Amplification of the Downstream Wave Train during Extratropical Transition: Sensitivity Studies

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ABSTRACT

A tropical cyclone (TC) undergoing extratropical transition (ET) may support the amplification of a Rossby wave train in the downstream midlatitudes. Within the context of downstream baroclinic development, the TC acts as an additional source of eddy kinetic energy (\(K_e\)). Previous studies concluded that the impact depends, in particular, on the phasing between the TC and the midlatitude flow and the continuation of the \(K_e\) generation during ET. These studies did not quantify the impact of ET on the \(K_e\) within a downstream Rossby wave train.

The present study uses ensemble sensitivity analysis to examine the sensitivity of downstream Rossby wave train amplification to the \(K_e\) budget of the transitioning TC and of the upstream midlatitude features for Typhoon Choi-Wan (2009) and Hurricane Hanna (2008) in ECMWF ensemble forecasts. The amplification of the downstream wave train is measured using the amplitude of its associated \(K_e\) maxima. The sensitivity of the \(K_e\) maximum’s intensity at a particular forecast time to the \(K_e\) budget terms of the TC and the upstream midlatitudes at earlier forecast times is determined. The results show that increasing the \(K_e\) budget terms within Choi-Wan (Hanna) by one standard deviation can result in an up to 36% (23%) more intense downstream \(K_e\) maximum. This is favored by the phasing between Choi-Wan and the midlatitude trough, and the reintensification of Hanna, respectively. By contrast, weaker contributions to downstream Rossby wave amplification arise from \(K_e\) budget terms associated with flow features in the upstream midlatitudes.

1. Introduction

The extratropical transition (ET; Jones et al. 2003) of tropical cyclones, and in particular the impact of an ET event on the downstream midlatitude flow, was the subject of numerous studies in recent years. During ET the tropical cyclone (TC) interacts with the midlatitude baroclinic flow. Thereby, the system may transform from a symmetric tropical to an asymmetric extratropical cyclone (Klein et al. 2000) and reintensify as a strong baroclinic midlatitude cyclone (Klein et al. 2002). At the same time, the TC circulation, and the associated ascent of warm and moist air along the baroclinic zone, may strongly modulate the midlatitude flow configuration. This complex interaction often enhances forecast uncertainty in downstream regions (e.g., Anwender et al. 2008; Harr et al. 2008; Pantillon et al. 2013b; Grams et al. 2015; Aiyyer 2015). A detailed understanding and knowledge of the significant processes involved, and information about their representation in current weather forecasting models, may improve future ET event forecasts (e.g., Jones et al. 2003; Harr 2010).

Diabatic processes associated with the transitioning cyclone or the precipitation along the baroclinic zone (e.g., Riemer et al. 2008; Torn 2010a; Grams et al. 2011; Pantillon et al. 2013a) reduce potential vorticity (PV) in the ascending air mass. The divergent upper-level outflow of the TC advects low-PV air toward the midlatitude baroclinic zone. This strengthens the PV gradient, accelerates the upper-level midlatitude jet, and may trigger or strengthen the amplification of an upper-level ridge directly downstream of the transitioning storm (e.g., Atallah and Bosart 2003; Riemer et al. 2008; Grams et al. 2011, 2013a,b; Griffin and Bosart 2014). Later in the development, the ridge amplification is supported by the cyclonic
circulation of the decaying TC and the divergent component of the upper-level flow, which still comprises contributions from the TC outflow (Riemer et al. 2008; Archambault et al. 2015; Quinting and Jones 2016). The interaction may result in a phase locking between the decaying TC and the upper-level flow. Overall, the TC can be seen to act as a local wave maker, which may decelerate the propagation of the upper-level midlatitude wave pattern, while also contributing to its amplification (Riemer et al. 2008).

The initial ridge amplification may trigger the development of a midlatitude Rossby wave train (RWT), propagating the potential impact of an ET system far beyond the region of the actual interaction (e.g., Riemer et al. 2008; Harr and Dea 2009; Riemer and Jones 2010; Cordeira and Bosart 2010; Keller et al. 2014). As a result, the amplitude and elongation of Rossby wave packets (RWP)s downstream of ET events are significantly above average in the western North Pacific (Torn and Hakim 2015; Quinting and Jones 2016). However, RWPs associated with transitioning TCs in the North Atlantic are less amplified than RWPs of extratropical cyclones (Torn and Hakim 2015) and tend to result in Rossby wave breaking over Europe (Pantillon et al. 2015). More information on the climatological characteristics of RWPs can be found in, for example, Souders et al. (2014) and Glatt and Wirth (2014).

The amplification and downstream propagation of an RWT can be assessed by analyzing the local eddy kinetic energy ($K_e$) budget within the context of the downstream baroclinic development paradigm of Orlanski and Sheldon (1995). Based on analysis data for several ET cases, Harr and Dea (2009) showed the transitioning TC to act as an additional source of $K_e$, supporting the amplification and downstream dispersion of an RWT. Keller et al. (2014) applied the approach of Harr and Dea (2009) to forecast scenarios for the ET of Hurricane Hanna (2008) and Typhoon Choi-Wan (2009), derived from the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (ECMWF EPS). They found that the position of the transitioning TC with respect to the midlatitude flow, as well as the duration of baroclinic conversion of $K_e$ during the ET process, were both crucial factors for the generation and downstream dispersion of $K_e$.

Besides providing information on forecast scenarios and their uncertainty, ensemble forecasts also enable identification of sensitivities and hence reveal dynamical dependencies between distinct forecast variables. This approach is known as “ensemble sensitivity analysis” (Hakim and Torn 2008) and was successfully applied to investigate the effect of initial condition uncertainty (or perturbations) on short-range ensemble forecasts (e.g., Hawblitzel et al. 2007; Sippel and Zhang 2008; Torn and Hakim 2008; Torn 2010a,b; Torn and Cook 2013) or for revealing the dynamical and physical dependencies in operational medium-range ensemble forecasts (e.g., Schumacher 2011; Chang et al. 2013; Zheng et al. 2013).

The studies by Harr and Dea (2009) and Keller et al. (2014) focused on the impact of the transitioning TC on the downstream RWT. The contribution to RWT amplification by preexisting $K_e$ maxima upstream of the TC was only discussed tangentially. Harr and Dea (2009) assessed the total increase in volume-integrated $K_e$ over the Pacific in the aftermath of an ET event. However, the amount of additional $K_e$ within the midlatitude RWT that results from ET has not been quantified yet. The present study aims to answer the following questions: 1) What is the role of the upstream midlatitudes in the amplification of the RWT downstream of the ET event? 2) How sensitive is the downstream $K_e$ to processes associated with the transitioning TC and upstream midlatitude flow conditions? Ensemble sensitivity analysis is applied to the $K_e$ budget for two different ET cases to address these questions. Both the $K_e$ analysis and the ensemble sensitivity analysis can be used for the investigation of important aspects of ET (Harr and Dea 2009; Torn and Hakim 2009; Torn 2010a; Keller et al. 2014; Quinting and Jones 2016). To the author’s knowledge, the present study is the first that combines the two analysis techniques to make use of the $K_e$ analysis for an operational EPS in a way that goes beyond the investigation of several forecast scenarios.

The paper is organized as follows. Section 2 introduces the database used in the study, while an outline of the analysis methods is provided in section 3. The investigation and interpretation of the results (section 4) is followed by a discussion and conclusions (section 5).

2. Cases and data

To address the questions outlined above, this study investigates the extratropical transition of the two storms discussed in Keller et al. (2014): Typhoon Choi-Wan (2009) and Hurricane Hanna (2008). More details on the synoptic evolution and the downstream impact of the two storms are provided in sections 4a and 4b. The study employs the same 10-day ensemble forecasts from the ECMWF EPS (Table 1) that were used by Keller et al. (2014). The forecast for Hurricane Hanna, initialized at 0000 UTC 5 September 2008, was developed with an experimental setup of the ECMWF EPS (Lang et al. 2012; Cycle36r1, T639L62; unpublished data), which comprises initial perturbations from singular vectors and an analysis ensemble. It offers output on more pressure levels than the operational ECMWF EPS forecasts, especially for the vertical velocity $\omega$, making it more suitable for deriving the $K_e$ budget. As this dataset
is unavailable for Typhoon Choi-Wan, a forecast from the operational ECMWF EPS [ECMWF (2008); Cycle35r3, T639L62] is used instead. This forecast was initialized at 0000 UTC 15 September 2009, and has its initial perturbations derived only from singular vectors. As a result of the reduced number of pressure levels, the magnitude of the baroclinic conversion derived from this dataset is expected to be weaker, while the overall spatial distribution is reproduced well (cf. Keller 2012). All 51 members of the ECMWF EPS are considered in the study and the data are used at 0.5° latitude–longitude resolution with output every 12 h. In general, the signals obtained through ensemble sensitivity analysis might become more and more confined with an increasing number of ensemble members (Hakim and Torn 2008; Zheng et al. 2013) and a multimodel approach like the THORPEX Interactive Grand Global Ensemble (TIGGE; Swinbank et al. 2016) could have been an option to overcoming this limitation. Beside the fact that vertical velocity (required for $K_e$ budget) is not archived in TIGGE, the impact of variability introduced by combining single ensemble forecast with 51 members is not clear yet. Hence, we focus on the ECMWF EPS as a single ensemble forecast with 51 members.

### 3. Description of analysis methods

#### a. Eddy kinetic energy budget

The development and downstream propagation of mid-latitude wave trains can be explained in terms of the downstream baroclinic development paradigm (Orlanski and Sheldon 1995). This approach investigate the localized $K_e$ budget to reveal information on wave train dynamics. For this, $K_e$ is defined as the deviation of the kinetic energy from a 30-day running mean, centered on the date of investigation. The local $K_e$ budget can be derived by partitioning its contributing components into a mean (index $m$) and an eddy (dashes) part. The resulting budget equation is

$$\frac{1}{g} \int_{p_1}^{p_2} \frac{\partial K_e}{\partial t} dp = \frac{1}{g} \int_{p_1}^{p_2} \left\{ (-v' \cdot \nabla_p \phi') - \nabla_p \cdot (vK_e) \right\} dp \right.$$  

in which

$$\frac{1}{g} \int_{p_1}^{p_2} \left[ (v' \cdot \nabla_p \phi') - \nabla_p \cdot (vK_e) \right] dp = -\frac{1}{g} \int_{p_1}^{p_2} \nabla_p \cdot (v' \phi') dp \text{ residual} \right.$$  

The local $K_e$ center might be altered by generation of $K_e$ [first term on the right-hand side in Eq. (1)], $K_e$ advection with the total wind $v$ (i.e., downstream propagation by phase velocity; the second term), and barotropic conversion of kinetic energy between the eddy and the mean flow (third term), which is typically about an order of magnitude smaller than the other budget terms (Danielson et al. 2004). Friction is captured in the residual. The generation of $K_e$ is composed of the baroclinic conversion of $K_e$ when eddy available potential energy is converted into $K_e$ through lifting of warm and sinking of cold air masses [first term on the right-hand side in Eq. (2)], and the divergence of the ageostrophic geopotential flux (second term), which disperses $K_e$ from one center to another (i.e., downstream propagation by group velocity).

As in Harr and Dea (2009), all quantities are vertically integrated between $p_1 = 1000$ and $p_2 = 100$ hPa, and normalized by the standard gravity $g = 9.81$ m s$^{-2}$, to obtain units of joules per square meter for $K_e$ and watts per square meter for the budget terms (J. H. Keller 2012, unpublished data).

#### b. Ensemble sensitivity analysis

Ensemble sensitivity analysis (ESA) is based on the idea that small deviations of a state variable $X$ (e.g., geopotential height; see Fig. 1) from the ensemble mean at a specific forecast time are correlated with deviations of a forecast metric $J$ (e.g., core pressure of extratropical cyclone; Fig. 1) from the ensemble mean at later forecast times, with the assumption of a linear error growth relationship. In this way, ESA can be used to examine the impact of different flow features (like the midlatitude trough; cf. Fig. 1) on the development of the forecast metric (i.e., the intensity of the storm; cf. Fig. 1). The sensitive regions further indicate where, for example, the initial perturbations have the strongest impact on the forecast and, potentially, where additional observations could be most beneficial (Torn and Hakim 2009).

### Table 1. Overview on forecast data and times used in sensitivity calculations.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Forecast initialization</th>
<th>Forecast metric time</th>
<th>Time of sensitivity to budget fields</th>
<th>No. of members considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typhoon Choi-Wan</td>
<td>0000 UTC 15 Sep</td>
<td>0000 UTC 20 Sep</td>
<td>0000 UTC 18 Sep–0000 UTC</td>
<td>Rear: 47</td>
</tr>
<tr>
<td>(2009)</td>
<td></td>
<td></td>
<td>19 Sep</td>
<td>Front: 50</td>
</tr>
<tr>
<td>Hurricane Hanna</td>
<td>0000 UTC 5 Sep</td>
<td>1200 UTC 10 Sep</td>
<td>1200 UTC 8 Sep–1200 UTC</td>
<td>Max: 50</td>
</tr>
<tr>
<td>(2008)</td>
<td></td>
<td></td>
<td>9 Sep</td>
<td></td>
</tr>
</tbody>
</table>

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According to Torn and Hakim (2008), sensitivity is defined as the regression between the (independent) state variable \( X \) and a (dependent) forecast metric \( J \):

\[
sens = \frac{\partial J}{\partial X} \cdot \sigma_x = \frac{\text{cov}(J, X)}{\text{var}(X, X)} \cdot \sigma_x.
\]

While \( X \) refers to a forecast field from each of the ensemble members, \( J \) comprises only a single value for every member in this study. Normalization using the standard deviation of the forecast field \( \sigma_x \), instead of a constant value, accounts for the generally lower forecast variability at lower latitudes (Garcies and Homar 2009) and provides the change of the forecast metric \( J \) with respect to a change of \( 1\sigma_x \) in the state variable. This makes the sensitivity of one forecast metric comparable to different state variables (Torn and Hakim 2009). To consider only significant relationships between the forecast metric and state variables and to eliminate sampling errors due to a rather small ensemble size (51 members), regions are only considered when the sensitivity is statistically significant at the 95\% level (Torn and Hakim 2008).

Since initial perturbations in the ECMWF EPS partially result from singular vectors, the initial condition uncertainty may not properly resemble the probability distribution of the analysis and the data should only be used for sensitivity studies after the “memory to initial perturbations” is lost (Hakim and Torn 2008). Hence, we restrict our sensitivity calculations to forecast lead times of +48 h and beyond.

c. Investigation setup

To investigate the impact of the transitioning TC on the midlatitude flow, we derive our forecast metric \( J \) from the \( K_r \) center on the rear flank of the downstream trough at a particular forecast time, and determine the
sensitivity of this metric to the $K_{e}$ budget terms (state variable $X$) at earlier forecast times. To obtain the forecast metric $J$ from the $K_{e}$ field, we follow the object identification procedure from the Method for Object-Based Diagnostic Evaluation (MODE; Davis et al. 2006). For every ensemble member a mask is developed. The $K_{e}$ field is smoothed (convolution radius = 10 grid points) and a threshold is applied to the smoothed field so that all but the upper 5% of the $K_{e}$ values in the maximum are masked out. Using the upper 5% allows us to focus on compact $K_{e}$ maxima that can be identified in most ensemble members. This mask is applied to the full $K_{e}$ field of the ensemble member to extract the $K_{e}$ maxima of interest. The magnitude of $K_{e}$, averaged over the identified $K_{e}$ object, is then used as the forecast metric (Fig. 2a). With this, the sensitivities indicate how 1$\sigma_{e}$ changes in the $K_{e}$ budget field (state variable) affect the intensity of the downstream $K_{e}$ maximum (metric, in $10^{5}$ J m$^{-2}$ per 1$\sigma_{e}$). The changes in the forecast metric that are implied by the sensitivity results generally affect both the intensity and size of the forecast metric: for a strong $K_{e}$ maximum, the upper 5% of $K_{e}$ values might capture a larger area. However, this of course also depends on the $K_{e}$ gradient within the $K_{e}$ center. In the remainder of the study we focus on the intensity of the maximum and neglect its spatial structure. A guide for interpreting the sensitivity results is provided in Fig. 2b.

This approach for identifying the forecast metric is beneficial over just using the $K_{e}$, averaged over a box around the ensemble mean for $K_{e}$. The latter would tend to miss $K_{e}$ maxima that are outliers to the west or east of the predefined box as a result of phase differences in the developing RWT, especially at later forecast times. Tying the threshold to a percentage of the absolute value, here the upper 5%, instead of using a fixed threshold, allows consideration of members with weaker $K_{e}$ maxima. Choosing another percentage threshold (e.g., upper 10%) only affects the absolute sensitivity values, because of changes in the ensemble mean, but not the shape and identification of sensitive regions. For a small number of ensemble members (cf. Table 1), the respective $K_{e}$ maximum might not be identifiable (because its maximum $K_{e}$ value is smaller than $1 \times 10^{5}$ J m$^{-2}$). In this case, the metric value remains undefined and this ensemble member is not considered when computing the sensitivity.

In this study we focus on forecast intervals of up to 48 h between the definition of the state variable and the forecast metric, assuming an approximately linear error growth relationship over this time interval. For geopotential height, Chang et al. (2013) successfully traced sensitivity signals in forecast intervals of up to 168 h. For the $K_{e}$ budget, however, we assume that a nonlinear relationship in error growth between the forecast metric and the state variable may affect the evolution earlier than for the standard synoptic fields. In addition, sensitivity in our case also depends on the presence of $K_{e}$-affecting processes that may impact the growth of our forecast metric. Hence, sensitivity to particular processes, for example, downstream dispersion of $K_{e}$ emanating from the TC, might not occur before this process starts. The best suitable forecast metric times are chosen based on the group velocity of the wave train. The group velocity describes the downstream dispersion of $K_{e}$ (Orlanski and Sheldon 1995) and indicates the time that energy fluxes may be required to affect the downstream $K_{e}$ maximum, after they emanated from the TC or the upstream midlatitudes.

The investigation starts by determining the sensitivities of four consecutive (in time) forecast metrics to the $K_{e}$ budget terms at one particular forecast time, respectively. Sensitive regions that are consistent for different metric times highlight those features of the $K_{e}$ budget terms that continuously impact the growth of the $K_{e}$ maxima, that is, those that are linked to dynamical processes. Changes in the sensitivity of the four metrics may result from changes in the ensemble mean. Stronger sensitivity for later metric times than for earlier ones is caused by the overall increase in the standard deviation of the metric with forecast time. Occurrence or disappearance of sensitivity signals from one metric time to another may indicate that the metric has not been sensitive yet or is no longer sensitive to a particular feature of the $K_{e}$ budget. The detailed analysis for each of the two storms then discusses the sensitivity of one particular forecast metric to the $K_{e}$ budget terms at earlier forecast times in detail to quantify the contribution of the TC and the upstream midlatitudes in the amplification of the metric.

4. Results

a. Typhoon Choi-Wan

Typhoon Choi-Wan (September 2009) recurved ahead of a midlatitude trough, interacted, and eventually merged with a preexisting extratropical disturbance. Thereafter, the ex-TC reintensified and moved eastward. Choi-Wan’s ET was followed by a strong amplification of the downstream midlatitude wave train that led to a heat wave over western North America and cold-air outbreaks over the Great Plains. As shown in Keller et al. (2014), the amplification of the downstream wave train depended strongly on the phasing and interaction between the transitioning TC, the midlatitude wave train, and an extratropical disturbance. In some
ensemble members the amplification also depended on the $K_e$ fluxes from another cyclone upstream of Choi-Wan. The relative roles of the transitioning TC, the extratropical disturbance, and the upstream cyclone (indicated as TY, FW, and UP, respectively, in Fig. 3) as sources of $K_e$, and in particular their quantitative contributions to the amplification of the RWT, have not been identified yet and are revealed in this work. To quantify the amplification of the RWT, the magnitudes of the $K_e$ maxima (cf. section 3c) on the rear and front flanks of the downstream trough are considered as forecast metrics (and referred to as REAR and FRONT, respectively; Fig. 3). Focusing on a 48-h time window between the forecast metric and the state variable.
ensures the ability to capture the impact of the TC and the frontal wave on REAR. With a group velocity\(^1\) of \(v_{\text{group}} = 25 \text{ m s}^{-1}\) and a median distance of 3500 km between the transitioning TC and REAR at a reference latitude of 40\(^\circ\)N, the time after which the \(K_e\) fluxes from the TC may influence the \(K_e\) maxima can be estimated as 38 h. For fluxes that emanate from the frontal wave and the upstream extratropical cyclone, the times are shorter and longer, respectively.

1) CONSISTENCY IN SENSITIVITY

As outlined in section 3c, we will first determine the sensitivities of a series of forecast metrics to the \(K_e\) budget at one particular forecast time. As forecast metrics, we use the \(K_e\) maximum REAR at four consecutive forecast times. The forecast times chosen (Table 1) compose the period during which REAR underwent intensification: 0000 UTC 19 September–1200 UTC 20 September 2009 (metrics denoted by 1900, 1912, 2000, and 2012). This is at least 48 h after a first connection between Choi-Wan and the midlatitude trough became obvious in the 500-hPa geopotential height field (0000 UTC 17 September 2009). The sensitivity of each of those metrics to the generation\(^2\) of \(K_e\) at 1200 UTC 18 September 2009 is determined. This is the only forecast time that accommodates sensitivity calculations for all four metrics, given the restriction of a maximum 48-h time window between the forecast metric and state variable (cf. section 3b). For all four metric times, the \(K_e\) maxima objects in the ensemble members are clearly aligned with the rear and front flanks of the downstream trough (Fig. 3, ellipses with REAR in red.)

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\(^1\) Derived from a Hovmöller diagram of upper-level meridional winds.

\(^2\) Ageostrophic geopotential flux + baroclinic conversion; cf. Eq. (2).
and FRONT in blue). The variances in their shape and position become more pronounced with increasing forecast time, as indicated by the spread of their center of gravity (Fig. 3, dark red and cyan markers).

Comparing the sensitivities of the four metrics (1900, 1912, 2000, and 2012 UTC) to the $K_e$ generation at 1200 UTC 18 September 2009 (Figs. 4a–d) indicates that the mean $K_e$ of REAR is consistently sensitive to the same specific flow features for all four consecutive metric times. As can be derived from the ensemble mean of $K_e$ generation (black contours) and the 500-hPa geopotential height (gray contours) at 1200 UTC 18 September 2009 in Fig. 4, these flow features are the $K_e$ generation associated with the transitioning TY, FW, as well as the entrance region of REAR itself. Later metric times (2012 UTC) show a stronger sensitivity to $K_e$ generation on this particular day than earlier metric times (1900 UTC), due to an increase in the standard deviation of REAR.

Similar results are found for all other $K_e$ budget terms and all other forecast times, between 0000 UTC 17 September 2009 and the respective metric times. Before 0000 UTC 17 September 2009, the sensitivity regions are less well defined and change shape and position for different metric times (not shown). This might be attributable to the fact that Choi-Wan does not start to interact with the midlatitude flow before that time and a strong sensitivity to significant synoptic features is lacking. It may also result, however, from a nonlinear relationship in error growth between the forecast metric and the $K_e$ budget that may spoil the sensitivity results, in particular for longer forecast intervals between the metric and the $K_e$ field. The fact that the sensitivity shows reasonable results for shorter time intervals legitimates our approach within the indicated restrictions (48-h time window).

Overall, the consistency in sensitivity underpins the dynamical relation between the forecast metric and the highlighted flow features. It is illustrated here for the metric REAR, but also holds true for the metric FRONT.

2) IMPACT OF $K_e$ BUDGET ON WAVE TRAIN AMPLIFICATION

The consistent sensitivity allows us to focus on the results for the forecast metrics REAR and FRONT at 0000 UTC 20 September 2009 only. These metrics show comparably strong sensitivities (Fig. 4c) and clearly defined $K_e$ maxima (Fig. 3c; REAR could be identified in all but 4 of the 51 overall members and FRONT in all but 1; cf. Table 1). We investigate their sensitivities to all five terms in the $K_e$ budget at 0000 UTC 19 September and 0000 UTC 18 September 2009 (i.e., 24 and 48 h prior to the metric time).

The results from Keller et al. (2014) suggest that the amplification of the downstream midlatitude RWT should be sensitive to the phasing between the TC and the midlatitude trough, as well as the interaction with the extratropical disturbance. We are now seeking to quantify the respective contributions of these features, and the upstream midlatitudes, to the intensification of REAR.

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The sensitivity of REAR to baroclinic conversion at 0000 UTC 19 September 2009 (24 h prior to metric time) indicates that the amplification of REAR depends on the release of $K_e$ because of baroclinic conversion along the baroclinic zone and within the frontal wave (Fig. 5a). The averaged maximum $K_e$ in REAR is up to
FIG. 5. Statistically significant sensitivity (shaded in $10^3 \text{J m}^{-2}$) of $K_e$-object REAR for TY Choi-Wan at 0000 UTC 20 Sep 2009 to (a) baroclinic conversion, (b) convergence of ageostrophic geopotential flux, (c) generation of $K_e$, (d) advection of $K_e$ by the total wind, and (e) barotropic conversion at 0000 UTC 19 Sep 2009. As reference for flow configuration, the ensemble means of the 500-hPa geopotential height (gray contours, 520–570 gpdm with 10-gpdm interval) and $K_e$ budget term (black contours) are shown in $\pm$5, 10, 15, 20, and 25 W m$^{-2}$ for barotropic conversion, to account for weaker magnitude, and in $\pm$10, 30, 50, and 70 W m$^{-2}$ for all other terms (convergence: generation, solid; divergence: destruction, dashed).
7.5 × 10^{5} \text{J m}^{-2} \text{h}^{-1} \text{ higher if baroclinic conversion is enhanced by } 1\sigma_{r}, \text{in the shaded regions } (35^\circ-45^\circ \text{N}, 140^\circ-170^\circ \text{E}). \text{With REAR having an intensity of about } 28 \times 10^{5} \text{J m}^{-2} \text{in the ensemble mean, this implies an intensification of about } 27\%. \text{The sensitivity dipole near the storm center } (25^\circ \text{N}, 140^\circ-150^\circ \text{E}) \text{indicates that REAR is weaker by about } 7.5 \times 10^{5} \text{J m}^{-2}, \text{or } 27\%, \text{if the storm's maximum baroclinic conversion is located at a more south-western position, and stronger by the same amount if the maximum remains at a more northeastern position. This reflects the proposed sensitivity to the relative position between the TC and the trough. Quantitative assessment indicates that the larger-scale baroclinic conversion along the baroclinic zone contributes more strongly to the amplification of REAR than the baroclinic conversion within the TC. Of course, this baroclinic conversion along the baroclinic zone is partly fed by warm and humid air that is advected along the eastern side of the storm. The sensitive regions south and east of the storm will be discussed for other budget terms.}

Sensitivity to ageostrophic geopotential flux divergence and convergence along the midlatitude wave train (Fig. 5b) indicates that REAR is intensified by about 9 \times 10^{5} \text{J m}^{-2} \text{or } 32\% \text{ if the ageostrophic geopotential flux convergence is enhanced by } 1\sigma_{r}, \text{in the confluence region between the transitioning TC and the upstream midlatitude trough (along } 140^\circ \text{E}). \text{As converging ageostrophic geopotential fluxes describe the } K_{e}, \text{release through work done by pressure forces, this may reflect the acceleration of air masses from the storm into the trough. Negative sensitivity to the divergence along the baroclinic zone (along } 150^\circ \text{E}) \text{indicates that REAR is up to } 9 \times 10^{5} \text{J m}^{-2} \text{ (32\%) stronger per } 1\sigma_{r}, \text{ increase in downstream dispersion of } K_{e}, \text{from Choi-Wan into the downstream midlatitudes. The same applies to the positive sensitivity associated with the convergence in the entrance region of REAR (near } 50^\circ \text{N}, 160^\circ \text{E}). \text{Negative sensitivity to divergence in its exit region points to the downstream dispersion of } K_{e}. \text{The sensitivity dipole that encloses the ageostrophic geopotential flux convergence along the eastern flank of the TC (15^\circ \text{N}, 130^\circ \text{E} \text{to } 35^\circ \text{N}, 160^\circ \text{E}) \text{also indicates the impact of phasing. The magnitude of REAR is reduced by about } 7 \times 10^{5} \text{J m}^{-2} \text{or } 25\% \text{ if convergence is enhanced south of the ensemble mean ageostrophic geopotential flux convergence (black contours). In contrast, REAR's } K_{e}, \text{is about } 9.5 \times 10^{5} \text{J m}^{-2} \text{(nearly } 34\%) \text{ stronger if convergence is enhanced east-northeast of the storm (30^\circ \text{N}, 150^\circ-160^\circ \text{E}) in a region with weak ensemble mean convergence (below the contour level). A few ensemble members show the TC and hence the divergence and convergence of the ageostrophic geopotential flux at this northeastern position. These members are characterized by the strongest amplification of REAR (not shown), which causes the sensitivity in this region. Finally, diverging ageostrophic geopotential fluxes southwest of Japan, along the rear flank of the trough with which Choi-Wan is interacting, lead to an 18\% increase of about } 5 \times 10^{5} \text{J m}^{-2} \text{in REAR. In some members, this rear-flank } K_{e}, \text{maximum is tied to a weak secondary trough approaching Choi-Wan from the west (not shown). Overall, sensitivity to the ageostrophic geopotential flux divergence and convergence underpins the importance of phasing and interaction between the TC and the midlatitude trough. Thereby, a slightly stronger impact on } K_{e}, \text{magnitude in REAR is found for the } K_{e}, \text{budget within the trough. Only a weak contribution to the amplification of REAR is found for the upstream midlatitudes.}

Sensitivity to the total generation of } K_{e}, (Fig. 5c) \text{reflects a combination of the sensitivity to baroclinic conversion and the convergence/divergence of the ageostrophic geopotential flux. Again, the strongest contribution to the amplification of REAR stems from } K_{e}, \text{generation in the confluence region between the TC and the midlatitude trough and the entrance region of REAR (up to } 10 \times 10^{5} \text{J m}^{-2} \text{or } 36\%). \text{Slightly weaker is the sensitivity to the total generation dipole around the TC, with up to } 9.5 \times 10^{5} \text{J m}^{-2} \text{(nearly } 34\%) \text{ more or about } 6 \times 10^{5} \text{J m}^{-2} \text{(21\%) less } K_{e}, \text{in REAR if the total generation is enhanced east-northeast of the storm, or decreased southwest of the TC's mean position, implying a sensitivity to the phasing between the storm and the trough.}

REAR is also sensitive to the divergence and convergence of advective } K_{e}, \text{fluxes in the midlatitudes, as well as within the storm (Fig. 5d). In summary, REAR is enhanced by about more than } 30\% \text{ or } 8.5 \times 10^{5} \text{J m}^{-2} \text{if the divergence and convergence of advective fluxes in the confluent region between the trough and the TC and along the midlatitude wave train are enhanced. Again, the effect of } K_{e}, \text{within the storm has a slightly weaker contribution, with } K_{e}, \text{ in REAR being reduced by } 21\% \text{ or } 6 \times 10^{5} \text{J m}^{-2} \text{if divergent advective fluxes associated with the TC are at a more south-western position.}

Barotropic conversion describes } K_{e}, \text{conversion between the eddy and the mean flow and is thus stronger for a more amplified flow. The strong sensitivity to barotropic conversion within the first downstream ridge } (10 \times 10^{5} \text{J m}^{-2}, 36\%; \text{Fig. 5e}) \text{indicates that REAR is stronger if the first downstream ridge is amplified more strongly. Thereby, stronger ridge amplification may result from baroclinic conversion along the baroclinic zone (cf. Fig. 5a) and/or the divergent upper level outflow, as shown by Teubler and Riemer (2016).}

As outlined in Majumdar et al. (2010) and Chang et al. (2013), the ability to trace sensitivity patterns backward
through forecast time enables the separation of genuine from spurious sensitivities. In the case of Choi-Wan, the sensitivity dipole around the TC can be traced back in time (e.g., 48 h prior to metric time, 0000 UTC 18 September 2009; Figs. 6a–e), indicating REAR’s sensitivity to the position of the TC even prior to ET. The sensitivity regions around the baroclinic zone basically do not develop before Choi-Wan impinges on the midlatitude flow and initiates baroclinic conversion. This may indicate that the storm has to “connect” to the midlatitude flow to fully act as an additional source of $K_e$. Beside its sensitivity to the phasing, REAR is sensitive to the $K_e$ budget in other midlatitude flow features 48 h prior to metric time: REAR is about 36% more intense (contains $10^5$ J m$^{-2}$ more $K_e$) if baroclinic conversion and downstream dispersion are enhanced along the rear and front flanks of the midlatitude trough (along 125° and 135°E; Figs. 6a,b). The $K_e$ budget in the rear flank of the trough, with which Choi-Wan is interacting, seems to play an important role: REAR is intensified by nearly 34% or $9.5 \times 10^5$ J m$^{-2}$ if generation is enhanced in this region (Figs. 6b–e; west of 120°E). Only weak sensitivities are tied to the extratropical cyclone farther upstream over Siberia. As discussed above, a nonlinear relationship in error growth may also affect the sensitivities for longer lead times.

The sensitivity of the second downstream $K_e$ maxima FRONT further elucidates the dynamics of the wave train and its dependency on Choi-Wan as an additional source of $K_e$. In accordance with the theory of downstream baroclinic development (Orlanski and Sheldon 1995), FRONT shows the strongest sensitivity to baroclinic conversion and ageostrophic geopotential divergence in its upstream maximum REAR (Figs. 7a,b). About $9 \times 10^5$ J m$^{-2}$ more $K_e$ is found in FRONT, if the ageostrophic geopotential flux convergence (divergence) is in REAR’s entrance (exit) region, or baroclinic conversion is enhanced by $10^5$ J m$^{-2}$ in the ensemble mean; hence, the increase in $K_e$ due to the ageostrophic geopotential flux accounts for about 22.5%. In addition, the $K_e$ content in FRONT is increased by up to $9 \times 10^5$ J m$^{-2}$ (22.5%) through its own baroclinic conversion, which is tied to the development of an extratropical cyclone ahead of the trough. The strong sensitivity to advection of $K_e$ in REAR (Fig. 7d) can further be interpreted as a measure for the intensity of REAR. In general, FRONT is more amplified if REAR is stronger, and thus it has stronger advective and dispersive fluxes.

b. Hurricane Hanna

Hurricane Hanna recurved along the east coast of North America in September 2008. Just off the coast of Newfoundland, the remnants of Hanna moved ahead of an incipient short-wave trough and reintensified as an extratropical cyclone, while propagating toward Europe. Hanna’s ET coincided with a moderately amplified midlatitude wave train that peaked in a dominant trough over the eastern North Atlantic and Ireland (Fig. 8), with the remnants of Hanna being embedded in this trough. Wave breaking over Europe triggered the development of a Mediterranean cyclone and local high-impact weather events (Grams et al. 2011). The baroclinic conversion of $K_e$ within Hanna was identified as the key player in the amplification of the downstream wave train (Keller et al. 2014). However, up to now, it is not clear how the upstream midlatitudes, in particular an extratropical cyclone that developed off the coast of Newfoundland, contributed to the amplification of the downstream wave train. This question will be addressed here, along with a quantitative estimation of the $K_e$ that is transferred from the TC into the midlatitudes. To measure the amplification of the wave train, the $K_e$ maximum at the leading edge of the midlatitude wave train will be used as forecast metric and referred to as MAX.

1) Consistency in Sensitivity

At 0000 UTC 09 September 2008, the $K_e$ centers of Hanna and the rear flank of the downstream trough (Fig. 8a) are still separated. They merge about 12 h later, propagate eastward, and intensify until 1200 UTC 10 September 2008 (Figs. 8b–d). Again, the relevant $K_e$ maximum is determined as a metric at a subsequent series of forecast times (0000 UTC 9 September–1200 UTC 10 September 2008, denoted by 0900, 0912, 1000, and 1012). Prior to merging (0900; Fig. 8a), MAX’s intensity is sensitive to $K_e$ generation in the transitioning cyclone (Fig. 9a). Negative sensitivity east of the TC points to the importance of $K_e$ destruction within MAX itself at 1200 UTC 8 September 2008: less $K_e$ destruction results in a more intense MAX. For later forecast metrics (i.e., 0912, 1000, and 1012), after Hanna’s $K_e$ maximum has merged with the $K_e$ maximum along the rear flank of the trough (Fig. 8b), sensitivity of MAX to the $K_e$ budget at 1200 UTC 8 September is strongest to $K_e$ generation in the upstream midlatitudes (60°–80°W; Figs. 9b–d), in particular along a developing wave south of Newfoundland. In contrast, weaker sensitivity is found over the central North Atlantic in the vicinity of Hanna. Sensitivity to $K_e$ generation along the flanks of the European trough (40°W–0°) indicates that a stronger MAX is associated with a more amplified trough. The propagation of sensitivity from the TC into the midlatitudes may indicate the relative role of Hanna and the surrounding extratropical flow in the amplification of MAX. In the beginning, the transitioning TC has a
Sensitivity to $K_e$ Budget at 00 UTC 18 September 2009

Fig. 6. As in Fig. 5, but for $K_e$ budget fields at 0000 UTC 18 Sep 2009.
FIG. 7. Statistically significant sensitivity, shaded, in $10^5$ J m$^{-2}$ of $K_e$-object FRONT for TY Choi-Wan at 0000 UTC 20 Sep 2009 for budget terms at 0000 UTC 19 Sep 2009. Budget terms, colors, and contours are as in Fig. 5.
strong impact on the amplifying downstream wave train, but once the two $K_r$ maxima merge, the surrounding midlatitudes become the dominating factor.

To reveal the contributions of Hanna and the midlatitude surroundings to the amplification, we focus on the forecast metric at 1200 UTC 10 September 2008 (1012), which corresponds to the time when $K_r$ has reached its peak intensity (cf. Fig. 8d). For this metric time, the sensitivity to the $K_r$ budget at earlier forecast times is found to be weaker than the sensitivity of the other metrics. This might result from local processes (e.g., baroclinic conversion within MAX itself) becoming the main contributor to the final amplification of MAX. This coincides with findings from Orlanski and Chang (1993) that downstream development may first be triggered by energy dispersion from an upstream $K_r$ maximum and grow further by local $K_r$ release due to baroclinic conversion. This final amplification takes place between 0000 and 1200 UTC 10 September 2008 and is, thus, not reflected in our sensitivity results.

2) IMPACT OF $K_r$ BUDGET ON TROUGH AMPLIFICATION

At the forecast metric time chosen, MAX can be identified in all but one of the 51 members and hence sensitivities can be determined by using nearly the full dataset. Again, our main interest will be the sensitivity of MAX to the $K_r$ budget 24 and 48 h prior to the metric time (i.e., 1200 UTC 8 and 9 September 2008, respectively). The investigation times for this forecast are well after the ET of Hanna when the storm had already weakened or even dissolved in some of the members.

Fig. 8. Shown are the ensemble mean for $K_r$ (shaded) and 500-hPa geopotential height (black contours), as well as $K_r$-object MAX results (magenta ellipses), with their centers of mass (orange markers) after the ET of Hurricane Hanna at (a) 0000 UTC 9 Sep, (b) 1200 UTC 9 Sep, (c) 0000 UTC 10 Sep, and (d) 1200 UTC 10 Sep 2008. The panels on the right are close-ups showing the region indicated in the left panels.
This results in overall weaker $K_e$ budget terms, compared to the case of Choi-Wan.

The $K_e$ content of MAX is strongly influenced by baroclinic conversion along the rear and front of the transitioning storm 24 h prior to metric time. MAX contains up to $7.5 \times 10^5$ J m$^{-2}$ more (less) $K_e$ per 1$\sigma$, increase (decrease) in baroclinic conversion within the former TC (Fig. 10a). With an ensemble mean intensity of $33 \times 10^5$ J m$^{-2}$, this makes up to 22.5% more (less) $K_e$. These sensitive regions are associated with positive baroclinic conversion, pointing to ascending warm air ahead of the storm and descending cold air behind, which agrees with the conceptual model of Klein et al. (2000). As shown by Keller et al. (2014), baroclinic conversion within the rather slowly progressing transitioning TC that continued until the storm got caught up by the midlatitude trough was crucial for the amplification of the downstream wave train. In contrast, if baroclinic conversion disappeared earlier and the TC remnants proceeded across the Atlantic fairly quickly, less baroclinically converted $K_e$ was accumulated. Our sensitivity results reflect this, as MAX' intensity is reduced by about 6$\times$10$^5$ J m$^{-2}$ or 18% if the storm is already farther east.

Barotropic conversion itself is weak, with its ensemble mean being often below the chosen contour interval (Fig. 10c). The negative sensitivity over Europe is associated with negative barotropic conversion; wave...
FIG. 10. Statistically significant sensitivity, shaded, in $10^5 \text{ J m}^{-2}$ of the $K_e$ object for Hurricane Hanna at 1200 UTC 9 Sep 2008 to (a) baroclinic conversion, (b) convergence of ageostrophic geopotential flux, (c) generation of $K_e$, (d) advection of $K_e$ by the total wind, and (e) barotropic conversion at 1200 UTC 9 Sep 2008. Budget terms, colors, and contours are as in Fig. 5.
breaking and dissipation of $K_e$ to kinetic energy of the mean flow reduces $K_e$ in MAX by about $8 \times 10^5$ J m$^{-2}$ or 24%. Conversion of mean kinetic energy to $K_e$ along the trailing edge of Hanna’s remnants (around 60$^\circ$W), and destruction of $K_e$ on its leading edge (around 30$^\circ$W), increase $K_e$ in MAX by about $5.5 \times 10^5$ J m$^{-2}$ (16.5%).

Parts of the sensitivity of MAX to the $K_e$ budget can also be traced back 48h prior to the metric time, but overall its magnitude decreases, and assignments to specific flow features become less clear (not shown).

5. Discussion and conclusions

A transitioning TC may act as an additional source of $K_e$, assisting in the amplification of a midlatitude wave train by means of downstream baroclinic development (Harr and Dea 2009). Keller et al. (2014) further demonstrated how this impact of a TC on the downstream $K_e$ budget depends on the phasing and interaction with the midlatitude flow in different forecast scenarios, derived from an ECMWF ensemble forecast. The present study is the first that actually quantifies the respective contribution of $K_e$-affecting processes within the TC and the surrounding midlatitude flow to the amplification of the downstream RWT. In addition, this work draws on the full ensemble forecast instead of selected forecast scenarios only. It determines the sensitivity of the amplification of the midlatitude RWT (measured in terms of the intensity of its $K_e$ centers) to the local $K_e$ budget in the transitioning TC and the surrounding midlatitudes. The results indicate by how much the $K_e$ changes through the $K_e$ supply because of the TC (or a lack thereof). Though it is not a full budget analysis, this methodology enables estimation of the quantitative contributions from the different $K_e$-affecting processes.

For Typhoon Choi-Wan, REAR’s intensification mainly depends on $K_e$ generation (36%) within the storm and along the confluence region between the storm and the midlatitude trough, indicating the sensitivity to phasing. Thereby, the sensitivity to the divergence of ageostrophic geopotential flux divergence surpasses sensitivity to baroclinic conversion. The strong sensitivity to processes happening in the confluence region confirms the results of Quinting and Jones (2016). They identified a clear link between the amplification of RWT packets and the convergence of ageostrophic geopotential fluxes in this confluence region on a climatological basis. Archambault et al. (2015) showed how advection of low-PV air with the irrotational upper-level wind results in a phase locking between the TC and the midlatitude trough, aiding the further amplification of the wave train. From a $K_e$ perspective, this phase locking and amplification of the adjacent downstream ridge results from the dispersion of $K_e$ from the TC into the midlatitudes and, in particular, into this sensitive confluence region. The importance of the vertically integrated moisture flux, associated latent heat release, and PV reduction for the strong and long-lasting amplification of the downstream RWT (Grams et al. 2011; Torn and Hakim 2015) is reinforced by strong sensitivity to baroclinic conversion along the baroclinic zone. At earlier lead times, the generation of $K_e$ in the midlatitude trough is also important but is still slightly weaker compared to the contribution that results from processes associated with ET and the baroclinic zone. Only weak sensitivity signals are found in the midlatitude flow farther upstream over Mongolia and Siberia.

The aspect of phasing that was discussed in several previous studies (e.g., Klein et al. 2002; McTaggart-Cowan et al. 2003; Ritchie and Elsberry 2003, 2007; Riemer and Jones 2010; Grams et al. 2013a) is clearly reflected in the sensitivity dipoles that enclose the $K_e$ budget terms near the TC. What is not clear yet, however, is whether the sensitivity found along the confluence region and baroclinic zone is in the end a by-product of position sensitivity. It may indicate a flow configuration that favors downstream dispersion of $K_e$ but arises as a result of a favorable phasing. Further experiments are required to separate out the effects of position sensitivity.

For Hurricane Hanna, the amplification of MAX is sensitive to baroclinic conversion within the transitioning storm and, to a lesser extent, to baroclinic conversion in the upstream midlatitude trough and the developing upstream cyclone. These dependencies point to the importance of warm conveyor belts ascending along the baroclinic zone east of Hanna and east of the upstream cyclone. Associated latent heat release and PV reduction amplify the respective downstream ridges and thus thin Hanna’s trough into a PV streamer. This corroborates the importance of diabatic processes for ridge amplification during ET, in accordance with Grams et al. (2011) for Hurricane Hanna. Western North Pacific ET systems proceed eastward quickly and without strong reintensification if they move into a midlatitude circulation that is dominated by a large quasi-stationary cyclone to their northeast [i.e., northeast circulation pattern; Harr et al. (2000)]. The combination of our sensitivity results for Hanna in the North Atlantic points in the same direction: MAX is weaker (about 25%) if the ageostrophic geopotential flux divergence, and hence the trough, northeast of the storm is stronger, and if Hanna is at a more northeastern position or proceeds eastward faster. In contrast to the case of Choi-Wan, the position sensitivity does not refer to phasing between the TC and the midlatitude trough, but rather to the
development and reintensification stage of Hanna while it crosses the Atlantic basin.

Overall, the guiding questions about the role of the upstream midlatitudes and the relevant $K_r$ affecting processes can be answered as follows.

- **Typhoon Choi-Wan:**
  - Strong contributions to downstream wave amplification result from the TC, the midlatitude trough, the frontal wave, and baroclinic zone. No strong sensitivity signals were found for regions farther upstream.
  
- **Hurricane Hanna:**
  - The phasing between the TC and the trough, and the accumulation of $K_r$ in the confluence region west of the storm, may strengthen the first downstream $K_r$ maximum by up to 36%. Thereby, the impact of ageostrophic geopotential fluxes slightly dominates over contributions from baroclinic conversion.
  
- **Baroclinic conversion and ageostrophic geopotential flux divergence and convergence within the transitioning TC may amplify the $K_r$ maximum by up to 23%. A weaker contribution is found for baroclinic conversion in a cyclone developing farther upstream.
  
- **The amplification is suppressed if Hanna moves into a flow configuration that is dominated by a trough northeast of the transitioning TC.**

The findings of our study could be further corroborated by investigating sensitivities between the amplification of the downstream wave train to the $K_r$ budget during ET in a reanalysis-based climatology (e.g., Garcia and Homar 2009). Ensemble reforecast datasets may also offer a larger database for further extending the work. However, their smaller number of ensemble members may become a limiting factor for reliable sensitivity results.

This study is based on operational ECMWF EPS forecasts, in which stochastic physics perturbations represent uncertainties due to model errors. Up to now, the impact of these stochastic perturbations on the ensemble sensitivity results has not been investigated. Sensitivity experiments with two sets of ensemble forecasts—with and without stochastic simulations of forecast errors—would elucidate the effects of stochastic perturbations on the sensitivity results.

Overall, the sensitivities indicate those processes that play an important role in the amplification of the downstream midlatitude wave train during the interaction of the TC with the midlatitude flow. To further elaborate the processes relevant for ET, these sensitivity results may offer guidance for conducting additional measurements, for example, in upcoming field campaigns.

Data-denial experiments in sensitive regions could further corroborate the impact of these processes on forecast uncertainty associated with the amplification of midlatitude Rossby wave trains during ET events.

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