow being perpendicular to the PV tendency bands. A synchronised movement of the PV tendency bands and the air parcels is revealed as the cause, with the WCB outflow being the driver of such organisation. Coherent PV modification by turbulence is achieved by this delicate coupling of the large-scale flow and individual air parcels, contrasting the more straightforward pathway of PV modification in the upper-level jet-front system as examined in detail in Part 1. Taken together, this two-part study therefore demonstrates that turbulence is capable of modifying PV systematically in the UTLS even in complex flow situations involving different non-conservative processes. It also reveals the importance of weather systems in imparting the necessary spatial and temporal coherence for turbulence to generate a systematic feedback to larger scales in the form of substantial PV modification. The exact consequences of this upscale effect of turbulence on the dynamics in the UTLS and therefore on medium-range predictability remain to be explored in future studies.



## 25 1 Introduction

Turbulence in the upper troposphere and lower stratosphere (UTLS) has been continuously studied due to its relevance to aviation safety (Sharman and Lane, 2016). A related line of research, which is however less explored, concerns the influence of the small-scale turbulence on the large-scale dynamics near the tropopause. One way to study this is to consider turbulence as a diabatic and/or frictional process in the potential vorticity (PV) framework (Eliassen and Kleinschmidt, 1957; Hoskins et al., 1985) and assess how the PV of air parcels is modified by turbulence. Based on these PV changes, the upscale effect of turbulence can be inferred because the distribution of PV encapsulates the essence of the larger-scale balanced atmospheric flow. PV is given by (Ertel, 1942):

$$Q = \frac{1}{\rho}(\zeta_a \cdot \nabla \theta) \quad (1)$$

where  $Q$  is PV,  $\rho$  is density,  $\theta$  is potential temperature,  $\zeta_a = \nabla \times \mathbf{u} + 2\mathbf{\Omega}$  is the absolute vorticity (with  $\mathbf{u} = (u, v, w)$  being the velocity and  $\mathbf{\Omega}$  the angular velocity of Earth's rotation).

As early as the 1970s, Shapiro (1976) utilised research flight measurements to show that the turbulent heat flux is of first-order importance to the formation of the observed positive PV anomaly on the cyclonic shear side of the jet core. Numerical studies were later conducted and confirmed a significant role of turbulence in modifying PV in the vicinity of the jet (Gidel and Shapiro, 1979) and the dissipation of the associated tropopause fold (Hartjenstein, 2000). More recently, Spreitzer et al. (2019) quantified the PV modification by different non-conservative processes using an operational numerical weather prediction model and established turbulence as the key driver of many of the PV changes found near the tropopause in a synoptic situation exhibiting a strong upper-level jet.

In particular, Spreitzer et al. (2019) repeatedly observed a vertical tripole pattern in the turbulence-induced instantaneous PV tendency field as well as in the accumulated PV change. This tripole was also present in the two-dimensional simulation by Hartjenstein (2000). Part 1 of this study (Lee et al., 2026) provided a mechanistic understanding of the formation of this vertical tripole by introducing an idealised, quasi-two-dimensional framework. The vertical tripole was shown to be a consequence of the divergence of the non-advective PV flux from the turbulent layer, which is a characteristic of PV modification by turbulence in this idealized framework. The analytical results were validated with a simulation of an upper-level jet-front system using the Integrated Forecasting System (IFS) from the European Centre for Medium-Range Weather Forecasts (ECMWF) and a very good correspondence between the two was found. Coherent and systematic PV modification by turbulence over time was also diagnosed in air parcels travelling along the jet, which emphasised the potential of turbulence to influence the large-scale flow.

It is notable that all aforementioned studies on turbulence-induced PV modification in the UTLS are focusing on upper-level jet-front systems. Given the fact that turbulence in the UTLS is usually encountered in proximity to the upper-level jet stream (e.g., Bannon, 1952; Ellrod et al., 2015), it is logical to select this as the starting point when studying PV modification by turbulence. However, this confined scope prompts an inquiry into the generalisability of the results to other synoptic flow



situations. This is especially the case for the analysis conducted in Part 1 (Lee et al., 2026), as the synoptic conditions associated with the upper-level jet-front system appear to be chosen specifically for the application of the analytical framework. Therefore, an additional case study featuring a more complex and dynamic flow situation is necessary to address this issue explicitly.

A nice candidate to serve this purpose would be an upper-level flow influenced by a warm conveyor belt (WCB; Browning et al., 1973; Madonna et al., 2014b), which is a coherent ascending airstream in extratropical cyclones with strong latent heating. As a first reason, we mention the recent result that a significant portion of upper-level turbulence encountered by commercial aircraft occurs in WCB ascent regions (Lee and Sprenger, 2025). Small-scale mixing due to turbulence in the UTLS was also identified above a WCB outflow region (Kunkel et al., 2019). Second, the divergent outflows of WCB may interact with the upper-level flow, or specifically the isentropic PV gradient near the jet, which acts as a Rossby waveguide (Vishnupriya et al., 2025), typically resulting in a more amplified or disturbed flow situation. Previous studies have shown that WCBs can significantly influence the downstream evolution, including ridge amplification (e.g., Grams et al., 2011), Rossby wave initiation (e.g., Grams and Archambault, 2016; Röthlisberger et al., 2018), or Rossby wave breaking (e.g., Madonna et al., 2014a), and therefore substantially modulate the upper-level flow. Third, different diabatic processes associated with WCBs are involved in modifying PV in the upper troposphere, allowing an assessment of the relative importance of the contribution of turbulence. Diabatic heating due to condensation and other cloud-microphysical processes associated with WCB ascents and the embedded convection can significantly modify PV, which is well-documented in the literature (e.g., Wernli and Davies, 1997; Joos and Wernli, 2012; Oertel et al., 2020, 2023). It thus provides an opportunity to investigate whether the effect of turbulence on PV modification would be overshadowed due to the presence of other diabatic processes. Furthermore, though the effect of vertical shear on PV tendencies associated with diabatic heating in WCBs has been explored (Harvey et al., 2020; Oertel et al., 2020), there is no study dedicated to how turbulence modifies PV in WCB outflow regions. A case study on a synoptic situation with a WCB may hence also broaden the current understanding of the role of WCBs in PV modification.

Consequently, we extend the analysis of Part 1 of this study (Lee et al., 2026) and assess the effect of turbulence on PV modification in a WCB outflow region by applying the same methodology as used in Part 1 to another dedicated IFS simulation. Particularly, this second part aims to address the following research questions:

1. Can turbulence systematically modify PV instantaneously in the WCB outflow region?
2. Assuming an affirmative answer to the former, is the idealised framework developed in Part 1 also applicable to describe how turbulence modifies PV in the WCB?
3. When accumulated over time, are the material PV changes induced by turbulence coherent, and their amplitudes important compared to other non-conservative processes?
4. What are the similarities and differences of the turbulence-induced PV modification associated with the WCB outflow compared to the upper-level jet-front system examined in Part 1?

The subsequent sections of this paper are organised as follows. The data and methods are summarised in Sect. 2, including a description of the synoptic situation of the simulated case. Section 3 explores the instantaneous PV tendencies due to turbulence



in the WCB outflow region and examines the validity of the idealised framework. Section 4 continues with assessing the effect of turbulence on PV modification accumulated over time in this complex flow condition. Section 5 discusses the connection to Part 1 and the significance of the results, before Sect. 6 ends the paper with the major conclusions.

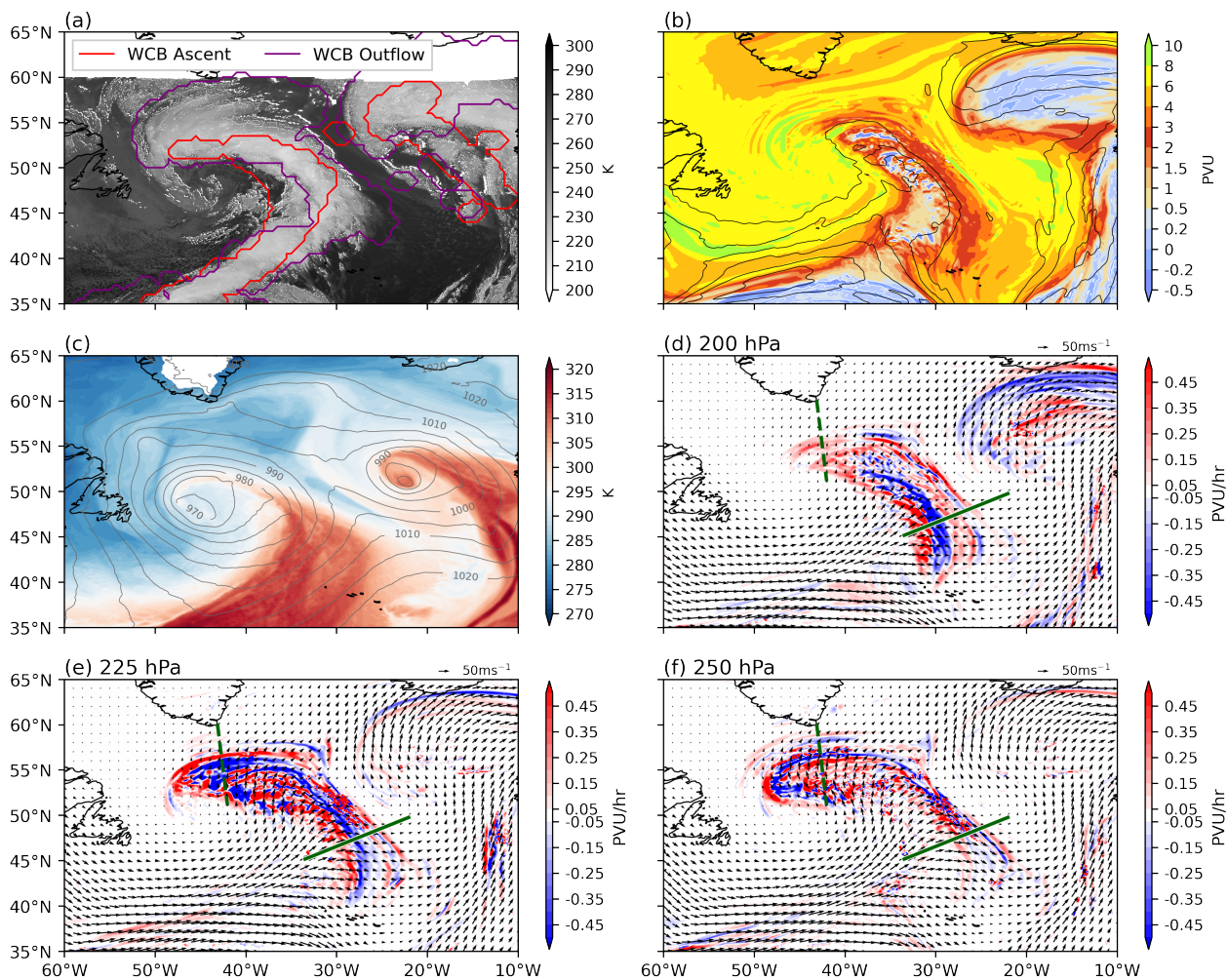
## 2 Data and method

The current study relies on a dedicated simulation performed with the IFS, which provides additional output of temperature and momentum tendencies from each parametrised non-conservative process. The simulation data thus allow us to quantify the PV modification by each process directly by deriving the individual instantaneous PV tendencies and accumulating the resultant PV changes over time using offline trajectory calculations. Since the methods are the same as those applied in Part 1 (Lee et al., 2026), we refer readers there for the technical details. Instead, the following sections only present the essential parts of the methodology, which include the description of the simulated case in Sect. 2.1, that of the instantaneous PV tendencies in Sect. 2.2, and a brief summary of the Lagrangian analysis, which complements the analysis of instantaneous tendencies, in Sect. 2.3.

### 2.1 Dedicated IFS simulation

A dedicated IFS simulation was performed, based on the model version Cy47r3. The model settings are the same as in Part 1 (Lee et al., 2026). The horizontal resolution is approximately 9 km and output was interpolated to a  $0.1^\circ$  regular latitude-longitude grid. As stated in Sect. 1, a synoptic situation that featured a WCB and a perturbed upper-level flow is the targeted condition of this study. Therefore, an episode in the North Atlantic basin was chosen by examining the WCB masks identified from ERA5 reanalysis (Hersbach et al., 2020), as detailed in Heitmann et al. (2024). Figure 1a displays the WCB masks overlaid on the infrared brightness temperature measured by satellites (Janowiak et al., 2017) at 17 UTC on 25 December 2019. Two typical comma-shaped cloud bands associated with extratropical cyclones are present in the North Atlantic and both are collocated with the ascent and outflow masks of the respective WCBs. The presence of the large masks indicates that the flow situation is strongly influenced by the ascents and outflows of the WCBs. The WCB to the west is the focus of the subsequent analyses.

The simulation is then initialised from the analysis at 12 UTC on 24 December 2019. The lead time of 27 h relative to the flow situation shown in Fig. 1a was chosen to minimise the deviation of the simulation from reality, but also to permit the investigation of the short-term PV modification by non-conservative processes. The PV and wind speed on 225 hPa in the simulation at 17 UTC on 25 December 2019 are shown in Fig. 1b. The PV field is in good agreement with the satellite observations, with the ridge-trough conjugate matching the cloud bands and clear sky regions. At around  $35^\circ\text{W}$ , there is a narrow ridge region corresponding to the WCB of interest, with the cloud bands observed aligning closely with the simulated dynamical tropopause (defined as the 2 PVU isosurface, where  $1 \text{ PVU} = 1 \times 10^{-6} \text{ K kg}^{-1} \text{ m}^2 \text{ s}^{-1}$ ). While there is a jet streak upstream ( $48^\circ\text{W}$ ,  $38^\circ\text{N}$ ), the flow is seemingly obstructed in the ridge region by the PV trough between the two WCB outflow regions. The simulated sea level pressure and equivalent potential temperature on 850 hPa (Fig. 1c) show consistent lower tropospheric



**Figure 1.** (a) Satellite infrared brightness temperature (shading; Janowiak et al., 2017) at 17 UTC on 25 December 2019, with WCB ascent (red contour) and outflow (purple contour) masks derived from ERA5 reanalysis (Heitmann et al., 2024) overlaid. (b) PV (shading) and wind speed (black contours, starting from  $30 \text{ m s}^{-1}$ , every  $10 \text{ m s}^{-1}$ ) on 225 hPa, and (c) equivalent potential temperature on 850 hPa (shading) and sea level pressure (contours, every 5 hPa) at 17 UTC on 25 December 2019 of the dedicated IFS simulation. (d-f) Instantaneous PV tendency due to turbulence (shading) on (d) 200, (e) 225, and (f) 250 hPa at 17 UTC on 25 December 2019 of the dedicated IFS simulation, with wind vectors overlaid. The solid and dashed green lines indicate the locations of the 'SE' and 'NW' cross sections in, e.g., Fig. 2.

flow conditions, with two cyclones with clear frontal structures in the expected locations. This overall correspondence indicates that the dynamics of the WCB-perturbed upper-level flow should be captured reasonably well by the IFS simulation.



## 2.2 Instantaneous PV tendencies derived from the IFS simulation

In addition to the standard meteorological variables, the instantaneous temperature tendencies  $\dot{T}$  and momentum tendencies  $\mathbf{F} = (\dot{u}, \dot{v}, 0)$  of the parametrised processes in the IFS (ECMWF, 2021) are additionally archived hourly. From them, the instantaneous PV tendency can be derived according to:

$$\frac{DQ}{Dt} = -\frac{1}{\rho} \nabla \cdot \left( -\zeta_a \dot{\theta} + \nabla \theta \times \mathbf{F} \right), \quad (2)$$

where  $\dot{\theta}$  is the diabatic heating rate (or potential temperature tendency) converted from  $\dot{T}$ , and  $\mathbf{F}$  is the non-conservative force (or momentum tendency). Equation (2) is arranged such that the material change of PV depends on the divergence of the vector field  $-\zeta_a \dot{\theta} + \nabla \theta \times \mathbf{F}$ , which we collectively refer to as the non-advective PV flux. A convergent non-advective PV flux leads to an increase of PV with time, and a divergent flux to a decrease.

The tendencies output of the IFS is further subdivided into five different groups of processes, including shortwave radiation, longwave radiation, convection, cloud microphysics, and turbulence, with the turbulence group containing vertical diffusion and gravity wave drag from both orographic and non-orographic sources (see Part 1 for details). As Eq. (2) is linear, the PV tendency due to an individual process group  $i$  can be derived. Similar partitioning was also employed in previous studies that investigated PV modification by non-conservative processes using the IFS (e.g., Spreitzer et al., 2019; Attinger et al., 2019, 2021; Volonté et al., 2026).

Figures 1d-f show the PV tendency due to turbulence at 200, 225, and 250 hPa, respectively, at 17 UTC on 25 December 2019. At 200 and 225 hPa, regions with significant PV tendencies due to turbulence are found in the form of elongated bands in the narrow ridge region (Fig. 1b), resembling a series of circular arcs. The PV tendency bands appear to match the cloud edges as well as the WCB ascent and outflow masks to a large extent (Fig. 1a), hinting at an important role of the WCB in generating these banded structures. Similar banded structures are also present at 250 hPa (Fig. 1f), but the coherent signals are limited to the region south of Greenland, with many small-scale features dominating the area near the PV trough. In the following, we focus on the 200 and 225 hPa surfaces, with the signal on 250 hPa supplementing the discussion. The wind fields on the three isobaric surfaces are also overlaid, which shows that the local flow is generally at a large angle, or even perpendicular to the elongated PV tendency bands induced by turbulence. This observation has important implications, as will be discussed subsequently.

## 2.3 Lagrangian analysis

Similar to Part 1, we further assess the accumulated effect of turbulence on PV modification in the UTLS by analysing the Lagrangian history of individual air parcels. Based on reverse domain filling (e.g., Sutton et al., 1994; Schoeberl and Newman, 1995; Liniger and Davies, 2003), we compute backward trajectories with LAGRANTO (Sprenger and Wernli, 2015) and integrate the PV tendencies along each trajectory to obtain the accumulated PV change (APV). Similar to the PV tendencies, APV can also be partitioned into individual processes  $i$ , allowing the comparison of the contribution of different processes to the material PV change. Simultaneously, we may follow the backward trajectory and examine the material PV change ( $\Delta Q$ )



155 during the same period directly. Given a fixed accumulation time, the two quantities are related by:

$$\Delta Q = \sum_i \text{APV}_i + \text{residue.} \quad (3)$$

A residue is present in practice owing to the errors arising from interpolation (trajectory calculation), time discretisation (integration using hourly output), and non-conservation of PV by the dynamical core.

160 In this study,  $\Delta Q$  and APV are computed for the UTLS region at every grid point ( $0.1^\circ$  regular grid) on isobaric surfaces with a 25 hPa interval using 18 h backward trajectories initialised at 17 UTC on 25 December 2019. Since the qualitative behaviour of coherent features in the APV field does not vary significantly with accumulation time (Chapter 6.3 in Lee, 2025), only the results with a 12 h accumulation time window are shown for simplicity.

By combining both  $\Delta Q$  and APV for individual processes, we may assess the relative importance of a process in causing the material PV change of an air parcel, which is especially interesting in the current case with expected contributions from  
165 diabatic processes other than turbulence. In the case of positive  $\Delta Q$ , the dominant cause of  $\Delta Q$  is attributed to the term which has the largest positive values on the right-hand side of Eq. (3), including residue (and analogously the term with the largest negative values for negative  $\Delta Q$ ). If the residue is the dominant term,  $\Delta Q$  is interpreted as having an uncertain cause since a majority portion of the PV change is not captured by the method. Otherwise, the process which has the largest  $\text{APV}_i$  with the same sign as  $\Delta Q$  is named the dominant cause of the PV change. This attribution method has already been used in the first  
170 part of this study.

### 3 Arc-shaped PV tendency bands in the WCB outflow

As shown in Fig. 1d-f, elongated PV tendency bands arise in the UTLS region due to turbulence, displaying an arc-like shape. Although the boundaries of these arc-shaped bands are less sharp when compared to the bands in the upper-level jet-front system in Part 1, coherent bands with alternating signs remain discernible. For instance, there is a clear pair of positive and  
175 negative PV tendency bands on 200 hPa at around  $30^\circ\text{W}$  from  $40^\circ\text{N}$  to  $50^\circ\text{N}$  (Fig. 1d), situated at the southeastern quadrant of the extratropical cyclone. A fainter positive band is also visible east of this pair, forming the tripolar pattern. This banding structure extends further outward from the cyclone on 225 hPa (Fig. 1e), with more prominent bands on the northwestern side, which are also present on 250 hPa (Fig. 1f).

These tripolar patterns show some similarity to those observed in Part 1 along the jet axis, but also display significant  
180 differences. A major difference is the orientation of the bands relative to the local flow. While the bands in Part 1 stretch along the jet axis and are parallel to the wind direction, those formed here are almost perpendicular to the flow direction (Fig. 1d-f). This is most prominent in the southeastern quadrant of the cyclone, with southwesterlies impinging on the PV tendency bands, which align along the northwest-southeast direction. At the northwestern parts of the arc, the southerlies are also roughly perpendicular to the bands oriented mostly in a west-east direction.

185 The similarities and contrasts between the PV tendency bands found in this simulation and those examined in Part 1 lead to several questions, which we explore one by one in this section:



- Are the elongated bands formed here also the result of the divergent non-advective PV flux from the turbulent layer, as discussed in Part 1?
- If the former is true, how similar or different is the current flow situation compared to that analysed in Part 1?
- 190 – What is the role of the large-scale flow pattern in the formation of these coherent bands?

First, we recall the idealised framework developed in Part 1 (Sect. 3.1) and examine whether the formation of the PV tendency bands can be explained by this framework by considering selected vertical cross sections (Sect. 3.2). Then, we continue with the analysis of the vertical sections to reveal the origin of the turbulence-induced structures and compare with that identified for the upper-level jet-front system in Part 1 (Sect. 3.3). Lastly, we connect the results obtained from the selected vertical sections to the large-scale flow and elucidate the role of the WCB outflow in generating these coherent PV tendency bands due to turbulence (Sect. 3.4).

### 3.1 Summary of the idealised two-dimensional framework

Before examining the formation of the observed PV tendency bands, it is essential to first briefly restate the relevant equations and the idealised framework developed in Part 1 (Lee et al., 2026). A major simplification of the idealised framework is the quasi-two-dimensional approximation, which assumes the existence of a coherent horizontal direction along which variations are negligible. We align the x-direction of the local Cartesian coordinates with this coherent direction, such that  $\frac{\partial}{\partial x}(\dots) \ll \frac{\partial}{\partial y}(\dots)$ , and restrict the discussion to the two-dimensional  $yz$  plane. In this vertical plane, if we assume  $\mathbf{F} = (\dot{u}, \dot{v}, 0)$  (with no vertical momentum tendency, same as that implemented in the IFS), Eq. (1) and (2) can be simplified as:

$$Q = \frac{1}{\rho} \left( \frac{\partial \theta}{\partial y} \frac{\partial m}{\partial z} - \frac{\partial \theta}{\partial z} \frac{\partial m}{\partial y} \right) \quad (4)$$

$$205 \quad \frac{DQ}{Dt} = -\frac{1}{\rho} \nabla \cdot (\mathbf{H} + \mathbf{M}), \quad (5)$$

with

$$\mathbf{H} = -\dot{\theta} \left( \frac{\partial m}{\partial z} \right) \hat{\mathbf{j}} + \dot{\theta} \left( \frac{\partial m}{\partial y} \right) \hat{\mathbf{k}} \quad (6)$$

$$\mathbf{M} = \dot{u} \left( \frac{\partial \theta}{\partial z} \right) \hat{\mathbf{j}} - \dot{u} \left( \frac{\partial \theta}{\partial y} \right) \hat{\mathbf{k}}, \quad (7)$$

where  $m = u - fy$  is the absolute momentum in this cross section (with  $f$  the Coriolis parameter). As Eq. (5) retains the form of Eq. (2), the vectors  $\mathbf{H}$  and  $\mathbf{M}$  can be interpreted as the two-dimensional equivalent of the heating term  $-\zeta_a \dot{\theta}$  and the momentum term  $\nabla \theta \times \mathbf{F}$  of the non-advective PV flux.

In Part 1, after adopting the flux-gradient theory description of turbulent fluxes, the non-advective PV flux due to turbulence was found to be divergent from the turbulent layer in most situations if the environment is statically ( $\frac{\partial \theta}{\partial z} > 0$ ) and symmetrically stable ( $Q > 0$ ) (Lee et al., 2026). As a result, PV in the turbulent layer is expected to decrease (Eq. 5), while PV above and below the turbulent layer is likely to increase owing to the associated convergence of the non-advective PV flux. They together



compose the vertical PV tendency tripoles that are observed above and below the jet core in the upper-level jet-front system analysed in Part 1. As the variations are small along the coherent direction, these vertical PV tendency tripoles form elongated bands in this horizontal direction. Since similar tripolar signals are again identified in the UTLS in the current simulation, we wonder if the idealised framework can also explain these signals.

220 In the following sections, we trace backwards along the causal chain from the observed tripolar bands and first examine if they are caused by the divergent non-advective PV fluxes in the two-dimensional plane. Then we search for the origin of the coherent direction, along which the shear required to generate turbulence is also found. Therefore, we select vertical sections across these arc-shaped tripolar bands and compute the non-advective PV fluxes to check the validity of the framework. The positions of the cross sections are indicated in Fig. 1d-f, with the one on the southeastern quadrant of the cyclone (solid line)  
225 referred to as the ‘SE’ cross section, and the one in the northwestern part of the arc (dashed line) referred to as the ‘NW’ cross section.

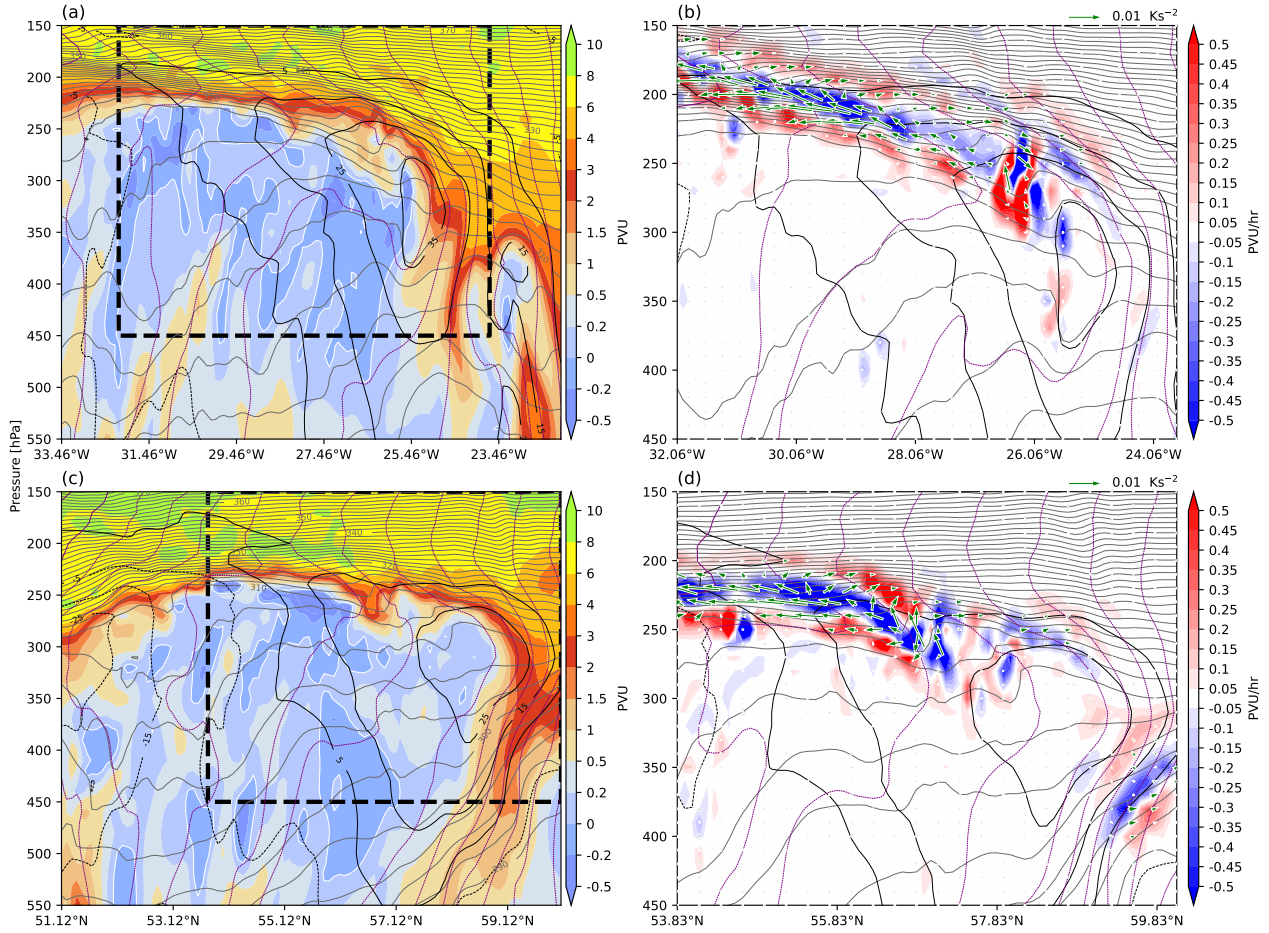
### 3.2 Tripolar signals and divergent non-advective PV fluxes

Figures 2a and b display the PV and PV tendency due to turbulence in the vertical section ‘SE’ (marked in Fig. 1), respectively. The cross section has an elevated dynamical tropopause on the western side, which corresponds to the narrow ridge region in  
230 Fig. 1a, and reaches the PV trough to the east, indicated by the lowered tropopause. Patches of negative PV are found in the troposphere in the ridge region ( $32^{\circ}\text{W}$ - $25.5^{\circ}\text{W}$ ), possibly related to the moist processes associated with the WCB ascent.

The black contours overlaid are the isotachs of the wind normal to the cross section, i.e.,  $u$  in the idealised framework. A localised maximum of  $u$  can be seen at around  $25.4^{\circ}\text{W}$  on 300 hPa, which is in proximity to the sharp change in the height of the dynamical tropopause (Fig. 2a). The setting appears to be the same as that for an upper-level jet (examined in Part 1)  
235 despite lower values of  $u$ , and one may expect the tripole of PV tendency due to turbulence to arise in the shear zone above the “jet core”. However, the signal directly above the maximum of  $u$  is noisy, with only an incomplete tripolar pattern (Fig. 2b). Instead, the prominent tripole is located further west, extends to higher altitudes in the stratosphere, and is seemingly not correlated with the vertical shear of  $u$ . This tilted tripolar pattern of PV tendency due to turbulence is the one that intersects the elongated bands identified on isobaric surfaces in Fig. 1d-f. This implies that the flow situation is different from the upper-level  
240 jet-front system previously analysed in Part 1.

Despite the unexpected location of occurrence, this tilted PV tendency tripole shows a good agreement with the non-advective PV fluxes projected onto the cross section (Fig. 2b). For instance, the green arrows, which are the projections of  $-\zeta_a \dot{\theta} + \nabla \theta \times \mathbf{F}$  (reducing to  $\mathbf{H} + \mathbf{M}$  with the quasi-two-dimensional approximation), show a divergent pattern from the region where negative PV tendency is found and converge towards the neighbouring area with positive PV tendency. We further  
245 compute the PV tendency only due to the divergence of the non-advective PV fluxes in this cross section (not shown) and the tilted tripole remains, verifying that the signal is not a coincidence due to variations normal to the cross section.

Similar results are also obtained from the vertical cross section ‘NW’, as displayed in Fig. 2c and d. The most prominent tripolar pattern of the turbulence-induced PV tendency (Fig. 2d) is found in the area between  $54^{\circ}\text{N}$  and  $57^{\circ}\text{N}$  near 225 hPa, which also corresponds to the banded structure in Fig. 1e. It is located right at the tropopause, extends downward towards



**Figure 2.** Vertical sections (a) across the southeastern quadrant (‘SE’) and (c) the northwestern quadrant (‘NW’) of the cyclone, with their positions marked in Fig. 1d-f by the solid and dashed green lines, respectively. Panel (b) and (d) are enlarged views of the dashed boxes in (a) and (c), respectively. Colour shading indicates (a,c) PV and (b,d) the instantaneous PV tendency due to turbulence at 17 UTC on 25 December 2019. Isentropes (grey contours, 2 K interval), isotachs of  $u$  (black contours,  $10 \text{ m s}^{-1}$  interval), and isopleths of absolute momentum  $m$  (purple contours,  $10 \text{ m s}^{-1}$  interval) are overlaid. The green arrows in (b,d) indicate the vector field  $-\zeta_a \dot{\theta} + \nabla \theta \times \mathbf{F}$  projected onto the cross section, and they are approximately equal to  $\mathbf{H} + \mathbf{M}$ .

the north, and stops before reaching the region above the maximum of  $u$ . The divergence and convergence of the projected non-advective PV fluxes are consistent with the negative and positive parts of the PV tendency tripole. We also verified that the contributions from the non-advective PV fluxes normal to the ‘NW’ cross section to this tripole are comparatively much smaller (not shown), ruling out variations in the normal direction as the cause of this pattern.

In cross section ‘NW’, however, turbulence also creates a PV tendency tripole below the maximum of  $u$  in the region of a stratospheric intrusion (Fig. 2c,d), with enhanced vertical shear of  $u$ . A less obvious and incomplete tripole in the shear



zone above the maximum of  $u$  can be found as well, which makes this part of the cross section very similar to the one across the upper-level jet discussed in Part 1. This further raises the question of the origin of the more prominent signals discussed previously, as they are further away from the “jet core” and likely possess another cause for the occurrence of turbulence.

From the examination of the two vertical cross sections ‘SE’ and ‘NW’, we may conclude that the vertical tripoles of PV tendency due to turbulence that intersect the arc-shaped bands on isobaric surfaces shown in Fig. 1d-f are the immediate result of divergent non-advective PV fluxes in the  $yz$  planes. Nevertheless, they are displaced from the shear zones associated with the maxima of  $u$ , and located further towards the side of the ridge region. This appears to suggest a different cause of the turbulence and hence the tripole pattern when compared to the jet-front system studied in Part 1.

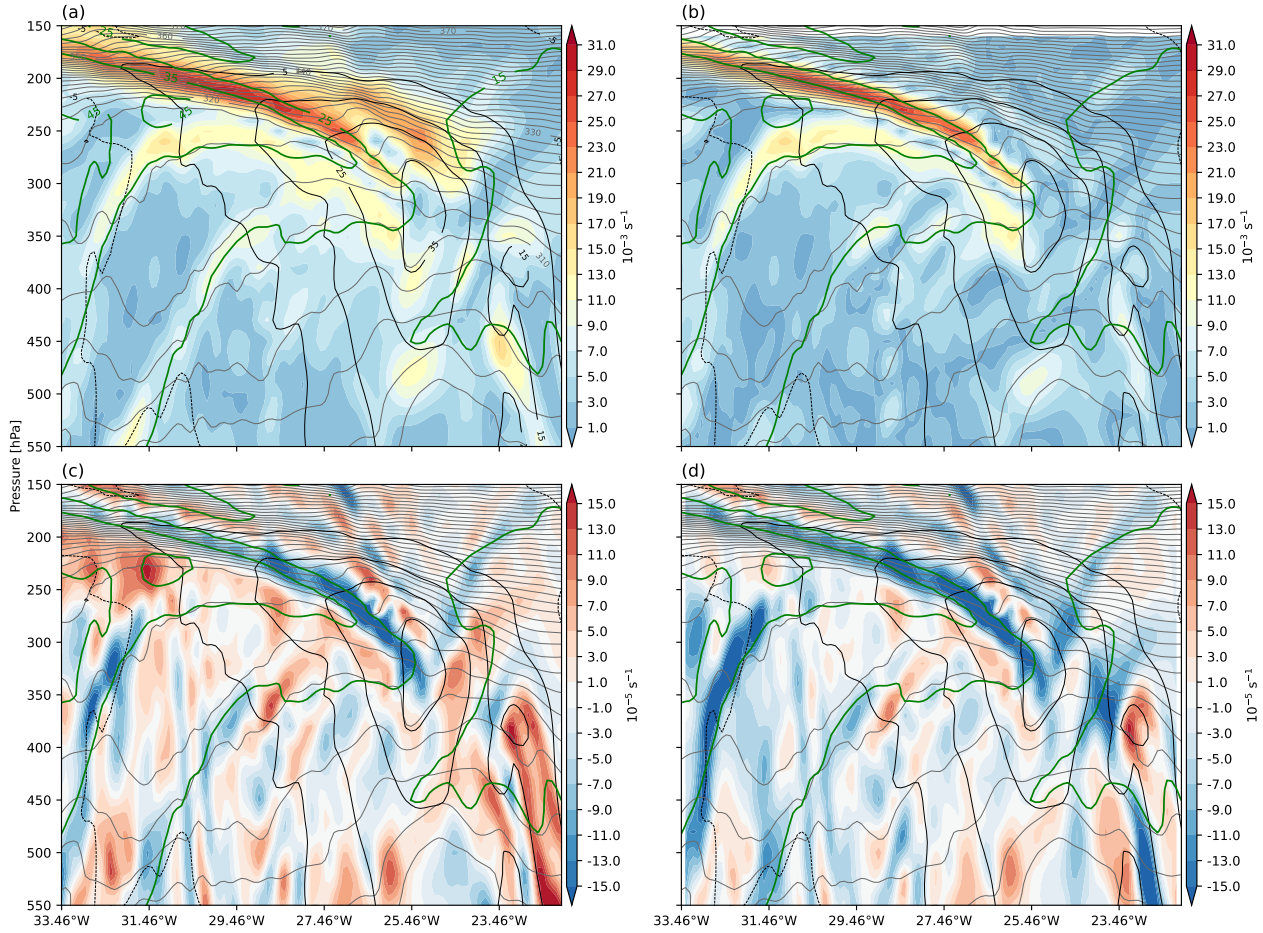
### 3.3 Cause of turbulence and the vertical tripole

To study the cause of turbulence, and thus the induced vertical PV tendency tripole, we focus on the cross section ‘SE’, as the tripolar pattern there is more coherent and has a larger spatial extent. Since the exchange coefficients of the turbulent scheme in the IFS are parametrised as a function of vertical wind shear and static stability, we first check if there is enhanced shear or reduced stability in the region close to the vertical tripole in Fig. 2b. With the static stability being high in the region (indicated by the packed isentropes), the more probable cause is the enhancement of vertical wind shear  $\sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$ , which is shown in Fig. 3a along the section ‘SE’.

In this cross section, there is a clear primary band of enhanced shear that extends from around 175 hPa at the westernmost part of the section to around 250 hPa at around 27°W, with a secondary band located east of this zone and above the maximum of  $u$ . While the secondary band can be understood from the distribution of the isotachs of  $u$ , the primary band can hardly be explained by it. The green contours overlaid are the isotachs of the tangential wind  $v$  along the cross section, and the primary band of enhanced shear aligns well with the more densely spaced isotachs of  $v$ , above a local maximum. The magnitude of the vertical shear of the tangential wind  $\left|\frac{\partial v}{\partial z}\right|$  is explicitly shown in Fig. 3b, which verifies that the primary band of enhanced shear is mostly due to the change in  $v$ . The primary band is also collocated with the vertical tripole of PV tendency due to turbulence in Fig. 2b and may thus explain the generation of the turbulence associated with this tripolar signal.

This illustrates an interesting fact about the flow situation of the current case. In Sect. 3.2, we have shown that the PV tendency tripole due to turbulence is mostly the result of the divergence of the non-advective PV fluxes in the  $yz$  plane. This implies that the variations and tendencies of  $u$  (see  $m$  in Eq. 6 and  $\dot{u}$  in Eq. 7) contribute most to the PV tendencies. However, the triggering of turbulence itself is mostly due to the vertical shear of  $v$ , the wind tangential to the cross section. This is different from the upper-level jet-front system studied in Part 1, where both the vertical wind shear and PV tendencies induced are mostly due to variations in  $u$ . This difference actually adds a small complication to the idealised framework developed in Part 1, mainly concerning the collocation of the dipole of  $\dot{u}$  with the turbulent layer. Since this issue is not critical in the current case, we delay the discussion to Sect. 5.1.

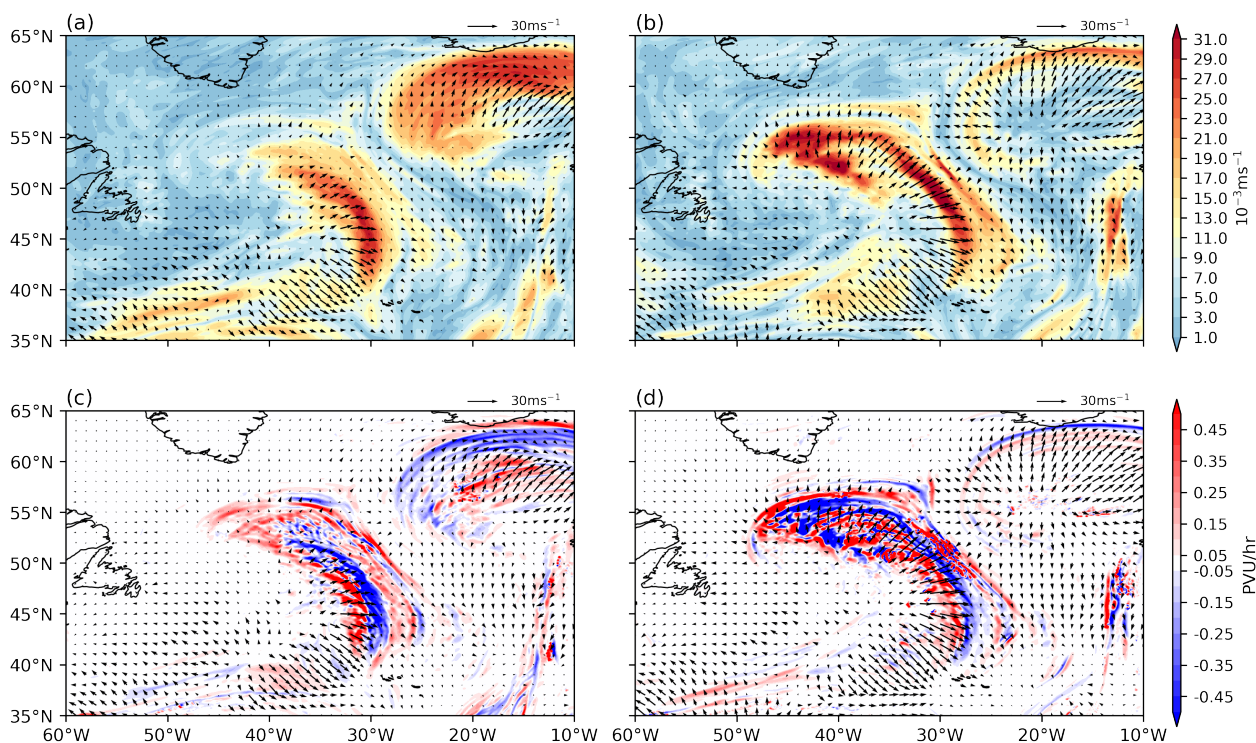
With the cause of turbulence attributed to the enhancement of  $\left|\frac{\partial v}{\partial z}\right|$ , we continue to explore the origin of the large  $\left|\frac{\partial v}{\partial z}\right|$  (Fig. 3a). Figure 3c shows the horizontal wind divergence  $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$  and a band of strong convergence is found collocated with the primary band of enhanced shear. This band is mostly due to  $\frac{\partial v}{\partial y}$ , as displayed in Fig. 3d. With the vertically tilted



**Figure 3.** Vertical section ‘SE’ (as shown in Fig. 2a, b; location indicated by green solid line in Fig. 1d-f) with (a) vertical wind shear  $\sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$  and (b) horizontal wind divergence  $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$  at 17 UTC on 25 December 2019. The vertical wind shear due to the tangential wind only (i.e.,  $\left|\frac{\partial v}{\partial z}\right|$ ) is shown in (c), while horizontal wind divergence caused by the tangential wind (i.e.,  $\frac{\partial v}{\partial y}$ ) is shown in (d). Overlaid are isentropes (grey contours, 2 K interval), isotachs of  $u$  (black contours,  $10 \text{ m s}^{-1}$  interval), and isotachs of  $v$  (green contours,  $10 \text{ m s}^{-1}$  interval).

shape, it appears that the deceleration of  $v$  associated with the convergence in the horizontal direction is projected onto the vertical direction, leading to large vertical shear of  $v$ . The similarity of the overall spatial patterns of Fig. 3c and d additionally demonstrates that the quasi-two-dimensional approximation is likely valid, as the variations in the x-direction ( $\frac{\partial u}{\partial x}$ ) are small compared to those in the y-direction ( $\frac{\partial v}{\partial y}$ ).

The collocation of enhanced vertical shear and horizontal convergence connects to the synoptic situation discussed in Sect. 2.1, where we have identified WCB ascent and outflow in the ridge region (Fig. 1c). As WCB ascent is usually accompanied by an upper-level divergent outflow, it possibly triggers horizontal wind convergence in other regions as compensation.



**Figure 4.** (a,b) Vertical wind shear and (c,d) instantaneous PV tendency due to turbulence on (a,c) 200 and (b,d) 225 hPa at 17 UTC on 25 December 2019. The arrows overlaid indicate the divergent wind at the corresponding isobaric surface.

Moreover, as mentioned, the edges of the ridge region and the cloud bands associated with WCB ascent match very well with the arc-shaped PV tendency bands (Fig. 1a, c-f), further supporting this potential linkage. Since the WCB appears to be the key to connecting all the different findings presented, its influence is investigated in the next section.

### 300 3.4 Role of the WCB outflow

To assess the role of the WCB, we first characterise its outflow using the divergent component of the wind field. The divergent wind on 200 and 225 hPa are shown in Fig. 4a and b, respectively, together with the vertical wind shear. On both isobaric surfaces, the divergent wind is strongest roughly along a circular arc with an imaginary centre roughly at (35°W, 45°N), and abruptly decelerates radially outward. The deceleration implies convergence, which is also perfectly collocated with the regions with enhanced vertical wind shear. This nicely connects to the tilted bands of strong vertical wind shear and horizontal convergence identified in the cross section ‘SE’ (Fig. 3), with the large magnitude of  $v$  possibly attributed to this arc of strong divergent wind.

Figures 4c and d show the PV tendencies due to turbulence on 200 and 225 hPa, with only the divergent wind overlaid, illustrating the good alignment of the strengthened divergent flow with the arc-shaped PV tendency bands. In particular, the



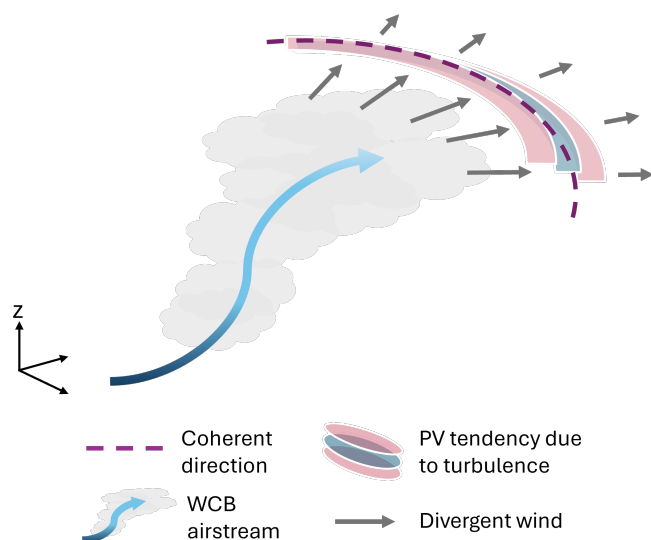
310 arc-shaped features in divergent wind, vertical wind shear, and the PV tendency bands on 225 hPa (Fig. 4b and d) are displaced radially outward compared to those on 200 hPa (Fig. 4a and c), which is also in agreement with the vertical tilt observed for the corresponding features in the cross section ‘SE’ (Fig. 2a, b and Fig. 3).

Summarising the various observations, we may reconstruct a possible pathway by which this WCB contributes to the formation of the identified PV tendency bands, illustrated schematically in Fig. 5. As the WCB transports mass vertically upward in the troposphere, it creates a divergent outflow at upper levels. The divergent outflow pushes its surrounding air radially outward from the region of ascent, possibly in a dome-like shape, as indicated by the expanding circular arcs of increased divergent wind at decreasing altitudes (Fig. 4). The outflow then likely encounters obstruction in the ridge amplification process (Fig. 1a), leading to its deceleration and hence forming an arc of horizontal convergence (Fig. 4). Owing to the dome-like geometry of the flow, the zone with wind convergence is tilted vertically, enhancing vertical wind shear along this arc (Fig. 3). This quasi-radial symmetry along the arc associated with the WCB outflow serves as the coherent direction described in the idealised framework, as the flow variations along the arc are likely smaller than those across the arc. The shear-induced turbulence then generates non-advective PV fluxes, whose divergence on the vertical plane normal to the arc creates the vertical tripole of PV tendency (Fig. 2). The arc-shaped PV tendency bands due to turbulence are then the aggregation of these vertical tripoles along the coherent direction (Fig. 1d-f), which originates from the WCB outflow. This explains the existence of the PV tendency bands in proximity to the cloud edges (Fig. 1c).

These admittedly rather complicated mechanisms involved in the formation of turbulence-induced PV tendency bands in the WCB outflow region distinguish the current case from the upper-level jet-front system analysed in Part 1. The complexity of the generation mechanisms may further explain the numerous substructures embedded in the tripolar PV tendency bands (e.g., Fig. 1d-f, Fig. 2b,d), which may be the result of flow variations at smaller scales along the coherent direction (e.g., the remaining discrepancies between Fig. 3c and d). Nevertheless, as the WCB itself is a coherent airstream on larger scales, its outflow provides the spatial coherence required for the application of the idealised quasi-two-dimensional framework (Part 1), leading to the organisation of these elongated PV tendency bands in the turbulent zones. The current case therefore demonstrates that coherent structures of instantaneous PV tendency due to turbulence may also emerge in the UTLS in flow situations more complicated than those associated with an upper-level jet-front system (Part 1).

#### 335 4 Accumulated PV changes in WCB outflow region

While turbulence was shown to induce spatially coherent instantaneous PV tendency bands in Sect. 3, for the resultant PV modification to have a significant influence on the large-scale flow, air parcels have to accumulate notable material PV changes in time. A major challenge for the flow situation associated with the WCB outflow arises from the fact that the local flow is perpendicular to the arc-shaped PV tendency bands. A simple assumption would be that air parcels that currently experience positive or negative PV tendency would travel to regions with PV tendencies of the opposite sign in a few hours, assuming the PV tendency bands are quasi-stationary. If true, this would result in a significant cancellation of the PV changes, leading to hardly any systematic PV modification. However, we now perform a Lagrangian analysis to show that this simple assumption



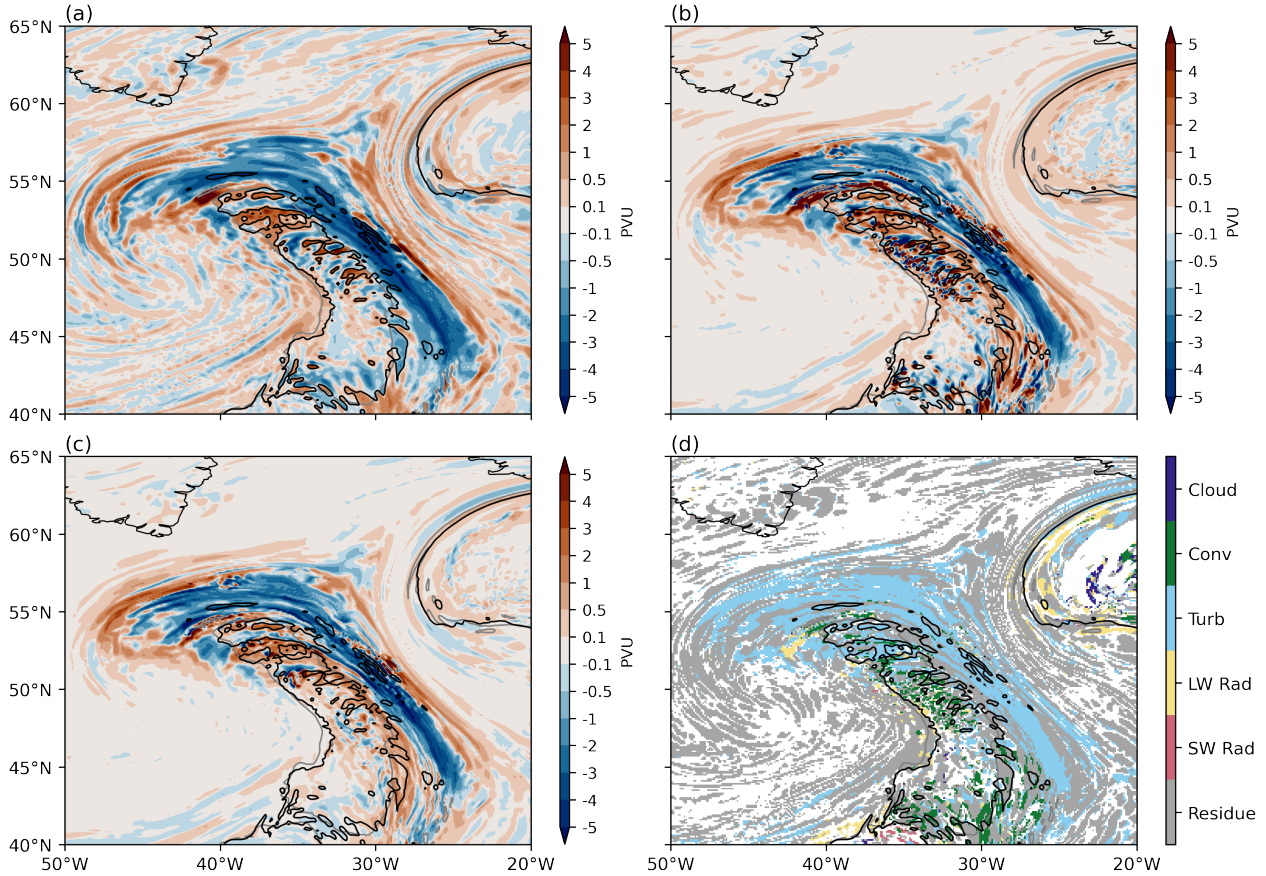
**Figure 5.** Summary schematic showing the formation of the arc-shaped PV tendency bands due to turbulence in the region of a WCB outflow. See text for details.

is inaccurate. First, material changes of PV are explored in Sect. 4.1 to identify coherent features that are generated by turbulence predominantly. The temporal evolution of the environmental conditions experienced by individual air parcels along their trajectories is then studied in Sect. 4.2 to explore the formation of these features. Finally, the role of the WCB outflow in the coherent accumulation of PV changes is examined in Sect. 4.3.

#### 4.1 Relevance of turbulence to accumulated PV changes

Using the reverse domain filling technique, we trace PV values and integrate the instantaneous PV tendencies along backward trajectories to compute the material PV changes ( $\Delta Q$ ) and the accumulated PV changes (APV).  $\Delta Q$  and total APV in the previous 12 h of trajectories initialised on 225 hPa are shown in Fig. 6a and b, respectively. In the  $\Delta Q$  field (Fig. 6a), there are many irregular, small-scale features in the stratosphere as well as in the ridge region. Nevertheless, coherent PV modification can still be identified, for instance, a large area with a decrease in PV of 2 PVU or more in the last 12 h appears near the tropopause along the northeastern side of the ridge. This negative  $\Delta Q$  band again extends in the form of an arc, recalling the shape of the instantaneous PV tendency bands discussed in Sect. 3. The overall pattern continues to show a high resemblance to that of the instantaneous PV tendency due to turbulence (see Fig. 1e), which is notable given the potential cancellation of PV changes in time.

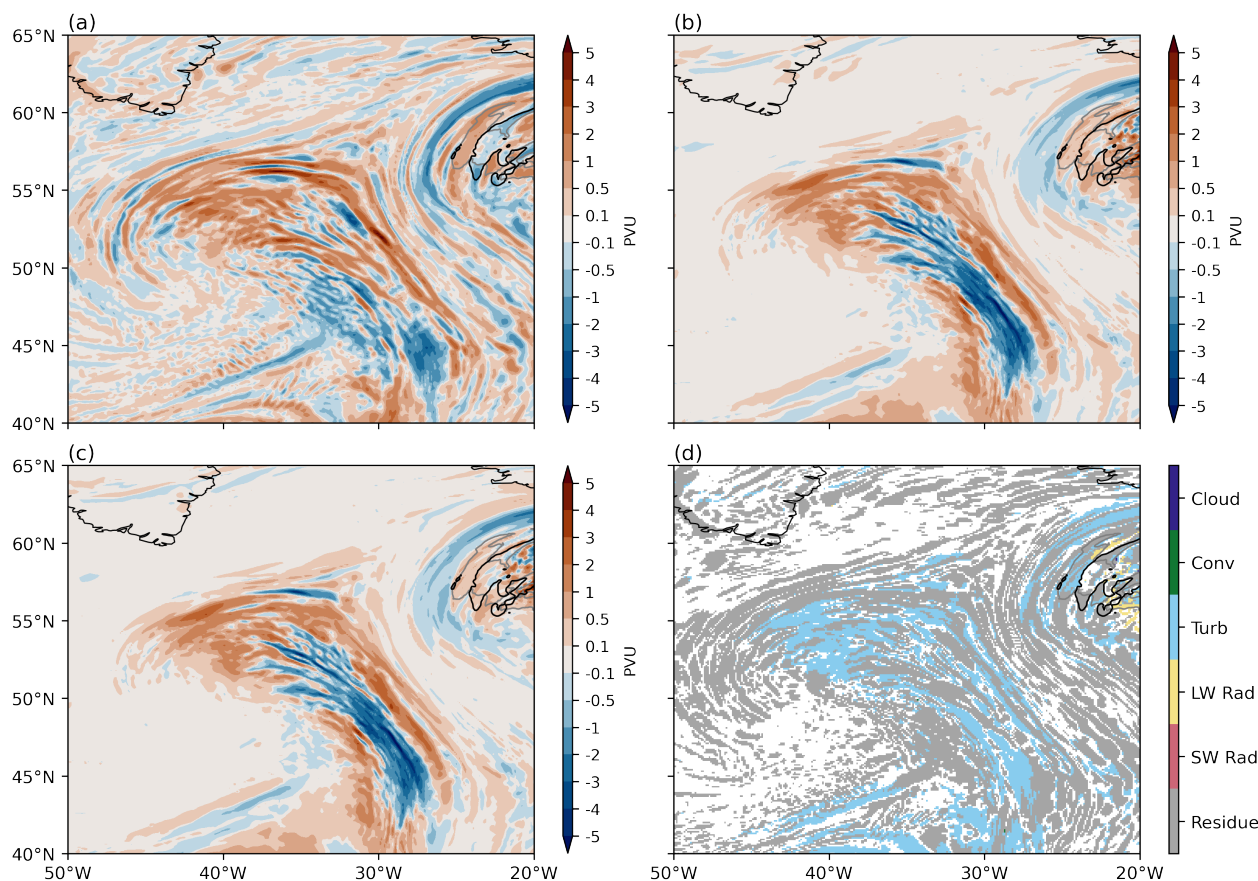
Total APV (Fig. 6b) is qualitatively similar to  $\Delta Q$ , with some erratic patches of high APV found within the ridge, and reveals the same major band of PV decrease discussed for  $\Delta Q$ . However, on the southwestern side of this band closer to the ridge, APV values are positive along the 2-PVU tropopause. This is different from  $\Delta Q$ , where the band is fully negative even in



**Figure 6.** Results from the analysis of Lagrangian PV modification: (a)  $\Delta Q$ , (b) total APV, (c) APV due to turbulence, and (d) dominant processes attributed to  $\Delta Q$  with an accumulation time of 12 h on 225 hPa at 17 UTC on 25 December 2019. The black and grey lines indicate the 2 PVU contours of PV and the advected PV from 12 h ago, respectively. Grid points with  $|\Delta Q| < 0.2$  PVU are masked in (d). Labels for processes: Cloud: Cloud microphysics; Conv: Convection; Turb: Turbulence; LW Rad: Longwave radiation; SW Rad: Shortwave radiation.

360 areas close to the tropopause. This additional positive APV band near the tropopause, together with another positive APV band further east (e.g., the band extending from 27°W, 50°N towards the southeast), flank the major band of negative APV to form a tripolar signal along the northeastern edge of the ridge. Figure 6c displays APV due to turbulence in the past 12 h and it is clear that the large-scale banded structures in total APV can mostly be attributed to turbulence. The differences between Fig. 6b and c are mainly restricted to the ridge region, especially for the patches of spurious APV values, indicating the influence of  
 365 processes other than turbulence in the ridge.

The main responsible process can be identified using the attribution method introduced in Sect. 2.3, and convection appears to be the predominant cause of these localised APV peaks in the ridge (Fig. 6d). This is physically consistent with the synoptic situation that the ridge region is influenced by the WCB ascent and outflow, possibly reflecting the effects of embedded



**Figure 7.** As Fig. 6, but on 200 hPa.

convection (Oertel, 2020). The process attribution also allows us to conclude that the major negative APV band discussed is  
 370 predominantly the result of turbulence (Fig. 6d). However, the residue between  $\Delta Q$  and total APV is non-negligible in many  
 regions, including the narrow positive APV bands flanking the major negative APV band. Hence, this results in an uncertain  
 cause of  $\Delta Q$  and the APV signals in these locations must therefore be interpreted with caution, since the diagnosed evolution  
 of PV ( $\Delta Q$ ) is not fully captured by our Lagrangian PV tendency accumulation (APV).

This is further exemplified by the trajectories that are launched from 200 hPa, as shown in Fig. 7. When the fields of  $\Delta Q$   
 375 (Fig. 7a) and total APV (Fig. 7b) are compared on this level, they show even larger differences than those observed previously  
 on 225 hPa. In particular, the major negative APV band and the associated tripolar pattern in total APV (Fig. 7b), which  
 are dominated by the turbulence parametrisation (Fig. 7c), are smeared out in the  $\Delta Q$  field and replaced by many small-scale  
 filaments (Fig. 7a). Consequently, the cause of  $\Delta Q$  in many regions on 200 hPa cannot be easily determined and is deemed  
 uncertain (Fig. 7d).



380 Despite the lack of direct evidence, the most probable cause of the coherent PV modification on these two isobaric surfaces remains turbulence. First, when ignoring the locations where the cause of  $\Delta Q$  is uncertain, regions with turbulence-dominated PV changes are the largest in both Fig. 6d and 7d. On 200 hPa (Fig. 7d), turbulence is basically the only process attributed as the main cause of  $\Delta Q$  if the residue is not dominant. Moreover, the pronounced tripolar patterns that emerge in both Fig. 6b and 7b are reminiscent of the signature of the instantaneous PV tendency due to turbulence, suggesting a potential role of turbulence.

385 Last and most importantly, the most significant and coherent feature identified in  $\Delta Q$  and total APV, which is the band on 225 hPa near the tropopause with a marked PV decrease (Fig. 6a, b), is attributed to the influence of turbulence (Fig. 6d). Taken together, these findings point towards the high relevance of turbulence to the coherent PV modification in the current case.

## 4.2 Formation of the APV bands

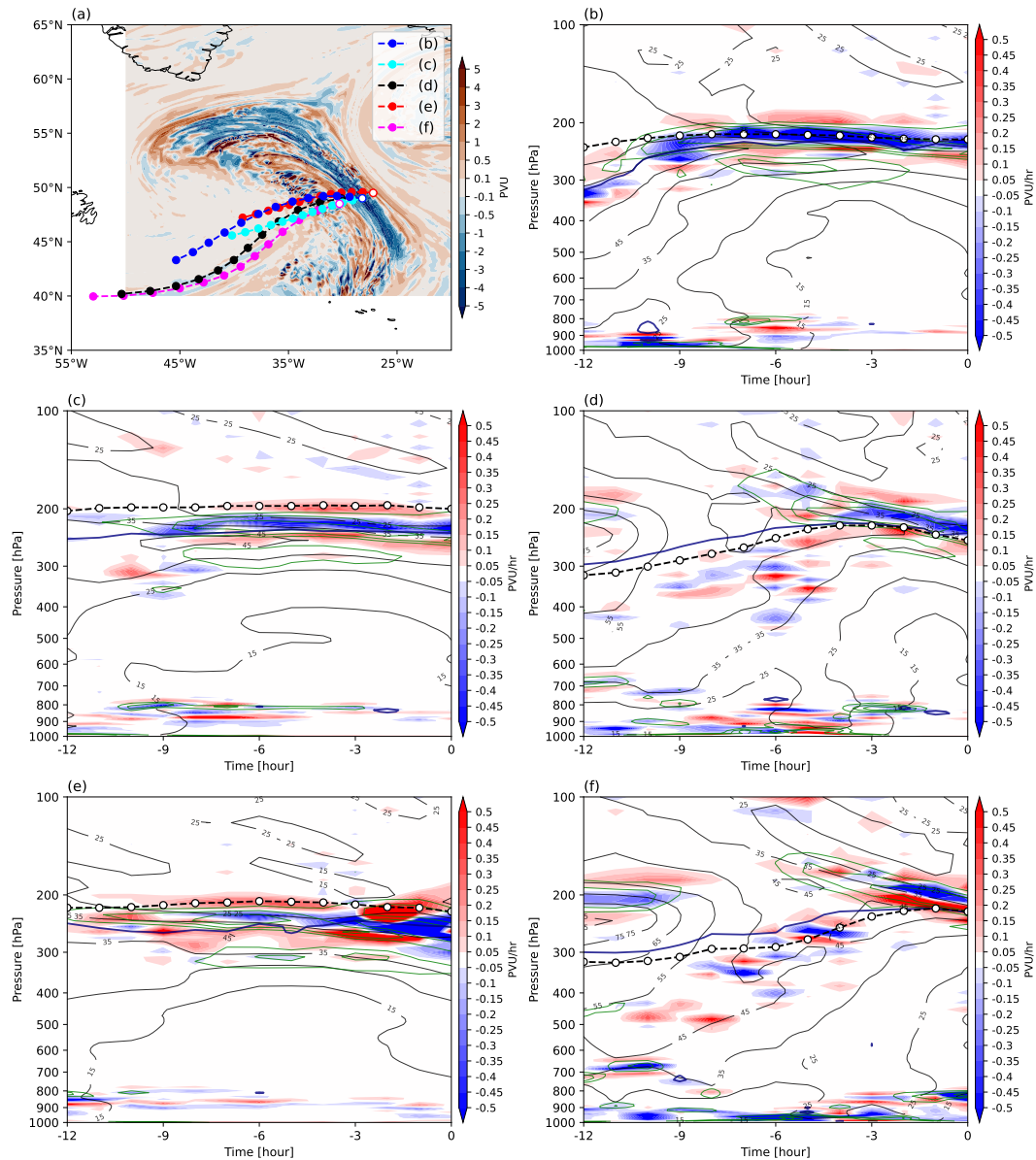
To further clarify the effect of turbulence when accumulated over time, we focus on the major negative APV band on 225 hPa, which is, according to our diagnostic, mainly due to turbulence. The Lagrangian history of selected trajectories in the neighbourhood of this band is examined by extracting the vertical profiles along the trajectories. The analysis of the temporal evolution of the environmental conditions experienced by the trajectories provides useful insight into the formation of these APV signals. This is particularly interesting to investigate as the spatial pattern of the instantaneous PV tendency due to turbulence is seemingly retained (e.g., Fig. 6a and 1e) despite the local flow being perpendicular to the PV tendency bands.

395 Figure 8a displays the APV field on 225 hPa, as in Fig. 6b, but with hourly positions of five selected trajectories overlaid on the map. The backward trajectories are started in the vicinity of the major negative APV band, and all of them have turbulence as their major contributor to  $\Delta Q$ . For simplicity, the trajectories and the corresponding air parcels are referred to by the figure number and the label given in Fig. 8a. For instance, the navy blue trajectory in Fig. 8a will be referenced as trajectory ‘8b’.

Trajectories ‘8b’, ‘8c’, and ‘8d’ are initialised at the same horizontal location (28.2°W, 49°N), but on different vertical levels (225, 200, and 250 hPa, respectively). On 225 hPa, this location is within the negative APV band, but APV of trajectories ‘8c’ (200 hPa) and ‘8d’ (250 hPa) is actually positive (Fig. S1), which suggests the presence of a vertical tripole pattern in APV. The temporal evolution of the vertical profiles of PV tendency due to turbulence along trajectory ‘8b’ is first examined (Fig. 8b). In contrast to the previously postulated cancellation among instantaneous PV tendencies at different time steps, the figure shows a pronounced and uninterrupted vertical tripole spanning the last 8 h along the trajectory. The air parcel ‘8b’

405 does not pass through regions with alternating positive and negative PV tendencies, but – rather surprisingly – experiences negative PV tendencies continuously due to turbulence for more than 9 h, explaining the large negative APV value attained. The temporal evolution of the vertical profiles of turbulence-induced PV tendencies looks very similar to that examined in Part 1 for trajectories initialised near the upper-level jet (e.g., Fig. 8 in Part 1), with both featuring the vertical tripole pattern.

This tripole pattern is also present in the temporal evolution along trajectories ‘8c’ (Fig. 8c) and ‘8d’ (Fig. 8d), with the former experiencing positive PV changes in the upper part of the tripole pattern for more than 6 h and the latter in the lower part of the tripole pattern in the last 3 h. While air parcel ‘8c’ stays roughly at the same pressure level, parcel ‘8d’ first ascends from around 300 hPa, reaches the lower part of the tripole at 225 hPa, later descends with the tripole to 250 hPa and crosses the tropopause. The vertically tilted tripole in Fig. 8d recalls a similar PV tendency pattern shown previously in the vertical



**Figure 8.** (a) Total APV on 225 hPa at 17 UTC on 25 December 2019 with an accumulation time of 12 h (same field as shown in Fig. 6b but in a larger domain) Five backward trajectories are shown, labelled (b) to (f), and their horizontal positions in the last 12 h are shown by filled circles (white filling at  $t = 0$ h). Note that trajectories b-d share the same horizontal position, but are initialised on 225, 200, and 250 hPa, respectively (see text for details). (b-f) Temporal evolution of the vertical profile of the PV tendency due to turbulence (in colours) along the backward trajectories (dashed lines) with the corresponding label defined in (a). Contours show wind speed (grey,  $\text{m s}^{-1}$ ), vertical wind shear (green,  $0.015$  to  $0.03 \text{ s}^{-1}$  at  $0.005 \text{ s}^{-1}$  intervals), and PV (blue for  $2 \text{ PVU}$ ).



section ‘SE’ (Fig. 2b). If one compares the location of the cross section ‘SE’ (Fig. 1d) and that of trajectory ‘8d’ in the last 3 h  
415 (Fig. 8a), they cover a similar area. The tripole in Fig. 8d is hence possibly the trace of the vertically tilted PV tendency bands  
discussed earlier as the parcel travels relative to them.

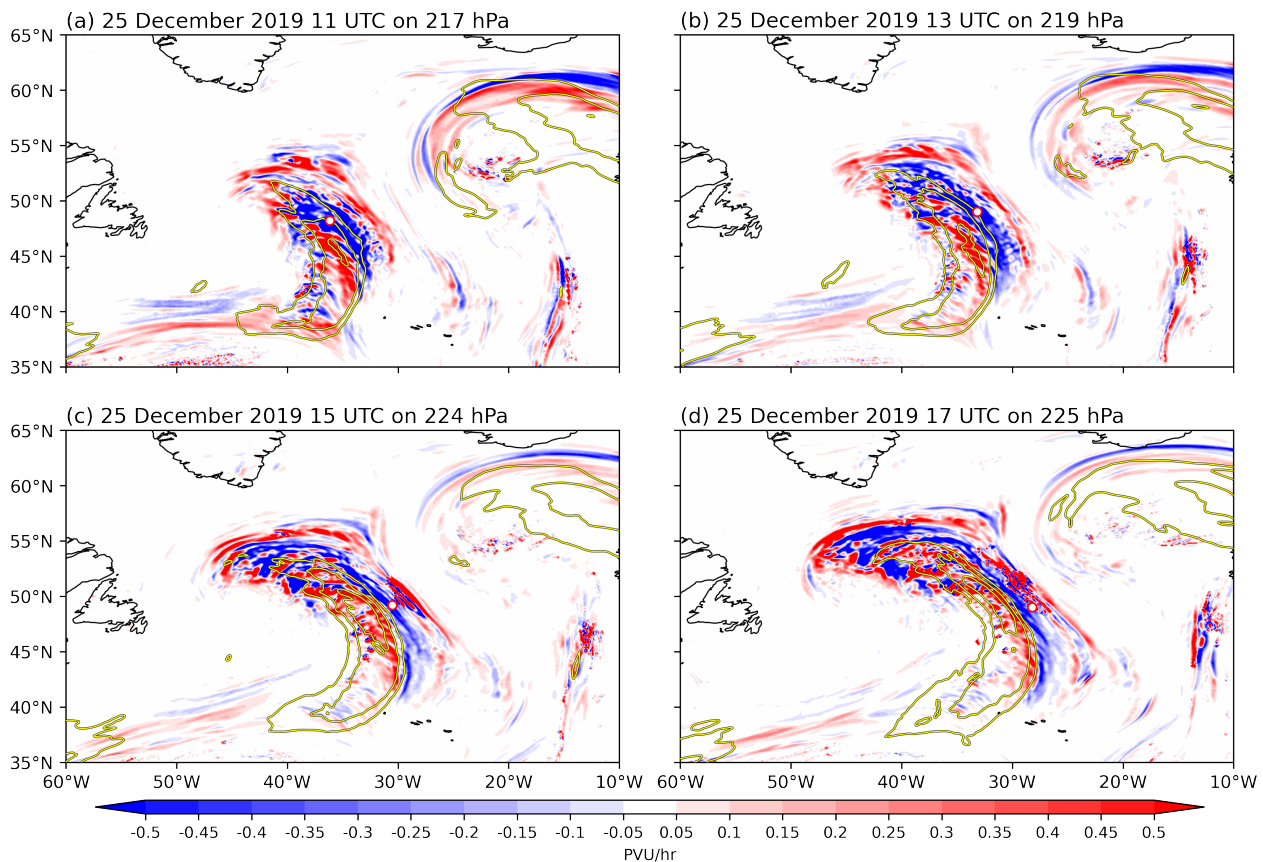
Two additional trajectories, ‘8e’ and ‘8f’, are initialised on 225 hPa in the positive APV bands located east and west of the  
negative APV band, respectively (Fig. 8a), with the vertical profiles of PV tendency due to turbulence along trajectories shown  
in Fig. 8e and 8f. The time evolution plots of trajectories ‘8e’ and ‘8c’ are analogous to each other, and those of trajectories  
420 ‘8f’ and ‘8d’ are also similar. When the horizontal locations of the trajectories are compared (Fig. 8a), the two pairs also have  
great similarities in terms of the distance travelled and the origin of the air parcels. The linkages of trajectories ‘8e’ with ‘8c’  
and trajectories ‘8f’ with ‘8d’ are hence further indications that the APV bands likely originate from the time integration of the  
vertically tilted tripole pattern of the PV tendency field.

Thus far, the temporal evolution plots in Fig. 8 along selected trajectories suggest that air parcels accumulate PV changes  
425 steadily and continuously over time, and the APV signals are related to a vertical PV tendency tripole. While the APV signals  
of parcels that accumulate PV changes in a short time window (e.g., ‘8d’ and ‘8f’ ) can still be connected to the tripolar  
pattern identified in the instantaneous PV tendency due to turbulence in Sect. 3, the APV signals related to parcels consistently  
accumulating PV tendencies over longer times and travelling at a consistent position relative to the tripole pattern (e.g., ‘8b’ and  
‘8c’) remain challenging to understand since at least partial cancellation is expected when the local flow direction is considered  
430 (i.e., the flow being perpendicular to the arc-shaped PV tendency bands in Fig. 1e). To elucidate this counter-intuitive behaviour,  
we examine trajectory ‘8b’ in greater detail.

### 4.3 Organisation over time within a complex flow field

Since the considered trajectories (e.g., Fig. 8b) show a steady accumulation of PV changes instead of the speculated series of  
cancellations, we have to reconsider the assumptions that have led us to such an expectation. At the beginning of Sect. 4, we  
435 extrapolated the location of the air parcels relative to a stationary PV tendency field, which led to the hypothesis that the parcels  
travel across the PV tendency bands with alternating signs. However, if the PV tendency field is also changing in time, there  
may exist a non-trivial but possible coordinated movement between the air parcel and the PV tendency field such that the PV  
tendency experienced by the parcel remains coherent, i.e., of the same sign.

To explore this hypothesis, we investigate the PV tendency due to turbulence at pressure levels where the air parcel ‘8b’  
440 is located at the corresponding time step. The time series of these horizontal fields is shown in Fig. 9 and the PV tendency  
field indeed evolves significantly with time. While the tripolar banded structures (Sect. 3) are discernible during the entire  
6 h period, they move northeastward, extend on both ends, and become more elongated. Most importantly, the cluster of PV  
tendency bands moves such that air parcel ‘8b’ is always located within the negative PV tendency band. This is consistent with  
the continuous negative PV tendency experienced by the air parcel since 6 h ago, as shown in Fig. 8b. Also, the prominent  
445 PV tendency signals in Fig. 8b are located at similar pressure levels even though the instantaneous tripole is vertically tilted  
(Fig. 2b) because there is minimal relative movement between the air parcel and the PV tendency tripole, making the signals



**Figure 9.** PV tendency due to turbulence on 25 December 2019, at (a) 11 UTC on 217 hPa, (b) 13 UTC on 219 hPa, (c) 15 UTC on 224 hPa, and (d) 17 UTC on 225 hPa. Air parcel ‘8b’ (Fig. 8) is on the selected pressure level at the horizontal position indicated by the white circle with red boundary. Contours of the magnitude of the divergent component of the wind on 225 hPa (yellow, starting from  $10 \text{ m s}^{-1}$  at  $5 \text{ m s}^{-1}$  intervals) are overlaid.

stay at similar altitudes. Therefore, it is this synchronised movement of the PV tendency field with the air parcels that permits the steady and consistent accumulation of PV changes.

Furthermore, and very importantly, the coordination required for this synchronised movement and PV tendency accumulation  
 450 originates from the WCB outflow. The isotachs of the divergent component of the wind field on 225 hPa in Fig. 9 indicate areas with enhanced divergent wind. In Sect. 3.4, we already used this field as a proxy for the influence of the WCB outflow in generating the PV tendency bands. Over time, the arc-shaped area of enhanced divergent wind expands outward and migrates northeastward. During this period, it overlaps nicely with the southwestern part of the cluster of PV tendency bands, indicating a convergence zone slightly northeast, close to the bands. This is highly consistent with the findings in Sect. 3.4, which  
 455 demonstrated the connection between the convergence zone and the vertical PV tendency tripole due to turbulence. It is also



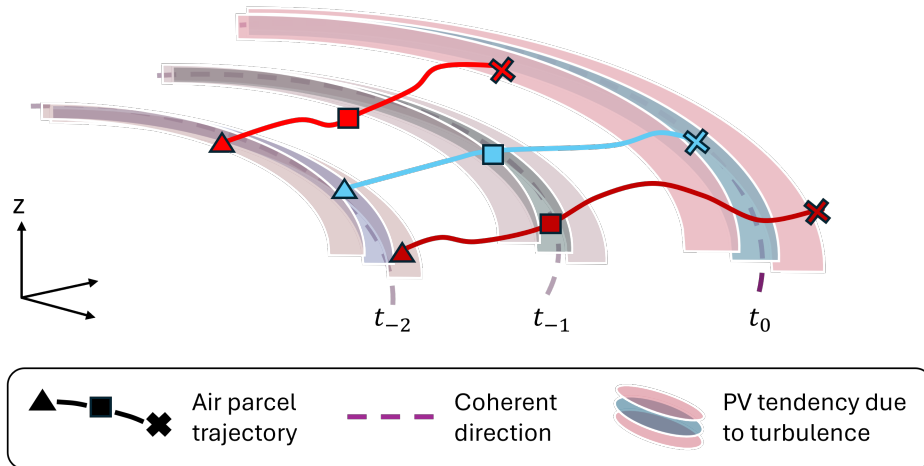
fascinating to see that air parcel ‘8b’ as well as the major negative PV tendency band are usually ahead of the enhanced divergent wind, moving in a synchronised manner.

Consequently, the role of the WCB outflow is twofold. On one hand, the temporal evolution of the outflow determines the position of the convergence zone, triggers turbulence there due to enhanced vertical shear, and eventually generates the arc-shaped PV tendency bands that expand and translate northeastward. On the other hand, the outflow also influences the flow field in the UTLS and guides individual air parcels to move in concert with the PV tendency bands, ultimately allowing coherent PV modification over time.

Nevertheless, such perfect coordination is not always possible, with the complicated spatial pattern of the PV tendency field being the first hurdle. Apart from the major negative PV tendency band that is roughly in the middle of the cluster, most neighbouring bands are less well defined or intertwined with many irregular patches. In particular, the two positive bands flanking the major negative band are not always prominent, with small-scale extreme values showing up sometimes (e.g., immediately northeast of air parcel ‘8b’ in Fig. 9c). This is possibly the reason for the interruptions seen in Fig. 8b for the positive PV tendencies above and below the trajectory. For trajectory ‘8e’, the complicated PV tendency field northeast of the major negative band also likely explains the variations of the PV tendency profile shown in Fig. 8e.

This may also partially explain the discrepancies between  $\Delta Q$  and total APV seen in Fig. 6 and 7. As mentioned before, the main difference between  $\Delta Q$  and total APV on 225 hPa is the missing (or unclear) positive APV bands flanking the major negative APV band (Fig. 6a, b). Since these positive PV tendency bands are more susceptible to the influence of the smaller-scale features, as shown in Fig. 9, some counteracting PV tendencies (i.e., negative) in these regions may be present at model-internal time steps. However, as APV is derived from the hourly output of the simulation only, this effect is not captured, making the positive APV bands more pronounced than their counterpart in the  $\Delta Q$  field. Moreover, as the PV tendency bands are in general narrow, a slight misalignment of the trajectory with the movement of the PV tendency bands may cause partial cancellation in PV changes. These small variations in PV may again not be captured by the hourly output, leaving a more prominent tripolar pattern in total APV on 200 hPa compared to the  $\Delta Q$  field (Fig. 7a, b).

To synthesise all the findings regarding both the consistency and the heterogeneity of PV modification associated with the WCB outflow, we may conclude by drawing an analogy to a surfer navigating a wave (Fig. 10). As the WCB outflow reaches the upper troposphere, it induces an area of enhanced divergent wind that propagates outward from the ascent region. Instantaneous PV tendency bands are hence formed according to the mechanism detailed in Sect. 3, with each arc-shaped band acting as a “wave crest”. Air parcels then “surf” on the PV tendency bands and move with them in time. The PV changes accumulated by the air parcels then depend on the coordinated movement of the “surfer” and the “wave”. If the air parcels are travelling in a region with PV tendency bands interlacing with each other or the movements are not nicely coordinated due to fluctuations in the flow field, the air parcels may likely “topple” and create irregular substructures in the APV field. In contrast, if there is a nice synchronisation between the movement of the parcels and that of the PV tendency bands, a consistent and steady build-up of PV changes can be observed. The coupling between the major negative PV tendency band and air parcel ‘8b’ in time serves as an example of such synchronised movement, resulting in a prominent band of PV decrease due to turbulence on 225 hPa



**Figure 10.** Schematic illustration of the temporally evolving PV modification by turbulence in the region of a WCB outflow. The locations of the air parcels at  $t_{-2} < t_{-1} < t_0$  are indicated by triangles, squares, and crosses, respectively. The light blue trajectory represents an air parcel that moves synchronously with the PV tendency bands and thus experiences consistent PV changes over time. The red and dark red trajectories represent air parcels that move less coordinated with the PV tendency bands and therefore have larger fluctuations in PV changes over time, forming the irregular substructures in the APV field.

490 (Fig. 6). It also demonstrates that coherent PV modification by turbulence in a complex flow situation is possible, given the organisation provided by the WCB outflow.

## 5 Discussion

### 5.1 Complementarity to Part 1

As mentioned in Sect. 1, this study is an extension of the analysis performed in Part 1 of this study, which focused on the PV  
495 modification by turbulence in the UTLS associated with an upper-level jet-front system (Lee et al., 2026). A major objective of this paper is to assess whether the results obtained in Part 1 can be applied more generally, especially to more complex flows associated with other weather systems. In Sect. 3 and 4, we examined both the instantaneous and accumulated effects of turbulence on PV modification in a flow situation featuring a WCB outflow. The analyses not only demonstrate that many of the characteristics of turbulence-induced PV modification discussed in Part 1 are transferable to the current WCB case but also  
500 deepen our understanding of the idealised framework.

The major difference between the flow situation explored here and in Part 1, which makes the two cases complementary to each other, is the coherent direction (direction along which variations are small) relative to the large-scale flow. Here the coherent direction is perpendicular to the local flow, whereas it was parallel in Part 1. The current case with a WCB outflow shows that the two directions are disentangled, with the coherent direction spanning the arc perpendicular to the wind vectors.



505 However, the results in Sect. 3 illustrate that once a weather system is capable of (i) creating a coherent direction with small variations along this direction, and (ii) also triggering turbulence, then a vertical PV tendency tripole generated by the divergent non-advective PV fluxes from the turbulent layer emerges and forms the elongated PV tendency bands observed in Fig. 1d-f. This WCB outflow case nicely demonstrates the difference between the coherent and flow directions and that the idealised quasi-two-dimensional framework is still applicable, independent of their relative alignment.

510 Moreover, the WCB outflow case also unveils the role of the tangential component of horizontal wind  $v$  in PV modification by turbulence, which is hidden in the simpler flow situation analysed in Part 1. Since the local flow is almost perpendicular to the coherent direction, the wind projects more onto the tangential component  $v$  than the normal component  $u$  with respect to the  $yz$  plane introduced in the idealised framework. Despite its larger magnitude, the influence of  $v$  on PV modification is eliminated from the relevant equations, i.e., Eq. (5)-(7), after taking the quasi-two-dimensional approximation. However, 515 as discussed in Sect. 3.3, the triggering of turbulence itself relies heavily on the vertical shear of  $v$ . To be precise, the effect of  $v$  is hidden in the eddy diffusivity of heat  $K_h$  and eddy viscosity coefficient  $K_m$ , which are functions of vertical wind shear. Turbulent mixing, i.e.,  $\hat{\theta}$  and  $\hat{u}$ , on the  $yz$  plane is hence indirectly affected by  $v$ , and leads to PV modification in the quasi-two-dimensional framework according to Eq. (5).

The involvement of  $v$  in the WCB outflow case actually slightly invalidates the collocation of the  $\hat{u}$  dipole and turbulent 520 layer (Sect. 3.3), which is an implicit assumption in the idealised framework. The turbulent fluxes in the idealised framework are based on the flux-gradient theory, where the magnitude of the fluxes depends on both the exchange coefficient ( $K_m$ ) and the background gradient ( $\frac{\partial u}{\partial z}$ ). For the turbulent momentum flux associated with the upper-level jet-front system discussed in Part 1, where the vertical shear is primarily contributed by  $u$ , both the exchange coefficient and the background gradient are mostly dependent on  $|\frac{\partial u}{\partial z}|$ . As such, the strongest turbulent flux will be found at the layer with the highest  $|\frac{\partial u}{\partial z}|$ , which 525 typically collocates with the turbulent layer. In contrast, as  $v$  is the major driver of vertical wind shear in the WCB outflow case, the turbulent layer is tied to the maximum of  $|\frac{\partial v}{\partial z}|$ , which is independent of the maximum of  $|\frac{\partial u}{\partial z}|$ . This additional degree of freedom allows a slight shift of the vertical location of the  $\hat{u}$  dipole relative to the turbulent layer. Although this deviates from the assumption of the idealised framework, the consistency of the results in Sect. 3 with the framework suggests that this collocation assumption is not a very restrictive assumption. The idealised framework can still explain and capture most of the 530 characteristics of the PV modification by turbulence, though the flow situation does not strictly satisfy all the assumptions.

Most importantly, the WCB outflow case illustrates that turbulence may systematically modify PV in the UTLS over time, even with the perpendicular alignment of the coherent direction to the flow. For the upper-level jet-front system in Part 1, the steady accumulation of PV changes over time is straightforward to understand as the air parcels travel along the coherent direction in which also the PV tendency bands are oriented. The formation of the extensive band of PV decreases on 225 hPa 535 (Fig. 6) in the WCB outflow case is, in contrast, much more complex. Detailed analysis in Sect. 4 reveals that the systematic PV modification originates from the synchronised movement of the air parcels and the PV tendency bands, which in turn are coordinated by the WCB outflow. This special arrangement in the flow field permits the steady and consistent accumulation of PV changes by air parcels, leading to pronounced and coherent PV modification. Together with the case in Part 1, the two



simulations thus demonstrate the possibility of turbulence in modifying PV systematically in the UTLS region under various  
540 flow situations.

## 5.2 The significance of turbulence in PV modification associated with the WCB outflow

While it is exciting to observe the existence of coherent PV modification by turbulence in the WCB outflow case (i.e., the major band with PV decreases), one should also admit that the Lagrangian analysis method has limitations in explaining the PV changes in many regions of this simulation. As already pointed out in Sect. 4.1, the residue between  $\Delta Q$  and total APV is  
545 non-negligible in a large area, making the cause of  $\Delta Q$  uncertain at those locations. Nonetheless, turbulence is still considered to be a highly relevant, if not the predominant, process that influences the PV modification at the two isobaric levels examined (200 and 225 hPa). The supporting argument stems from the spatial distributions of grid points with turbulence-dominated  $\Delta Q$  in Fig. 6d and 7d, which give a first indication that their neighbouring regions are likely also affected by turbulence.

Now, with the trajectory analysis of selected air parcels presented in Sect. 4.2 and 4.3, the complex formation process of  
550 the APV signals helps explain the large residues in  $\Delta Q$  found in Fig. 6d and 7d, further suggesting that the grid points with substantial residues are probably influenced significantly by turbulence. As pointed out in Sect. 4.3, consistent accumulation of PV changes can only be achieved by the co-movement of the PV tendency bands and the air parcels. However, this delicate coordination is susceptible to variations in both space and time, possibly leading to the fine-scale features seen in the  $\Delta Q$  field (Fig. 6a and 7a). The integration of hourly PV tendencies is effectively a “low-pass” filter, capturing only the PV changes over  
555 a lower frequency or larger spatial scales. This is reflected in the accumulated PV tendencies of, for instance, air parcels ‘8c’ and ‘8e’ (Fig. S1c,e), which show a notable discrepancy from the evolution of  $\Delta Q$  over time. Nevertheless, only turbulence is active in causing PV changes for the two air parcels during the accumulation period.

This behaviour of having notable residues is also observed in other studies that employed the same method to examine PV modifications in flow situations that are highly heterogeneous in space and time (e.g., Volonté et al., 2026; Oertel et al., 2023),  
560 which is an inherent limitation of the method. It should be noted that PV non-conservation by the dynamical core and numerical diffusion can also contribute to the residue, as illustrated in Saffin et al. (2016). Therefore, the relatively large residue of  $\Delta Q$  should not diminish the conclusion that turbulence is a highly relevant physical process in modifying PV coherently in the UTLS with flow situations associated with WCB outflows.

## 6 Conclusions

565 As an extension of Part 1 (Lee et al., 2026) of this study, here we explored PV modification by turbulence in the UTLS in the region of a WCB outflow. A dedicated IFS simulation is utilised to investigate both the instantaneous and accumulated effects of turbulence in this synoptic condition, which is significantly different from the upper-level jet-front system examined in Part 1. Turbulence is shown to be capable of modifying PV systematically and coherently in the WCB outflow region, with the underlying formation process explainable by the analytical framework developed in Part 1. This two-part study thus



collectively provides a thorough understanding of turbulence-induced PV modification in the UTLS and offers insights into the upscale influence of turbulence on the large-scale flow.

In the WCB outflow region, elongated PV tendency bands are generated by turbulence and are organised into the shapes of circular arcs. The arc shape is the consequence of the divergent WCB outflow, which is forced to converge at the ridge-trough interface, leading to enhanced shear and hence turbulence. The WCB outflow thus establishes a coherent direction along the arc-shaped interface, permitting the application of the quasi-two-dimensional framework derived in Part 1. The resultant divergent non-advective PV fluxes from the turbulent layer lead to the formation of a vertically tilted PV tendency tripole, as illustrated in cross sections, explaining the tripolar banded structures identified on isobaric surfaces.

The coherence of PV modification by turbulence is surprisingly preserved when accumulated over time, as unveiled by the Lagrangian analysis. The material PV change reveals an extensive band of PV decrease in the WCB outflow region. The cause of this PV change can be predominantly attributed to turbulence, indicating its relevance in PV modification in the UTLS amid the presence of other diabatic processes associated with WCBs. While the air parcels are travelling perpendicular to the instantaneous PV tendency bands due to turbulence, the flow evolves such that the bands move synchronously with the air parcels. The co-movement (of “surfers” on a “wave crest”) is steered by the expansion of the divergent WCB outflow, demonstrating its pivotal role in allowing air parcels to accumulate PV changes steadily. Therefore, the WCB outflow not only favours the formation of coherent PV tendency bands by turbulence instantaneously but also supports the accumulation of PV changes and thus a systematic PV modification over time.

Synthesising the straightforward upper-level jet-front system example in Part 1 and the complex WCB outflow condition here, the role of weather systems in facilitating turbulence-induced PV modification in the UTLS is more clearly depicted. First, for a weather system that possesses a coherent direction and can generate turbulence along this direction, the vertical PV tendency tripole would likely emerge due to divergent non-advective PV fluxes. Second, the flow field associated with the weather system may provide the organisation required for individual air parcels to experience consistent PV changes over time. A systematic PV modification by turbulence hence substantially relies on the spatial and temporal coherence imparted by weather systems. Despite the examples of the upper-level jet-front system and the WCB outflow being vastly different, the importance of weather systems in allowing coherent turbulence-induced PV modification is manifested clearly in both cases, making them complementary to one another.

This paper also extends the literature on the PV modification associated with WCBs by illustrating how turbulence at the WCB outflow boundary contributes to the formation of coherent PV changes. As stated in the introduction, most previous studies on the effect of WCBs on PV focus on the diabatic heating due to cloud microphysical processes (e.g., Joos and Wernli, 2012; Oertel et al., 2023), with some recent efforts to quantify the effect in a vertically sheared environment (e.g., Harvey et al., 2020; Oertel et al., 2020). To our understanding, the current study is the first to focus on the PV modification due to turbulence associated with a WCB outflow. With the complexity involved in order to create coherent PV changes as shown in this case study, it is difficult to comment on the generality of the results to other WCB outflows. However, it clearly underscores the possibility of WCBs to modify PV in the UTLS coherently by triggering turbulence in the outflow region, and thus potentially influence the large-scale flow evolution.



605      Given its systematic behaviour of PV modification in the UTLS, turbulence may thus influence the dynamics in the tropopause region. For instance, with significant PV changes introduced, the PV gradient across the tropopause may be modulated by turbulence and subsequently affect Rossby wave dynamics (e.g., Harvey et al., 2016). Also, while the contribution of turbulence to the exchange across the tropopause, i.e., stratospheric-troposphere exchange (STE; Stohl et al., 2003), has long been recognised (e.g., Shapiro, 1980), most studies that connected the exchange with the underlying driver are restricted to single cases.

610      A generalisation to a climatological study that quantifies the contribution of turbulence to STE, similar to that for radiation by Mürsepp et al. (2026), would be likely valuable. By highlighting the significance of turbulence in modifying PV in the UTLS, this two-part study invites further exploration of other possible upscale effects of turbulence to deepen our understanding of this minute, yet potentially far-reaching phenomenon.

*Code and data availability.* Trajectory calculations are performed using the LAGRANTO tool v2.0 (Sprenger and Wernli, 2015), which is

615      available at <https://iacweb.ethz.ch/staff/sprenger/lagranto/>. The infrared brightness temperature is available on Goddard Earth Sciences Data and Information Services Center (GES DISC): <https://doi.org/10.5067/P4HZZB9N27EQU> (Janowiak et al., 2017). Other data are available upon request to the authors.

*Author contributions.* MHFL and MS formulated and designed the study. RF implemented the changes to the IFS source code for this study. MHFL performed the simulation, data analysis and wrote the manuscript. MS, HJ and HW contributed significantly to the interpretation of

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