



Assessing diabatic influences on extratropical cyclone development using complementary diagnostics

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Abstract. Extratropical cyclones are a key driver of midlatitude weather variability, including high-impact events with heavy precipitation and severe wind gusts. Cyclone intensification results from the complex interplay of baroclinic dynamics and diabatic heating, the latter being closely linked to cloud-related processes within warm conveyor belts (WCBs). Focusing on four representative intense European cyclones, this study contrasts two commonly used methods — pressure tendency equation (PTE) and piecewise potential vorticity (PV) inversion — to assess the methodological uncertainty in quantifying the role of diabatic processes for cyclone intensification. The methods are complemented by a deep learning-based WCB identification diagnostic. Although for most cyclones PTE and PV inversion yield consistent results regarding the role of diabatic processes, substantial differences are found for at least one cyclone. Cyclones with strong diabatic heating contributions tend to be associated with enhanced low- to mid-level PV forcing. For two diabatically influenced cyclones, PV contributions are concentrated in the frontal circulation. In contrast, for one cyclone, the mid-level forcing is more strongly linked to shear in the jet region rather than diabatic heating. Overall, our results demonstrate the benefit of combining complementary diagnostic approaches to better constrain the contribution of diabatic processes to extratropical cyclone intensification. The clear link between the diagnostics highlights the potential of both methods for systematic evaluations of weather and climate models.

1 Introduction

Extratropical cyclones (hereafter referred to as cyclones) are a key feature of the climate of the midlatitudes that aid in the release of baroclinic instability (e.g., Charney, 1947; Eady, 1949) and the transport of heat, moisture, and momentum from the equator to the poles (e.g., Starr, 1948; Held, 2019). Given its location at the end of the North Atlantic storm track, cyclones are the primary mechanism by which weather extremes occur across Europe, including extreme rainfall, windstorms, and other compound weather extremes (e.g., Fink et al., 2009; Ulbrich et al., 2009; Dowdy and Catto, 2017).

Cyclones tend to form and travel in localized zones known as storm tracks due to the concentration of strong horizontal temperature gradients (i.e., baroclinic instability) and the position of upper-level jet streams (e.g., Hoskins and Valdes, 1990; Chang et al., 2002; Shaw et al., 2016). In the Northern Hemisphere, there are two main storm tracks across the North Pacific and



North Atlantic Ocean basins (e.g., Blackmon et al., 1984; Shaw et al., 2016). Cyclones have been studied for over 100 years, with different theories on the primary mechanism for cyclogenesis during this time. The Bergen school of thought explained cyclone development as oppositely moving air streams along a pre-existing frontal boundary leading to cyclonic flow and eventually occlusion of the warm air mass (e.g., Bjerknes and Solberg, 1922). In contrast, other scientists focused on the role of horizontal divergence near the tropopause, but data limitations initially made calculations of this divergence difficult (e.g., Dines, 1912; Namias and Clapp, 1949). More recent work used the potential vorticity (PV) framework to describe cyclogenesis as the interaction and eventual phase locking of counter-moving Rossby waves on the tropopause and surface (e.g., Hoskins et al., 1985; Davies and Bishop, 1994).

One of the key dynamical mechanisms that impacts cyclone development is latent heat release (Wernli and Gray, 2024). Due to the three-dimensional circulations around frontal zones, cyclones often contain a warm conveyor belt (WCB), a region of isentropic lift within the warm sector in a poleward direction ahead of the cold front (e.g., Carlson, 1980; Wernli, 1997a). As the warm, moist air rises in the WCB, large-scale latent heating produces a cyclonic PV anomaly below the region of maximum latent heating and an anticyclonic PV anomaly above (e.g., Wernli, 1997b; Madonna et al., 2014). The upper-level anticyclonic PV anomaly can act to strengthen a downstream ridge (e.g., Davis et al., 1993) and help to redirect the cyclone to propagate more poleward (e.g., Tamarin and Kaspi, 2017). Surface fluxes from the ocean, especially over the Gulf Stream, can also aid in strengthening cyclones across the North Atlantic (e.g., Bosart, 1981; Ludwig et al., 2014). These surface fluxes can then help to organize embedded convection within the cyclone, creating a positive feedback loop resulting in even more positive PV generation (e.g., Gyakum, 1983).

Because of the importance of understanding the contributions of diabatic processes to cyclone intensification, different diagnostics and analysis methods have been used in past studies. One such method is PV inversion, a method used since the early 1990s (Davis and Emanuel, 1991). PV inversion leverages that given a PV distribution, the importance of individual PV anomalies to cyclone intensity can be quantified. Other studies have utilized this method to study individual cyclones of interest (e.g., Griffiths et al., 2000; Beaty et al., 2025), to create climatologies of different development pathways for extratropical cyclones (e.g., Quinting et al., 2019; Seiler, 2019), and to analyze the development of a case of jet superposition (e.g., Winters and Martin, 2017). An alternative is the pressure tendency equation (PTE) approach (Fink et al., 2012), a cyclone-centered perspective to quantify diabatic heating contributions to cyclone deepening. Applying the PTE, Pirret et al. (2017) showed that the relative importance of diabatic processes varies between storms, reaching up to 60 %. Also using the PTE, for cyclones in the eastern North Atlantic associated with extreme wind events, increased diabatic contributions were found by Stanković et al. (2024). Using idealized climate simulations, Chen et al. (2024) showed that the absolute contribution of diabatic heating increases in a warmer climate, while cyclone intensity remains unchanged as this increase is compensated by changes in other processes.

Both methods exhibit certain limitations (Spengler and Egger, 2009; Egger and Spengler, 2018) such that it is not an easy task to identify the dynamical drivers of cyclone intensification and to quantify diabatic heating contributions. Therefore, this paper aims to compare two methodologies (PTE and PV inversion) commonly used for quantifying the contribution of different



processes to cyclone development. Both methods are applied to four selected cyclones to better understand how each method diagnoses diabatic heating contribution to cyclone development. The following research questions are addressed:

1. Are cyclones consistently classified as diabatically-driven using both methods?

60 2. Do cyclones classified by the PTE as diabatically driven actually exhibit a stronger contribution from mid- and lower-tropospheric PV anomalies? When in the lifecycle does diabatic heating contribute to cyclone intensification, and through which features does PV contribute to cyclone intensification?

3. How much does the cyclone tracking method applied contribute to uncertainty in the PTE method?

In section 2, we introduce the concepts of PTE and piecewise PV inversion. Section 3 introduces the four cases, and Section 65 4 presents the results obtained with both methods, which are compared and discussed in Section 5. The paper concludes and summarizes our results in Section 6.

2 Methods

In this study, we analyse the intensification of four impactful cyclones over Western Europe using the pressure tendency equation (PTE, Section 2.3) and piecewise PV inversion (Section 2.4). These cases occurred in the winter season (DJF) and 70 reached their peak intensity west of the Greenwich Meridian (0°W). Following Christ et al. (2025), we choose these cases comprising two cyclones with relatively large and two with small diabatic heating influence on cyclone intensification. The whole analysis is based on ERA5 reanalysis data (Hersbach et al., 2020). The PTE and PV inversion methods described in the following section can be applied to different cyclone tracking algorithms. While most of this study is based on Hodges tracking algorithm (Hodges, 1994, Section 2.2), one source of methodological uncertainty arises from the choice of tracking algorithm. 75 Therefore, parts of the analysis are also performed using the Pinto tracking algorithm (Pinto et al., 2005, Section 2.1).

2.1 Pinto tracking algorithm

We apply the cyclone tracking algorithm described by Pinto et al. (2005) following the methodology of Murray and Simmonds (1991) to the Northern Hemisphere (20 to 90°N) ERA5 reanalysis data with a 6 h temporal resolution remapped from 0.28° to a regular 1° latitude-longitude grid. The algorithm first identifies the maximum Laplacian (lapIP) of mean sea level pressure 80 (MSLP) at each time and then finds the nearest MSLP minima and combines them into a cyclone track. To filter non-synoptic relevant low-pressure centers, a minimum lifetime of 24 h are preconditioned (Pinto et al., 2009), as well as a travel distance of at least 1000 km. Cyclones over high orography (1500 m) are discarded. The cyclone tracks resulting from this method align well with those from other similar tracking methods, though the method tends to build longer tracks than most other methods (Neu et al., 2013). For these Pinto tracks, peak intensity is defined as the minimum of MSLP along the entire cyclone track.



85 2.2 Hodges tracking algorithm

The Hodges cyclone tracking algorithm, which is a widely used method (e.g. Priestley and Catto, 2020), is based on the methods of Hodges (1994, 1995, 1999) and is described in more detail in Hoskins and Hodges (2002). Cyclones are identified using the 850 hPa relative vorticity field derived from ERA5 (Hersbach et al., 2020) that has been spectrally truncated at T42 with planetary wavenumbers less than 5 removed. A candidate cyclone track is initiated when a value of relative vorticity greater than $1 \times 10^{-5} \text{ s}^{-1}$ is identified. Subsequent time steps are linked to form a track using B-spline interpolation and steepest ascent maximization to create a smooth, contiguous cyclone track. Candidate tracks are retained if they last for at least 48 h and if the length of the track exceeds 1000 kilometers. This method was included in the comparison of cyclone tracking methods by Pinto et al. (2016). For these Hodges tracks, peak intensity is defined as the maximum relative vorticity along the entire cyclone track.

95 2.3 Pressure tendency equation approach

Cyclone formation is largely influenced by baroclinic conversion and diabatic processes (radiation and latent heat release). As formulated by Knippertz and Fink (2008) and Knippertz et al. (2009), the PTE can be applied to determine the contributions to surface pressure change from different physical processes (Equation 1). The pressure tendency equation is reformulated such that the main variable is virtual temperature. We calculate the PTE terms for each cyclone track, following Fink et al. (2012); therefore, we integrate vertically and average in a $6 \times 6^\circ$ box around the cyclone center. This approach is applied to a vertical column from the surface to 100 hPa (as in Chen et al., 2024) using pressure levels from 1000 hPa to 100 hPa every 10 hPa. Note that data below the surface are not included. The PTE equation is

$$\underbrace{\frac{\partial p_{\text{sfc}}}{\partial t}}_{\text{Dp}} = \underbrace{\rho_{\text{sfc}} \frac{\partial \phi_{p_2}}{\partial t}}_{\text{ColHeight}} + \underbrace{\rho_{\text{sfc}} R_d \int_{p_{\text{sfc}}}^{p_2} \frac{\partial T_v}{\partial t} d \ln p}_{\text{Temp}} + \underbrace{g(E - P)}_{\text{Mass}} + \text{RES}_{\text{PTE}}, \quad (1)$$

and the vertically integrated virtual temperature tendency is

$$\text{Temp} = \rho_{\text{sfc}} R_d \left[\underbrace{\int_{p_{\text{sfc}}}^{p_2} -\mathbf{v} \cdot \nabla_p T_v d \ln p}_{\text{TempAdv}} + \underbrace{\int_{p_{\text{sfc}}}^{p_2} \left(\frac{R_d T_v}{c_p p} - \frac{\partial T_v}{\partial p} \right) \omega d \ln p}_{\text{VertMot}} + \underbrace{\int_{p_{\text{sfc}}}^{p_2} \frac{T_v \dot{Q}}{c_p T} d \ln p}_{\text{Diab}} \right] + \text{RES}_{\text{Temp}}, \quad (2)$$

where p_{sfc} is surface pressure, ρ_{sfc} is air density at the surface, ϕ_{p_2} geopotential at p_2 (at 100 hPa), R_d the gas constant for dry air, T_v the virtual temperature, and g the gravitational acceleration. T is temperature, $\mathbf{v}$ and ω the horizontal and vertical wind components, c_p the specific heat capacity at constant pressure, and $\dot{Q}$ the diabatic heating rate.

The surface pressure tendency (Dp, Equation 1) is the sum of: (1) the change in the upper boundary geopotential at 100 hPa (ColHeight), (2) the vertically integrated virtual temperature tendency (Temp), (3) the mass change due to differences of precipitation and evaporation (Mass), and (4) the residuals from errors in data, discretizations, and vertical integration. This means



if the height of an air column stays constant, warming causes the air to expand horizontally, leading to a reduction in mass within the column through divergence, resulting in a surface pressure drop. Likewise, if only the upper boundary of the column is lowered, the pressure drops, as it has to be related to mass evacuation by divergent winds. The vertically integrated virtual temperature tendency term (Temp from Equation 1, given in Equation 2) itself is the sum of: (1) horizontal temperature advection (TempAdv, i.e. baroclinic conversion), (2) vertical motion (VertMot, typically associated with rising surface pressure), (3) diabatic heating (Diab), and (4) a residual term. The Diab term is estimated as the residual after subtracting the TempAdv and VertMot terms from the Temp. Consequently, the Diab term includes not only diabatic heating, but also residual components arising from closing the temperature tendency equation (Equation 2). Although this approach has limitations, tests using explicit heating rates in auxiliary material in Pohle (2010); Fink et al. (2012) show that the explicitly calculated Diab term and the Diab term calculated from the residual are usually fairly similar. Additionally, we calculate the percentage of Diab (called DiabCont) relative to the total virtual temperature pressure tendency (Temp) following the method of Fink et al. (2012, Equation 3):

$$\text{DiabCont} = \begin{cases} \frac{|\text{Diab}|}{|\text{Temp}| + |\text{VertMot}| + |\text{Diab}|} \times 100, & \text{if } \text{sgn}(\text{Diab}) = \text{sgn}(\text{Temp}) = \text{sgn}(\text{VertMot}) \\ \frac{|\text{Diab}|}{|\text{Temp}| + |\text{Diab}|} \times 100, & \text{if } \text{sgn}(\text{Diab}) = \text{sgn}(\text{Temp}) \wedge \text{sgn}(\text{Diab}) \neq \text{sgn}(\text{VertMot}) \\ \frac{|\text{Diab}|}{|\text{VertMot}| + |\text{Diab}|} \times 100, & \text{if } \text{sgn}(\text{Diab}) = \text{sgn}(\text{VertMot}) \wedge \text{sgn}(\text{Diab}) \neq \text{sgn}(\text{Temp}). \end{cases} \quad (3)$$

This allows us to quantify the relative contribution of Diab and to compare the relative contributions of Diab to TempAdv and VertMot. It has to be noted that the cyclone deepening rate, defined as the change in MSLP along the cyclone track, differs from the quantity Dp , which represents the box-averaged surface pressure change at a fixed location over a 6-hour period. Therefore, a direct equivalence between the two cannot be assumed.

2.4 PV inversion approach

The PV inversion technique is based on the work of Davis and Emanuel (1991) and performed in the same manner as Quinting et al. (2019). A brief description of the mathematical basis for this technique follows below. By assuming the atmosphere is in hydrostatic balance and that the total wind can be approximated by the non-divergent component of the wind, potential vorticity can be expressed as,

$$\text{PV} = \frac{gR_d\pi}{c_p P} \left[(f + \nabla^2 \Psi) \frac{\partial^2 \Phi}{\partial \pi^2} - \frac{1}{a^2 \cos^2 \phi} \frac{\partial^2 \Psi}{\partial \lambda \partial \pi} \frac{\partial^2 \Phi}{\partial \lambda \partial \pi} - \frac{1}{a^2} \frac{\partial^2 \Psi}{\partial \phi \partial \pi} \frac{\partial^2 \Phi}{\partial \phi \partial \pi} \right], \quad (4)$$

where Φ is the geopotential, Ψ is the non-divergent streamfunction, f is the Coriolis parameter, $P_0=1000$ hPa, a , λ and ϕ take their usual meaning of radius of the Earth, longitude and latitude, and π is the Exner function,

$$\pi = c_p \frac{P}{P_0}^{\frac{R_d}{c_p}}. \quad (5)$$

The balance conditions of Charney (1955), given by

$$\nabla^2 \Phi = \nabla \cdot (f \nabla \Psi) + \frac{2}{a^4 \cos^2 \phi} \frac{\partial(\frac{\partial \Psi}{\partial \lambda}, \frac{\partial \Psi}{\partial \phi})}{\partial(\lambda, \phi)}, \quad (6)$$



140 can be derived by taking the horizontal divergence of the horizontal momentum equation under the same set of assumptions to relate geopotential and streamfunction to each other and create a closed set of equations.

Boundary conditions for streamfunction and geopotential are prescribed on the lateral boundaries of the PV inversion domain, while the vertical derivatives are set to be constant on the top (50 hPa) and bottom (1000 hPa) boundaries. In addition, any regions of negative PV or static instability are adjusted to be slightly positive or stable so the equations can converge on a
145 solution. For all four cyclones, PV inversion is run on a domain from 81–1°W and from 30–70°N from the start of the cyclone tracks in the Hodges algorithm to 24 h after peak intensity. The resulting PV field is decomposed into a mean and perturbation field, where the mean PV is calculated using a 10-day running mean. Perturbation PV anomalies can be used to reconstruct the perturbation wind fields using the following relationships.

$$u' = \frac{1}{a} \frac{\partial \Psi'}{\partial \phi}, v' = \frac{1}{\cos(\phi)} \frac{\partial \Psi'}{\partial \lambda} \quad (7)$$

150 From these perturbation wind fields, the contribution of PV anomalies to the 850 hPa relative vorticity field can be calculated to assess which atmospheric layer is contributing most to the intensity of the four cyclones. Contributions from low-level (950–850 hPa), mid-level (800–550 hPa), and upper-level (500–100 hPa) PV anomalies are assessed within a 6x6° box around the cyclone center to match the PTE methodology.

2.5 WCB detection - ELIAS

155 To evaluate WCB activity associated with the cyclones, we detect WCBs using the machine learning model ELIAS (EuLerian Identification of ascending AirStreams, Quinting and Grams, 2022). The machine learning model predicts conditional probabilities of WCB outflow, ascent, and inflow footprints from gridded, instantaneous fields, offering a computationally efficient alternative to trajectory-based methods (Quinting et al., 2022). The WCB outflow is defined as the part of the WCB in the upper troposphere, above 400 hPa, the WCB ascent as the part of the WCB between 800 and 400 hPa, and the WCB inflow
160 below 800 hPa. The U-Net convolutional neural network is applied to ERA5 reanalysis data remapped from 0.28° to a regular 1° latitude-longitude grid with a 6 h temporal resolution. To combine cyclone tracks with the WCB masks, we match the WCB masks and the cyclone tracks using a radius of 700 km around the cyclone center (average cyclone influence radius, Rudeva and Gulev, 2007). If the WCB mask overlaps with at least one grid cell of the radius around the cyclone center at a given time, this WCB mask is matched to the cyclone trackpoint at that time.

165 3 Four case studies

In this study, we compare the PTE and PV inversion approaches for classifying cyclones using four case studies. Two cyclones with a relatively large influence of diabatic heating on cyclone intensification, at least according to the PTE, are compared to two cyclones with a relatively small diabatic influence. The influence of diabatic heating on cyclone intensification is quantified using the PTE, and the classification into diabatically and non-diabatically influenced cyclones is based on the distribution of
170 the mean diabatic heating contribution (MeanDiabCont) in Christ et al. (2025, Figure 2c therein). The two cyclones strongly



influenced by diabatic heating are Tini (also called Darwin) in February 2014, and Harry (named Barra by the MetOffice) in December 2012. The other two cyclones are Kerstin in January 2000, and Friedhelm in December 2011.

Tini, Harry, and Friedhelm are secondary frontal wave cyclones (Hewson and Neu, 2015). Kerstin originated in the lee of Greenland and is associated with a short-wave trough. Tini, Harry, and Friedhelm are associated with a bent-back front, a T-bone frontal structure, and a warm seclusion consistent with the Shapiro–Keyser cyclone model (Shapiro and Keyser, 1990). Tini and Friedhelm were also both associated with a sting jet (Baker et al., 2013; Volonté et al., 2018). All four cyclones impacted western Europe (Figure 1). Kerstin induced strong wind gusts over Scotland, northern Germany, and Denmark. Harry was most extreme in Ireland, while Friedhelm generated the most intense wind gusts over southern and central Scotland. Tini made landfall over the British Isles during its mature stage, primarily affecting the coastal regions of Wales and northwest England.

3.1 Cyclone Tracks

The cyclone tracks from the Pinto and the Hodges tracking algorithm (see Sections 2.1 and 2.2) are shown in Figure 1. The cyclones reach their peak intensity in the European domain. Tini and Harry originate in the Gulf Stream region, Friedhelm originates north of the Gulf Stream region, and Kerstin originates in the Labrador Sea. Harry and Friedhelm propagate zonally, as does Kerstin, while being further north, which is in contrast to Tini, which propagates more northward, indicative of a large diabatic contribution (Tamarin and Kaspi, 2017).

Generally, the location of the cyclone tracks around peak intensity aligns quite well. However, Harry has an earlier genesis in the Hodges track, Tini has an earlier genesis in the Pinto track, and the genesis location of Kerstin is different with the two approaches. Overall, the Hodges track locations are slightly shifted to the southwest compared to those obtained using the Pinto tracks. This is consistent with the typical location of the maximum relative vorticity located southwest of the cyclone core, defined by the minimum sea level pressure. The peak intensity of Tini is on 12 February at 12 UTC in both tracks. For Harry, peak intensity is reached on 7 December at 12 UTC (based on minimum of MSLP) in the Pinto track and at 18 UTC in the Hodges track (based on maximum relative vorticity). Kerstin reaches peak intensity on 29 January at 00 UTC in the Hodges track and at 12 UTC in the Pinto track. For Friedhelm, peak intensity is on 8 December at 18 UTC in both tracks. For completeness, we also report the peak intensity in terms of maximum lapIP for the Pinto tracks (light green in Figure 1). Although the corresponding peak intensity times differ slightly from those based on minimum MSLP, they do not show better agreement with the Hodges track peak intensity times based on maximum relative vorticity. For the remainder of this study, we refer to the peak intensity time of the Hodges tracks, unless stated differently.

3.2 Cyclone strength

The peak intensity core pressures of Tini, Harry, and Friedhelm are similar with 956 hPa, 960 hPa, and 957 hPa, respectively (Figure 2a). Kerstin has the lowest core pressure along the Pinto track with 943 hPa, which can also be attributed to it being the most northern track. All four cyclones are bomb cyclones following the definition by Sanders and Gyakum (1980) based on MSLP along the Pinto tracks. The strongest deepening rate is found for Tini with a 49 hPa drop in 24h normalized to 60°,

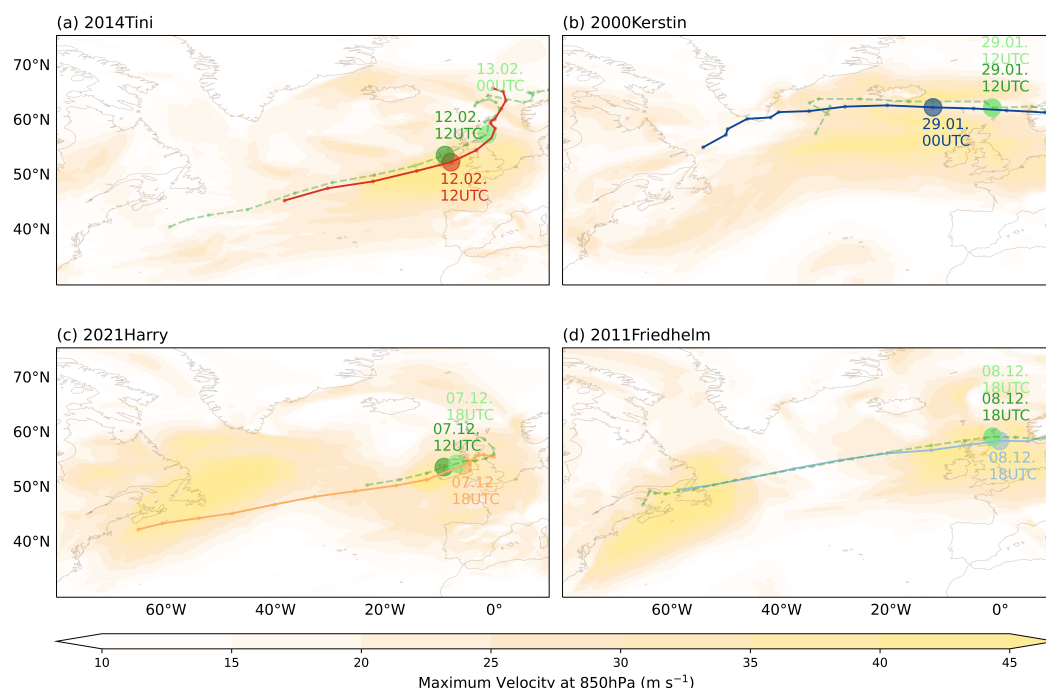


Figure 1. Wind speed footprints at 850 hPa -12 h to +6 h around peak intensity (maximum m s^{-1}) and cyclone tracks for Hodges and Pinto (green) tracking algorithm for (a) Tini (red), (b) Kerstin (dark blue), (c) Harry (yellow), and (d) Friedhelm (light blue). Peak intensity times are marked for both algorithms. For the Hodges track in terms of maximum relative vorticity (colors), for the Pinto, both in terms of maximum lapIP (bright green) and min MSLP (green).

followed by Friedhelm with $44 \text{ hPa } 24\text{h}^{-1}$, Kerstin with $43 \text{ hPa } 24\text{h}^{-1}$, and Harry with $38 \text{ hPa } 24\text{h}^{-1}$. Therefore, the deepening
 205 rates are strong for all cases, both those diabatically and non-diabatically influenced. In terms of relative vorticity maximum along the Hodges tracks, Friedhelm is the strongest cyclone with a maximum of $11.6 \times 10^{-5} \text{ s}^{-1}$, followed by Kerstin and Harry with $11.4 \times 10^{-5} \text{ s}^{-1}$ and $11.3 \times 10^{-5} \text{ s}^{-1}$ respectively, and Tini with $9.9 \times 10^{-5} \text{ s}^{-1}$ (Figure 2b).

3.3 Cyclone development

The cyclones are now compared in terms of their synoptic development. Harry crosses the jet stream, Friedhelm crosses a
 210 relatively weak jet stream, and Tini crosses a strong, zonal jet stream indicated in Figure 3. The jet at the time of Tini's development is associated with Rossby wave breaking at its flanks (Priestley et al., 2017). Kerstin intensifies at the left exit region of the jet stream.

Harry and Kerstin develop downstream of an upper-level trough, which is indicated in the 2-PVU line (black line in Figure
 3d,j) at 300 hPa, and the geopotential height at 500 hPa (blue contours in Figure 3). Additionally, Kerstin is associated with an
 215 upper-level PV anomaly. The positive PV associated with Kerstin can also be attributed to the orography of Greenland favoring

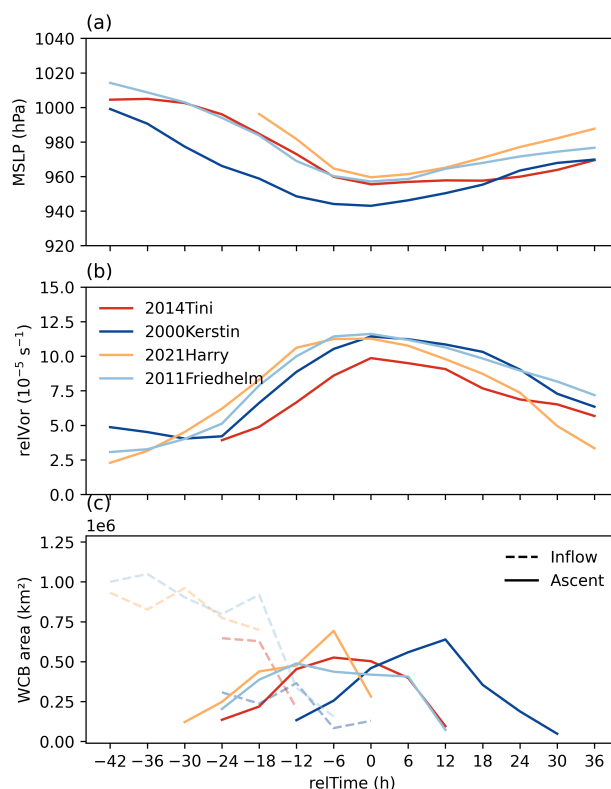


Figure 2. (a) MSLP along the cyclone of the Pinto tracks, centered on the peak intensity of the Pinto tracks. (b) Relative vorticity at 850 hPa at the cyclone center for Hodges tracks, centered on the peak intensity of the Hodges tracks. (c) WCB ascent (solid lines) and WCB inflow (dotted lines) mask associated with the Hodges cyclone tracks, centered on the peak intensity of the Hodges tracks. Tini (red), Kerstin (dark blue), Harry (yellow), and Friedhelm (light blue).

positive PV on the leeward side. Tini, Harry, and Friedhelm catch up with a region of positive upper-level PV at 300 hPa, during their development. Tini, Harry, and Friedhelm are associated with cyclonic PV at 850 hPa close to the cyclone center (not shown).

In the vertical cross sections 12 h before peak intensity in the lower-levels, for Harry and Tini, some most likely diabatically generated cyclonic PV close to the cyclone center can be found (Figure 4a,c). Though in the case of Friedhelm, the cyclonic PV is of smaller extent, and for Kerstin, there is relatively little cyclonic PV in the lower troposphere, but a strong cyclonic PV anomaly in the upper troposphere reaching downward (Figure 4b,d). In the upper troposphere for all cases, cyclonic PV, which at peak intensity time aligns with the lower-level cyclonic PV, builds a PV tower (not shown).

In the cases of Harry and Tini, frontogenesis is found 24 h before peak intensity at the cold front (not shown), also associated with upward velocities, which is still visible at -12 h for Harry in Figure 4c. For Kerstin and Friedhelm, no frontogenesis can be found in the cross section 24 h before peak intensity.

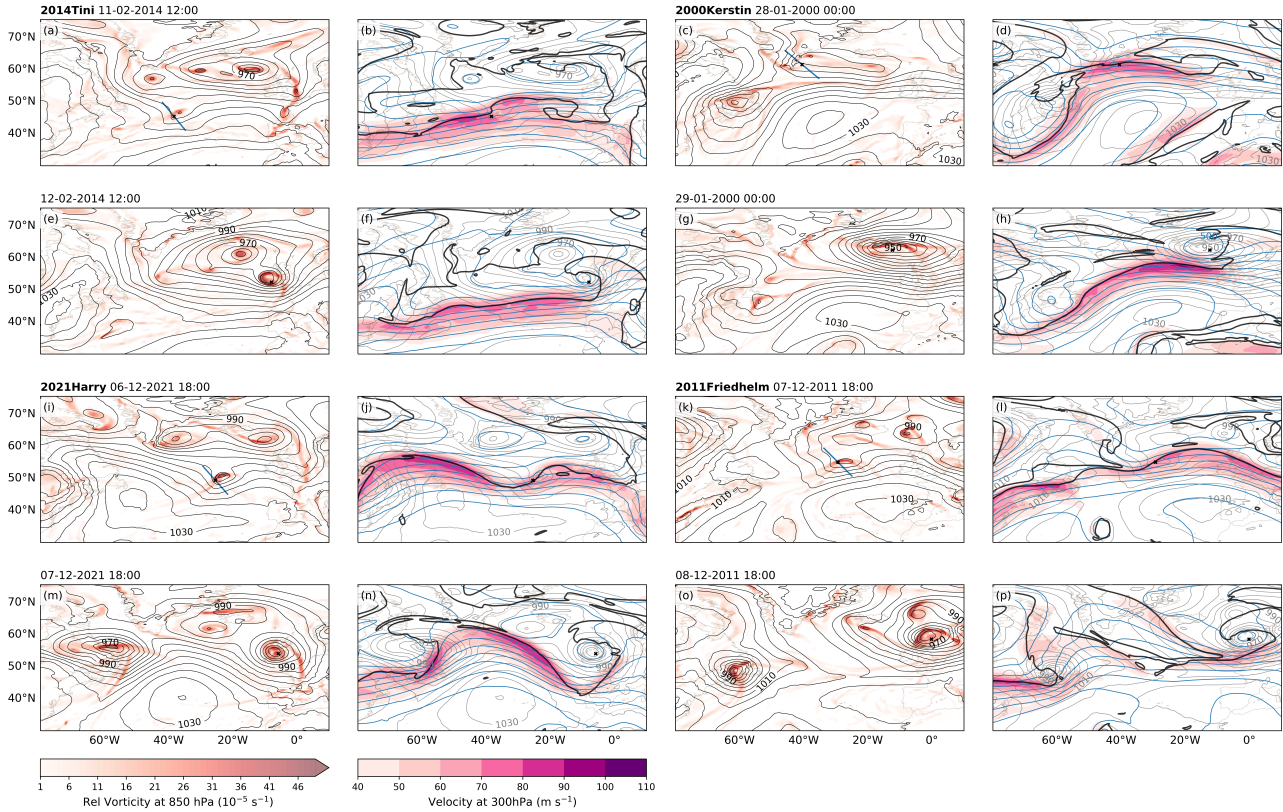


Figure 3. Relative Vorticity at 850 hPa (orange shading in 10^{-5} s^{-1}) and mean sea level pressure (MSLP, grey contours every 5 hPa). Wind speed at 300 hPa (pink shading in m s^{-1}), 2-PVU at 300 hPa (black line), geopotential height (blue contours every 10 gpdm), and MSLP (grey contours every 5 hPa). At peak intensity time according to Hodge's track and 24 h before, for (a-b, e-f) Tini, (c-d, g-h) Kerstin, (i-j, m-n) Harry, and (k-l, o-p) Friedhelm. (a,c,i,k) blue line indicates cross section in Figure 4.

3.4 Warm Conveyor Belt

All four cases are associated with WCBs. The WCB inflow masks associated with Harry and Friedhelm are larger and appear earlier compared to the inflow masks of Kerstin and Tini (Figure 2d). The WCB ascent masks are of similar maximum sizes for all cases (Figure 2c). For the Hodges tracks, the maximum WCB ascent size occurs close to peak intensity, except for Kerstin, for which it occurs after peak intensity. Notably, for Kerstin, the peak intensity time using the Pinto tracking approach is 12 h later, when the WCB ascent mask is also the largest. In the case of Tini, Harry, and Friedhelm 24 h before peak intensity, the WCB ascent is close to the cyclone center (Figure 7), while Kerstin is not associated with WCB ascent yet and at -12 h the WCB ascent associated with Kerstin is further away from the cyclone center (not shown). In summary, all four cyclone cases are associated with some WCB activity. For Tini and Harry, this WCB activity occurs initially during the cyclone intensification phase, whereas for Friedhelm, it occurs later. For Kerstin, the WCB ascent is probably too far away from the cyclone center to

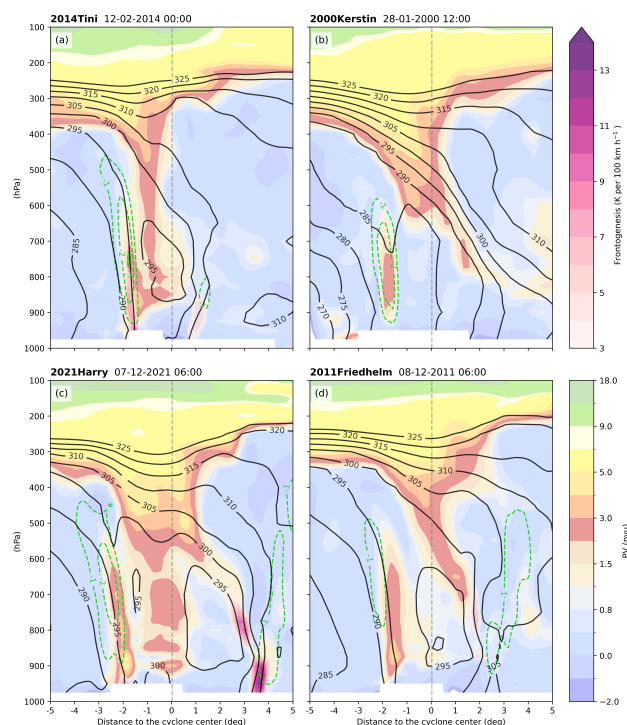


Figure 4. Vertical cross sections through the cyclone center in a -30° angle relative to a zonal line 12 h before peak intensity. PV (shading in PVU), equivalent potential temperature (black contours every 5 K), vertical velocity (green contours at every -1 Pa s^{-1} starting at -1 Pa s^{-1}), and the frontogenesis (purple shading in $\text{K } 100 \text{ km}^{-1} \text{ h}^{-1}$ starting at $3 \text{ K } 100 \text{ km}^{-1} \text{ h}^{-1}$) for (a) Tini, (b) Kerstin, (c) Harry, and (d) Friedhelm.

further intensify the cyclone through cyclonic PV generated by diabatic heating associated with the WCB ascent (Binder et al., 2016), partly explaining its low diabatic heating contributions.

4 PTE and PV inversion to characterize the cyclones

240 4.1 PTE

The PTE is used to attribute surface pressure changes to different physical processes (see Section 2.3). It combines the effect of the upper boundary geopotential changes (ColHeight), mass changes due to precipitation and evaporation (Mass), and changes in vertically integrated virtual temperature (Temp).

For the majority of cyclone tracks, the main contribution to the total pressure change originates from temperature changes (Temp, Figures 5a,e and 6a,e). This is particularly true for Tini and Friedhelm. Regarding Harry and Kerstin, Temp is most important as well, but also the ColHeight change, which indicates a stratospheric influence, also contributes substantially to surface pressure drop (Figures 5e and 6a). The amounts of evaporation and precipitation for all cases are not unusually small but do not substantially change surface pressure.

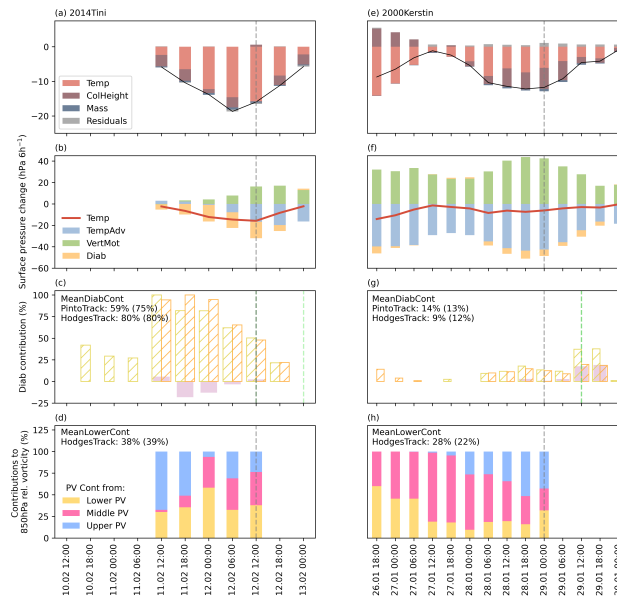


Figure 5. (a,e) Surface pressure tendency (black line in hPa 6 h⁻¹) and it's contributions of temperature tendency (Temp, red bars), of geopotential at the upper boundary (ColHeight, dark red bars), of mass loss by precipitation (Mass, dark blue bars), and of residuals (grey bars). Corresponding to Equation 1 see an explanation of the different terms in Section 2.3. (b,f) Temperature tendency (red line in hPa 6 h⁻¹) equivalent to Temp from (a,e). Horizontal temperature advection (TempAdv, blue bars), diabatic heating (Diab, yellow bars), and vertical motion (VertMot, green bars) contributions to Temp (in hPa 6 h⁻¹, corresponding to equation 2). (c,g) Ratio of diabatic heating contribution to temperature tendency (DiabCont, dashed yellow bars in %), additionally for Pinto's tracking algorithm (dashed green bars in %), and difference of Pinto's and Hodge's ratio (red bars in %). Mean diabatic heating contribution from genesis to peak intensity time for the Hodges and Pinto tracking algorithms and in brackets the mean over the overlapping times (first common time to earlier peak intensity time). (d,h) Contribution to 850 hPa relative vorticity from lower (yellow bars from 950–850 hPa), middle (magenta bars from 800–550 hPa) and upper PV (blue bars from 500–100 hPa). Mean lower level PV contribution over the intensification period and in parentheses for the overlapping cyclone track times. Peak intensity time (vertically grey dashed line), additionally peak intensity in terms of MSLP according to the Pinto's tracking algorithm (vertically green dashed line). For (a–d) Tini and (e–h) Kerstin.

The Temp contributions can further be divided into three components (Figures 5b,f and 6b,f): temperature advection (TempAdv, baroclinic contribution), diabatic processes (Diab), and vertical motion (VertMot). The four cases have been chosen based on their percentage of Diab contributions (DiabCont) averaged over the cyclone intensification phase (genesis to peak intensity, MeanDiabCont): for Tini and Harry, the diabatic heating is relatively large with a MeanDiabCont of 80 % and 53 % (according to the Hodges track, Figures 5c and 6c). On the other hand, Kerstin and Friedhelm feature a relatively small MeanDiabCont with 9 % and 19 % (Figures 6g and 5g).

Especially at the beginning of the tracks, the pressure change of Harry and Tini is dominated by Diab (Figures 5c and 6k). In the case of Harry (Figure 6c), the TempAdv is also important. For example, 24 h before peak intensity the Diab contribution

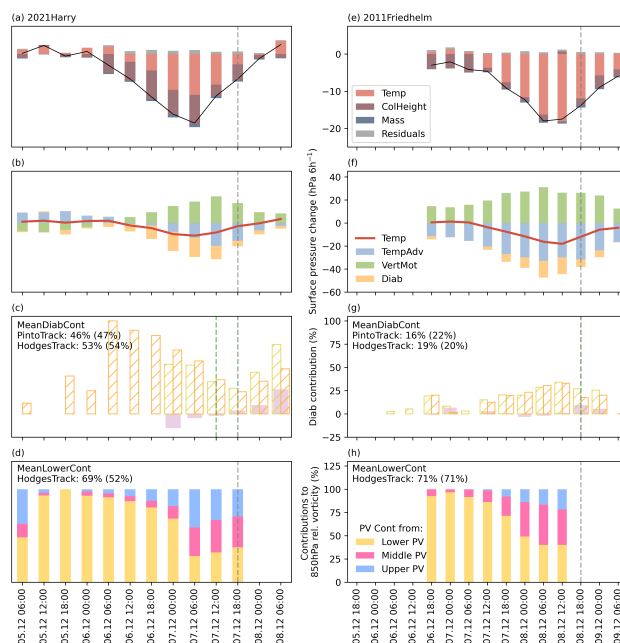


Figure 6. Same as Figure 5 for (a-d) Harry and (e-h) Friedhelm.

is spatially more extended and exhibits larger magnitude in the case of Harry and Tini (Figure 7a,c). The Diab contribution is found to be mainly present in the region of the warm sector, also associated with the WCB (see Section 3.4).

For Kerstin and Friedhelm, the TempAdv is the dominant contribution, while Friedhelm has some Diab contributions as well (Figure 5o). 24 h before peak intensity Diab is spatially less extended and exhibits smaller magnitudes (Figure 7b,d).

Overall, the Diab contributions are of larger spatial extent and magnitude in Tini and Harry compared to Kerstin. For Kerstin, TempAdv dominates and is of a much larger extent during the entire intensification phase, while only small Diab contributions are found closer to peak intensity, when also a WCB ascent mask is present. As expected for all four cases, the vertical motion, adiabatic cooling associated with rising motion, leads to an increase in the surface pressure (weakening the cyclone).

265 4.1.1 Sensitivity of PTE to tracking algorithm

The four cyclone cases have been tracked using two different cyclone tracking methods, the Pinto tracking and the Hodges tracking algorithm. In the following, we quantify how sensitive the PTE is to the choice of cyclone tracking algorithm. The PTE maps giving the different tendency terms at each gridpoint for one time step are the same, independent of the tracking algorithm. However, due to the cyclone tracks being at different locations at a given time, the $6 \times 6^\circ$ box averages around the cyclone trackpoints can differ. In Figures 5c,g and 6c,g the DiabCont (Equation 3) obtained with both tracking algorithms are shown at each timestep, together with the difference between the Pinto and Hodges tracks, which do not exceed 21 %. Generally, the differences at one timestep are mostly small. The MeanDiabCont is calculated for each track from genesis to peak intensity,

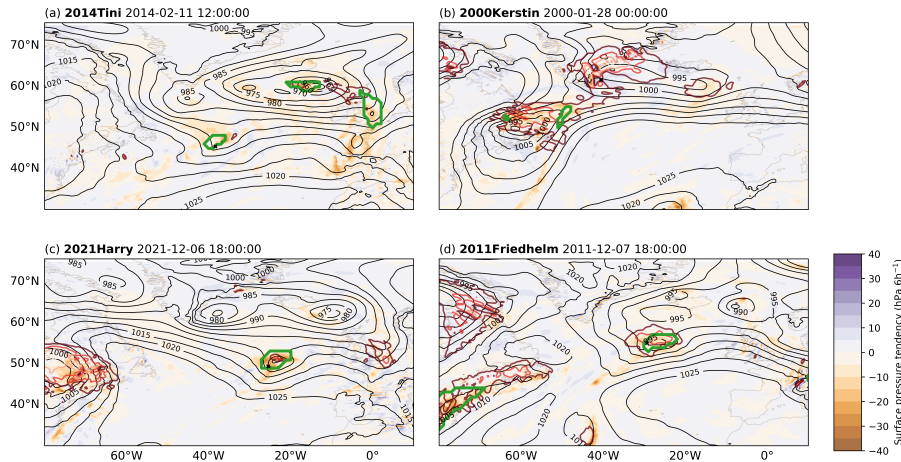


Figure 7. Diabatic heating contributions to Temp term of the PTE (shading in $\text{hPa } 6 \text{ h}^{-1}$), Temperature advection contributions (purple contours at -20 to -50 every $10 \text{ hPa } 6 \text{ h}^{-1}$), WCB ascent mask (green bold contours, see section 2.5), and MSLP (black contours every 5 hPa). 24 h before peak intensity time according to Hodge's track for (a) Tini, (b) Kerstin, (c) Harry, and (d) Friedhelm.

and the overlapping MeanDiabCont is calculated for the period when both tracking algorithms identify a track until the earlier peak intensity time. The largest difference in MeanDiabCont occurs for Tini, with 59 % for the Pinto track compared to 80 %
275 for the Hodges track. For Harry and Friedhelm, the MeanDiabCont is higher when estimated with the Hodges track compared to the Pinto track PTE. Regarding Kerstin, the MeanDiabCont is lower with the Hodges track compared to the Pinto track PTE. Concerning the overlapping MeanDiabCont, the difference between the Hodges and the Pinto tracks is smaller compared to the genesis to peak intensity MeanDiabCont differences. We conclude that the MeanDiabCont depends primarily on the length of cyclone tracks rather than on differences between individual timesteps. The classification of whether a cyclone is strongly
280 diabatically influenced or not remains robust and independent of the tracking algorithm applied to compute the PTE.

4.2 PV inversion

The PV inversion method helps to elucidate the relative contribution of PV anomalies at different atmospheric levels to 850-hPa relative vorticity in and around the cyclone (Davis and Emanuel, 1991). Low-level PV anomalies contribute around 69% to Harry's 850-hPa relative vorticity throughout its lifecycle in the Hodges track. The contribution of low-level PV anomalies is
285 strongest during the early development phase (54 to 18 h before peak intensity), while contributions from mid- and upper-level PV anomalies increase and become more important to the development of the cyclone (Figure 6d). In contrast, Tini has much larger contributions from mid- and upper-level PV anomalies throughout the development period, resulting in only 39 % of the total vorticity coming from the influence of low-level PV (Figure 5d). While the absolute contribution from low-level PV is relatively modest for Tini, the growth of mid-level PV contributions during the final 12 h before peak intensity corresponds



well with the growth of WCB ascent seen in Figure 2c. Therefore, the increased influence of mid-level PV anomalies closer to the time of peak intensity appears to still be attributable to diabatic processes, namely those within the WCB.

Cyclone Kerstin is another example where both the PTE and PV inversion agree in how they classify the cyclones' development. Mid-level and upper-level PV anomalies dominate the development of Kerstin, especially around 36 h of maximum intensity, with only 28 % of the 850-hPa relative vorticity coming from low-level PV anomalies. During the 24 hours before peak intensity, the mid-level and upper-level PV anomalies contribute nearly equally to the cyclone strength, with 40 % and 39 % of the 850-hPa relative vorticity, respectively (Figure 5h). Friedhelm has a much greater proportion (71 %) of its lifetime 850-hPa relative vorticity coming from low-level PV anomalies. However, this value decreases to 54 % for the 24 h before peak intensity, while mid-level and upper-level anomalies contribute 32 % and 14 %, respectively. Throughout its development, the total amount of 850-hPa relative vorticity attributed to low-level PV decreases as vorticity from mid-level and upper-level increases, so the growth and change in vorticity development is aligned more closely with the PTE method than the absolute sum of vorticity from any layer (Figure 6h).

One of the benefits of the PV inversion method is that the spatial structure of the perturbation vorticity and wind fields are retained, allowing for the examination of what synoptic processes are represented within each layer. 24 h before Harry reaches peak intensity, there is a large region of positive relative vorticity from 40–50°N that extends well to the west of the cyclone center associated with low-level PV anomalies. While the values for the inverted relative vorticity and winds are quite high, there is evidence of anomalously high (4–5 PVU) PV to the north and west of Harry in the cross section (Figure 4c). Closer to the center, the strongest vorticity values resemble the developing warm front to the northeast and trailing cold front much further to the west. The large region of cyclonic vorticity corresponds with a large-scale cyclonic circulation centered around 15° west of the cyclone. Because of this circulation, there is south-southwesterly flow over the cyclone center, implying strong warm air advection that allows Harry to continue strengthening (Figure 8a). At the time of peak intensity, the vorticity and wind are much weaker, with a loss of structure of cyclonic relative vorticity near the cyclone center. The predominant winds at this time are associated with an anticyclonic vorticity anomaly around 20°W, imposing northerlies over the cyclone that will aid in the weakening of the cyclone over the coming days (Figure 8b).

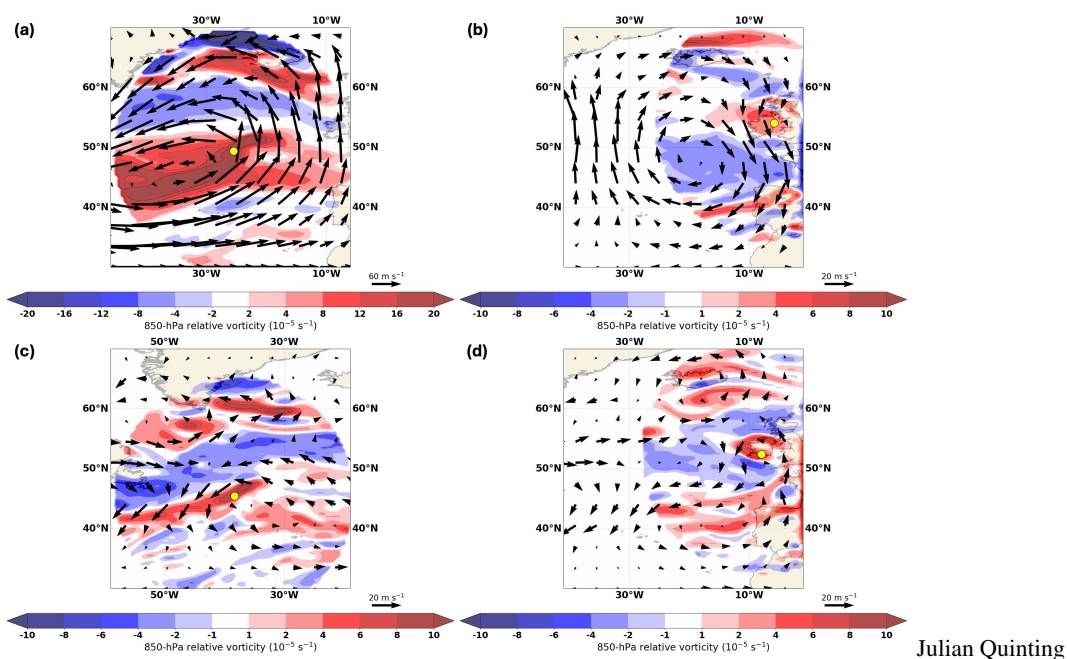
Tini has a prominent region of cyclonic relative vorticity near the cyclone center and to the south and west of it. This vorticity is linked to positive low-level PV anomalies. These features resemble the developing warm and cold frontal regions, with a long trailing cold front extending toward the eastern coast of North America. There are additional regions of cyclonic relative vorticity further away from the cyclone to the south of Greenland, as well as a larger region within the developing warm sector of the cyclone to the southeast. The strongest winds induced by the PV anomalies are just to the north and west of the cyclone, likely aiding in strengthening the temperature gradient along the cold front (Figure 8c). As the fronts continue to strengthen, they begin to expand upward and project more strongly into the 800–550 hPa layer, further adding to the increased contribution from mid-level PV anomalies. At the time of peak intensity, the regions of cyclonic relative vorticity are quite widespread near Iceland and off the coast of Iberia. The cyclonic vorticity field near the cyclone center resembles a warm seclusion (e.g., Shapiro and Keyser, 1990), along with the cold front extending well to the south and west of Tini. With the overall lower



magnitude of vorticity from the PV anomalies, the wind speeds are also weaker, creating a broad cyclonic circulation around
325 Tini but with weak winds near the cyclone center itself (Figure 8d).

Now examining mid-level PV anomalies contributing to the development of Kerstin, there are two regions of zonally-
extended cyclonic vorticity near 60°N and 55°N. These filaments of relative vorticity are located along the northern edge of
the jet stream at the time (Figure 3d), suggesting strong shear is contributing to the PV generation. The winds associated
with these PV anomalies are mostly cyclonic, with a center of circulation just to the west of Greenland resulting in weak
330 southwesterly flow over Kerstin. Similar to Harry, the southwesterly flow helps to rotate the prevailing temperature gradient to
have a zonal component, aiding in the cyclone development (Figure 9a). Kerstin remained zonally elongated through the time
of peak intensity, resulting in zonal bands of cyclonic relative vorticity surrounding the cyclone center. The strongest band of
relative vorticity is associated with the warm front and corresponds to the strongest winds over and to the east of Iceland. The
large spatial scale of Kerstin and the occluded structure of the relative vorticity field results in very weak 850 hPa winds near
335 the cyclone center at peak intensity (Figure 9b).

Unlike Kerstin, Friedhelm has relatively weak relative vorticity contributions 24 h before peak intensity. The pattern of
relative vorticity resembles the developing warm and cold frontal regions, similar to Tini. Winds induced by the PV anomalies
are generally weak, but result in southerly flow across the cyclone center and convergence to the southwest of the center
along the cold front (Figure 9c). By 6 h before peak intensity (chosen because peak intensity is too close to the Greenwich
340 Meridian), the strongest cyclonic relative vorticity is to the north of Scotland. The cyclone appears to be occluded, with a
cold front removed to the south and cyclonic relative vorticity over the cyclone center. The stronger vorticity values at this
time also align with the increasing contribution from mid-level PV anomalies as the frontal circulations increase in strength.
Winds associated with the mid-level PV anomalies are predominantly northeasterly along the northern edge of the cyclone,
with stronger southerly flow well away from the cyclone near western Iceland (Figure 9d).



<julian.quinting@uni-koeln.de> Di 28.07, 23:02 Hi Svenja, Many thanks

Figure 8. Perturbation 850 hPa relative vorticity (shaded, 10^{-5} s^{-1}) and wind speed (vector, m s^{-1}) associated with low-level potential vorticity anomalies (a) 24 h before peak intensity of Harry, (b) at peak intensity of Harry, (c) 24 h before peak intensity of Tini, and (d) at peak intensity of Tini. The cyclone center from the Hodges tracking algorithm at each timestep is denoted with the yellow circle.

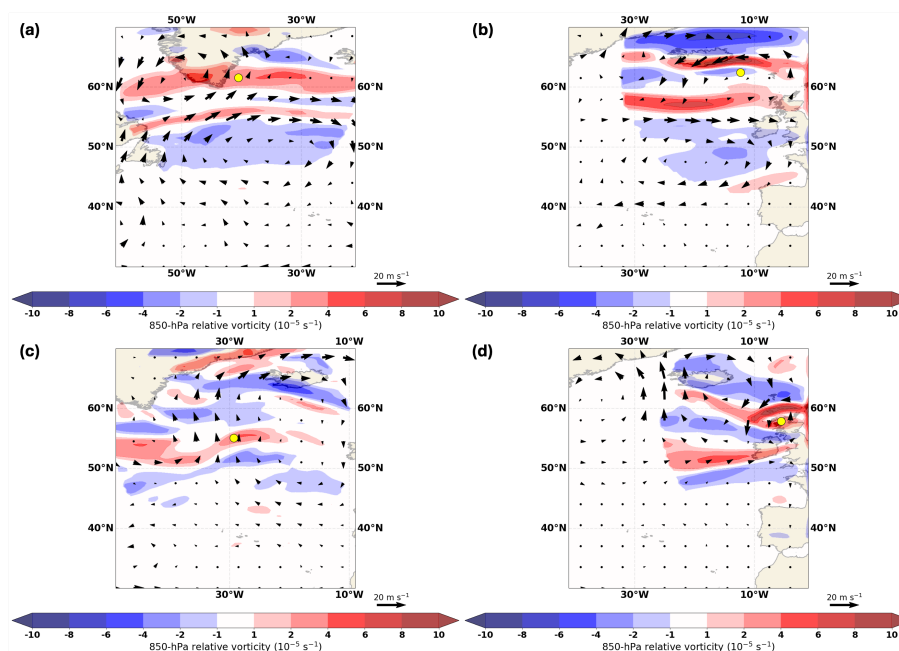


Figure 9. Perturbation 850 hPa relative vorticity (shaded, 10^{-5} s^{-1}) and wind speed (vector, m s^{-1}) associated with mid-level potential vorticity anomalies (a) 24 h before peak intensity of Kerstin, (b) at peak intensity of Kerstin, (c) 24 h before peak intensity of Friedhelm, and (d) 6 h before peak intensity of Friedhelm. The cyclone center from the Hodges tracking algorithm at each timestep is denoted with the yellow circle.



Table 1. Summary of the four analyzed cyclones. MeanDiabCont denotes the mean diabatic contribution to PTE, while PV inversion (PPVI) indicates the relative contribution from lower-, mid-, and upper-tropospheric PV to 850 hPa relative vorticity.

%	Tini	Kerstin	Harry	Friedhelm
MeanDiabCont	80	9	53	19
PPVI Lower	38	28	69	71
PPVI Mid	25	53	14	21
PPVI Upper	36	19	17	8

345 **5 PV inversion compared to PTE and Discussion**

Our objective is to evaluate the degree to which the PTE and PV inversion approaches consistently classify cyclones and identify the importance of diabatic heating to cyclone intensification. In the following, we discuss how well the results agree and to what extent they are comparable. Generally, the results obtained with the PTE and PV inversion agree well with results from other studies that applied the methods on cyclones before. While the choice of vertical partitioning of PV varies, our results are in line with the variability of other PV inversion studies (e.g., Seiler, 2019). The relative contributions from diabatic processes quantified with the PTE widely vary from case to case, and generally our results agree with other studies (Christ et al., 2025; Fink et al., 2012; Pirret et al., 2017).

Overall, the PTE and the PV inversion approach agree well for two of the cyclones, namely Harry and Kerstin, for Tini to a large extent. However, they indicate differences in the dominant contributions to cyclone intensification for Friedhelm (Table 1). With the PTE approach, Harry is classified as a diabatically driven cyclone, with substantial relative contribution of diabatic heating, in particular in the time from -36 to -12 h (Figure 6c). Also, the PV inversion method identifies strong lower-level forcing, indicating a diabatic heating contribution to cyclone intensification. Kerstin is classified as a baroclinically driven cyclone with the PTE, where horizontal temperature advection dominates the surface pressure decreases. With the PV inversion, mid-level PV forcing is found to dominate, supporting the conclusion drawn from the PTE. Tini is classified as a diabatically influenced cyclone with the PTE, with well above average mean diabatic heating contributions. Tini is a secondary frontal-wave cyclone associated with a sting jet and a WCB, which also suggests a strong diabatic influence. For Tini, the diabatic contributions are more indirectly supported by the PV inversion method, which does not attribute cyclone development solely to low-level PV forcing; mid and upper-levels are important as well. Diabatic contributions are supported by mid-level PV contributions corresponding well with the time of the WCB. Regarding Friedhelm, previous studies indirectly suggest a strong diabatic influence, as Friedhelm featured a sting jet and developed as a secondary frontal-wave cyclone (Gray et al., 2024). Moreover, Friedhelm is associated with a WCB. These characteristics indeed suggest that diabatic heating is important. The PV inversion method supports this interpretation by identifying strong low-level PV forcing. In contrast, the PTE approach does not classify Friedhelm as strongly diabatically influenced. Also using the PTE framework, the same conclusion regarding the diabatic contributions to Friedhelm is presented in Pirret et al. (2017). Notably, Friedhelm and Tini are smaller-scale systems



than Harry and Kerstin; this may contribute to discrepancies between the PTE and PV inversion methods. Regarding the WCB inflow, Friedhelm and Harry have a larger footprint compared to Tini and Kerstin. In comparison, WCB ascent is similar across all four cases. WCB ascent contributes to the generation and modification of low- to mid-level PV anomalies diagnosed in the PV inversion approach, which are reflected in the thermodynamic contributions to surface pressure deepening captured by the PTE method. Hence, WCBs provide a physical link between diabatic heating and cyclone intensification in both frameworks. Nevertheless, a direct scaling between WCB ascent footprint size and diabatic heating is not apparent for our four cases.

Both our methods rely on different approaches and therefore capture different aspects of cyclone development. PTE captures the thermodynamic contribution to cyclone deepening, whereas PV inversion resolves the dynamical pathways through which these contributions are expressed in different layers. The PTE approach considers the entire atmospheric column, whereas the PV inversion method differentiates between different vertical layers. For instance, temperature advection can occur in both the lower and upper troposphere, contributing to TempAdv in the PTE framework, irrespective of their vertical origin. In the PV inversion method, this would be attributed to different layers. Therefore, it is sensitive to the partitioning of PV anomalies across the choice of layers, which can influence the contribution of forcing mechanisms. This could be another reason for the discrepancies found between the PTE and the PV inversion. Further, the PV inversion only indirectly represents diabatic processes, as it captures them indirectly through PV anomalies. For example, lower-tropospheric PV contributions have been associated with diabatic heating by Dolores-Tesillos et al. (2022). A limitation of the PTE method as applied here is that diabatic heating tendencies are calculated as a residual. For instance, ICON simulations of Friedhelm, which explicitly resolve diabatic heating tendencies, indicate larger diabatic contributions (not shown). For this case, the residual-based approach yields positive residuals, which partially offset and thus reduce the diagnosed diabatic heating contribution. Nevertheless, tests using explicit heating rates in auxiliary material in Pohle (2010) and Fink et al. (2012) show that those implicitly calculated are usually fairly similar to diabatic heating tendencies calculated from residuals. Another limitation is that the PTE assumes a constant background state, which means that only the eddy effects are considered, while the influence of the background climatology is not accounted for. Still, we argue that the PTE is suitable for quantifying the different processes contributing to cyclone intensification. PV inversion relies on inverting only the rotational component of the total flow, assuming that the irrotational component of the flow is much smaller on the synoptic to planetary scale. While this assumption is often valid for similar cases (e.g., Davis and Emanuel, 1991; Beaty et al., 2025), it needs to be considered when interpreting the results. Moreover, the approach remains difficult to apply for a large number of cases due to its higher computational costs.

6 Summary and Conclusions

This study combines complementary diagnostic approaches to better constrain the importance of diabatic processes to the development and intensification of extratropical cyclones. By applying the PTE and PV inversion methods, we quantify uncertainties in the contribution of diabatic processes to cyclone intensification across four representative European winter storms. The role of WCB activity is assessed with ELIAS (Quinting and Grams, 2022), while uncertainties associated with cyclone



tracks are evaluated through the application of two independent tracking algorithms (Pinto and Hodges tracking algorithms). With respect to the main research questions (outlined in Section 1), the key findings can be summarized as follows:

1. Are cyclones consistently classified as diabatically-driven using both methods?

405 Cyclones are mostly consistently classified by the PTE and PV inversion methods, indicating a general agreement between the two approaches. Remaining differences arise in individual cases, reflecting that the methods emphasize different aspects of cyclone intensification.

2. Do cyclones classified by the PTE as diabatically driven actually exhibit a stronger contribution from mid- and lower-tropospheric PV anomalies? When in the lifecycle does diabatic heating contribute to cyclone intensification, and through which features does PV contribute to cyclone intensification?

410 Cyclones with strong diabatic heating contributions tend to be associated with enhanced low- to mid-level PV forcing, highlighting a clear link between the diagnostics. For the diabatically influenced cyclones Tini and Harry, PV contributions are concentrated in the frontal circulation. In contrast, Kerstin's mid-level forcing is more strongly linked to shear in the jet region rather than diabatic heating. Additionally, we find diabatic heating contributes to cyclone intensification within the WCB ascent region. For less diabatically influenced cyclones, diabatic contributions are mainly confined to the period close to peak intensity, whereas for diabatically driven cyclones, they appear earlier, extending up to 36 h before peak intensification.

3. How much does the cyclone tracking method applied contribute to uncertainty in the PTE method?

420 The PTE approach shows weak sensitivity to the choice of cyclone tracking algorithm, with the Pinto and Hodges methods yielding consistent results on the same dataset. This suggests that PV inversion would lead to similarly consistent conclusions, regardless of the tracking method used.

We concluded that both methods are useful to constrain the diabatic influence from complementary perspectives, and we demonstrate that both are able to quantify the role of diabatic processes in cyclone intensification. However, uncertainties remain on a case-by-case basis. The two methods can sometimes lead to different conclusions because they emphasize different aspects and have different strengths. The combination of PTE and PV inversion reveals that diabatic heating is not a single, uniquely defined quantity, but depends on the diagnostic perspective (Wernli and Gray, 2024). Both methods are able to distinguish processes that are important for cyclone development and therefore have the potential for a systematic evaluation of weather and climate models. A systematic analysis for a much larger sample of cyclones was already done with the PTE (Christ et al., 2025) and is planned for the PV inversion methods. Further, both diagnostics can be used to estimate uncertainties in the projected response of cyclones to a warming climate (Catto et al., 2019), specifically, to better understand how different processes interact and to assess how increased diabatic heating may feed back to cyclone intensity and impacts (Pinto et al., 2019). In future studies, the PTE will be applied to quantify diabatic heating contributions to changes in storyline simulations (Shepherd et al., 2018; Klimiuk et al., 2025) of windstorms and the PV inversion will be applied to a wider range of cyclones in climate models.



435 *Data availability.* ERA5 data used in this study are freely available in the Copernicus Climate Change Service Climate Data Store (doi.org/10.24381/cds.bd0915c6). The Pinto track data are available upon request, and WCB mask data are publicly available in RADAR4KIT (DOI: [10.35097/8bcudgfv56rb9uvk](https://doi.org/10.35097/8bcudgfv56rb9uvk)). The Hodges track data, PV inversion code, and output files of the PV inversion are available upon request.

Author contributions. SC, TL, JC, JQ, and JGP developed the design and conceptualization of this study. SC and TL performed the analyses and wrote the original draft of the manuscript. JM developed the PV inversion implementation. JQ provided the WCB masks dataset. SC
440 produced the PTE results, and JGP developed the Pinto tracking. All authors contributed to the discussions and revisions of the manuscript.

Competing interests. The authors have no competing interests to declare.

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