2D.4 THE STRUCTURE AND SENSITIVITY OF SINGULAR VECTORS ASSOCIATED WITH EXTRATROPICAL TRANSITION OF TROPICAL CYCLONES

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1. INTRODUCTION

During the extratropical transition of tropical cyclones (ET) low predictability is often seen in numerical weather prediction. This reduction in skill is associated both with the ET event and the downstream midlatitude flow. Strong error growth can occur in regions of the atmosphere that are unstable to small-amplitude perturbations. Singular vectors can be used to identify such regions and indicate the structure of the fastest growing perturbations over a given time interval. Therefore, the structure of singular vectors associated with the extratropical transition of a tropical cyclone could provide valuable information on the important dynamical and physical processes during such an event. This study is an investigation of singular vectors associated with tropical cyclones and their ET.

In the operational configuration of the ensemble prediction system (EPS) of the European Centre for Medium-range Weather Forecasts (ECMWF), singular vectors targeted on tropical cyclones are calculated with linearized diabatic physics and with respect to a total energy norm (Barkmeijer et al. 2001, Puri et al. 2001). They are used to construct the tropical initial condition perturbations. The calculations are performed with a horizontal resolution of T42 which is too low to represent the tropical cyclone properly.

For this study singular vector experiments are implemented to investigate the evolution of singular vectors targeted on tropical cyclones during their optimisation interval and to analyse their sensitivity to spatial resolution. Therefore, singular vectors are calculated with a horizontal resolution up to TL255. These high resolution singular vectors should give an improved representation of the dynamical and physical processes associated with a tropical cyclone.

2. EXPERIMENTS

To investigate the sensitivity of the singular vectors to spatial resolution and diabatic processes singular vector calculations are performed with a horizontal resolution of T42 ($\approx$ 320 km), TL95 ($\approx$ 210 km), TL159 ($\approx$ 125 km) and TL255 ($\approx$ 80 km). The optimization time for the calculations is 48h hours. At the ECMWF a two day forecast of the full (moist) nonlinear model with the same resolution as the singular vectors acts as the trajectory of the singular vector computations.

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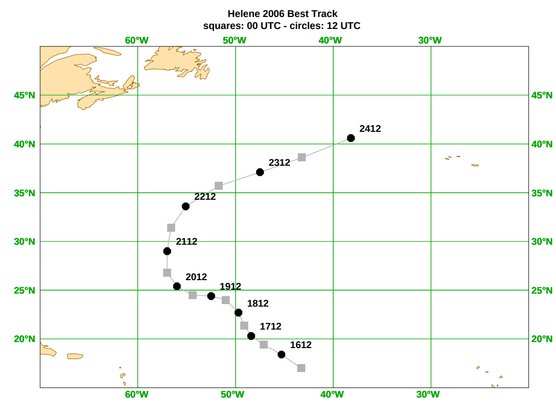

FIGURE 1: Track of Helene (2006) from 16.09.2006 00 UTC to 24.09.2006 12 UTC. Squares mark the position of Helene at 00 UTC and circles mark Helene's position at 12 UTC

We calculate so called moist and dry singular vectors. The moist singular vectors are calculated with the linearized physics package that includes linearized schemes for vertical diffusion, sub-gridscale 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 singular vectors the dry singular vectors are calculated only with the linearized scheme for vertical diffusion and surface drag. A dry total energy norm is used for the calculation of both, the dry and the moist singular vectors. The norm is defined as follows (Leutbecher and Palmer, 2008):

$$\mathbf{x}^T C \mathbf{x} = \frac{1}{2}\int_{p_0}^{p_1}\int_S (u'^2 + v'^2 + \frac{c_p}{T_r}T'^2)\,dp\,ds + \\ + \frac{1}{2}R_d T_r p_r \int_S \ln^2(p'_{sfc})\,ds$$

3. CASE STUDY

Hurricane Helene (2006) was selected for a first case study (fig. 1). It became a tropical depression on 12th September 12 UTC and reached hurricane strength on 16 September 12 UTC (Brown, 2006). Helene started to recurve on 21th September and was classified as an extratropical system on 25th September. For this study, singular vectors targeted on Helene have been calculated for the period from the 16th to the 24th of September. The initialisation time for the singular vector calculation was 12 UTC on each day.

4. HORIZONTAL DISTRIBUTION OF TOTAL ENERGY

We calculated composites of the sum of the vertical integrated total energy of the leading five singular vectors (VITE5) each initialisation date. For calculating the composites, the fields were centred on the position of the tropical cyclone on each date. Figure 2 shows the composite of the VITE5 for all initialisation dates.

In the moist case, the horizontal distribution of the VITE5 changes if the resolution of the singular vector calculations is increased. At TL95 resolution (fig. 2a) the maximum of the VITE5 is located north east of the tropical cyclone, approximately 400 to 500km from its centre. Here the VITE5 forms a curved structure. With higher resolution the maximum becomes more small scale and more distinct (compare figs. 2a and b). It moves closer to the centre of the tropical cyclone. At TL255 an annular structure around the centre emerges with a radius of approximately 100 to 200km (fig. 2b). In general higher resolution leads to higher growth rates of the singular vectors associated with Helene in our experiments.

With dry singular vectors the distribution of the total energy around the storm does not change as much as was the case with the moist singular vectors. At low as well as at higher resolution the VITE5 maximum is located east of the centre of the tropical cyclone (figs. 2c and d) and the curved structure remains. However, at higher resolution the singular vectors exhibit more small scale structure, higher growth rates and the structure of the VITE5 maximum is modified.

The structural modification of the maximum may be partially caused by the fact that the trajectories used for the singular vector calculations are nonlinear forecasts of the full model with the same resolution as the singular vector calculations (e.g. a TL95 forecast for the TL95 singular vector computations etc.). So the trajectories can differ from each other (e.g. the TC intensifies in the TL255 trajectory but weakens in the TL95 trajectory during the optimisation time).

While at lower resolution (TL95) the VITE5 of the moist and the dry singular vectors look similar (figs. 2a and c) at high resolution (TL255) the differences between moist and dry singular vectors become clear (figs. 2b and d). By examining individual initialization dates it becomes apparent, that the differences in the composites of the VITE5 between high resolution dry and moist singular vectors are mainly caused by the dates initialized before and during recurvature (not shown). After recurvature the leading dry and moist singular vectors become similar.

5. GROWTH MECHANISMS OF MOIST SINGULAR VECTORS

The high resolution moist singular vector possess a spiral structure. The spiral winds tightly and cyclonically around the PV tower of Helene. Figure 3a shows the total energy of the leading initial singular vector from the calculations initialized on 18.09.2006 12 UTC. The schematic picture at the lower left clarifiys the spiral structure of the singular vector. The spiral is orientated in such a way that it posses a tilt against the wind shear in the horizontal and in the vertical (in the vicinity of a tropical cyclone the wind speed decreases with height in the lower half of the troposphere). A perturbation that is oriented in such a way can extract energy from the basic current (Pedlosky, 1987). The horizontal and vertical tilt indicates growth by barotropic and baroclinic processes. Within 48 hours the initial singular vectors are transformed into the evolved singular vectors. The spiral is untilted by the flow and the leading singular vector develops a deep structure with a strong barotropic component in the mid to lower troposphere (within the PV tower of Helene). In the upper troposphere, the singular vector is distributed via Helene's outflow into the surrounding flow. This leads to a mushroom like appearance of the evolved singular vector (fig. 3b).

For dry singular vectors, Peng and Reynolds (2006) showed that the maximum of the vertically integrated total energy of the leading singular vectors targeted at tropical cyclones is located where the radial PV gradient changes sign (so that the condition for barotropic instability is fulfilled). Our analysis shows that in case of Helene (2006) the maximum amplitude of the high resolution moist singular vectors is located closer to the centre of the tropical cyclone at the radius where the highest vertical velocities occur (fig. 4a). At this radius also the strongest PV gradients are to be found. Figure 4b shows a latitudinal cut through the composites for the initialization dates from 16.09.2006 12 UTC to 24.09.2006 12 UTC. The black curve indicates the magnitude of the latitudinal PV gradient on model level 30 ($\approx$ 370 hPa) and the green curve shows the VITE5. The maxima of the magnitude of the PV gradient and of the VITE5 appear at the same distance from the centre of Helene. At this distance also the condition for baroclinic instability is fulfilled (not shown).

By increasing the resolution of the singular vector calculations the tropical cyclone in the trajectory is more intense with higher vertical velocities, higher horizontal windspeeds and lower stability within the tropical cyclone. This is due to the fact that high resolution is needed to properly represent the dynamics and strong gradients associated with such an intense system. The intensification of the tropical cyclone also leads to more favorable conditions for convection and large scale condensation. Therefore the moist singular vectors that are calculated with linearised schemes for convection and large scale condensation can grow more effectively within the tropical cyclone than their dry counterparts.

The differences between the dry and moist evolved singular vectors targeted on Helene are large in the upper troposphere within the outflow region of the tropical cyclone. This may lead to an underestimation of the downstream impact of Helene by the dry singular vectors during recurvature.

6. SUMMARY AND OUTLOOK

The sensitivity of singular vectors targeted on Helene (2006) to resolution and diabatic processes has been investigated. The moist singular vectors are more sensitive to resolution changes than the dry singular vectors. For Hurricane Helene (2006) the higher resolution leading singular vectors are located closer to the centre of Helene near the radius of strongest vertical motion and PV gradients. The singular vectors grow by baroclinic and barotropic effects.

The next step will be to analyse more cases and to assess the impact of high resolution singular vectors on the ensemble prediction system of the ECMWF.

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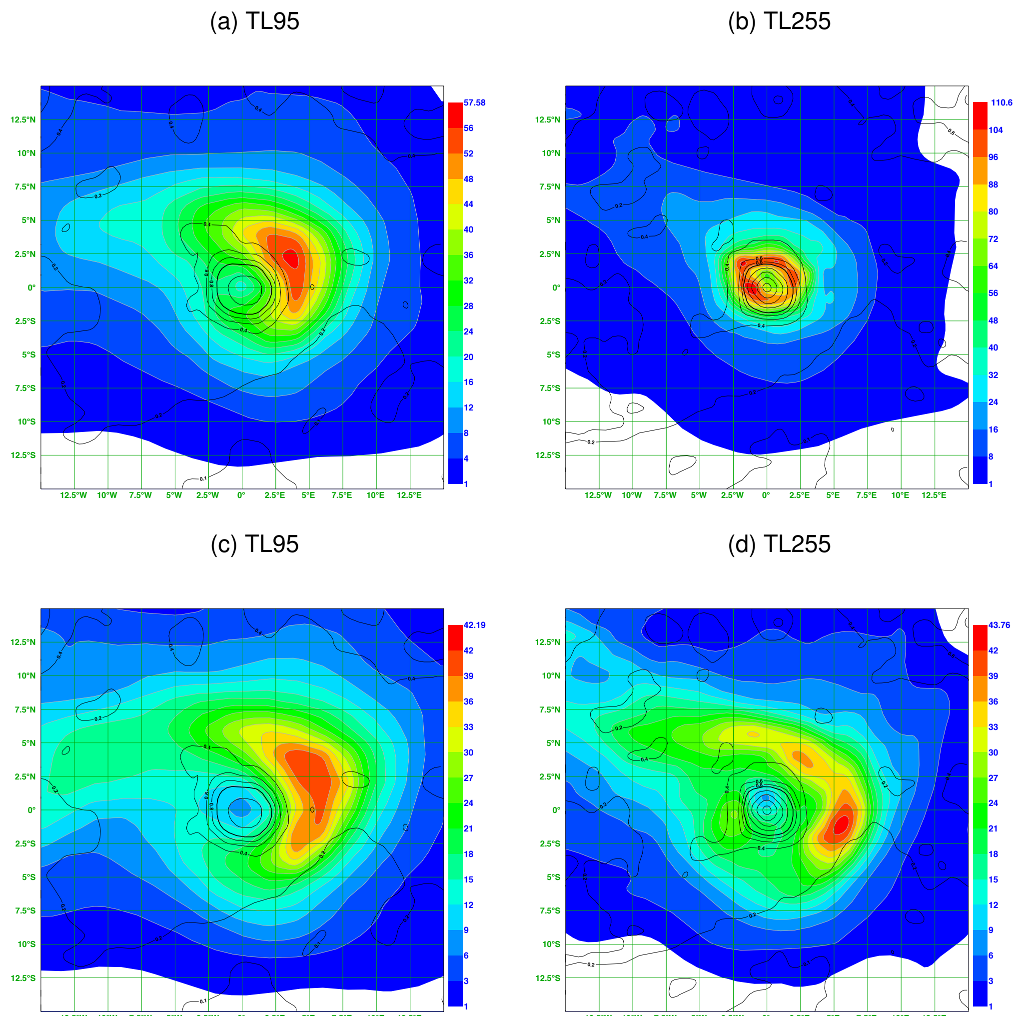

FIGURE 2: Composites of the sum of the vertical integrated total energy (in J kg^{-1}; shaded) of the leading five moist (top row) and dry (bottom row) initial singular vectors for initialisation from 16.09.2006 12 UTC to 24.09.2006 12 UTC and PV (in PVU, black contours) on model level 50 ($\approx$ 850 hPa)

(a) 18.09.2006 12UTC + 0h (b) 18.09.2006 12UTC + 48h

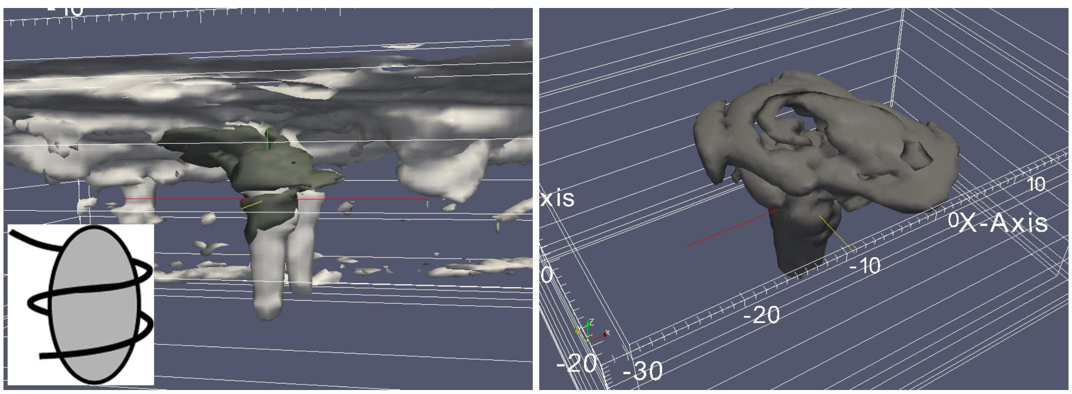

FIGURE 3: a) PV (1 PVU surface; light grey) and total energy (dark grey surface) of the leading moist singular vector targeted on Helene from 18.09.2006 12 UTC (view is from the the south; for further details see text). b) Total energy of the leading moist evolved singular vector from 18.09.2006 12 UTC (view is from the top south west corner).

(a) (b)

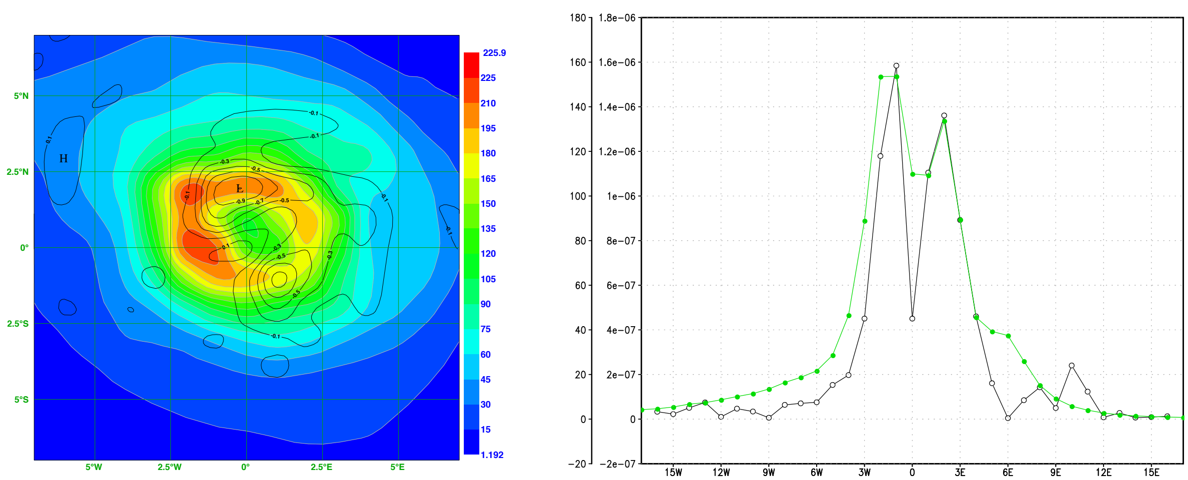

FIGURE 4: a) Composites of vertical velocity (ω in Pa s^{-1}; black contours) and VITE5 (in J kg^{-1}; shaded) for the initialization dates from 16.09.2006 12 UTC to 24.09.2006 12 UTC b) magnitude of latitudinal PV gradient (0.01 $Km^2 kg^{-1} s^{-1} km^{-1}$; black curve) on model level 30 ($\approx$ 370 hPa) and VITE5 (green curve; for further details see text).