A PV Perspective on the Vertical Structure of Mature Midlatitude Cyclones in the Northern Hemisphere

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ABSTRACT

Development of extratropical cyclones can be seen as an interplay of three positive potential vorticity anomalies: an upper-level stratospheric intrusion, low-tropospheric diabatically produced potential vorticity (PV), and a warm anomaly at the surface acting as a surrogate PV anomaly. This study, based on the interim ECMWF Re-Analysis (ERA-Interim) dataset, quantifies the amplitude of the PV anomalies of mature extratropical cyclones in different regions in the Northern Hemisphere on a climatological basis.

A tracking algorithm is applied to sea level pressure (SLP) fields to identify cyclone tracks. Surface potential temperature anomalies \( \Delta \theta \) and vertical profiles of PV anomalies \( \Delta PV \) are calculated at the time of the cyclones’ minimum SLP in a vertical cylinder around the surface cyclone center. To compare the cyclones’ characteristics they are grouped according to their location and intensity. Composite \( \Delta PV \) profiles are calculated for each region and intensity class at the time of minimum SLP and during the cyclone intensification phase.

In the mature stage all three anomalies are on average larger for intense than for weak winter cyclones [e.g., 0.6 versus 0.2 potential vorticity units (PVU; 1 PVU = \( 10^{-6} \) K kg\(^{-1}\) m\(^2\) s\(^{-1}\)) at lower levels, and 1.5 versus 0.5 PVU at upper levels]. The regional variability of the cyclones’ vertical structure and the profile evolution is prominent (cyclones in some regions are more sensitive to the amplitude of a particular anomaly than in other regions). Values of \( \Delta \theta \) and low-level \( \Delta PV \) are on average larger in the western parts of the oceans than in the eastern parts. Results for summer are qualitatively similar, except for distinctively weaker surface \( \Delta \theta \) values.

1. Introduction

a. Cyclone climatologies and climatologies of their characteristics

Extratropical cyclones are the most important actors in determining daily weather in midlatitudes because of the strong winds and intense precipitation typically associated with them. Therefore, understanding of their structure and dynamics is of great importance for providing a reliable weather forecast. Several recent climatological studies deal with extratropical cyclones and their properties. Most of them present regions of enhanced cyclone track density and regions of cyclone genesis or lysis (e.g., Whitaker and Horn 1984; Hoskins and Hodges 2002; Wernli and Schwierz 2006). Although using different methods of cyclone identification and tracking, they all found some pronounced features such as the Atlantic and the Pacific storm tracks and a secondary maximum of cyclone frequency over the Gulf of Genoa.

Several climatologies also consider other cyclone characteristics such as cyclone size, intensity, propagation velocity, asymmetry (e.g., Simmonds and Keay 2000; Gulev et al. 2001; Rudeva and Gulev 2007; Lim and Simmonds 2007; Rudeva 2008), or associated precipitation (Chang and Song 2006; Field and Wood 2007; Rudeva and Gulev 2011). The latter studies found the maximum of precipitation immediately to the northeast of the cyclone center. Chang and Song (2006) investigated North Pacific and North Atlantic cyclones and found large seasonal differences in the amount of precipitation. North Pacific cyclones have the highest amount of precipitation in fall and the lowest in summer, but the spatial extent of precipitation around the cyclone is the largest in winter.
Comparisons between seasons show that the differences are largest in the area of highest precipitation rate. The North Atlantic cyclones are slightly weaker and have all in all less precipitation. The maximum is approximately equal in fall and winter and weaker in spring and summer. The differences are equally distributed over the whole cyclone area. Field and Wood (2007) composited cyclones according to their intensity (in terms of surface winds speed) and moisture content. They show that for cyclones of the same wind speed intensity, those with more moisture have a slightly higher sea level pressure (SLP) than the drier ones. Therefore the dynamical effect of precipitation processes is also to produce stronger winds in the cyclones that do not have very low SLP.

Rudeva and Gulev (2011) found similar distributions of precipitation in North Atlantic cyclones of different intensity. They combined cyclones according to the stage of their life cycle and showed that precipitation is strong in the cyclone’s forward part in the first half of the life cycle and reduces rather quickly as the cyclone enters the decaying phase. They also found differences in the precipitation pattern in cyclones in different North Atlantic regions. Besides precipitation, they investigated the distribution of heat fluxes, heat content, and precipitable water in North Atlantic cyclones. Mass and Dotson (2010) considered the structure of the strongest cyclones in the northwestern United States. They found the strongest winds southeast of the cyclones and interestingly a cold temperature anomaly at 850 hPa in the center. A bent-back warm front was found to be a typical feature of these storms.

Considering the structure of extratropical cyclones is also an important aspect when evaluating climate model simulations. Bauer and Del Genio (2006) and Catto et al. (2010) compared composites of extratropical cyclones in general circulation models (GCMs) with those from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40). Bauer and Del Genio (2006) found fewer, weaker, and more slowly moving cyclones in a GCM. In addition, vertical velocities were underestimated, which has consequences for the evolution of water vapor, clouds, and precipitation associated with extratropical cyclones. Catto et al. (2010) used a high-resolution GCM and found that the general structure of the 50 strongest cyclones in the North Pacific and the North Atlantic in the GCM compared well with those in ERA-40, although the vertical velocity and relative humidity were not well represented.

A key element for the dynamical understanding and classification of extratropical cyclones is their vertical structure. Classically, cyclones develop along the leading edge of a pronounced upper-level trough moving over an intense baroclinic zone leading to a westward tilt with height of the axis of minimum geopotential or of the axis connecting the surface warm anomaly with the upper-level potential vorticity (PV) anomaly (Hoskins et al. 1985). Early studies emphasized this role of large-amplitude upper-level disturbances and made use of satellite imagery to investigate the structure of cyclones [see, e.g., the review by Reed (1990)]. Later, with the focus shifting to studying rapidly intensifying extratropical cyclones, low-level processes (e.g., thermal advection and surface fluxes) were also considered essential for understanding the evolution and structure of the storms (e.g., Uccellini 1990). Comparatively little attention has been paid so far to investigating the climatology of the vertical PV structure of extratropical cyclones. Wang and Rogers (2001) first presented composite vertical structures of PV and wind speed for explosively deepening cyclones in the North Atlantic. They showed an upper-level anomaly approaching before the deepening phase and a low-level PV generation shortly before the cyclones attain maximum intensity. At the time when both anomalies are developed, they create a coherent cyclonic circulation around the center from the tropopause all the way to the surface. This aspect of the generation of vertically coherent “PV towers” will be discussed further in the next subsection. Lim and Simmonds (2007) investigated cyclone characteristics on different levels between sea level and 500 hPa in the Southern Hemisphere. In their study vertically well-organized cyclones are larger and deeper and last longer than shallow systems. Most of the cyclones have a westward tilt in their mature stage and the surface center and the center at 500 hPa are 300 km apart. They found especially explosive cyclones to be vertically well organized, with a slightly larger tilt than for “normal” cyclones, which assists in releasing baroclinic energy in favor of the development of these cyclones. However, these explosive cyclones reach their maximum intensity earlier at the surface than at 500 hPa, which highlights the importance of surface fluxes, diabatically produced positive PV anomalies, and reduced static stability for the rapid development.

Deveson et al. (2002) classified 16 cyclones from the Fronts and Atlantic Storm Track Experiment (FASTEX) according to the contributions of the forcing from upper and lower levels to the vertical motion \((U/L)\) ratio and their vertical tilt. In addition to previously known type-A and type-B cyclones, they identified a new category of type-C cyclones. These are strongly upper-level-dominated cyclones with an increasing tilt during the development phase. Gray and Dacre (2006) applied this classification to a larger set of cyclones. They found that cyclones with a small \((U/L)\) ratio and higher values of low-level vorticity are more likely to be developing cyclones. Another detailed climatology of North Atlantic cyclones...
by Dacre and Gray (2009) showed that most developing cyclones are generated over the sea, which may be because of the availability of a moisture source and of reduced friction compared to land. Their study also showed that the cyclones generated in the eastern North Atlantic have lower SLP and higher relative vorticity in the center at the time of genesis than western North Atlantic cyclones, but the latter start in an environment with a stronger horizontal SST and wet-bulb potential temperature gradient. They found that PV at a height of 1 km at the time of horizontal SST and wet-bulb potential temperature gradient. They found that PV at a height of 1 km at the time of maximum cyclone intensity is higher for cyclones generated in the eastern North Atlantic and their $U/L$ ratio is lower throughout their life cycle than for eastern North Atlantic cyclones.

This paper adopts a PV perspective to investigate in a climatological way the vertical structure of mature extratropical cyclones and the relationship between the cyclones’ vertical PV structure and their intensity and geographical region. Since the study of Hoskins et al. (1985), PV has been established as the key variable that enables a fruitful view of dynamical processes and has been used in many studies on cyclogenesis. In this framework, cyclone evolution can be seen as the development and interaction of positive PV anomalies at different levels (including a positive potential temperature anomaly at the surface). A detailed analysis of the PV profile of a climatological set of cyclones can thus provide valuable insight into the processes involved in their development and the factors determining their intensity (measured in this study as the cyclones’ minimum sea level pressure).

### b. PV towers

From a PV point of view, mainly three distinct positive PV anomalies determine the evolution of an extratropical cyclone: an upper-level stratospheric intrusion, a low-tropospheric diabatically produced PV anomaly, and a warm surface anomaly of potential temperature $\theta$ that corresponds to a positive PV anomaly (e.g., Davis and Emanuel 1991; Kuo et al. 1991). As shown in several case studies, in the mature stage of the cyclone development the three involved anomalies often become vertically aligned and form a so-called PV tower, representing a troposphere-spanning column of air with anomalously high PV values [typically 1–4 potential vorticity units (PVU; $1 \text{ PVU} = 10^{-6} \text{ K kg}^{-1} \text{ m}^{2} \text{ s}^{-1}$)]. It induces a strong cyclonic circulation reaching from the surface to the tropopause. In this framework, cyclone formation and intensification can be regarded as the generation and interplay of these PV anomalies that form through both adiabatic (upper-level PV) and diabatic (low-level PV) processes.

Several studies of rapidly deepening extratropical cyclones found such a pronounced PV tower in the center of the cyclone, for example case studies of the “October storm” (Hoskins and Berrisford 1988), the “Presidents’ Day Cyclone” (Uccellini et al. 1987; Whitaker et al. 1988), the “Superstorm of 1993” (hereafter simply Superstorm; Bosart et al. 1996; Dickinson et al. 1997), and the winter storm “Lothar” (Wernli et al. 2002). A very recent example is the North Atlantic cyclone “Xynthia” that led to extreme winds in western Europe on 27–28 February 2010. Figure 1 shows vertical cross sections of PV through the centers of the mature cyclones Superstorm, Lothar, and Xynthia, respectively. The fields shown are calculated from interim ECMWF Re-Analysis (ERA-Interim) data. In all cases we can distinguish two distinct positive PV anomalies: one at upper levels of stratospheric origin and one at low levels that has been diabatically produced. PV values in this low-level anomaly reach up to more than 3 PVU, which is much higher than climatological tropospheric values of about 0.5 PVU. The corresponding surface $\theta$ anomalies are given in Table 1 together with the amplitude of the upper- and lower-level anomalies, calculated as the vertical average between 200 and 400 hPa, and 650 and 900 hPa, respectively. All variables are averaged within a circle around the cyclone with a radius of 200 km. All three storms have a low-level PV anomaly in approximately the same range. The anomaly in Lothar seems to be weaker, but this is due to the fact that the maximum of its low-level PV anomaly lies close to the upper end of the averaging interval. The surface anomaly of the Superstorm is clearly smaller than for Lothar and Xynthia, but its upper-level anomaly is particularly pronounced. These examples illustrate on the one hand the presence of the three aforementioned PV anomalies in intense cyclones, and on the other hand indicate a significant case-to-case variability in the relative magnitude of the three anomalies.

All these storms were extremely strong and caused considerable damage and casualties. However, a PV tower is also a typical feature of most “normal” mature cyclones. Rossa et al. (2000) investigated the life cycle of such a PV tower associated with a North Atlantic cyclone that developed from a frontal wave disturbance. Using a Lagrangian analysis technique they found that the high-PV air constituting the tower came from three separate regions: an adiabatic intrusion of stratospheric air at upper levels, a midtropospheric component originating from diabatically produced PV along the cold front, and a low-tropospheric component due to diabatic PV production in an airstream moving along the prominent warm front. A similar study (Reed et al. 1992) considered also the surface thermal anomaly, finding that the surface anomaly was primarily caused by northward transport of warm air into the vicinity of the cyclone. Similarly to the study of Rossa et al. (2000), the upper-level high-PV air subsided from the stratosphere and the low-level positive anomaly resulted from
condensational PV production during the rapid ascent of air at the warm front.

These and several other case studies highlight the crucial role of this diabatically produced part of the PV structure of extratropical cyclones. Numerical simulations with suppressed latent heating (e.g., Uccellini et al. 1987; Kuo et al. 1991, 1995; Wernli et al. 2002) produced much weaker cyclones than the full-physics control simulations, in agreement with the fact that in these simulations the low-level PV anomaly was missing. Moist processes therefore play an important role in the evolution of (intense) extratropical cyclones.

Davis and Emanuel (1991) were the first to use the technique of PV inversion to study the relative contribution of the three anomalies constituting a PV tower to the overall cyclonic circulation. Each anomaly contributed to the vorticity in the lower troposphere, but the contribution of the diabatically produced low-level PV was the largest, followed by the surface potential temperature anomaly. The upper-level anomaly accounted only for a small amount of the lower-tropospheric vorticity. Davis (1992) and Davis et al. (1996) used the same method to estimate the relative contributions from different levels to the intensification of a continental and a marine cyclone, respectively. In the continental cyclone, the largest contribution came from the surface anomaly, whereas in the marine cyclone both the tropopause-level and the low-level PV anomalies contributed more to the surface circulation than the warm surface anomaly. This indicates that because of their direct access to water, marine cyclones can typically produce a positive low-level PV anomaly sooner and more strongly than continental cyclones, which is most likely of relevance for the fact that most intense cyclones occur over the oceans (e.g., Wang and Rogers 2001; Dacre and Gray 2009).

Later, several other cyclones were investigated with the piecewise PV inversion technique (e.g., Huo et al. 1999) to diagnose the horizontal and vertical interaction of the distinct PV anomalies.

This study will investigate the vertical PV structure of mature extratropical cyclones and the amplitude of the surface potential temperature anomaly on a climatological basis in the Northern Hemisphere, for the winter and summer seasons. A comprehensive set of cyclones will be investigated to address the following three main questions:

(i) Is there a difference in the vertical structure between strong and weak mature extratropical cyclones (where cyclone intensity will be measured in terms of minimum SLP)?

(ii) Are there any structural differences between mature extratropical cyclones in different regions?

FIG. 1. West–east-oriented vertical sections of PV (PVU) across the center of three mature extratropical cyclones for (a) the Superstorm of 1993 at 39°N at 0000 UTC 14 Mar 1993, (b) Lothar at 49°N at 0600 UTC 26 Dec 1999, and (c) Xynthia at 46°N at 0000 UTC 28 Feb 2010.
Table 1. Upper-level PV anomaly (ΔPV; vertical average between 200 and 400 hPa, PVU), low-level PV anomaly (ΔPV, vertical average between 900 and 650 hPa, PVU), and surface θ anomaly (Δθ, K) for the three mature cyclones shown in Fig. 1.

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>ΔPV (200–400 hPa) (PVU)</th>
<th>ΔPV (650–900 hPa)</th>
<th>Δθ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstorm</td>
<td>3.14</td>
<td>1.16</td>
<td>2.76</td>
</tr>
<tr>
<td>Lothar</td>
<td>1.13</td>
<td>0.79</td>
<td>5.24</td>
</tr>
<tr>
<td>Xynthia</td>
<td>0.99</td>
<td>1.13</td>
<td>6.60</td>
</tr>
</tbody>
</table>

(iii) How does the PV profile typically evolve during the intensification of extratropical cyclones?

The answers to these questions will shed light on the relative importance of the processes involved in the formation of mature cyclones.

2. Data and methods

This study is based on the ERA-Interim dataset from 1989 to 2009. It has several advantages compared to the previous ERA-40 reanalysis related to improved model physics, increased resolution (T255L60 versus T159L60), and an advanced data assimilation procedure [four-dimensional variational data assimilation (4D-Var)] with a 12-h window versus 3D-Var]. The data are available every 6 h. The original fields were interpolated onto a 1° × 1° regular grid and the PV field was calculated from the wind and temperature fields on the model levels and then interpolated on a stack of pressure levels (every 25 hPa between 1000 and 100 hPa).

The cyclones were identified and tracked using the algorithm introduced by Wernli and Schwierz (2006). The algorithm searches for minima in the SLP field and, for every SLP minimum, identifies the outermost closed contour that does not enclose another minimum. Information such as the position of the surface cyclone center, its area, and the central SLP value are available for further analyses. The tracking algorithm joins central points of cyclones at consecutive time steps into cyclone tracks in order to follow the cyclones’ life cycles. For the first step, the algorithm links two sufficiently nearby points at the first and second time. For all further steps the first guess for the new cyclone position is calculated as a linear continuation of the track in the previous step. The minimum closest to the first guess is taken as the continuation of the track, if the distance does not exceed a certain threshold [1000 km; see Wernli and Schwierz (2006) for further details].

For every cyclone track, vertical profiles of PV anomalies ΔPV and potential temperature anomalies at the surface Δθ were calculated for each time step during the 24 h before the cyclone reached its minimum SLP. (If a cyclone’s track prior to reaching its minimum SLP is shorter than 24 h, then only the available time steps were considered.) Anomalies were defined as deviations from a climatological background value at the same location, taken as the 21-yr ERA-Interim winter [December–February (DJF)] and summer [June–August (JJA)] average, respectively. At each point of the 24-h cyclone track interval and at all levels between 975 and 100 hPa, PV was horizontally averaged in a circle with a radius of 200 km around the cyclone center. The resulting values at each level (every 25 hPa) constitute the cyclone’s PV profile at the given time. The horizontal averaging has been done in order to obtain a robust measure of PV close to the cyclone center. Accordingly, anomalies of potential temperature at the surface were calculated within circles with a radius of 200 km around each cyclone center. The choice of this particular radius will be commented on below in the results section. For the climatological investigation composites were computed from the individual ΔPV profiles and surface Δθ values for different categories of cyclones and during different stages of the cyclone evolution. The categories are based on cyclone intensity (measured in terms of minimum SLP) and the cyclones’ geographical position.

3. Results

a. The Superstorm of 1993

First, as an illustrative example, we consider the PV profile around the center of the Superstorm of 1993 at 0000 UTC 14 March 1993, when the cyclone reached maximum intensity, and 12 and 24 h prior to this time. The profiles of PV and ΔPV are shown in Fig. 2. One day before the time of maximum intensity, the central SLP was 994 hPa (according to the ERA-Interim data) and a significant positive low-level PV anomaly was already present. Averaged PV values between 900 and 650 hPa ranged between 1.3 and 1.5 PVU, about 1.1 PVU above the climatological background value. Above this anomaly, there was a region of low-PV air between 500 and 300 hPa and the dynamic tropopause (2-PVU line) was located near 250 hPa. This indicates the absence of a stratospheric intrusion directly above the cyclone center at this early time of the cyclone intensification. Note that the profiles are calculated vertically at the position of the surface cyclone center and therefore stratospheric air is only considered if it comes closer than 200 km to the center.

This happened in the next 24 h, which was also the time period of the strongest cyclone intensification. Between 0000 UTC 13 March and 0000 UTC 14 March the central SLP decreased by 33 hPa and reached a minimum value of 961 hPa. In this period a very pronounced stratospheric anomaly became located above the surface center, and
also the low-level PV anomaly further increased. Approaching of stratospheric air with high PV values can be seen in Fig. 2a as a lowering of the tropopause and in Fig. 2b as a lowering and growth of the upper-level anomaly, which, in the end, is largest between 200 and 300 hPa. At 0000 UTC 14 March the PV values are higher than 1 PVU throughout the whole troposphere, which Rossa et al. (2000) referred to as a PV tower. The low-level PV values are higher than 2 PVU and the 2-PVU tropopause pressure is approximately at 550 hPa. There is a PV minimum at approximately 700 hPa, which is the consequence of the fact that the two anomalies are not perfectly vertically aligned (cf. Fig. 1a). They are slightly tilted and therefore the anomalies do not lie wholly within the averaging radius.

The surface \(\theta\) anomaly in the core region of the cyclone increased in this 24-h time period from around \(-1\) to 2.76 K at the time of maximum intensity. Compared to other intensive extratropical cyclones, this value is not particularly high (see later). Therefore, it appears that the two PV anomalies in the interior of the atmosphere are more important for the high intensity of this particular cyclone.

b. Composites of Northern Hemisphere cyclones

A similar analysis was performed for all cyclones with a minimum lifetime of 24 h (and not lasting longer than 10 days) in the whole Northern Hemisphere. Figure 3 shows composite PV anomaly profiles for two intensity categories of Northern Hemisphere winter (DJF) cyclones at the time of maximum intensity. The black line represents the mean value on each level, and the interval between the 10th and 90th percentiles is shaded. The mean value and the percentiles are calculated on each level separately. Therefore the lines denoting the mean and the percentiles do not represent single profiles but just connect the separately calculated values on different levels.
In the left panel the profile for 1367 intense cyclones with a minimum SLP between 930 and 970 hPa is shown. The composite mean low-level PV anomaly has its maximum of 0.7 PVU at 825 hPa and the 90th percentile reaches up to 1.3 PVU. On average, PV anomalies are positive throughout the whole troposphere and higher than 0.5 on many levels. Note that climatological tropospheric PV values are approximately 0.5 PVU. The PV anomaly at upper levels is largest at 300 hPa (2.5 PVU). In contrast, for relatively weak cyclones (4222 cyclones with a minimum SLP between 990 and 1010 hPa, shown in the right panel), the average upper-level anomaly is much smaller (0.8 PVU) and the variability is larger. It is noteworthy that the formation of positive upper-level PV anomalies goes along with a lowering of the dynamical tropopause. Typically, more intense upper-level PV anomalies correspond to a higher tropopause pressure. At lower levels, the average PV anomaly value is about 0.3 PVU for the weak cyclones.

Surface $\theta$ anomalies are very similar for these two cyclone classes. The average value for the strong cyclones on the left is 5.7 K, and for the weaker cyclones 4.91 K. Overall the surface $\theta$ anomalies of the first three intensity classes are very similar if we consider all cyclones in the Northern Hemisphere and only the weakest cyclones have a distinctly lower surface anomaly (see Fig. 8b).

We have calculated all of these profiles using the same radius of 200 km. Figure 4 shows the same profiles calculated for different radii from $r = 100$ km to $r = 300$ km. The smaller the radius, the larger the $\Delta PV$ values, which points to the fact that high PV air is really concentrated in the center of a cyclone. Differences between the profiles occur only in the amplitude and not in the structure of the PV anomaly. The relatively large fractional variation of the low-level PV in the intense cyclones indicates that these PV anomalies are more compact than the ones at upper levels. Therefore we decided to use $r = 200$ km, which appears to be a reasonable choice to cover the spatial extent of the most important anomalies near the cyclone center and to not smear the differences between the profiles of different cyclone categories.

c. Regional differences

When investigating the regional variability of PV profiles associated with mature cyclones we focus on the regions shown in Fig. 5. They were subjectively chosen based on the cyclone frequency climatology of Wernli and Schwierz (2006). The cyclones are assigned to a certain region if they reach their maximum intensity within this region. Already here we notice that the number and the intensity of cyclones differ strongly between the various regions. For instance, there are relatively few cyclones that reach their maximum intensity in the western North Atlantic (referred to as Watl) and eastern North Pacific (Epac) regions, while the regions in the eastern North Atlantic (Eatl), between Greenland and Iceland (Green), and in the Gulf of Alaska (Alas) are well occupied. The strongest cyclones appear more often in the northerly regions (the tracks in Fig. 5 are colored with their central SLP value). The Mediterranean (Med) cyclones are quite numerous but they are much weaker compared to the cyclones in the other regions. We have found no cyclones with a minimum SLP below 970 hPa in the Mediterranean. The numbers of winter cyclones in different regions and for various intensity categories are summarized in Table 2. Hereafter we only consider the categories with at least five cyclones to assure some statistical reliability.

In Fig. 6 we compare the PV profiles of cyclones in the western North Pacific (Wpac) and in the eastern North Atlantic, again for deep and moderately intense cyclones. The most pronounced differences between the two regions occur for the strongest cyclones. While the average $\Delta PV$ values in the lower troposphere reach up to 1.5 PVU in the western North Pacific, they are less than 0.7 PVU in
the eastern North Atlantic. In both ocean basins, cyclones in the western part exhibit higher values of low-level PV than those in the eastern part (not shown). This is consistent with the results from Dacre and Gray (2009), who found that average PV values at 1-km height in cyclones in the eastern North Atlantic are slightly lower than those in the western North Atlantic cyclones. The weaker cyclones in the two regions have on average very similar values of low-level PV.

A comparison between the upper-level anomalies reveals that ΔPV in the upper part of the profile differs strongly in the two regions. The overall values are much higher in the eastern North Atlantic but the differences are larger in the western North Pacific. Variability of upper-level ΔPV is especially large for the weaker cyclones. The shaded area ranges from ~2 to 5 PVU in the eastern North Atlantic, and in the western North Pacific it is shifted to even more negative values. This could

FIG. 5. Regions where cyclone profiles have been evaluated. The symbols are used to mark cyclones from these regions in the following figures. The considered regions (see black boxes) are (a) the western North Atlantic (diamond) and the western North Pacific (circle), (b) the eastern North Pacific (horizontal triangle) and the eastern North Atlantic (pentagram), (c) the region between Greenland and Iceland (triangle) and the Mediterranean (cross), and (d) the Gulf of Alaska (square) and western Europe (asterisk). Cyclone tracks are shown for all winter (DJF) cyclones that reach their minimum SLP within the specified regions. They are colored according to their central SLP (hPa).
imply that some cyclones in these regions can develop in the absence of significant upper-level forcing. The average height of the upper-level $\Delta PV$ maximum in the eastern North Atlantic varies between 225 (weak cyclones) and 275 hPa (strong cyclones). We cannot see such a clear difference in the height of the upper-level anomaly in the western North Pacific, but the course of the 90th percentile suggests that the height is very variable for weaker cyclones there.

Surface $\theta$ anomalies are more intense in the western North Pacific but more variable in the eastern North Atlantic (cf. Fig. 8b). Strong western North Pacific cyclones are very warm with $\Delta \theta$ values of 6.5 K, while the anomaly of weaker cyclones amounts to 4.5 K. For eastern North Atlantic cyclones the corresponding values are 4.8 and 2 K, respectively.

Figure 7 compares the profiles in the region to the east of Greenland and over western Europe (Weur). The low-level PV anomalies are of similar amplitude in both regions, although we can see some structural differences for the weaker cyclones. Also, $\Delta PV$ at upper levels varies strongly between cyclones from different intensity classes in the Greenland region. The amplitudes of the upper-level anomalies are also much lower than in western Europe, where even weak cyclones still have high $\Delta PV$ values in the upper troposphere.

The key characteristics of the $\Delta PV$ profiles and surface $\theta$ anomalies of cyclones in different regions are summarized

<table>
<thead>
<tr>
<th>Region</th>
<th>All_nh</th>
<th>Alas</th>
<th>Green</th>
<th>Weur</th>
<th>Med</th>
<th>Wpac</th>
<th>Epac</th>
<th>Weur</th>
<th>Med</th>
<th>Wpac</th>
<th>Epac</th>
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<tr>
<td>930–970 hPa</td>
<td>1367</td>
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<td>218</td>
<td>33</td>
<td>0</td>
<td>21</td>
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<td>7</td>
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<td>59</td>
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</tr>
<tr>
<td>970–990 hPa</td>
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<td>134</td>
<td>64</td>
<td>18</td>
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<td>36</td>
<td>23</td>
<td>80</td>
<td></td>
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</tr>
<tr>
<td>990–1010 hPa</td>
<td>4222</td>
<td>49</td>
<td>46</td>
<td>75</td>
<td>283</td>
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<td>4</td>
<td>21</td>
<td></td>
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</tr>
</tbody>
</table>

Fig. 6. Average $\Delta PV$ profiles for cyclones with a minimum central SLP in the range of (a),(c) 930–970 and (b),(d) 990–1010 hPa for cyclones in (a),(b) the western North Pacific and (c),(d) the eastern North Atlantic. Shaded area is as in Fig. 3.
in Fig. 8. For various cyclone intensity categories the upper-level PV anomaly (averaged between 200 and 400 hPa) is displayed along the vertical axis, and the low-level PV anomaly (averaged between 650 and 900 hPa) along the horizontal axis in Fig. 8a. The surface potential temperature anomalies $\Delta \theta$ are shown in Fig. 8b. This representation allows us to easily compare the vertical PV structure of cyclones in different regions and for different intensity classes. Figure 8a shows that both the positive PV anomaly at upper levels and the diabatically
produced PV at lower levels are important for determining cyclone intensity. The most intense cyclones (blue symbol) have clearly higher values of all three variables than the weak ones (orange symbol). The averaged low-level ΔPV in weak cyclones in the whole Northern Hemisphere (symbols with a black edge) amounts to 0.2 PVU on average, while strong cyclones exhibit mean values of about 0.6 PVU. The surface \( \theta \) anomaly ranges from 2.7 to 5.7 K. Note that these ΔPV values are lower than the ones mentioned in the comparison of the PV profiles, because here we consider vertically averaged values and do not refer to the maxima. In this way it is easier to compare the different cyclones because the maxima are not always at the same height. It is also important to note that for the amplitude of the induced cyclonic circulation not only the maximum PV value in the vertical profile is relevant but also the contributions from several levels.

Again a look at characteristic values in different regions confirms the large regional variability. The symbols in Fig. 8 correspond to those used in Fig. 5. Comparing again four intensity categories, the western North Pacific cyclones (circles) have the largest variation in terms of low-level ΔPV (from 0.2 to 1.25 PVU), pointing to the crucial importance of this parameter for cyclone intensity in this region. Also cyclones in the eastern North Pacific and western North Atlantic exhibit large variability in this parameter. Differences in the upper-level ΔPV values are largest in the western North Pacific, eastern North Atlantic, and Greenland, western European, Mediterranean, and Alaskan (except the weakest) cyclones of different intensity categories exhibit less variability for both parameters.

The weakest cyclones near Greenland have rather high low-level PV values. These are stationary features above Greenland peaking between 700 and 800 hPa (peak values up to 4 PVU). Greenland is approximately 3000 m high and PV values on its surface can reach very high values, probably because of increased stratification due to diabatic cooling at the surface.

Figure 8b shows the corresponding surface \( \theta \) anomalies. As expected, the strongest cyclones have the highest positive potential temperature anomalies. The variability between the cyclones of different intensity categories is the largest for cyclones near Greenland and the smallest for cyclones in both North Pacific regions. The weakest Greenland cyclones even have a negative anomaly in the center, but since these are stationary cyclones above Greenland, this result might not be very representative of oceanic cyclones. We find the largest positive anomalies in the western parts of both oceans.

Several case studies have shown that very intense cyclones require diabatically produced low-level PV for their extreme deepening. This seems to be confirmed on a climatological basis by the results in Fig. 8. In the same area, more intense cyclones are on average associated with higher values of low-tropospheric PV (cyclones near Greenland being an exception). Interestingly, in particular Fig. 8a indicates sort of a kink in the relationship between the amplitudes of upper- and low-level PV; we cannot fit a straight line to the points in the plot. Obviously, the strongest cyclones (blue) differ from moderately strong cyclones (green) mainly in terms of the amplitude of low-level PV (and less so in terms of upper-level PV). This highlights the particular relevance of diabatic PV production for very intense cyclones. (Note that most case studies in the literature on the role of diabatically produced PV were made for very strongly intensifying systems.) This behavior also confirms the important role of interlevel interaction for cyclone intensification. Clearly, cyclones with strong anomalies on one level have the potential to strongly influence the flow on the other level, leading to strong interlevel interaction. It is also noted that cyclones that have a potential to become very strong often possess a significant low-level PV anomaly already at the beginning of the deepening phase (e.g., Gyakum et al. 1992).

Climatological studies (e.g., Wernli and Schwierz 2006) show that the cyclone frequency distribution changes with seasons. This is what we notice in this study, too. The numbers of summer (JJA) cyclones are displayed in Table 3. In Fig. 9 the same scatterplots shown in Fig. 8 for winter are now presented for summer. The number of cyclones in most of the selected regions is lower than in the winter, in particular of intense cyclones. Compared to the winter plot, some marks are missing in the summer plot because there were no cyclones with a certain intensity detected.

The pattern is similar to that in winter, but cyclones of a certain intensity class tend to have higher ΔPV values at both levels compared to winter cyclones. The low-level PV anomaly values of the cyclones with the central

<table>
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<th>Region</th>
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<th>Alas</th>
<th>Green</th>
<th>Weur</th>
<th>Med</th>
<th>Wpac</th>
<th>Epac</th>
<th>Watl</th>
<th>Eatl</th>
</tr>
</thead>
<tbody>
<tr>
<td>930–970 hPa</td>
<td>25</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>970–990 hPa</td>
<td>1634</td>
<td>28</td>
<td>105</td>
<td>16</td>
<td>0</td>
<td>14</td>
<td>1</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>990–1010 hPa</td>
<td>9606</td>
<td>130</td>
<td>145</td>
<td>99</td>
<td>126</td>
<td>177</td>
<td>26</td>
<td>76</td>
<td>104</td>
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<tr>
<td>1010–1030 hPa</td>
<td>323</td>
<td>13</td>
<td>12</td>
<td>15</td>
<td>10</td>
<td>3</td>
<td>8</td>
<td>29</td>
<td>44</td>
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SLP in the range of 970–990 hPa are on average 0.2 PVU higher than in winter. This tendency toward more pronounced values of diabatically produced PV might be explained by a larger supply of moisture evaporating from the warmer ocean surface (compared to winter). Cyclones in the eastern North Atlantic and western North Pacific show the largest increase in low-level PV anomaly compared to the winter, while the differences are not so obvious for cyclones in western Europe and around Greenland. On the contrary, the cyclones in western Europe show much more variability in terms of upper-level PV anomaly compared to winter. The surface potential temperature anomalies are much smaller than in winter, with values between 0 and 4 K (see Fig. 9b). They are especially low in the western North Pacific, both North Atlantic regions, and around Alaska. They do not always increase monotonically with the cyclone intensity, implying that in some regions the intensity of summer cyclones depends less on the amplitude of the surface \( \theta \) anomalies.

d. Statistical significance

To see whether these results are statistically significant, we performed a \( t \)-test analysis. We compared profiles of cyclones with different intensities, separately for the upper (200–400 hPa) and lower (650–900 hPa) parts, and the surface anomaly. Table 4 shows the test results for the western North Pacific. A value of 1 means that we can reject the null hypothesis that the profiles are identical at the 5% significance level, and 0 means that we cannot. Comparing intense cyclones with a minimum SLP value of 930–970 hPa to those with minimum SLP of 990–1010 hPa (and 1010–1030 hPa), we can reject the null hypothesis. The first of these comparisons is shown in Figs. 6a,b. The test shows that all parts of the two profiles in the figure are significantly different. For other profile comparisons we can reject the null hypothesis only for the lower part, the upper part, or the surface part. For weaker cyclones and for regions with very few cyclones the differences are not statistically significant at the 5% level both at upper and lower levels. However, since statistical significance itself does not necessarily imply also a physical relationship and vice versa, we believe that we can obtain important information also from the parts that do not differ significantly.

e. Profile evolution

So far the investigation of the \( \Delta P \) profiles and associated surface \( \theta \) anomalies has focused on the time when cyclones reached their maximum intensity. In this section some consideration is given to the temporal evolution of the cyclones’ \( \Delta P \) profiles during the 24 h prior to the time of minimum central SLP. Figure 10 presents the time evolution of the \( \Delta P \) profiles, the surface \( \theta \) anomalies, and the central SLP for two selected intensity categories and regions. The selected cyclone categories are the very intense western North Pacific cyclones with minimum SLP between 930 and 970 hPa (Figs. 10a,c) and moderately intense cyclones with central pressure between 990 and 1010 hPa over western Europe (Figs. 10b,d). For the first category we can see large and rapid changes with time. The value of \( \Delta P \) in the lower troposphere increases on average

<table>
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<th>TABLE 4. Significance table for comparisons of different categories of western North Pacific cyclones. Values are given for PV anomaly differences at upper levels, lower levels, and the surface, respectively (a value of 1 indicates statistical significance; a value of 0 indicates that the PV anomalies of the two cyclone categories are not statistically different).</th>
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<td>970–990 hPa</td>
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by 0.7 PVU in 24 h and the upper-level anomaly by 2.3 PVU. The peak of the low-level anomaly slightly rises and approaches the upper-level anomaly. The surface $u$ anomaly increases from 5.3 to 6.5 K (Fig. 10c) 12 h prior to the SLP minimum and then slightly decreases. This development of the anomalies is reflected in the evolution of SLP, which shows a rapid drop by more than 30 hPa in 24 h. Some of the cyclones in this region can therefore be categorized as rapidly deepening cyclones or “bombs.” However, most of the cyclones do not undergo such a strong development, and the vertical PV structure of most of the weaker cyclones changes only slightly during the considered 1-day time period, as illustrated in Fig. 10b. The surface $u$ anomaly of intense cyclones is on average above 4 K in all regions, while for the weaker cyclones it ranges from 0 K around the central SLP.

4. Summary and discussion

The vertical structure of extratropical cyclones has been analyzed using composite $\Delta PV$ profiles and surface $\Delta \theta$ values close to the surface cyclone center. Until now, this aspect of the vertical structure of cyclones has been investigated mainly in case studies. The statistical analysis performed in this study, based upon the climatology of cyclone tracks in the ERA-Interim dataset, provides new insight into the structure of extratropical cyclones in different geographical regions and for different intensity categories. Recalling the questions posed in the introduction, we can draw the following conclusions:

(i) On average, more intense cyclones (in terms of central SLP) are associated with more prominent low-tropospheric and upper-tropospheric positive PV anomalies ($\Delta PV$ values), the latter going along with an increased pressure at the dynamical tropopause. The stronger cyclones also have a more intense positive surface potential temperature anomaly close to their center. In winter, the averaged low-level $\Delta PV$ values in the most intense cyclones (with central SLP between 930 and 970 hPa) in all regions are higher than 0.5 PVU, with the highest values of more than 1 PVU in the western and eastern North Pacific and western North Atlantic. In contrast, the low-level PV values in weaker cyclones (where central SLP ranges between 990 and 1010 hPa) reach up to only about 0.4 PVU. The surface $\theta$ anomaly of intense cyclones is on average above 4 K in all regions, while for the weaker cyclones it ranges from 0 K around
The time evolution of PV profiles showed that the average. However, surface cyclones, both PV anomalies have larger amplitudes on We also found a significant seasonal dependency. Al-

(ii) We have found large variability between vertical cyclone structures in different regions. Western North Pacific and western North Atlantic cyclones exhibit large differences in low-level PV anomalies between strong and weak cyclones. This is an indication that condensational processes that produce the low-level PV may be especially important for their intensification. Cyclones in the eastern North Atlantic, in the region east of Greenland, and also in the western North Pacific are very variable in terms of their upper-level $\Delta$PV values. Low-level $\Delta$PV values are generally higher over the oceans. Also, surface $\theta$ anomalies are the highest in the western parts of oceans.

(iii) The time evolution of PV profiles showed that the strongest ocean cyclones experience a marked intensification in terms of both the upper-level and the diabatically produced low-level PV anomalies during the 24 h prior to minimum SLP. Their surface $\theta$ anomalies are relatively high. The concomitant growth of the PV anomalies points to the positive mutual interaction of the anomalies for explosively intensifying cyclones. The temporal evolution of the PV profiles and surface $\theta$ anomalies differs strongly between the regions.

We also found a significant seasonal dependency. Although summer cyclones are typically weaker than winter cyclones, both PV anomalies have larger amplitudes on average. However, surface $\Delta \theta$ values are lower, which might be related to smaller differences between temperatures of water and air.

Our method also has some caveats that we would like to comment on. The method is slightly sensitive to the choice of the radius within which the horizontally averaged values have been calculated. If the radius is too small, it can happen that we do not consider all the important parts of the PV structure. But if the radius is too large, the differences between the cyclones become very weak because of averaging over a (too) large area. The choice of a radius of 200 km appeared as a reasonable compromise between the two options. Another issue is related to the vertical tilt of most cyclones. Cyclones are never completely vertical, especially not during their intensification phase. We have tried to account for the cyclones’ tilt by calculating tilted profiles using the method by Deveson et al. (2002). The drawback of this approach was that we lost a large amount of information from the PV in the lower troposphere, since the low-level PV anomaly (up to about 600 hPa) is often quasi-vertical. Also, because mature cyclones become more and more vertical when the upper-level anomaly approaches the position of the cyclone center, we then decided to calculate only vertical profiles. The use of central SLP as an intensity measure can also be slightly problematic. We have chosen minimum SLP as a simple and widely used metric for cyclone intensity, but we recognize that it is not an optimal choice when comparing cyclones in different regions of the world. Therefore we grouped cyclones in different regions and focused mainly on intensity differences for cyclones in the same region.

All in all, our investigation points to the importance of all three tropospheric PV anomalies (including warm air at the surface) for the development of extratropical cyclones. We have shown that on a climatological basis, in addition to a pronounced upper-level positive PV anomaly, the diabatically produced low-tropospheric PV anomaly and a warm surface $\theta$ anomaly are important for the development of intense cyclones. This confirms results from earlier modeling studies (e.g., Uccellini et al. 1987; Kuo et al. 1991, 1995; Wernli et al. 2002) and studies that used piecewise PV inversion (Davis 1992; Huo et al. 1999).

A rather new finding from this study is the large regional variability of the vertical structure of extratropical cyclones. This topic was addressed previously by Wang and Rogers (2001) and Dacre and Gray (2009), but only for cyclones in the North Atlantic. Wang and Rogers (2001) found a lower tropopause and higher (absolute) PV values in explosive eastern Atlantic cyclones compared to those in the western North Atlantic, which is partially in agreement with our results. For our cyclones the tropopause was indeed higher in the eastern North Atlantic, but $\Delta$PV is not always larger than in the western North Atlantic. A direct comparison of the results is hampered by the fact that Wang and Rogers (2001) used somewhat different regions. They further found that the low-level PV anomaly is stronger in cyclones in the eastern North Atlantic at the beginning of the development, which then weakens rapidly. In their study the low-level PV anomaly of western North Atlantic cyclones develops more slowly but reaches a higher value and remains present for a longer time period. Our study also identified cyclones with higher low-level PV values in the western part of the North Atlantic. Also, our study included several other regions in the Northern Hemisphere and extended previous results to identify further important characteristics of cyclone variability between different regions.

The variability in the relative importance of the three PV anomalies in determining cyclone intensity may present
a significant forecasting issue. The correct representation and evolution of upper-level troughs should be particularly relevant for instance for eastern North Atlantic cyclones; in contrast, diabatic processes in the lower troposphere and the formation of surface temperature anomalies crucially determine cyclone intensity in the western parts of the oceans. Considering the typical scales of these processes, one might hypothesize that cyclone intensity is particularly difficult to predict in the western ocean basins. A verification study would be rewarding to investigate this issue. However, the interaction of all three anomalies is key for intensification and therefore probably presents the largest problem for forecasting.

Addressing these issues might constitute a fruitful continuation of this work. The identification of processes in models that lead to false representations of disturbances contributing to cyclone development would enable improvements of forecasts of intense cyclones. However, there are also issues of basic dynamical understanding that would deserve further attention. For instance, the relative role of diabatic PV production along the cold front and close to the cyclone center for the cyclone’s structure and intensity has not yet been fully investigated.

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Dacre, H. F., and S. L. Gray, 2006: Classifying dynamical forcing contributing to cyclone development would enable improvements of forecasts of intense cyclones. However, there are also issues of basic dynamical understanding that would deserve further attention. For instance, the relative role of diabatic PV production along the cold front and close to the cyclone center for the cyclone’s structure and intensity has not yet been fully investigated.

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