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ABSTRACT

Extratropical transition (ET) of tropical cyclones involves distinct changes of the cyclone's structure that are not yet well understood. This study presents for the first time a comprehensive Lagrangian description of structure change near the inner core. A large sample of trajectories is computed from a convection-permitting numerical simulation of the ET of Tropical Storm Karl (2016). Three main airstreams are considered: those associated with the inner-core convection, inner-core descent, and the developing warm conveyor belt. Analysis of these airstreams is performed both in thermodynamic and physical space. Prior to ET, Karl is embedded in weak vertical wind shear and its intensity is impeded by excessive detrainment from the inner-core convection. At the start of ET, vertical shear increases and Karl intensifies, which is attributable to reduced detrainment and thus to the formation of a well-defined outflow layer. During ET, the thermodynamic changes of the environment impact Karl's inner-core convection predominantly by a decrease of $\theta_e$ values in the inflow layer. Notably, notwithstanding Karl's weak intensity, its inner core acts as a "containment vessel" that transports high-$\theta_e$ air into the increasingly hostile environment. Inner-core descent has two origins: (i) mostly from upshear-left above 4-km height in the environment and (ii) boundary layer air that ascends in the inner core first and then descends, performing rollercoaster-like trajectories. At the end of the tropical phase of ET, the developing warm conveyor belt comprises air masses from several different source regions, and only partly from the cyclone's developing warm sector, as expected for extratropical cyclones.

1. Introduction

The structure of midlatitude cyclones is often described based on the notion of coherent airstreams (e.g., Carlson 1991). These airstreams are usually referred to as conveyor belts. An increased understanding of cyclone dynamics is gained by better understanding the structure of and the physical processes along these airstreams (e.g., Wernli and Davies 1997; Papritz and Schemm 2013; Joos and Forbes 2016; Crezee et al. 2017). Coherent airstreams are best described from a Lagrangian perspective (i.e., by analysis of a comprehensive set of trajectories).

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Tropical cyclones (TCs) are less often described from a trajectory perspective. The reason may partly be that mature TCs can be approximated, to lowest order, as axisymmetric, steady-state systems. Streamlines in a radius–height cross section may therefore be used as an approximation of the airstreams that depict the TC's secondary circulation (e.g., Riehl 1954; Emanuel 1986) and streamlines in a comoving, horizontal cross section outside of the eyewall as the airstreams that depict the primary circulation (e.g., Willoughby et al. 1984; Riemer and Montgomery 2011). In addition, trajectory analysis of TCs requires resolution of convective-scale motion, which requires high temporal and spatial resolution of the data underlying the trajectory calculation (i.e., large datasets for trajectory calculations from model data). Often, however, the assumptions of axisymmetry and/or stationarity are not sufficiently well justified, in particular when TCs are embedded in environmental flow that
exhibits notable vertical wind shear. As one example, one demonstrated weakening mechanism of TCs in vertical shear, the flushing of the TC’s inflow layer with cold and dry air from above, may be fully understood only when considering the three-dimensional motion of air masses near the TC center (Riemer et al. 2010, 2013; Riemer and Montgomery 2011). Few studies so far have undertaken comprehensive trajectory analysis to examine different aspects of TCs in vertical shear (e.g., Cram et al. 2007; Stern and Zhang 2013; Riemer and Laliberté 2015).

The evolution of airstreams during the transition of a TC into an extratropical cyclone (i.e., during extratropical transition (ET); Jones et al. 2003; Evans et al. 2017) has not yet been investigated by comprehensive trajectory analysis. The most salient characteristics of ET include an increase of vertical shear, the interaction with a baroclinic zone, and the translation of the TC into a thermodynamic environment that gradually becomes less favorable for tropical development, namely a drier and cooler environment, including decreasing sea surface temperature. The transition from a tropical to an extratropical cyclone is a highly asymmetric process with rapidly changing dynamics. The involved airstreams during ET can therefore be expected to be nontrivial variants of the airstreams of mature TCs and of the conveyor belts of extratropical cyclones. In addition, the change in cyclone structure during ET exhibits substantial case-to-case variability (e.g., Davis et al. 2008). A conceptual synoptic to meso-a-scale model of ET in the northwest Pacific (Klein et al. 2000) includes hypothesized airstreams, which, however, consider the mesoscale environment of the TC only. Our goal here is to extend this conceptual model toward smaller scales by an extensive trajectory analysis of airstreams that pass through the inner core and are associated with latent heat release there.

The motivation to focus on inner-core latent heat release is twofold. First, the intrusion of environmental air with lower moist entropy into the inner-core convection, so-called ventilation, is one important mechanism that affects TC intensity in vertical shear (e.g., Tang and Emanuel 2010). Different pathways of ventilation have been demonstrated in the literature (e.g., Simpson and Riehl 1958; Frank and Ritchie 2001; Riemer et al. 2010; Gu et al. 2015) and it is not yet clear which pathway operates under which combination of environmental and TC conditions. In addition, the relative importance of intrusion into versus detraining from the inner-core convection for the midlevel ventilation paradigm is still unclear (Riemer and Laliberté 2015). Related to its impact on intensity, latent heat release near the cyclone center has been demonstrated to increase the resiliency of the TC-vortex during ET (Davis et al. 2008). Thereby, convection within the cyclone may play an important role in the overall evolution of the cyclone.

Our second motivation is that the representation of convection in numerical weather prediction models is associated with significant uncertainty. Convection within the TC undergoing transition has been hypothesized to be one source of the observed large forecast uncertainty associated with intensity and structure evolution during ET (Jones et al. 2003). A detailed trajectory analysis of inner-core convection may be helpful to gain more insight into this convective-scale uncertainty and its relation to the thermodynamic properties of the involved air masses, and to study how convective-scale uncertainty eventually affects the cyclone structure. Furthermore, upper-tropospheric divergent outflow associated with latent heat release below plays, in general, an important role in how convective-scale uncertainty grows upscale to eventually increase synoptic-scale forecast uncertainty (Baumgart et al. 2019). This is particularly important during ET, as uncertainty in the evolution of the ET cyclone projects onto the larger-scale midlatitude flow [see review by Keller et al. (2019)]. Besides the outflow from TC convection, upper-tropospheric outflow from the developing warm conveyor belt during ET is essential in modifying the midlatitude flow (e.g., Torn 2010; Grams et al. 2013). Our trajectory analysis will therefore consider also the development of the developing warm conveyor belt, which occurs outside of the cyclone’s inner core.

To our knowledge, trajectory analysis focusing on latent heat release during ET on a convection-permitting scale has not been performed before. Few studies have comprehensively investigated changes in the inner-core structure during ET using trajectories [e.g., Evans and Hart (2008) with a focus on the evolution of the wind field, or Lentink et al. (2018) on the role of orography in modifying the thermodynamic properties of the TC environment]. With respect to the developing warm conveyor belt, the transition from upright convection during the tropical phase of ET to more slantwise ascent during the extratropical stage has been illustrated in a case study (Grams et al. 2013). That study, however, used a grid spacing of 0.25° and a convective parameterization as compared to our convection-permitting simulation with a grid spacing of 0.025°. Here, we will explore the inner-core and developing warm conveyor belt airstreams in a case-study framework also: the ET of Tropical Storm Karl (2016) in the North Atlantic.

The ET of Karl occurred during the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX; Schäfler et al. 2018) and has been identified
as one of the “triggers” for midlatitude impact during this period (Schäffer et al. 2018). In the extratropical phase of ET, Karl merged with a weak, preexisting cyclone and formed an unusually strong jet streak downstream, which initiated further development that resulted in a high-impact precipitation event in Norway. Intense observation periods and additional ground observations were dedicated to Karl’s extratropical phase and the associated downstream impact during the NAWDEX campaign. An ensemble sensitivity analysis revealed that the high-impact precipitation event in Norway showed sensitivity to the evolution of Karl during ET (Kumpf et al. 2019).

After introducing our methods (section 2) and providing an overview of the evolution of Tropical Storm Karl (section 3), we will first consider inner-core trajectories in thermodynamic space [section 4; following the approach of Riemer and Laliberté (2015)]. This approach provides a first insight into the intensification of (simulated) Karl after recurvature and how the increasingly cool and dry environment impacted inner-core convection. A detailed analysis of the spatial structure of the involved airstreams is presented in section 5, complemented by an analysis of the developing warm conveyor belt. The salient Lagrangian features of Karl’s transition are summarized in section 6. The usual caveat for a single case study applies and further case studies are needed to draw a more general picture of the evolving inner-core airstreams during ET.

2. Methods

a. Convection-permitting COSMO simulation of TC Karl

We have performed a convection-permitting simulation of tropical storm Karl (2016) over a period of 66 h between 0000 UTC 23 September and 1800 UTC 25 September with the Consortium for Small-Scale Modeling (COSMO; Steppeler et al. 2003) model, version 5.04. COSMO is a nonhydrostatic limited-area atmospheric prediction model. The model is based on nonhydrostatic hydro-thermodynamical equations for fully compressible flow and it has been designed for both operational numerical weather prediction and scientific applications. Convection-permitting simulations with the COSMO model have been successfully used before to investigate structure changes of a TC during ET (Lentink et al. 2018).

For our numerical simulation, COSMO is used in default settings: the heating rate due to radiation is calculated by the parameterization scheme of Ritter and Geleyn (1992). Surface heat, moisture and momentum fluxes are parameterized by a turbulent kinetic energy-based surface transfer scheme formulated in conservative thermodynamic variables. While the parameterization of deep convection is turned off, a shallow convection scheme after Tiedtke (1989) is used. Microphysical processes are described by an extended cloud ice scheme (graupel scheme; Doms et al. 2011) based on the warm-rain scheme by Kessler (1969). The model enables the use of a rotated spherical coordinate system, where the model poles can be positioned such that the model equator runs through the center of the domain. The convergence of the meridians is thus minimized and the grid spacing on the chosen domain is near-constant. A detailed description of the COSMO model is given by Doms and Schättler (2002).

The rotated coordinate system, with the model equator being shifted to 35° north, is used with a horizontal grid spacing of 0.025° (~2.8 km). There are 49 levels between 0 and 21 km, with an enhanced vertical resolution in the boundary layer with 17 levels below 2 km. The simulated domain covers a large part of the North Atlantic with a size of 1200 × 1280 grid points. At initial time, Karl is located in the southwest of the domain, with the center about 450 km away from the domain boundary. During the simulation, Karl moves northeast and farther away from the boundary. As boundary conditions, as well as initial conditions, we use archived operational analysis data from the European Centre for Medium-Range Weather Forecasts.

A comparison of the model track and intensity with the best track analysis by the National Hurricane Center (NHC; Pasch and Zelinsky 2016) shows that shortly after recurvature, between 1200 UTC 24 September and 0000 UTC 25 September, Karl in the COSMO simulation exhibits a faster translation speed, resulting in a track error of approximately 200 km at 0000 UTC 25 September (Fig. 1a). Subsequently, the COSMO track leads the NHC track but besides this, the overall track representation is good. The intensity evolution in the COSMO simulation compares well with the best track analysis until the tracks start to diverge (Fig. 1b). From this time, Karl in the COSMO model intensifies faster and more strongly and reaches hurricane intensity shortly after 0000 UTC 24 September. While there are some notable differences, we consider the overall evolution in our simulation to be sufficiently realistic to serve as the basis of our process-oriented study.

b. Trajectory calculation and transformation in thermodynamic space

Trajectories are calculated from the model output utilizing a fourth-order Runge–Kutta scheme with a
time step of 2 s and linear interpolation in space and time for four representative stages. The model data are available every 5 min. A comparison with the much simpler Euler-method leads to very similar results and it can therefore be assumed that the solutions of the trajectory calculation have converged. The results from the trajectory calculation are stored every 5 min, at the same times as the underlying model data. We did not find a sensitivity of the results to the numerical scheme used for the calculation and therefore conclude that the calculated trajectories are of sufficient accuracy for the purpose of this study.

The trajectories are seeded in a cylinder with 2.5° radius around the storm center. The center is defined by the centroid of the Okubo–Weiss parameter (Okubo 1970; Weiss 1991) at 950 hPa. The horizontal spacing of the seeding locations is identical to the model grid (0.025° = 2.8 km). In the vertical, we seed on pressure levels with a spacing of Δp = 20 hPa, starting from half that distance (10hPa) above the sea surface until a height of 150 hPa. An air parcel represented by one of our trajectories has a mass of approximately 1.6 × 10^9 kg. A total number of approximately 1.3 × 10^6 trajectories are calculated per time step of interest. The trajectories are calculated 6 h forward and backward in time. The trajectories thus represent a 12 h time period around the time step of interest. Hereafter, the end positions of the 6 h backward calculation will be referred to as the “initial positions” of the air parcels and the end positions of the 6 h forward calculation will be referred to as the “end positions” of the air parcels.

We aim to distinguish between trajectories that contribute to latent heat release in the inner core and those outside. To select trajectories, we follow Riemer and Laliberté (2015). An inertial stability (I^2) threshold is defined,

\[ I^2 = (\zeta + f_0)(\frac{\nu}{r}) , \]  

where \( \zeta \) is the relative vorticity, \( f_0 \) is the Coriolis parameter, \( \nu \) is the tangential wind component, and \( r \) is the distance from the storm center. Here, the inertial stability threshold is adapted to the storm’s intensity and varies between \( I^2 = 2 \times 10^7 \text{ s}^{-2} \) for the first two stages and \( I^2 = 4 \times 10^7 \text{ s}^{-2} \) for the last two stages. Furthermore, thresholds of relative humidity greater than 90% and a vertical velocity greater than \( w > 0.5 \text{ m s}^{-1} \) are applied to select those air parcels near saturation and with a strong ascent. Only those trajectories that satisfy the defined thresholds at seeding time are considered. The so chosen air parcels are used to characterize the latent heat release in the deep convection.

Further following Riemer and Laliberté (2015), we transform the computed trajectories from the three-dimensional (x, y, z) space to a two-dimensional entropy-temperature space. Here, the moist entropy \( s \) is expressed in terms of the equivalent potential temperature \( \theta_e \), \( s = c_p \ln \theta_e \), where \( c_p \) is the specific heat capacity of dry air at constant pressure. For tropospheric values, the entropy is approximately a linear function of \( \theta_e \). For simplicity we use \( \theta_e \), calculated after Bolton (1980), as our metric for entropy. The transformation maps the material tendencies into discrete bins of the thermodynamic space:

\[
F_{\theta_e,T}(\theta_e^n, T^n) = \frac{1}{\tau} \sum_{n=1}^{N} \frac{D}{Dt}(\theta_e, T)(t, n) \delta[\theta_e(t, n) - \theta_e^n] \delta[T(t, n) - T^n],
\]  

In Eq. (2) the superscript \( b \) denotes the respective bin value with a bin size of \( \Delta x = 1 \text{ K} \) for both \( T \) and \( \theta_e; D/Dt \)
denotes the material derivative and the Dirac-$\delta$ is approximated by the top-hat function:

$$\delta(x) = \begin{cases} 1 & \text{for } 0 \leq x \leq \Delta x \\ 0 & \text{elsewhere} \end{cases}$$

(3)

Here $F_{\theta_e,T}$ is the vector that depicts the material rate of change of $\theta_e$ and $T$, and thus the rate of mass flowing through specific sections of the ($\theta_e$, $T$) space, integrated over all $N$ air parcels and averaged over all time steps $\tau$ of the trajectory calculation.

### 3. Overview of Karl and its structural evolution

In this section the storm structure and environmental conditions in the simulation will briefly be described at four selected stages during Karl’s transition. This description provides the context for the Lagrangian analysis presented in the subsequent sections.

#### a. Synoptic overview

A synoptic overview of Karl is given by Pasch and Zelinsky (2016): Karl originated from a low pressure system close to the Cabo Verde Islands that developed from an easterly wave crossing the west coast of Africa on 12 September 2016. The low was classified as a tropical depression by 0600 UTC 14 September. The depression moved west-northwestward and strengthened into a tropical storm at 0600 UTC 15 September. Karl moved farther westward with no significant change in intensity. On 21 September, Karl moved near an upper-level low to the west and weakened to a tropical depression. Karl turned northwest at 1800 UTC 22 September and it regained tropical storm strength after the upper-level low moved southward and Karl’s cloud pattern became better organized. The cyclone intensified further while turning north and northeast around the western periphery of a midlevel anticyclone and proceeded toward the east-northeast while accelerating. Karl reached its peak intensity of 60 kt (1 kt = 0.5144 m s$^{-1}$) at 0600 UTC 25 September. On the same day Karl became embedded within a frontal zone and was classified as an extratropical cyclone at 1200 UTC.

#### b. Structure change in the numerical simulation

The numerical simulation of Karl starts during the recurvature of the storm. The environment of Karl at the early stage of the simulation (after 36 h, valid at 1200 UTC 24 September) is characterized by tropical air masses ($330 < \theta_e < 335$ K at 700 hPa, Fig. 2a), with an approximately axisymmetric moist envelope (Willoughby et al. 1984; Riemer and Montgomery 2011) of $\theta_e > 350$ K within 200–300 km of the center. At this time, Karl is embedded in a region with weak environmental (deep layer) vertical wind shear (approximately 4 m s$^{-1}$ from the southwest, Fig. 3a). Strong vertical updrafts are mostly found in the downshear-left quadrant at this time, which is true also for all subsequent times considered. This is consistent with the observation-based analysis of Typhoon Sinlaku (2008) by Foerster et al. (2014). Updrafts occur near the edge of the inner core (depicted by an inertial stability threshold in Fig. 3) and in a rainband complex in the downshear-left quadrant.
indicated by the banded structure of the near-saturated relative humidity. Relative humidity is high also in the inner core. Karl in the simulation, however, never forms a well defined eyewall, which is true also for real-world Karl, as indicated by satellite imagery (not shown). This early stage will hereafter be referred to as “tropical storm stage.”

In the subsequent 9 h (Fig. 3b, valid at 2100 UTC 24 September), vertical wind shear increases to approximately 10 m s⁻¹. Despite this increase in vertical shear, Karl intensifies and the updrafts in the downshear-left quadrant at the edge of the inner core become stronger. Karl begins to approach a low-level baroclinic zone to its northwest and an elongated, mesoscale band of convection develops to the northeast of Karl, parallel to the baroclinic zone. Except for this band, Karl exhibits clear signatures of a tropical cyclone in moderate vertical wind shear and this stage will hereafter be referred to as “intensification stage.”

A further 9 h later (Fig. 3c, valid at 0600 UTC 25 September), the shear has increased to approximately 16.9 m s⁻¹ and Karl now interacts more prominently with

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**Fig. 3.** Structure change of tropical storm Karl during tropical phase of ET between 1200 UTC 24 Sep and 1200 UTC 25 Sep at 3000-m height. Red: upward motion greater than 0.5 m s⁻¹, blue: downward motion smaller than −0.25 m s⁻¹, gray: relative humidity greater than 90%, black contourline: inertial stability ($I^2$) threshold that indicates the inner core ($2 \times 10^{-7}$ s⁻² for 1200 and 2100 UTC 24 Sep and $4 \times 10^{-7}$ s⁻² for 0600 and 1200 UTC 25 Sep), and black arrow: deep-layer shear vector between 200 and 800 hPa at seeding time. Dark and light purple contours are the 320- and 324-K equivalent potential temperature contours at 500 m.
the baroclinic zone. The convection near the edge of the inner core and that in the elongated band to the north-east start to merge. In the upshear-left quadrant, air descending in the inner core is apparent, which is consistent with Foerster et al. (2014), who show descent in the upshear direction of typhoon Sinlaku (2008) with increasing deep-layer vertical shear. At this stage, Karl begins to lose its tropical characteristics and therefore we refer to this as the “intermediate stage” hereafter.

In the subsequent 6 h (Fig. 3d, valid at 1200 UTC 25 September), vertical shear further increases as Karl farther approaches the baroclinic zone. Low-θ_e air from the northwest starts to wrap around into the upshear left quadrant within 100–200 km of the inner core (Fig. 2b). A dipole of vertical motion has developed and ascent in the downshear-left quadrant is now indistinguishable from that within the band to the northeast. Due to the proximity to and clear interaction with the baroclinic zone, and due to the dipole evident in vertical motion, this stage is hereafter referred to as “extratropical storm stage.”

4. Thermodynamic mass flux analysis of inner-core convection

The first part of our analysis focuses on the thermodynamic mass flux of the inner-core convection, defined in Eq. (2). Figure 4 depicts the mass flux $\mathbf{F}_{\theta_e, \tau}$ and the divergence of the mass flux for the four chosen time periods of Karl’s ET in the $(\theta_e, \tau)$ space. The mass flux illustrates how air masses change their thermodynamic properties. The divergence of the mass flux $(\nabla \cdot \mathbf{F}_{\theta_e, \tau})$ depicts the rate at which air masses with specific $\theta_e$ and $\tau$ values are accumulated.

![Fig. 4. Thermodynamic mass flux $\mathbf{F}_{\theta_e, \tau}(\theta_e, \tau)$ for air masses rising in the inner-core convection for the chosen seeding times. (a) The tropical storm stage, (b) the intensification stage, (c) the intermediate stage, and (d) the extratropical storm stage. Gray to black colors and arrows indicate the magnitude and the direction of the mass flux. Brown to green colors indicate the divergence of the mass flux $\nabla \cdot \mathbf{F}_{\theta_e, \tau}(\theta_e, \tau)$.](image-url)
or depleted in the thermodynamic space over the 12 h time frame of the trajectory calculation. Positive values of divergence indicate a depletion and negative values (convergence) an accumulation of air masses. Due to the temperature–height relationship, the temperature on the ordinate can be considered as the vertical axis. Note that temperature increases from top to bottom, and \( \theta_e \) increases from right to left. In the case of Karl, the boundary layer can be approximately identified by air masses with a temperature of \( T > 295 \text{ K} \) and the outflow layer by air masses with a temperature of \( T < 250 \text{ K} \).

It is interesting to compare the mass flux and divergence of Karl with the idealized numerical experiment of a mature TC in Laliberté (2015), in particular during tropical storm stage and intensification stage, when Karl is still largely possessing tropical characteristics. During these stages, in contrast to the idealized, mature TC [Figs. 4 and 5 in Laliberté (2015)], the air masses that rise out of the boundary layer near Karl [identified by positive divergence in \( (\theta_e-T) \) space for \( T > 295 \text{ K} \) in Fig. 4] do not exhibit a radial gradient of \( \theta_e \), outside of or underneath the radius of maximum winds (RWM) during tropical storm stage and an increase of only 2 K at intensification stage between a local minimum in \( \theta_e \) outside of the RWM and underneath or just inside of the RWM. Apparently, Karl does not strongly couple to the underlying ocean by extracting enthalpy from the ocean locally. This lack of a distinct ocean coupling is reminiscent of the preWISHE stage (Molinari et al. 2004) that describes the evolution of weak TCs in vertical shear before the TC reaches sufficient intensity such that wind-induced surface heat exchange (e.g., Emanuel 1986) becomes the dominant local process.

Another interesting difference from the idealized, mature TC is the presence of a weak overturning circulation at \( \theta_e \) values lower than that of the inner-core ascent, \( \theta_e < 345 \text{ K} \) for tropical storm to intermediate stage (Figs. 4a–c) and \( \theta_e < 340 \text{ K} \) for the extratropical storm stage (Fig. 4d). The upper branch of this circulation is near the melting level, which indicates that this circulation is related to latent heat absorbed during melting (i.e., related to ice microphysics). The absence of this circulation in the idealized case of Laliberté (2015) corroborates this idea because the numerical experiment considered in that study did not include ice microphysics.

At all stages, the majority of air parcels ascend at similar \( \theta_e \) values to their initial values. Their \( \theta_e \) values then decrease approximately 2–5 K until they reach the freezing level. From the freezing level upward, \( \theta_e \) slightly increases until \( T = 240 \text{ K} \). This behavior is consistent with results by Fierro et al. (2009), who have demonstrated that air parcels originating below cloud base in the boundary layer first experience a decrease in \( \theta_e \) as a result of entrainment of low-\( \theta_e \) ambient air before \( \theta_e \) increases again due to latent heat release by ice processes. In addition, some air parcels drastically increase \( \theta_e \) below \( T = 200 \text{ K} \), except during the extratropical storm stage, indicating convective overshoot into and subsequent mixing within the model stratosphere.

The magnitude of the mass flux undergoes noticeable changes during ET. For the tropical storm stage (Fig. 4a), the magnitude of the mass flux is a maximum for \( 270 \leq T \leq 290 \text{ K} \) and considerably weakens above. While the mass flux exhibits a prominent region of divergence underneath the maximum of the mass flux, a clear signal of convergence in the upper levels is not present. The latter is consistent with the lack of a well-defined outflow layer. Subsequently, coincident with the increase in vertical wind shear, the inner-core mass flux notably increases (Figs. 4b,c). This relation between vertical shear and vertical mass flux may qualitatively be explained based on quasigeostrophic theory, wherein differential advection of vorticity by vertical shear is associated with vertical motion to maintain thermal wind balance, and has previously been emphasized by Davis et al. (2008). At intensification (Fig. 4b) and intermediate stage (Fig. 4c), the prominent region of convergence at \( T \leq 220 \text{ K} \) indicates the existence of a well-defined outflow layer at these times. This outflow layer during intensification stage is approximately 10 K colder than during the intermediate stage. At extratropical storm stage (Fig. 4d), the outflow layer is again less well defined and extends from \( 220 < T < 250 \text{ K} \). It is interesting to note that the intensification of Karl manifests in the increase of the formation of a well-defined outflow layer whereas there is no significant increase in inner-core \( \theta_e \) during intensification.

The evolution of the outflow is visible also in the thermodynamic histograms in Fig. 5, which illustrate the relative distribution of end positions of the air parcels. Here, the development of a prominent outflow layer between tropical storm stage (Fig. 5a) and intensification stage (Fig. 5b) can be seen by the much higher density of air parcels at lower temperatures. The relative distribution of end positions further corroborates the increase of the average outflow temperature from the
intensification stage (Fig. 5b) to the extratropical storm stage (Fig. 5d).

At low levels, the magnitude of the divergence, which signifies the inflow, increases between the tropical storm stage and the intensification stage (Figs. 4a,b, respectively), consistent with the increased inner-core mass flux noted above. Subsequently, in the intermediate stage and the extratropical storm stage (Figs. 4c,d, respectively), the region of divergence gradually covers a broader range of \( \theta_e \) values and shifts to lower \( \theta_e \) values. Consistently, prominent inner-core vertical mass flux at extratropical storm stage covers a broad range of \( \theta_e \) values also, ranging from approximately 355 to 345 K.

The mass flux in thermodynamic space and its divergence provide a first description of how the inner-core convection of Karl evolves during the tropical phase of ET. In the following section we will examine the spatial characteristics of different airstreams to gain further insight into how the intrusion of different air masses into the inner-core convection is associated with this evolution. In addition to the inner-core convection, descending inner core airstreams will be examined, along with airstreams that contribute to latent heat release by ascending outside the inner core.

5. Origin and fate of air masses

This section complements the purely thermodynamic perspective of the previous section with an analysis of the initial and end positions of air parcels. To this end, the thermodynamic histograms are helpful to discuss air masses with distinct thermodynamic characteristics. In addition, airstreams will be examined that further contribute to inner-core vertical motion, namely descending air masses, and those that are further associated with latent heat release, namely ascent outside of the inner core and in the developing warm conveyor belt.

a. Evolution of Karl’s inflow and a containment-vessel hypothesis

At tropical storm stage, the air parcels entering the inner-core convection mostly originate from a region with temperatures between \( 290 \leq T \leq 300 \) K and equivalent potential temperatures between \( 345 \leq \theta_e \leq 360 \) K (Fig. 6a). This signal is that of the typical inflow

![Fig. 5. Relative distribution in thermodynamic space of end positions of the trajectories fulfilling the inner-core convection criteria at seeding time. (a) The tropical storm stage, (b) the intensification stage, (c) the intermediate stage, and (d) the extratropical storm stage. Blue to yellow color indicates the density in the 1 K × 1 K sized bins.](image-url)
FIG. 6. (left) Relative distribution in thermodynamic space of initial positions of the trajectories fulfilling the inner-core convection criteria at seeding time and (right) corresponding height distribution (colored) of initial positions for all four time periods. (a),(b) The tropical storm stage. (c),(d) The intensification stage. (e),(f) The intermediate stage. (g),(h) The extratropical storm stage. Not shown in the height distribution are air parcels that originate from inside the inner core ($345 < \theta_e < 355$ K, $260 < T < 290$ K in the corresponding...
layer of warm and moist air masses from low altitudes in the vicinity of a tropical storm. The slope of the maximum of the distribution represents approximately the vertical $\theta_e$ gradient within the inflow layer. The spatial distribution of the air parcels’ initial positions is shown in Fig. 6b, which confirms that most air parcels originate from low levels. Air parcels originate from within a distance of up to $3^\circ$ from the storm center. Few air parcels originate from above 2-km height, mostly from within or from close vicinity of the inner core. The envelope of the low-level initial positions is fairly symmetric around Karl’s center, with some shift toward the southeast (to the right of the deep-layer shear vector); 70% of the air parcels originate from right of shear. The distribution of the initial positions illustrates the quasi-symmetric inflow expected for a tropical cyclone in weak environmental flow.

Subsequently, the inflow pattern gradually becomes more asymmetric (Fig. 6d). Clearly, air parcels from the right of shear (southeast) originate from larger radii (up to 4°–5°) than from left of shear. This change in the inflow pattern signifies the increasing low-level storm-relative flow associated with the increasing vertical wind shear (Riemer and Montgomery 2011). In addition to the asymmetric nature of the inflow, air parcels originate from regions with gradually decreasing $\theta_e$ values: The 350 K moist-isentrope in Figs. 6f and 6h illustrates that Karl moves into an environment with gradually decreasing low-level $\theta_e$ values after intensification stage. This change in the thermodynamic characteristics of the environment is evident also in Figs. 6e and 6g by the $\theta_e$ values of high-$T$ initial positions. It is important to note that the low-$\theta_e$ air originates from the warm side of the baroclinic zone. Examination of trajectories originating from the cold side (not shown) shows that these air parcels, during the 12 h considered in our trajectory calculation, move westward around Karl and then trail the storm while Karl is rapidly moving northward. The movement of these air parcels relative to the center of Karl indicates that Karl moves fast enough relative to its environment to evade an intrusion of these low-$\theta_e$ air masses from north of the baroclinic zone.

Besides the inflow layer, the thermodynamic histograms in Fig. 6 indicate a second prominent source region of air parcels that contribute to the inner-core convection. These air parcels are identified by $345 < \theta_e < 355$ K and $260 < T < 290$ K, most evident in Figs. 6e and 6g. Air parcels from this region in the thermodynamic space originate from altitudes mainly between 2 and 6 km and almost completely from inside the inner-core at all stages (shown for the intermediate and extratropical storm stage in Fig. 7). Further analysis of the full trajectories of the “contained” air parcels (not shown) confirms that the vast majority of these air parcels stay within a radius of less than $0.6^\circ$ from the storm center before seeding time. This air parcel behavior indicates that the inertial stability of Karl is large enough to contain these air masses in the inner core. This observation suggests that, despite the weak intensity of Karl and the absence of an eyewall, the inner core of Karl acts as a containment vessel for high-$\theta_e$ air masses. The contained air masses are taken into an increasingly hostile environment, as shown in Fig. 7. Similar to the reservoir of high-$\theta_e$ air identified in the eye of Hurricane Bonnie (1998; Cram et al. 2007), these air masses potentially provide an extra source of high-$\theta_e$ air to maintain deep convection during the ET of Karl.

b. Detrainment of inner-core convection and outflow development

While the previous subsection considers the source region of air masses, this subsection examines the fate of the air parcels that are associated with the inner-core convection. At tropical storm stage, the thermodynamic histogram indicates two maxima in the distribution of the end positions, one located between $260 < T < 280$ K and the other between $220 < T < 240$ K (Fig. 5a). The maximum at warmer temperatures in this distribution indicates that a large number of air parcels from the inner-core convection do not reach the outflow layer in the examined 6 h time period since seeding. In this sense, the inner-core updrafts are ventilated and therefore, based on axisymmetric theory that includes the effect of ventilation by prescribing entropy fluxes across the eyewall, a detrimental impact on storm intensity is expected (Tang and Emanuel 2010). The spatial distribution of the end positions in Fig. 8a illustrates that air parcels detrained with $T > 250$ K (Fig. 5a), approximately between 2- and 8-km height, end up mostly
downshear but stay within or in close vicinity of the inner core during the considered time period. This suggests that the detrained air parcels can be mixed back into the inner-core convection later, consistent with the observation that the initial positions of air parcels for inner-core convection are partly also found in the close vicinity of the inner core at midlevels (Fig. 6b). The second maximum in the thermodynamic histogram (Fig. 5a) at lower temperatures is more reminiscent of the signature of an outflow layer. In Fig. 8a, these air parcels reach heights above 8 km. The azimuthal distribution of these air parcels is more symmetric around the center than that of the midlevel air detrained downshear, but the radial distance from the storm center is not substantially different. The latter observation can be attributed to the weak upper-level environmental winds in the vicinity of Karl at this time. The fraction of trajectories from the inner-core convection that reach temperatures below 250 K is shown in Fig. 9. For the tropical storm stage, approximately half of the trajectories of the inner-core convection reach a region with $T < 250$ K, but only 20% reach a region with a temperature below $T = 220$ K.

As discussed above, the outflow characteristics significantly change during the intensification stage when Karl transports air masses farther up to colder temperatures, signified by the distinct maximum in the thermodynamic histogram of final temperatures below $T = 220$ K (Fig. 5b). The percentage of air parcels reaching a temperature below $T = 250$ K increases to 70% and nearly half of the air parcels now reach a temperature below $T = 220$ K (Fig. 9). The spatial distribution for the intensification stage (Fig. 8b) shows a more distinct outflow region with the majority of air parcels reaching heights above 12 km. Most of the outflow at this height is rapidly transported away from the center toward the downshear-left, which is a consequence of the increased magnitude of the environmental upper-level winds at this time.

During the intermediate and the extratropical storm stages (Figs. 8c,d), it is clear that the vast majority of air parcels associated with inner-core convection are evacuated downshear and the evacuation occurs more rapidly (not shown), consistent with the further increase in vertical wind shear. The height of the outflow decreases to mostly below 12 km during extratropical storm stage (Fig. 8d), consistent with the distinct increase of outflow temperatures: the amount of air parcels reaching a temperature below $T = 220$ K drops below 5% at extratropical storm stage (Fig. 9). The amount of trajectories that reach a temperature below $250$ K is less than 60% (Fig. 9) at extratropical storm stage, which corresponds to the increase in detrainment in midlevels. This detrainment is also evident in the thermodynamic histogram (the local maximum for $T > 260$ K and $\theta_e < 340$ K in Fig. 5d). The end positions of the majority of the detrained air parcels between 2 and 10 km are located downshear and at larger radial

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1 The relatively warm outflow temperature here is not due to subsidence and associated adiabatic warming by compression of air parcels from the outflow layer, a class of trajectories that has been noted in idealized numerical experiments in mature TCs in moderate to strong vertical shear (Riemer and Laliberté 2015). Less than 2% of the trajectories reach $T < 215$ K and subsequently warm to $T > 220$ K.
distance from the center than at the earlier stages (cf. Figs. 8a–d). This larger downshear displacement of the detrained air masses is arguably due to larger storm-relative flow at the respective levels than during earlier stages.

c. Descending air masses in the inner core and a rollercoaster hypothesis

It is clear from Fig. 3 that Karl’s inner core is only partly represented by ascending air masses. In particular at the intensification stage and the later stages, there are descending air masses in the inner core also. These descending air masses comprise a potential further pathway by which environmental air may intrude into the inner core. To gain further insight on this potential intrusion, we examine in more detail those air masses with a relative humidity below 70% and a relatively strong descent with a vertical velocity below $-0.25 \text{ m s}^{-1}$ inside the inner core at seeding time. Here, the main interest is the origin of these air masses and thus we focus on the initial positions of these air parcels. A substantial number of air parcels fulfill the criteria for dry inner-core descent, namely more than half as many as air parcels fulfilling the criteria for inner-core ascent, except for the tropical storm stage, when the number is less than 25% (Fig. 9). We therefore focus our analysis of the inner-core descent at the intensification and later stages.

The initial positions of the air parcels at intensification stage are within a $3/8$ radius around the storm center (Fig. 10b). The majority of air parcels originate from inside the inner core and from its close vicinity downshear between 2 and 12 km. These inner-core air masses can be identified in the thermodynamic histogram (Fig. 10a) by values between $345 \leq \theta_e \leq 350 \text{ K}$ for $T > 260 \text{ K}$ and $350 \leq \theta_e \leq 352 \text{ K}$ for $T < 260$. These values are similar to those of the end positions of air parcels ascending in the inner core (Fig. 5b). Another similarity between the inner-core convection and the

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**Fig. 8.** Height distribution (colored) of the end positions of air parcels seeded in the inner-core convection. (a) Tropical storm stage. (b) Intensification stage. (c) Intermediate stage. (d) Extratropical storm stage. Note that the horizontal scale is different at different stages. The black cross marks the storm center at 950 hPa and the black contour line depicts the smoothed inertial stability threshold at 3000 m. Background $\theta_e$ field at 500 m is shown by gray contour lines. The black arrow indicates the deep-layer shear vector between 200 and 800 hPa at seeding time.
inner-core descent is the distribution at $T > 290\,\text{K}$ (Fig. 10a) that looks similar to the boundary layer inflow pattern in Fig. 6c. The spatial distribution of this inflow layer is also similar, and is mostly from the southeast below 2 km (cf. Figs. 10b and 6d). This similarity in the inflow layer is also found for the later two stages (cf. Figs. 10c,e and 6e,g and Figs. 10d,f and 6f,h). It seems counterintuitive to see air masses from the boundary layer at the initial positions when looking at downward motions of air parcels in the inner core. The fact that air parcels from the same region are part of the inner-core convection (Figs. 6d,f,h) indicates that air parcels in the inner core of Karl perform a rollercoaster-like movement while circulating upward inside the core. Since the seeding of the trajectories in the inner core is a snapshot of the current state at seeding time, some of those air parcels originating from the inflow layer are captured during a downward motion, while others are captured during upward motion. To provide a quantitative estimate of the relative occurrence of this air parcel behavior, we calculate the fraction of “rollercoaster” air parcels relative to the total number of “inner-core descent” air parcels. To do so, we select air parcels that start in the inflow layer (specifically: below 2-km height) and that perform substantial up–down–up altitude changes. Specifically, we select air parcels with an initial ascent of at least 1.5 km to a local altitude maximum prior to their seeding time, a subsequent descent of at least 1 km, ongoing at seeding time, to a local altitude minimum after seeding time, and a subsequent ascent of again at least 1.5 km. A further criterion is that the air parcels are within 1° radius from the storm center at the time of their first maximum altitude and at the time of their subsequent minimum altitude. These criteria are fulfilled by the following percentages of all “inner-core descent” air parcels that originate from below 2-km height: 8% during tropical storm stage, 21% during intensification stage, 38% during intermediate stage, and 1% during extratropical storm stage. The rollercoaster-like movement is most prominent at intensification stage and intermediate stage, when Karl resembles a tropical storm in moderate vertical wind shear. Relaxing the inner-core descent criteria to also include air parcels with a relative humidity between 70% and 85% tends to yield similar results (12% at intensification stage and 35% at intermediate stage) but also shows that the rollercoaster movement is more prominent for drier air masses. These results indicate that the rollercoaster-like movement becomes more prominent as the magnitude of vertical shear increases, but only to an extent to which a storm exhibits the characteristic of a Lagrangian vortex (i.e., air parcels indeed revolve around the center), which is apparently no longer the case during the extratropical storm stage.

Above 6-km height, at intensification stage, there are air masses that originate from well-outside the inner core, one region directly upshear and the second from left of the shear vector (Fig. 10b). These air masses exhibit $\theta_e$ values at their initial positions that are smaller than that of the inner core. The distinction of these air masses in thermodynamic space becomes clearer during the later stages by a cluster of initial positions with $341 \leq \theta_e \leq 349\,\text{K}$ and $230 \leq T \leq 245\,\text{K}$ and a cluster with $332 \leq \theta_e \leq 336\,\text{K}$ and $250 \leq T \leq 258\,\text{K}$ at the intermediate stage (Fig. 10e). At extratropical storm stage (Fig. 10e), a cluster of initial positions can be identified with $346 \leq \theta_e \leq 353\,\text{K}$ and around $210 \leq T \leq 242\,\text{K}$ and another cluster with $330 \leq \theta_e \leq 340\,\text{K}$ and $240 \leq T \leq 260\,\text{K}$. Two distinct airstreams above 6 km, originating from upshear and from left of shear are clearly visible at the intermediate stage (Fig. 10d) and appear as a southern airstream from upshear above 10-km height and a northern airstream from upshear between 6- and 10-km height at the extratropical storm stage (Fig. 10f). In addition, air masses descend into the inner core at this time originating between 2 and 6 km mostly from downshear left. While the horizontal distribution of initial positions in Fig. 10f suggests that the airstream from downshear left is connected to that from upshear, a closer analysis reveals that these are distinct airstreams, separated in height on average by 2–4 km (not shown).

d. Development toward a warm conveyor belt

The previous discussion focused on the air masses inside the inner core of Karl. Here, we complement this
perspective by analyzing upward motion outside of the inner core, which is preferentially found on the downshear side (Fig. 3d). Our focus is on the extratropical storm stage, because at this time the interaction with the baroclinic zone is strongest and the transition from convection within a vertically sheared tropical cyclone to the development of the warm conveyor belt of an extratropical cyclone is most apparent. We apply the same relative humidity threshold of RH > 90% and vertical velocity threshold of $w > 0.5$ m s$^{-1}$ as for the identification of the inner-core convection, but now consider air parcels only that are below the inertial stability threshold of $I^2 = 4 \times 10^{-7}$ s$^{-2}$ that defines the inner-core region. The defined thresholds must again be met at seeding time. Air parcels seeded outside of the inner core but restricted to our seeding region, which is

![Figure 10](image-url)

Fig. 10. Inner-core descent of air masses. (left) Thermodynamic histogram with relative distribution (colored by density) of initial positions for the (a) intensification stage, (c) the intermediate stage, and (e) the extratropical storm stage. (right) Corresponding height distribution (height denoted by colors) of source regions for (b) the intensification stage, (d) the intermediate stage, and (f) the extratropical storm stage. Note that the horizontal scale is different at different stages. The black cross marks the storm center at 950 hPa and the black contour line depicts the smoothed inertial stability threshold at 3000 m. Background $\theta_e$ field at 500 m is shown by gray contour lines. The black arrow indicates the deep-layer shear vector between 200 and 800 hPa at seeding time.
within a radius of 2.5° from the center, are therefore considered. The majority of the air masses ascending outside of the inner core originate from the right-of-shear quadrants (70%, Fig. 11a) and end up in the downshear-left quadrant (80%, Fig. 11d). A close visual inspection of the spatial distribution of air parcels indicates four distinct source regions of air ascending downshear of Karl. Two source regions are, 6 h before the ascent, right of shear: one below 1 km at a radius of approximately 5° from the center, and one between 2 and 6 km at a radius of 2°–3° (Fig. 11a). Between these two regions is a steep height gradient from southeast toward northwest with air parcels between 1 and 2 km. This gradient further steepens in the subsequent time steps (Fig. 11b). A third region is located upshear and in close vicinity of the inner core and extends up to 4-km height. Air masses from these regions move cyclonically around the inner core (Fig. 11b) and converge downshear of Karl into the region of ascent (Fig. 11c). These cyclonically moving air masses are highlighted by representative air parcels for each airstream in Figs. 11a and 11b. The fourth source region is left of shear, along the baroclinic zone, and ranges from 0- to 10-km height. The systematic vertical distribution of the air parcels, decreasing in height from southwest to northeast, is a signature of the vertical shear of the environmental flow. At seeding time, by design, these air parcels are located at different heights in the coherent airstream of the emerging warm conveyor belt to the northeast of the storm center (indicated in Fig. 11c 1 h before seeding). The sequence from Fig. 11a to Fig. 11c illustrates how the tilted airstream “un-tilts” in the vertical shear.

The end positions of the ascent outside of the inner core are presented in Fig. 11d. The majority of the air masses within 2.5° from the center are considered.

FIG. 11. Height distribution (colored) of airstreams evolving into a warm conveyor belt that were seeded at extratropical storm stage (1200 UTC 25 Sep). (a) 0600 UTC 25 Sep, 6 h prior to seeding, and (b) 0900 UTC 25 Sep, 3 h prior to seeding, show three different airstreams cyclonically moving around the storm center. The airstreams are highlighted by six air parcels from each airstream, stringed along red lines. (c) 1100 UTC 25 Sep, 1 h prior to seeding, shows the convergence of those airstreams downshear of the inner core. (d) 1800 UTC 25 Sep, 6 h after seeding, shows the ascent of air parcels outside of the inner core. Note that the horizontal scale is different at different stages. The black cross marks the storm center at 950 hPa. Background 𝜃_e field at 500 m is shown by gray contour lines. The black arrow indicates the deep-layer shear vector between 200 and 800 hPa at seeding time. For clarity only every second air parcel is shown.
parcels exhibit the signature of warm-conveyor-belt outflow with substantial ascent near the baroclinic zone and anticyclonic curvature that indicates ridge building downstream of Karl. A minority of the air masses, mostly below 4-km height, continue to move cyclonically around the center and their end positions are found upshear. These air masses apparently ascend along the baroclinic zone downshear of Karl and again descend along the baroclinic zone upshear. Below 1-km height, some of these air parcels move very quickly upshear relative to the storm center. A similar behavior is described in section 4a for air parcels that originate from the cold side of the baroclinic zone and that pass by Karl due to the fast movement of the storm.

This trajectory analysis sheds new light on the formation of a warm conveyor belt during ET. Previous work has illustrated in a case study how the upright convection during the tropical phase of ET subsequently transitions into more slantwise ascent (Grams et al. 2013). Detailed trajectory analysis has recently demonstrated both convective and slantwise ascent in warm conveyor belts of midlatitude cyclones (Rasp et al. 2016), confirming the “elevator-escalator” concept (Neiman et al. 1993) from a Lagrangian perspective. The results presented herein demonstrate that the developing warm conveyor belt during ET comprises air masses of very different source regions and partly only from the cyclone’s developing warm sector, which is the predominant source region of warm-conveyor-belt ascent in midlatitude cyclones. In this sense, the characteristic of the warm-conveyor-belt source region is similar during the ET of Sinlaku (2008; Schäffer and Harnisch 2015, their Fig. 4), although that study did not address explicitly the issue of different source regions.

6. Summary and conclusions

This study provides a Lagrangian description of evolving airstreams during the ET of Tropical Storm Karl (2016) based on extensive trajectory analysis. The airstreams comprise those associated with inner-core convection, descent in the inner core, and the developing warm conveyor belt at the end of the tropical phase of Karl’s ET. Following previous work of a mature TC in an idealized numerical experiment (Riemer and Laliberté 2015), we first focus on the thermodynamic properties of air masses in entropy–temperature ($\theta_e - T$) space. Partly based on a subjective identification of clusters in $\theta_e - T$ space, this perspective is then extended by a spatial analysis of the source regions and the end points of the associated trajectories.

The trajectory calculation is based on a 66-h convection-permitting simulation with the COSMO-model of the German Weather Service. Although the model somewhat overestimates the forward speed and the intensification of Karl, we deem the simulation to be realistic enough for the purpose of this study. Four key stages are identified during the tropical phase of Karl’s ET: (i) tropical storm, (ii) intensification, (iii) intermediate, and (iv) extratropical storm stage. At these stages, trajectories are seeded within 2.5° radius of the storm center and calculated forward and backward in time for 6 h. To examine inner-core convection, dry descent inside the inner core, and the developing warm conveyor belt, threshold criteria for relative humidity, vertical velocity, and inertial stability are applied to filter the trajectories.

The mass flux in $\theta_e - T$ space, complemented by the start and end positions of trajectories in that space, provides a general overview of Karl’s evolution. During tropical storm stage and intensification stage, Karl’s inflow shows virtually no increase in $\theta_e$ in the 6 h preceding ascent in the inner-core convection. This observation indicates that there is no substantial local coupling between Karl and the underlying ocean surface, reminiscent of the pre-WISHE stage hypothesized by Molinari et al. (2004). Importantly, the intensification of Karl was not accompanied by a stronger coupling and thereby an increase in inner-core $\theta_e$ values but rather with the development of a distinct outflow layer at cold temperatures. Apparently, at tropical storm stage when Karl was a weak tropical cyclone, intensification is impeded by excessive detrainment of air from the inner-core convection at levels between the inflow and the tentative outflow layer. Karl’s intensification occurred during the increase of vertical wind shear and it is thus plausible that convective organization and an increase of vertical mass flux by the shear (Davis et al. 2008) promoted intensification. Karl’s intensification occurred also in a favorable upper-level environment, namely in the right entrance region of the jet streak that developed downstream of Karl. It is thus possible that upper-level features have further promoted Karl’s intensification, but these features are not in the focus of the current study.

In addition to a downshear shift of the convection, the changes in the environment during ET are felt by Karl’s inner-core convection mostly through a decrease of the inflow layer $\theta_e$ values when Karl moves into a cooler and drier environment. Arguably, this decrease in the inflow layer $\theta_e$ governs the gradual decrease of $\theta_e$ in the inner-core convection and the gradual increase of the outflow temperature. The spatial distribution of trajectory start positions reveals that not only do the thermodynamic characteristics of the inflowing air changes, but also the source regions relative to the storm center change.
systematically. With the increase of vertical shear during transition, this source region becomes gradually more asymmetric and air masses originate from much larger radii right of shear (up to $5^\circ$ radius for the large shear values during the extratropical storm stage) than from left of shear (where the inflow is confined to $1^\circ$–$2^\circ$ radius). This confinement implies that no air masses from the cold side of the baroclinic zone are part of the inner-core convection. Based on the trajectories of air parcels from the cold side of the baroclinic zone, we hypothesize that Karl’s fast movement relative to the environmental flow isolates the inner-core convection from air masses from that region.

Above the inflow layer, and below the outflow layer, the most substantial interaction with the environment is detrainment from the inner-core convection. Detrainment occurs at all levels and the detrained air masses stay in close vicinity of the inner core, except at extratropical storm stage, and preferentially downshear. Compared to air parcels that detrain, fewer air parcels intrude into the inner core convection, mostly below 6-km height, and preferentially from downshear, too. Detrainment into and intrusion from the same region indicates that some of the detrained air masses are potentially recycled in the inner-core convection. Notably also is that Karl’s inner core, notwithstanding the weak intensity and the absence of an eyewall, acts as a “containment vessel” that transport high-$\theta_e$ air into an increasingly hostile environment, where these air masses potentially contribute to maintaining deep convection during the ET of Karl [in analogy of the high-$\theta_e$ air in the low-level eye identified by Cram et al. (2007)].

Air masses that descend in the inner core and that originate from the inflow layer have very similar source regions as those air masses that ascend in the inner core. This similar origin of descending and ascending air masses in the inner core of Karl indicates that it is partly the same air masses that perform upward and downward motion inside the inner core. Air parcels may therefore perform a rollercoaster-like movement. This movement becomes more prominent in Karl with increasing vertical shear from the tropical storm stage to the intermediate stage. The important consequence of this observation is that instantaneously observed descent in a TC’s inner core does not need to be associated with descending air originating from higher levels in the environment. Partly, however, the descent in the inner core does originate from the environment, mostly from upshear and left of shear and from heights above 4 km. These airstreams become more prominent as vertical shear increases and Karl approaches the baroclinic zone. As hypothesized by the conceptual model of Klein et al. (2000), and supported by observational data during the ET of Sinlaku (2008) (Quinting et al. 2014), our results further indicate that these descending dry intrusions are an essential part of structure evolution during ET because they herald the cold air masses descending along the baroclinic zone in a midlatitude cyclone.

The trajectory analysis also elucidates the formation of a warm conveyor belt during Karl’s ET. While previous work has illustrated the transition of upright (tropical) convection to more slantwise ascent (Grams et al. 2013), our results demonstrate that the apparent warm conveyor belt during transition may comprise air masses from very different source regions. Only partly does the developing warm conveyor belt at this time during Karl’s ET originate from the cyclone’s developing warm sector. Upper-tropospheric outflow from the developing warm conveyor belt is essential in projecting the uncertainty in the evolution of the ET cyclone onto the midlatitude flow (Keller et al. 2019). Insight into the air masses that constitute this airstream may therefore be useful to constrain, or at least to better understand, this source of uncertainty for the midlatitude flow in the future.

The presented Lagrangian analysis provides a useful framework to examine the evolution of prominent airstreams during ET. The specific case of Karl is characterized, inter alia, by the weak intensity and fast movement of the cyclone. It is well known that ET exhibits a large case-to-case variability and the results from this study should not be generalized. Further case studies are needed to identify commonalities and differences between different ET scenarios and to relate their Lagrangian characteristics to the characteristics of the transitioning TC and of the environment. To apply our Lagrangian analysis to a large number of cases, however, will require a semiautomated approach. Once such an approach is available, the application of the Lagrangian analysis in an ensemble framework to investigate the evolution of uncertainty associated with different airstreams is a fruitful objective for future endeavors.

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