Sensitivity, Structure, and Dynamics of Singular Vectors Associated with Hurricane Helene (2006)

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ABSTRACT

The sensitivity of singular vectors (SVs) associated with Hurricane Helene (2006) to resolution and diabatic processes is investigated. Furthermore, the dynamics of their growth are analyzed. The SVs are calculated using the tangent linear and adjoint model of the integrated forecasting system (IFS) of the European Centre for Medium-Range Weather Forecasts with a spatial resolution up to TL255 (~80 km) and 48-h optimization time. The TL255 moist (diabatic) SVs possess a three-dimensional spiral structure with significant horizontal and vertical upshear tilt within the tropical cyclone (TC). Also, their amplitude is larger than that of dry and lower-resolution SVs closer to the center of Helene. Both higher resolution and diabatic processes result in stronger growth being associated with the TC compared to other flow features. The growth of the SVs in the vicinity of Helene is associated with baroclinic and barotropic mechanisms. The combined effect of higher resolution and diabatic processes leads to significant differences of the SV structure and growth dynamics within the core and in the vicinity of the TC. If used to initialize ensemble forecasts with the IFS, the higher-resolution moist SVs cause larger spread of the wind speed, track, and intensity of Helene than their lower-resolution or dry counterparts. They affect the outflow of the TC more strongly, resulting in a larger downstream impact during recurvature. Increasing the resolution or including diabatic effects degrades the linearity of the SVs. While the impact of diabatic effects on the linearity is small at low resolution, it becomes large at high resolution.

1. Introduction

In the Ensemble Prediction System (EPS) of the European Centre for Medium-Range Weather Forecasts (ECMWF), singular vectors (SVs) are used to generate perturbations to the initial condition (Leutbecher and Palmer 2008; Buizza et al. 2008). The rationale behind using SVs, the fastest-growing perturbations over a finite time interval, is to sample the dynamically most relevant structures that will dominate the uncertainty sometime in the future (Ehrendorfer and Tribbia 1997). For the EPS, SVs are calculated for the extratropics of the Northern and Southern Hemisphere. Extra sets of SVs are added for tropical cyclones (TCs) (Puri et al. 2001). A further area where SV techniques are applied is for targeted observations (Palmer et al. 1998; Leutbecher 2003). SV calculations are carried out usually at relatively low resolution [T42 (~320 km) for the operational EPS] and therefore the forecast used to calculate the SVs is not able to represent a TC properly because of the strong gradients associated with such an intense system. In this study we investigate the sensitivity of SVs with respect to different modeling configurations in order to evaluate the dynamical relevance of SVs computed in one configuration but applied to another. For ensemble forecasts as well as for observation targeting, the actual analysis uncertainty is also relevant [Barkmeijer
et al. 1998, 1999; Reynolds et al. 2007; Lawrence et al. 2009; see Berliner et al. (1999) for a discussion of the problem of optimal observation network design].

The sensitivity of extratropical SVs to physical processes has been investigated by Coutinho et al. (2004). They found that so-called moist (diabatic) SVs show enhanced growth due to reduced stability if moist effects are taken into account, and that higher resolution is more appropriate for moist SVs. Ancell and Mass (2006, 2008) tested the impact of spatial resolution and the representation of physical processes on adjoint sensitivities. They found large impacts and speculated that the same should be true for SVs since SVs and adjoint sensitivities are related (Errico 1997). In the case of TCs, moist processes are especially important and the inclusion of diabatic effects in the tangent-linear model has a significant effect on the SVs (Barkmeijer et al. 2001; Puri et al. 2001). Komori and Kadowaki (2010) investigated the effect of spatial resolution (up to TL159, \( \sim 125 \) km) on dry SVs targeted on a TC for a single forecast. Kim and Jung (2009a) assessed the impact of moist effects and of different norms on the growth and structure of SV associated with a TC in a local area model for constant resolution (100 km) and for a single initialization date.

Recently, various studies investigated the dynamics of SVs associated with TCs (Peng and Reynolds 2006; Kim and Jung 2009b; Chen et al. 2009). Peng and Reynolds (2006) linked their growth to barotropic instability in the TC outer region, 500–700 km away from the storm center. Yamaguchi and Majumdar (2010) investigated the growth of the initial-condition perturbations of different ensemble prediction systems with respect to TCs. They found that the perturbations of the ECMWF EPS grow because of barotropic and baroclinic energy conversions in a vortex and baroclinic energy conversion in midlatitude waves. To assess the utility of the SVs for observation targeting and for ensemble construction, it is important to elucidate the dynamical processes that lead to the growth of the SVs and how this depends on resolution and diabatic processes.

In this paper, we investigate the characteristics of SVs for Atlantic Hurricane Helene (2006). In section 2 we give a brief review of SVs and our analysis methods, in section 3 the design of our experiments is described, and in section 4 an overview of the development of Helene is given. In section 5 the sensitivity of the SVs to spatial resolution and physical processes is presented, while in section 6 the mechanisms that lead to the growth of the SVs are investigated. The potential impact on the ECMWF EPS of higher-resolution SVs than used in the operational configuration is assessed in section 7 and the justification of the linearity assumption of the SVs is tested in section 8. Section 9 contains the conclusions.

2. Theoretical background

2.a. Singular vectors

The SVs identify the fastest-growing perturbations to a given solution of the nonlinear equations describing the time evolution of the atmospheric state (referred to as the linearization trajectory) within a finite time interval (the optimization interval) in a linear framework (Lorenz 1965; Buizza 1994; Palmer et al. 1998). Here, growth is defined with respect to a certain metric \( E \). At ECMWF the metric used is dry total energy and is defined as follows (Leutbecher and Palmer 2008):

\[
x^T E x = \frac{1}{2} \int_P \int_S \left( \nabla^2 + \frac{c_p}{T_r} \nabla^2 \right) dp \, ds
+ \frac{1}{2} R_d T_r p_r \int_S \left[ \ln(p_{atm}) \right]^2 \, ds,
\]

where \( x \) is a perturbation to the atmospheric state vector, \( \nabla u^2 \) and \( \nabla v^2 \) refer to perturbations of the wind components, \( T' \) denotes the perturbation of the temperature, and \( \ln(p_{atm}) \) is the perturbation of the logarithm of surface pressure. The gas constant is given by \( R_d \), while \( c_p \) denotes the specific heat at constant pressure of dry air, \( T_r \) a reference temperature (300 K), and \( p_r \) a reference pressure (800 hPa).

By employing a local projection operator \( P \) (Buizza 1994) it is possible to compute SVs targeted on a specific weather system such as a TC. The local projection operator sets a vector to zero outside a specific geographical domain and above (or below) a certain vertical level. The initial SVs define an \( E \)-orthonormal set of vectors at initial time, while the linearly evolved SVs form an \( E \)-orthogonal set at optimization time in the domain defined in \( P \). The growth of the initial SVs is given by their respective singular value [a detailed description of the SV formalism can be found in Kalnay (2003)]. At ECMWF the SVs are calculated numerically by an iterative approach, using the forward tangent and adjoint model of the nonlinear forecast model (Buizza et al. 1993).

2.b. Energy flow analysis

Kwon and Frank (2008) derived the energy equations for a moist hurricane vortex. Their analysis describes the energy conversion relative to a time-varying axisymmetric background state. For this purpose the trajectory is separated into an azimuthal mean state (centered on the TC) and the deviation from the azimuthal mean. The governing equations are the energy equation for azimuthal mean kinetic energy, azimuthal mean available
potential energy, eddy kinetic energy, and eddy available potential energy. The authors define a baroclinic energy conversion term that represents a conversion between mean potential energy $A$ and eddy potential energy:

$$\frac{\partial A}{\partial t} \text{baroclinic} = -\left( \frac{h}{\kappa} \right)^2 \left( u_r' \frac{\partial A}{\partial r} + \omega' \frac{\partial A}{\partial \rho} \right),$$

(2)

where $h = (R/P)(P/P_R)^{\kappa}$ and $\kappa = (R/C_P)$, with the gas constant $R$ and a reference pressure $P_R$. An overbar denotes an azimuthal mean. The stability parameter is defined by $s^2 = -h(\partial \theta / \partial p)$. Radius and pressure are denoted by $r$ and $\rho$, while $u_r'$ and $\omega'$ are the eddy radial and eddy vertical velocities. Here the potential temperature is split into a base state that depends only on height and deviations therefrom $[\theta(r, \lambda, \rho, t) = \theta_0(\rho) + \theta_A(r, \lambda, \rho, t)$, where $\theta_A$ is the azimuthal mean potential temperature and $\theta'_A$ the eddy potential temperature].

The barotropic energy conversion term represents a conversion between mean kinetic energy $K$ and eddy kinetic energy. It is defined as follows:

$$\frac{\partial K}{\partial t} \text{barotrop} = -ru_r'v_r' \frac{\partial (v_r')}{\partial r} - u_r'\omega' \frac{\partial r}{\partial \rho} - v_r'\omega' \frac{\partial r}{\partial \rho}$$

$$- \frac{u_r'}{r} v_r' u_r',$$

(3)

where the eddy tangential velocity is $v_r'$, the azimuthal mean tangential velocity $v_r$, and the azimuthal mean radial velocity $u_r$.

c. Linearity indices

To quantify the impact of nonlinearities associated with the nonlinear growth of SV perturbations, Gilmour et al. (2001) define the relative nonlinearity

$$\Theta(\hat{\delta}, \|\hat{\delta}\|, t) = \frac{||\hat{\delta}^+(t) + \hat{\delta}^-(t)||}{0.5\{||\hat{\delta}^+(t)|| + ||\hat{\delta}^-(t)||\}}$$

(4)

with the unit vector $\hat{\delta}$. Here $||\cdot||$ denotes a norm defined by an inner product. The difference between an unperturbed forecast and a forecast in which an SV is either added ($\hat{\delta}^+$) or subtracted ($\hat{\delta}^-$) from the analysis is denoted by $\delta$. The relative nonlinearity measures relative magnitudes as well as the orientations of the evolved perturbations. Gilmour et al. (2001) note that if the evolution of the positive and negative perturbation is linear then $\Theta = 0$ (since $\hat{\delta}^+ + \hat{\delta}^- = 0$), while $\Theta = 0.5$ implies that the error caused by assuming linear evolution will be at least 50% of the average magnitude of the evolved perturbations. The time at which “nonlinearity becomes dominant” is defined by Buizza (1995) as the time when the anticorrelation between the negative and the positive perturbation becomes smaller than 0.7. The anticorrelation is given by

$$I = -\frac{\langle \hat{\delta}^+(t), \hat{\delta}^-(t) \rangle}{||\hat{\delta}^+(t)|| ||\hat{\delta}^-(t)||}$$

(5)

If $I = 1$ the perturbations are completely antiparallel. A value of 0.7 equals a deviation by about 45° from that state (from the definition of the inner product). In this case, assuming linear evolution of the perturbations would result in an error of at least 75% of the mean magnitude of the evolved perturbations. This corresponds to $\Theta > 0.75$ (Gilmour et al. 2001).

3. Experiments

a. Singular vector experiments

Our experiments are designed to investigate the sensitivity of the SVs to spatial resolution and diabatic processes. SV calculations are performed with a horizontal resolution of T42 (~320 km, the operational resolution for SVs in the ECMWF EPS), TL95 (~210 km, a typical resolution for SVs for targeted observations at ECMWF), TL159 (~125 km), and TL255 (~80 km), all with 62 vertical levels. We calculate the leading five SVs. As ECMWF a forecast from the full (moist) nonlinear model with the same resolution as the SVs acts as the trajectory of the SV computations. The optimization time for the calculations is 48 h. A local projection operator is employed to target the SVs on a specific region (see section 2a).

The geographic domain over which TC SVs are optimized (the optimization region) is based on the predicted positions of the TC from the previous EPS forecast (van der Grijn et al. 2004; Leutbecher 2007). First, a box is chosen in such a way that it includes all the 48-h forecast positions of the TC from the previous EPS forecast [a detailed description of the operation EPS configuration is given in Leutbecher and Palmer (2008)]. Then the box is extended 7° to the east and west and 5° to the north and south. If the TC cannot be identified in more than 10 ensemble members, then a 22.5° × 30° box is centered on the reported position of the TC. In addition, we calculated SVs optimized over the global tropical band (30°N–30°S).

We calculate so-called moist (diabatic) and dry SVs. For the moist SVs, the ECMWF linearized physics package is included in the tangent linear and adjoint model (Barkmeijer et al. 2001). This package contains linearized schemes for vertical diffusion, subgrid-scale orographic effects, large-scale condensation, surface...
drag, and deep convection (Mahfouf 1999; Tompkins and Janiskova 2004; Lopez and Moreau 2005). In contrast to the moist SVs, the dry SVs are calculated only with the linearized scheme for vertical diffusion and surface drag. The dry total energy norm is used to calculate both dry and moist SVs. The SVs are optimized over the depth of the troposphere (from the surface to 200 hPa). For this study, SVs targeted on Hurricane Helene (2006) have been calculated daily from 16 to 24 September. The initialization time for the SV calculation was 1200 UTC.

b. EPS experiments

In addition to the SV calculations, we conducted idealized experiments with 10 ensemble members. These were used to assess the potential impact of the higher-resolution SVs on the EPS, to carry out the energy flow analysis, and to quantify the nonlinearities. The EPS experiments have a resolution of TL255. Each ensemble member was perturbed with only one of the leading five SVs by either adding or subtracting it from the analysis.

For our experiments, all SVs are scaled with the same fixed value, chosen to make their amplitude correspond to estimates of analysis errors [see Leutbecher and Palmer (2008) for a detailed discussion of the scaling of the SVs for ensemble generation]. In our experiments the maximum zonal wind perturbation in 500 hPa ranges between 0.8 and 1.9 m s\(^{-1}\). In the operational EPS configuration, the weighting factors of the SVs are drawn from a multivariate Gaussian distribution and the ensemble members are perturbed by a linear combination of different sets of SVs. However, we chose a fixed scaling factor to concentrate on the impact of the SV structure on the EPS forecasts and to filter out effects due to variable scaling. Also, in order to investigate the nonlinear growth of the SVs, different scaling factors were tested. In contrast to the operational setup, the EPS forecasts and the SV computations are started from the same analysis. In the operational setup the SV trajectory is initialized from a 6-h forecast (Leutbecher 2005).

4. Observed evolution of Helene

Hurricane Helene (2006) was selected for this case study as it exhibited a classical recurvature and extratropical transition (ET) over the Atlantic (Fig. 1), so that the interaction with the midlatitude flow can be considered without taking into account structural modifications during landfall. Helene formed as a tropical depression on 1200 UTC 12 September 2006 and reached hurricane strength on 1200 UTC 16 September (Brown 2006). It started to recurve on 21 September and was classified as an extratropical system on 25 September.

Thus, our experiments cover the period from before recurvature to ET (see section 3).

Between 17 and 19 September 2006, Helene intensified and developed a strong asymmetric outflow jet, a so-called outflow channel (Figs. 2a,b). At this time Helene moved northwestward, while to the northwest Hurricane Gordon (located around 35°N, 54°W) moved into the midlatitudes. At 1200 UTC 19 September, Helene continued to move northwestward and approached an upper-level positive potential vorticity (PV) anomaly (Hoskins et al. 1985) that was about to cut off (Fig. 2b). This PV anomaly formed during the interaction of Hurricane Gordon with the midlatitude jet. The approaching PV anomaly strengthened the PV gradient between the low PV of Helene’s outflow and the surrounding flow (Figs. 2b,c). This led to a further enhancement of Helene’s outflow, which then started to interact with the positive PV anomaly. During this process the PV anomaly thinned and elongated markedly. At 1200 UTC 21 September the remnants of the PV anomaly were adveected around Helene’s outflow anticyclone (Fig. 2c). An upstream trough located at approximately 40°N, 70°W (Fig. 2c) moved toward Helene from the northwest and steered the TC into the midlatitude flow. During this process Helene’s outflow interacted with the midlatitude jet, advecting low-PV air into the ridge forming downstream of Helene (Fig. 2d).

5. Sensitivity of singular vectors

The structure and location of the initial SVs in the vicinity of Helene changes systematically if the resolution of the SV calculations is increased and diabatic effects are accounted for. Thus, different regions of the
flow are identified by the SV formalism as being most favorable for perturbation growth. These dependencies are illustrated in Fig. 3 using composites of the sum of the vertically integrated total energy of the leading five SVs for all initialization dates for each category (different resolutions; dry or moist). The composite fields are centered on the position of the TC on each date.1

The trajectory for the SV calculations is a forecast of the full nonlinear model with the same resolution as the SV calculations (see section 3a). Thus there could be differences between the trajectories at different resolutions concerning the strength and position of Helene and other synoptic systems. Comparisons of the structure and the tracks of Helene in the higher- and lower-resolution trajectories show that there are rather small differences of the position of Helene and surrounding features of the flow (e.g., of the upstream upper-level positive PV anomaly) between higher and lower resolution. However, there is a systematic difference of the intensity of Helene. As would be expected, Helene is a more intense system at higher resolution than at lower resolution. Initially these intensity differences arise solely through interpolation, since the operational high-resolution analysis (TL799; approximately 25 km) is interpolated to initialize the lower-resolution SV calculations. Within the forecast range the intensity differences become larger, since the gradients present in the initial fields are still too large to be sustained in the lower-resolution trajectory, even after the interpolation of the initial fields to coarser resolution. An adjustment process occurs within the first hours of the forecast during which the TC weakens and broadens. Larger-scale systems like the midlatitude jet are weakened also, but to a lesser extent than the TC. The trajectories of dry and moist SVs calculations with the same resolution are identical.

In general, higher resolution leads to higher growth rates of the SVs in our experiments and, as indicated by total energy spectra (not shown), more small-scale structure. This is consistent with the resolution dependence of extratropical SVs (Hartmann et al. 1995; Buizza et al. 1997; Coutinho et al. 2004). Also, at higher resolution more energy is associated with the TC than at

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1 For the composites, the SVs are not weighted with their respective singular value. However, the qualitative structure of the composites is not altered if weighting is applied.
FIG. 3. Composites of the sum of the vertically integrated total energy (shaded) of the leading five (a),(c),(e) dry and (b),(d),(f) moist initial SVs for initialization dates from 1200 UTC 16 Sep to 1200 UTC 24 Sep 2006 and PV (PVU, black contours) on model level 50 (~850 hPa), for (a),(b) TL95, (c),(d) TL159, and (e),(f) TL255 resolution.
lower resolution, for which more energy is associated with other synoptic features (e.g., the subtropical high or the midlatitude jet region upstream of Helene; cf. Figs. 4a,c). Here our composites support the findings of Komori and Kadowaki (2010), who investigated the resolution dependence of dry SVs targeted on a TC for a single initialization date.

The horizontal distribution of the vertically integrated total energy of the leading five initial SVs is more sensitive to changes in resolution in the moist case than in the dry case. At TL95 resolution (Fig. 3b) the maximum of the total energy curves around the eastern and northeastern side of the TC, approximately 300–500 km from its center. This typical distance was also found in previous studies (e.g., Peng and Reynolds 2006; Kim and Jung 2009a). At higher resolution the maximum becomes more small scale and more pronounced (cf. Figs. 3b,d,f). At TL159 resolution it moves closer to the center of Helene and for our high-resolution TL255 SVs an annular structure around the center emerges with a radius of approximately 100–200 km (Fig. 3f).

The distribution and amplitude of the total energy of the dry SVs around the TC does not change as much with resolution as in the case of the moist SVs. At lower as well as at higher resolution the maximum is located east of the center of the TC (Figs. 3a,c,e) and the curved structure remains. The dry SVs at higher resolution do exhibit more small-scale structure and higher growth rates than the lower-resolution SVs, as is seen for the moist SVs. However, even though the structure of the maximum of the total energy is somewhat modified and more energy is associated with the outer core region of the TC, the curved structure persists in all calculations.

At lower resolution (TL95) the vertically integrated total energy of the leading five initial moist and dry SVs looks similar (Figs. 3a,b), even though the area of high vertically integrated total energy is located somewhat closer to the center of the TC and more energy is associated with the TC for the moist SVs in comparison to other synoptic systems (cf. Figs. 4a,b). This is in line with studies by Peng and Reynolds (2006) and Kim and Jung (2009a). However, at TL255 resolution the differences between dry and moist SVs within Helene’s core are striking (e.g., Figs. 3e,f). These differences are caused only by the inclusion of moist processes in the SV calculations since the trajectories are identical for the moist and dry SVs of the same resolution.

By examining individual initialization dates it becomes apparent that the differences in the total energy composites between higher-resolution dry and moist SVs are largest for forecasts initialized before and especially during recurvature. After recurvature, the total
energy signatures of the leading dry and moist SVs become more similar in the vicinity of Helene (especially for the first SVs), with the maximum of the total energy at some distance from Helene’s center. At all resolutions the region of high total energy stretches to the northwest, indicating the importance of other synoptic systems, especially the upstream jet region during and after recurvature.

The potential for increased growth with increased resolution and diabatic effects can be larger for SVs associated with TCs than for SVs associated with phenomena that are already well resolved at lower resolution. As a consequence the SVs associated with TCs can be found within the leading global SVs at higher resolution. This is depicted using the total energy of the leading 20 initial SVs (Fig. 5) optimized for the global tropical band (30°N–30°S). The calculations are initialized at 1200 UTC 17 September 2006. At low resolution (T42) there is no signal of Helene within the leading 20 moist SVs (Fig. 5a). This is in line with the results of Puri et al. (2001), who found that tropical T42 SVs do not isolate TCs as major sources of perturbation growth. However, our results show that at higher resolution (TL255) some of the leading moist SVs are associated with Helene (Fig. 5b). Now, Northern Hemisphere midlatitude systems that could not be properly resolved at lower resolution also appear in the leading high-resolution SVs.

6. Growth mechanisms

To identify the processes leading to the growth of the SVs we investigated the three-dimensional structure of the SVs and performed an energy flow analysis following Kwon and Frank (2008) (see section 2b). We illustrate some features of the SV structure using the leading (first) TL255 SV from the calculation initialized at 1200 UTC 17 September (Fig. 6). In the PV of the trajectory (gray surface) the PV tower of Helene in the middle of the plot extends to the tropopause (indicated by the high PV values at upper levels). It is apparent that the tropopause in the vicinity of Helene is richly structured. The upper-level positive PV anomaly, which Helene encounters during its recurvature, is located northwest of Helene.

A significant part of the total energy of the leading high-resolution (TL255) moist SV is embodied in a spiral structure (Fig. 6a). The spiral winds tightly and cyclonically going upward around the upper part of Helene’s PV tower. The spiral observed here is oriented in such a way that it tilts in the horizontal and vertical against the shear of the TC (Figs. 7a,b). In Helene the wind speed decreases with height above approximately 900 hPa (Fig. 7b). A perturbation that is oriented in such a way can extract energy from the basic current (Zeng 1983; Buizza and Palmer 1995) and grow by transient
mechanisms (Orr 1907; Nolan and Farrell 1999). The horizontal and vertical tilt indicates growth by barotropic and baroclinic processes (Zeng 1983). Most of the total energy is located around model level 30 (≈300 hPa), where the vertical shear of the azimuthal velocity has its maximum.

A large part of the total energy of the leading TL255 dry SVs is also wrapped around the TC (Fig. 6b) but the structure is deeper, possesses a smaller vertical tilt, and is not wound as tightly around the PV tower of Helene as in the case of the leading moist SV. If a surface were chosen that encloses a higher percentage of the total energy, it would become apparent that part of the structure that is dominant for the dry SV is still present for the moist SV. So a part of the energy of the leading moist SVs is shifted from one region where the dry SV detects the largest instability to a “new” one that features even stronger growth in the presence of diabatic effects.

For the moist SV, the total energy [Eq. (1)] is dominated by the potential energy (associated with the temperature perturbation $T'$). The maximum of the potential energy is located around 300 hPa, while most of the kinetic energy (associated with the wind perturbations $u'$ and $v'$) is located between 700 and 200 hPa (Fig. 8a). For dry SVs, the total energy is split more
equally between kinetic and potential energy (Fig. 8b). Here, most of the kinetic energy is located in the mid- to lower troposphere around 600 hPa and most of the potential energy between 500 and 200 hPa.

Within the optimization interval the spiral structures of the initial SVs are untilted by the flow. The total energy of the evolved SVs is dominated by the kinetic energy and thus the wind perturbations are more pronounced than the temperature perturbation (not shown). Examination of the perturbation vorticity indicates that the leading (moist and dry) SV develops a deep dipole structure in the mid to lower troposphere. The dipole is associated with a horizontal displacement of the TC. However, from the structure of the dipole, it is apparent that the leading evolved SVs, if added to the trajectory, would not only cause a horizontal displacement but also a structural modification of the TC.

After 48 h the PV tower of Helene is enclosed by the total energy signature of the evolved SV (Figs. 6c,d). At upper levels, around 200 hPa, the leading evolved moist SV is associated with the low PV anomaly of Helene’s outflow, which possesses a larger horizontal extent than Helene’s PV tower. This leads to a mushroom-like appearance of the evolved moist SV. It is apparent that while the leading moist and the leading dry SVs show comparable growth in the lower to mid-troposphere, differences are large in the upper troposphere within the outflow region of Helene (Figs. 6e,f). Here the leading

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**FIG. 7.** (a) Azimuthally averaged azimuthal wind speed of linearization trajectory (m s\(^{-1}\); shaded) at 400 hPa and relative vorticity perturbation of leading TL255 moist SV (contours) at 1200 UTC 17 Sep 2006. Contour lines are drawn at \(-0.2 \times 10^{-5}\) (dashed) and \(0.2 \times 10^{-5}\) s\(^{-1}\) (solid). (b) Azimuth–pressure section around Helene at a radius of 200 km. The azimuthal angle is measured anticlockwise from north. Plotted are the azimuthal wind speed of the linearization trajectory (m s\(^{-1}\); shaded) and the temperature perturbation of the leading TL255 moist SV (contours). Contour lines are drawn at \(-0.3\) (dashed) and 0.3 K (solid).

**FIG. 8.** Averaged vertical profiles of the total energy of the sum of the leading five initial (a) moist and (b) dry SVs. Depicted are total energy (black), kinetic energy (solid gray), and potential energy (dashed gray). Horizontally integrated total energy (J kg\(^{-1}\) m\(^2\)) on the x axis and pressure (hPa) on the y axis.
moist SV grows more strongly than its dry counterpart. The leading five dry SVs do show a signal associated with upper tropospheric features. However, the signal is weaker than in the moist case and emphasizes structures associated with the approaching upper-level positive PV anomaly more strongly than those associated with the outflow region of Helene.

To further investigate and quantify the processes that lead to the growth of the initial SVs we apply the energy flow analysis (Kwon and Frank 2008) to our EPS experiments (see section 3b). We calculate the conversion terms for the unperturbed control forecasts and the perturbed forecasts. To analyze how the conversion terms are changed by the SV perturbations, the conversion terms of the unperturbed forecast are subtracted from the conversion terms of the perturbed forecasts. Since we focus on the initial SVs, and therefore investigate the energy fluxes at $t = 0$, the nonlinear evolution of the SVs does not impact the results discussed in this section. Figure 9 shows composites of the changes induced by the leading five initial SVs to the barotropic and baroclinic energy conversion terms (hereafter called energy fluxes). To generate the composites we sum the magnitude of the changes caused by the leading five SVs and average over all initialization dates. As done previously, the fields are composited relative to the cyclone center. Finally, the composites are integrated azimuthally. As a result, the composites display the areas where, on average, the largest changes to the energy fluxes are induced by the SVs.

The composite of the changes to the barotropic energy fluxes due to the higher-resolution (TL255) dry SVs indicates several regions where the SVs have an impact on the TC energetics. The changes to the barotropic energy fluxes are large in a region between 400 and 700 km from the center of Helene, with a local maximum between 700 and 500 hPa and another local maximum in the upper troposphere around 200 hPa (Fig. 9a). Furthermore, there is a region with high values at 200 hPa and approximately 1000 km from Helene’s center. This feature is connected to synoptic features of the storm environment. The changes to the baroclinic energy fluxes due to the dry SVs are largest in the upper troposphere between 300 and 200 hPa (Fig. 9b). These changes have a higher amplitude than the changes to the barotropic energy fluxes but are more localized.

In comparison to the dry SVs, the moist SVs induce larger changes to both baroclinic and barotropic energy fluxes. The maximum of the changes to the barotropic energy fluxes is located approximately 200 km from the center of the TC (Fig. 9c). This is significantly closer to the center than in the case of dry SVs. The two local maxima near 600 and 200 hPa observed in the dry SV case remain in the moist SV case. The moist SVs also induce stronger changes in the barotropic energy fluxes close to the surface (1000–925 hPa). The amplitude of the changes to the baroclinic energy fluxes (Fig. 9d) due to the moist SVs has a larger amplitude than the changes to the barotropic energy fluxes. The highest values are located around 300 hPa, and 100–300 km from the center of Helene. Thus the maximum is located at lower levels than for the dry SVs and it has a significantly larger amplitude. Again, the moist SVs show a mixture of structures present in the dry SVs and new structures not seen in the dry SVs.

The lower-resolution (TL95) moist SVs exhibit features of both higher-resolution moist and dry SVs. Their changes to the barotropic energy fluxes (Fig. 9e) are more similar to those of the TL255 dry SVs since the structures of the TL255 moist SVs close to Helene’s center are not present. The changes to the baroclinic energy fluxes (Fig. 9f) show some features of the TL255 moist SVs. The maximum is located at 300 hPa at a distance of approximately 300 km from Helene’s center. But the region of high values has a much smaller vertical extent than the maximum of the TL255 moist SVs and also a smaller amplitude. This is consistent with the differences of the horizontal distribution of the total energy of the TL255 and TL95 moist SVs (see section 6).

The SVs exploit different processes within and in the vicinity of Helene to achieve their growth. In the mid- to lower troposphere a local maximum of the TL255 dry SV is located approximately 600 km from Helene’s center. At this distance the radial PV gradient changes sign (Fig. 10a), the criterion for barotropic instability (Montgomery and Shapiro 1995), which was also observed by Peng and Reynolds (2006). For the dry SVs, baroclinic growth takes place at upper levels. Here the maximum is located at a height and at a distance from Helene’s center where the criterion for baroclinic instability is fulfilled (i.e., the radial PV gradient along an isentrope changes sign with height) (Kwon and Frank 2005). This is the case between the 350- and 360-K surfaces, 300 km from Helene’s center (Fig. 10b).

In our calculations the initial SVs are tilted against the shear of the TC and are located close to regions where instability criteria are satisfied. The horizontal and vertical tilt indicates growth by transient processes (Farrell 1982; Nolan and Farrell 1999). This may indicate that, after a phase of rapid initial growth, the SVs exploit the existing barotropic and baroclinic instability mechanisms of the flow. This behavior is consistent with studies of the growth of extratropical SVs (Badger and Hoskins 2000; Hoskins et al. 2000) and with the results of Yamaguchi et al. (2011), who assessed the growth of SVs targeted on idealized TC-like vortices in a barotropic
These studies show that if longer optimization intervals are applied the SVs exhibit a rapid initial growth phase followed by slower more modal growth. The inclusion of moist processes in the SV calculations brings the maximum of the SVs close to where the vertical shear of the azimuthal velocity is largest, at around 300 hPa (cf. Figs. 11a and 9c,d). In addition, as stated above, the structure of the SV becomes more baroclinic. This change in structure and location can be explained by considering growth mechanisms of...
extratropical SVs, which are usually located close to regions where shear is large (Buizza and Palmer 1995; Reynolds et al. 2001). This comparison is justified, since the low-level circular jet of a TC and its warm core can be viewed as analogous to a midlatitude jet (Nolan and Montgomery 2002; Yamaguchi and Majumdar 2010). In the Eady model for baroclinic instability, the maximum growth rate is proportional to vertical shear and inversely proportional to the static stability \( N \) (Badger and Hoskins 2000). Modal and transient growth in the Eady model is enhanced in the presence of latent heating (Tippett 1999; Badger and Hoskins 2000) because the effective static stability is reduced in saturated moist flow (Bennetts and Hoskins 1979). As a consequence, the baroclinic growth of extratropical moist SVs is enhanced (Coutinho et al. 2004). From our results we conclude that these arguments also apply for SVs associated with Helene’s TC core region.

The maximum changes to the baroclinic and barotropic energy fluxes due to the TL255 moist SVs tend to be collocated with regions where the saturated moist PV (calculated with the saturated moist potential temperature \( \theta^* \)) is negative (Figs. 10c,d). Thus, a further candidate for SV growth in our calculations is the exploitation of conditional symmetric instability (CSI; Bennetts and Hoskins 1979; Jones and Thorpe 1992). For a TC, CSI is considered to exist in the upper eyewall region (Emanuel 1989; Schultz and Schumacher 1999), which is consistent with our results.

It is apparent that no single process can be held responsible for the SV growth, but a mixture of processes is relevant. However, diabatic processes are necessary to attain the strong growth within the core region of Helene.

The SV perturbations propagate into regions of high wind speed within the optimization interval. This property
is seen also for extratropical SVs propagating upward to the jet level (Buizza and Palmer 1995). In contrast to extratropical SVs, which are usually located below the jet, the SVs in Helene are located between the upper-level outflow jet and the lower-level maximum winds (Fig. 12a). The perturbations then propagate upward and downward, as indicated by the position of the local total energy maxima at the different times (Figs. 12a–d). After 48 h, the local maxima of the total energy of the leading SVs are located at the lower and upper tropospheric maxima of the azimuthal wind speed (Fig. 12d). Before recurvature the strongest upper-level flow is associated with the anticyclonic outflow jet of Helene and later, when Helene moves into the midlatitudes, with the midlatitude jet also. The lower maximum is collocated with Helene’s radius of maximum winds.

As described in section 4, the TC is better resolved at TL255 resolution, resulting in a more intense system featuring larger vertical and horizontal velocities along with stronger vertical and horizontal shear. The static stability within the core of the TC is reduced. These effects become more pronounced within the forecast time. In addition, at lower resolution, the region of maximum vertical shear moves farther away from Helene’s center (cf. Figs. 11a,b). This explains the differences of the horizontal distribution of the total energy and the energy fluxes between the higher- and lower-resolution moist SVs.

7. Potential impact on the EPS

In the previous sections we described the characteristics of SV growth for Helene as a function of resolution and diabatic processes. The question arises of what is the impact of these different SVs on the EPS. To address this issue we conducted idealized EPS experiments, designed as described in section 3b. To compare the spread (ensemble standard deviation) of the different setups, the 200- and 850-hPa spread of the wind speed is integrated within the optimization region, area weighted, and then averaged over all initialization dates. The spreads after 48 h of the experiments with TL255 moist, TL95 moist, and TL255 dry SVs are listed in Table 1.

Varying resolution and including diabatic effects in the SV computations results in different spread characteristics. The EPS experiments initialized with TL255 moist SVs exhibit larger spread than the EPS experiments initialized with TL255 dry SVs and than the EPS experiments with lower-resolution moist and dry SVs. The spread differences between TL255 and TL95 moist SVs are larger than the differences between TL255 moist and dry SVs. When Helene is located within the tropics the spread at upper levels for the TL255 moist SVs is considerably larger in comparison to the TL255 dry SVs (up to 130%), with smaller differences at lower levels.

For the case initialized at 1200 UTC 17 September 2006 Helene is still located in the subtropics after 48-h forecast time. At 850 hPa (Fig. 13a) there is an increase of spread in the vicinity of and within the TC for the TL255 moist SVs relative to the TL255 dry SVs. There are some minor remote changes that are induced by very small changes of the initial fields caused by adding the localized SV perturbation to the spectral fields, which then amplify because of strong instabilities in dynamically unrelated locations (Hodyss and Majumdar 2007). At 200 hPa the differences between the experiments are associated with the outflow of Helene. The biggest differences are located along the outflow channel that Helene develops during the forecast (Fig. 13b; the outflow channel is indicated by the blue arrow). Here the streamlines are curved anticyclonically originating from...
Helene’s center (at 23°N, 53°W). This highlights the impact of the TC on the predictability of the upper troposphere. The differences between the EPS experiments travel along the outflow deep into the tropics. The differences between the TL255 moist and TL95 resolution SVs draw a qualitatively similar picture (not shown). The same structures as for TL255 moist SVs versus TL255 dry SVs emerge, but the differences are larger (as indicated by the mean values in Table 1).

For the case initialized at 1200 UTC 21 September 2006, Helene moves into the midlatitude flow and starts to undergo ET. After the 48-h forecast time the outflow of Helene has already started to interact with the midlatitude jet. In the lower to mid troposphere the largest differences between the TL255 moist and dry SVs are associated with ex-Helene itself (Fig. 13c; at this time Helene is located at 38°N, 47°W), but there is also a clear downstream impact. Large differences exist at upper levels, especially in the region downstream of Helene (Fig. 13d). These differences are injected by the outflow of Helene into a very broad region in the midlatitude flow, including the subtropical high east of Helene. This results in an increased spread within the subtropics that then propagates along the anticyclonic circulation of the subtropical high into the tropics. Therefore there is a midlatitude and a subtropical–tropical downstream effect to be observed. Again the differences between the

![Diagram](a.png) ![Diagram](b.png) ![Diagram](c.png) ![Diagram](d.png)

**Fig. 12.** Composites of the azimuthally integrated total energy of TL255 moist SVs (shaded) and the azimuthal velocity (m s⁻¹; black contours) of the TL255 linearization trajectory after the (a) 0-, (b) 12-, (c) 24-, and (d) 48-h forecast time. Distance from center (km) on the x axis and pressure (hPa) on the y axis.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Type</th>
<th>Mean spread at 850 hPa</th>
<th>Mean spread at 200 hPa</th>
<th>Mean ratio at 850 hPa</th>
<th>Mean ratio at 200 hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL255 Moist</td>
<td>1.8</td>
<td>2.9</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>TL255 Dry</td>
<td>1.6</td>
<td>2.6</td>
<td>1.11</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>TL95 Moist</td>
<td>0.8</td>
<td>1.4</td>
<td>2.29</td>
<td>2.11</td>
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</table>
TL255 moist and TL95 lower-resolution SVs show qualitatively similar structures but quantitatively larger differences. Both increasing the resolution of the SVs and including moist processes lead to a decrease in spread over the North American continent upstream of ex-Helene. This decrease is caused by the fact that a larger part of the total energy of the dry or lower-resolution initial SVs is associated with the upstream jet region than in the case of higher-resolution moist SVs.

For TCs the minimum pressure and track are important forecast parameters. Before recurvature the TL255 moist and dry SVs cause a similar spread of the position of Helene after 48 h. In the early tropical phase (16 and 17 September) the position spread caused by the TL255 dry SVs is slightly larger in comparison to the TL255 moist SVs (Fig. 14a). During and after recurvature the position spread caused by the TL255 moist SVs is larger. Furthermore, TL255 moist SVs cause larger spread in minimum pressure than TL255 dry SVs (Fig. 14b). The differences in the early tropical phase are consistent with the fact that for moist SVs more energy is located at higher levels and associated with the TC core. Apparently this leads to a stronger modification of TC intensity. At this time the TL255 dry SVs have larger amplitude at lower levels at some distance from the center, resulting in a larger spread of Helene’s track. However, the subsequent larger growth of the moist SVs compensates for this effect. The largest spread is observed for the EPS forecast at 1200 UTC 21 September 2006 as the TC moves into the midlatitudes.

8. Quantification of nonlinearities

If SVs are used to study atmospheric phenomena such as a TC, it is important to check whether the linearity assumption is justified and hence if the SVs evolve in a similar manner when they are added to the nonlinear model or the linear model. If this is the case, then the perturbations identified by the SV formalism are relevant for the nonlinear predictability of the phenomenon under consideration.

To quantify how linear the evolution of the SV perturbations is we follow the approach of Gilmour et al. (2001) and Buizza (1995) (see section 2c). The experiments to test the linear assumption were performed by evolving the SVs with the nonlinear model at a resolution
of TL255. The scaling of the SVs was carried out as described in section 3b. We use streamfunction variance at 500 hPa as the metric to calculate the anticorrelation and the relative nonlinearity.

The manner in which the linearity of the SVs in the nonlinear model changes if the resolution of the SVs is increased or diabatic effects are accounted for is given in Table 2. The measures of linearity are evaluated in the optimization region after the 48-h forecast time. The mean values of the anticorrelation and the relative nonlinearity are averaged for all SVs and initialization dates. In addition to the mean value, the upper and the lower bound of the linearity measures are given.

The upper bounds of the relative nonlinearity and the anticorrelation are given by the highest values that occur for all SVs from all initialization dates at the specific forecast time. Similarly, the lower bounds are given by the lowest values of the relative nonlinearity and anticorrelation that occur at the specific forecast time. An increase of resolution results in a decrease of linearity. This is indicated by both the relative nonlinearity and the anticorrelation (Table 2). In line with the mean, the upper and lower bounds of the linearity measures show a reduction of linearity. The inclusion of diabatic effects reduces the linearity also. While this effect is relatively small at low resolution, it becomes more pronounced at higher resolution.

The T42, TL95, and TL159 moist SVs meet the criterion ($l > 0.7, \Theta < 0.75$) of Gilmour et al. (2001) for the usefulness of the linear assumption, while the TL255 moist SVs have a lower mean anticorrelation (0.6) and a higher mean relative nonlinearity (0.86) than required. In contrast, the TL255 dry SVs still meet the criterion. However, by reducing the initial amplitude of the SVs by a factor of 2 it is possible to improve the linear assumption in the case of TL255 SVs (Table 2). The relative nonlinearity is reduced from above 0.8 to around 0.7 and the anticorrelation lies slightly above 0.7. A further reduction of the initial amplitude by a factor of 2 degraded the linearity due to a declined signal-to-noise ratio. The linearity is improved further if only the leading SV is taken into account (this does not change the results obtained in section 6), which was also reported by Kim and Jung (2009a). In this case, the relative nonlinearity for the TL255 moist SVs with reduced initial amplitude drops to 0.6 and their anticorrelation increases to 0.83. Examination of the streamfunction fields after the 48-h forecast time of the positive $\delta^+$ and negative $\delta^-$ perturbations reveals that often the patterns are shifted relative to each other, which results in a low anticorrelation (high relative nonlinearity) even though

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Moist/dry</th>
<th>SVs</th>
<th>$l$</th>
<th>$\Theta$</th>
<th>$\Theta^+$</th>
<th>$\Theta^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T42</td>
<td>Moist</td>
<td>1–5</td>
<td>0.85</td>
<td>0.85</td>
<td>0.31</td>
<td>1.19</td>
</tr>
<tr>
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<td>Moist</td>
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<td>0.80</td>
<td>0.97</td>
<td>0.16</td>
<td>0.63</td>
</tr>
<tr>
<td>TL159</td>
<td>Moist</td>
<td>1–5</td>
<td>0.70</td>
<td>0.94</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>TL255</td>
<td>Moist</td>
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<td>0.60</td>
<td>0.92</td>
<td>0.80</td>
<td>0.86</td>
</tr>
<tr>
<td>T42</td>
<td>Dry</td>
<td>1–5</td>
<td>0.87</td>
<td>0.97</td>
<td>0.64</td>
<td>0.52</td>
</tr>
<tr>
<td>TL255</td>
<td>Dry</td>
<td>1–5</td>
<td>0.78</td>
<td>0.95</td>
<td>0.42</td>
<td>0.67</td>
</tr>
<tr>
<td>TL255*</td>
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<td>1–5</td>
<td>0.71</td>
<td>0.97</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
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<td>0.96</td>
<td>0.17</td>
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<td>0.83</td>
<td>0.91</td>
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<tr>
<td>TL255*</td>
<td>Dry</td>
<td>1</td>
<td>0.87</td>
<td>0.95</td>
<td>0.69</td>
<td>0.51</td>
</tr>
</tbody>
</table>

![FIG. 14. Spread (standard deviation) of (a) Helene's position and (b) minimum pressure at the 48-h forecast time for the EPS experiment with TL255 moist SVs (solid black line) and TL255 dry SVs (dashed gray line).](image-url)

TABLE 2. Relative nonlinearity $\Theta$ and anticorrelation $l$ of the linearity experiments after 48-h forecast time. An overbar denotes the mean over all SVs and all initialization dates. The up arrow denotes the upper bound and down arrow denotes the lower bound of the linearity indices. The asterisk marks experiments with a reduced scaling of the initial amplitude of the SVs. The column labeled “SVs” indicates the SVs that are considered for calculating the linearity measures.
9. Summary

In this paper we investigated the SV characteristics for Hurricane Helene (2006). Our results show that if the resolution of the SV calculation is increased or diabatic effects are accounted for, more of the SV structures are associated directly with the TC in comparison to other flow features. Also, more small-scale structure occurs and the growth of the SVs is enhanced. This is consistent with previous studies that investigated either the resolution dependence of dry SVs (Komori and Kadowaki 2010) or the sensitivity of SV calculations to diabatic effects with fixed resolution (Peng and Reynolds 2006; Kim and Jung 2009a).

We have shown that in the vicinity of a TC moist SVs are more sensitive to resolution changes than dry SVs, and that both high resolution and diabatic effects are needed within the SV calculations to properly account for growth associated with processes within Helene’s core. Furthermore, we could explain the mechanisms that lead to the enhanced perturbation growth within Helene’s core in the presence of diabatic effects. We demonstrated that, if calculated with sufficient resolution, the SVs are able to identify TCs as one of the most uncertain systems in the tropics. Therefore, the need for targeting the SV computation around the vicinity of the TC disappears at sufficiently high spatial resolution. In the context of ensemble forecasting this yields benefits, since it opens the possibility to include SVs targeted on the whole tropics into the EPS instead of targeting individual TCs.

The SVs associated with Helene possess a three-dimensional structure with significant horizontal and vertical tilt. The energy flow analysis by Kwon and Frank (2008) indicates that the SVs exploit mechanisms associated with baroclinic and barotropic energy conversion for their growth. This is consistent with the results of Yamaguchi and Majumdar (2010), who analyzed ECMWF ensemble perturbations generated from lower-resolution (T42) SVs optimized below 500 hPa. In addition, we show that spatial resolution and including/neglecting diabatic effects significantly influences both the contributions of the barotropic and baroclinic processes to the growth of the SVs and the regions where the growth occurs.

In the vicinity of Helene, TL255 dry SVs show barotropic growth over the full depth of the troposphere, associated with transient growth and barotropic instability in the outer core region of the TC. Baroclinic growth dominates at upper levels and extends horizontally from near the core to outer regions. If moist processes are accounted for, baroclinic growth is enhanced and the SVs exploit new processes closer to the center of the TC. The TL255 moist SVs possess a large amplitude within the TC, close to regions of maximum vertical shear (around 300 hPa) and also tend to be located within regions where the conditions for CSI are fulfilled. This leads to a stronger modification of the TC outflow, highlighting the importance of moist effects for the coupling between outflow and core of the TC.

If used to initialize EPS forecasts, the higher-resolution moist SVs produce a larger wind spread within and near the TC and also in the upper troposphere as a result of modifications to the outflow of the TC. This leads to an increased downstream effect of the TC that influences the tropics during recurvature and the midlatitudes during ET. The TL255 moist SVs modify the track (except during the early tropical phase) and the intensity of Helene more strongly than dry and lower-resolution SVs.

When the SVs are included as initial perturbations in the nonlinear model, the growth of the higher-resolution SVs is less linear than its coarser-resolution counterpart. The same is true for the inclusion of diabatic effects. The differences in linearity between moist and dry SVs are small at low resolution (T42) but become large if the resolution is increased. For TL255 moist SVs the initial amplitude has to be decreased for their growth to remain closer to the linear regime.

Our results show that small-scale perturbations within the TC and within its core can cause large synoptic-scale forecast errors. This is a challenging problem for numerical weather prediction, since state-of-the-art global models still cannot resolve the TC core properly. The same is true for global data assimilation systems. The resolution and the physics of SV calculations need to be adapted to the scales relevant for the problem studied, since resolution changes and diabatic effects can change the relative importance of the different processes leading to perturbation growth. Since the TL255 SVs are still not able to resolve inner core instabilities such as barotropic instability of the eyewall (Schubert et al. 1999), it would be of interest to further increase the resolution of the SV calculations.

In future studies we plan to investigate more cases, conduct more tests with the EPS closer to the operational setup, and perform a statistical verification of the EPS performance regarding TC track and central pressure. For use in the EPS, it will be of particular interest to see whether the higher-resolution SVs show...
stronger sensitivities toward changes in the trajectory since these SVs are more strongly related to the inner core structure of the TC.

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