Stabilization of tropical cyclones against vertical wind shear by asymmetric diabatic heat release

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1 Introduction

Despite the immense progress over the last decades, rapid intensification (intensification of 1-minute sustained wind speed about $\sim$ 15 m/s in 24 h, *Glossary of NHC Terms*) still remains a key challenge in both, understanding and predicting tropical cyclones (TC). The inherent multiscale nature of TCs poses a problem of high mathematical complexity ultimately touching the fundamentals of fluid mechanics itself, especially when considering the interaction of the mid-troposphere circulation with the boundary layer. A comprehensive review of recent developments is given by Montgomery and Smith (2017).

In the context of rapid intensification resiliency of TCs against vertical shear appears to be a cornerstone in the evolution process from a tropical storm to a mature tropical cyclone. Reasor and Montgomery (2015) investigated intrinsic fluid dynamical mechanisms acting against externally imposed shear. They found that for weakly tilted vortices under environmental shear stabilizing mechanisms are connected to Vortex Rossby Waves (Reasor and Montgomery 2001).

Based on a balanced symmetric background state, Nolan and Montgomery (2002) built up a linearized model for TCs and investigated how small perturbations dynamically evolve over time.

Ubiquitously discussed in literature (Emanuel 2003, amongst others), organization of convection is key to the evolution of an incipient TC. It is found that under the influence of vertical wind shear convection is organized in a "downshear-left" fashion imposing asymmetric latent heat release (Gopalakrishnan et al. 2019). Furthermore, strong displacements of lower and upper-troposphere rotation centers are found to be typical for incipient TCs (Dunkerton et al. 2009).

Advances on the mathematical side seem to provide promising approaches to analyzing the structure of TCs by multiscale asymptotics. Päschke et al. (2012) developed a theory describing tropical cyclones by the principles of asymptotic analysis. For a strongly tilted atmospheric vortex, they revealed a candidate intensification mechanism based on both, symmetric and asymmetric diabatic heat release, and found that on this theoretical level symmetric and asymmetric contributions can be comparably efficient.

In Dörffel et al. (2017) we extended these theoretical findings to the cyclostrophic regime and assessed the theoretical implications with the aid of three-dimensional idealized numerical simulations. Indeed, we found that the asymmetric part of diabatic heat release can contribute with a substantial amount to the intensification.

Not yet discussed so far is the dynamics of the vertical structure under the combined influence of vertical shear and diabatic heat release. This touches upon the question of resiliency of tropical cyclones against vertical shear and rapid intensification.

2 Asymptotic analysis

The analysis of Päschke et al. (2012) is based on a coordinate transformation relative to the (tilted) centerline of the vortex. Horizontal coordinates and velocity transform according to

$$\boldsymbol{x} = \boldsymbol{X}(t,z) + \hat{\boldsymbol{x}} = \boldsymbol{X}(t,z) + r\boldsymbol{e}_r \tag{1}$$

$$\boldsymbol{u} = \frac{\partial \boldsymbol{X}}{\partial t} + \hat{\boldsymbol{u}} = \frac{\partial \boldsymbol{X}}{\partial t} + u_r\boldsymbol{e}_r + u_\theta \boldsymbol{e}_\theta \tag{2}$$

where $\boldsymbol{e}_r$ and $\boldsymbol{e}_\theta$ are radial and tangential unit vectors in the horizontal plane attached to the centerline $\boldsymbol{X}$. $\boldsymbol{x}$ and $\boldsymbol{u}$ are horizontal coordinates and velocity, respectively. u_r and u_θ are radial and tangential velocity components.

For those quantities leading-order tendencies are found as

$$\frac{\partial \boldsymbol{X}}{\partial t} = \hat{H} \cdot \boldsymbol{X} + a\frac{\partial \boldsymbol{X}}{\partial z} + \boldsymbol{S}_Q + \boldsymbol{u}_s \tag{3}$$

$$\frac{\partial u_\theta}{\partial t} + u_{r,00}\left(\frac{1}{r}\frac{\partial (r u_\theta)}{\partial r} + f\right) + w_0 \frac{\partial u_\theta}{\partial z} = -u_{r,*}\left(\frac{u_\theta}{r} + f\right) \tag{4}$$

$\hat{H}$ is a linear operator acting on $\boldsymbol{X}$ with a purely imaginary spectrum which depends on u_θ while a and $\boldsymbol{S}_Q$ depend on the symmetric and asymmetric structure of diabatic heat release. $\boldsymbol{u}_s$ is the (sheared) background wind velocity. $u_{r,00}$ and w_0 are radial and vertical velocity induced by symmetric heating and $u_{r,*}$ is an apparent radial velocity emerging from the choice of (tilted) coordinates and associated with the vertical transport of horizontal momentum due to the asymmetric part of the vertical velocity.

These equations are solved by standard numerical approaches under certain configurations of background wind shear and diabatic heat release.

3 Centerline motion in a sheared environment

Without any influence of diabatic heating or vertical wind shear, the centerline precesses cyclonically as the dynamical system is described by the Hamilton-like operator $\hat{H}$, see Figure 1. The solution for u_θ is trivially constant over time.

This is in agreement with Reasor et al. (2004) and Jones (1995) who already discussed this type of precession.

Imposing shear on the system u_θ is unaffected but the centerline precession is superimposed by the sheared vertical wind leading to a periodic modulation of the amplitude of the tilt, see Figure 2.

Without background wind shear, we find configurations of symmetric and asymmetric diabatic heat release for which tilt amplitude and velocity either attenuate (asymmetric heat release parallel to tilt vector) or increase (asymmetric heat release antiparallel to tilt vector).

The combined effects of shear and asymmetric heating might lead (depending on the configuration) to a stagnating solution where shear and tilt remain in a nearly constant configuration for a very long time, see Figure 3.

4 Conclusions

We found evidence that asymmetries in the convection steer both, tangential wind and the vertical structure of a tropical cyclone. The configuration in which asymmetric heat release is antiparallel to the tilt yields strong intensification and tilting of the vortex potentially leading to the disruption of the flow structure. The influence of external wind shear even further amplifies this tendency. As it is neither observed nor stable over the timescale of a TC lifetime, this is not a plausible candidate mechanism for rapid intensification.

It is rather plausible that an asymmetric heating dipole, oriented parallel to the tilt, acts to stabilize the vortex against the forcing of vertical environmental wind shear while weakening the mean tangential velocity whereas a superimposed monopole heating pattern (axisymmetric average) intensifies the vortex. In this case, the asymmetric and symmetric contributions of the heating pattern partially cancel each other. Thus, a balanced state formed in this way may transition into a new balanced state with higher (or lower) tangential wind speed. by changing either heating or background wind shear. This is in agreement with observations where rapid intensification often follows a phase of mediocre shear and downshear-left convection (Smith et al. 2017; Gopalakrishnan et al. 2019).

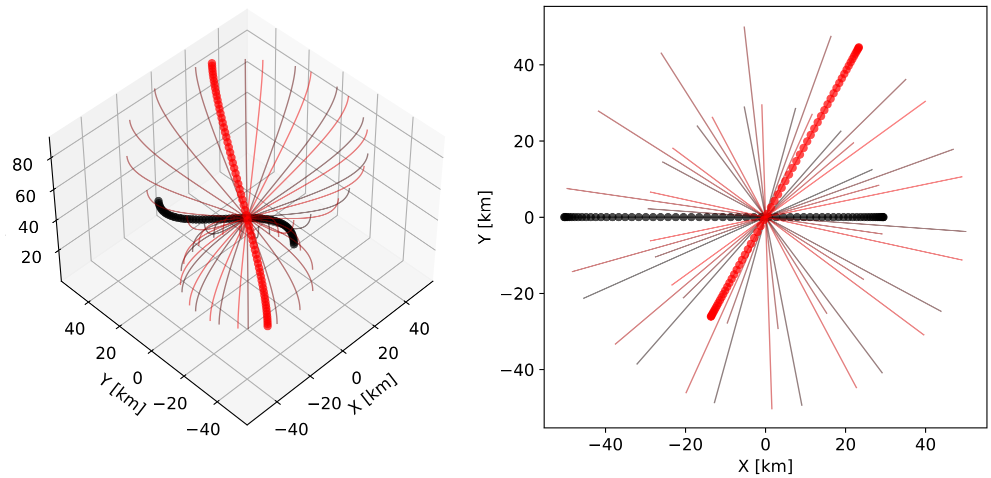

Figure 1: Centerline precession over 8 days, transition from black (initial data) to red (final time), perspective view (left) and top view (right). Initial and final data is additionally marked with dots.

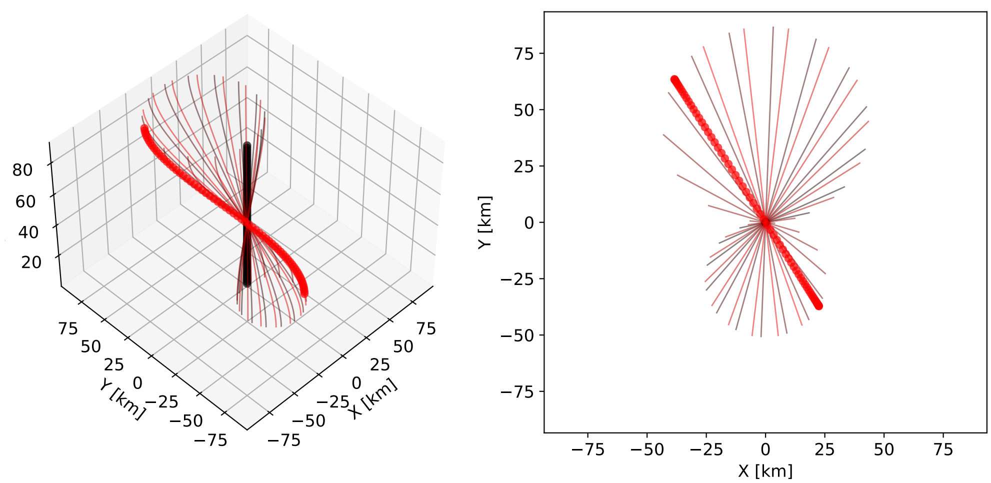

Figure 2: Same as Figure 1, but with imposed shear on initially vertical vortex.

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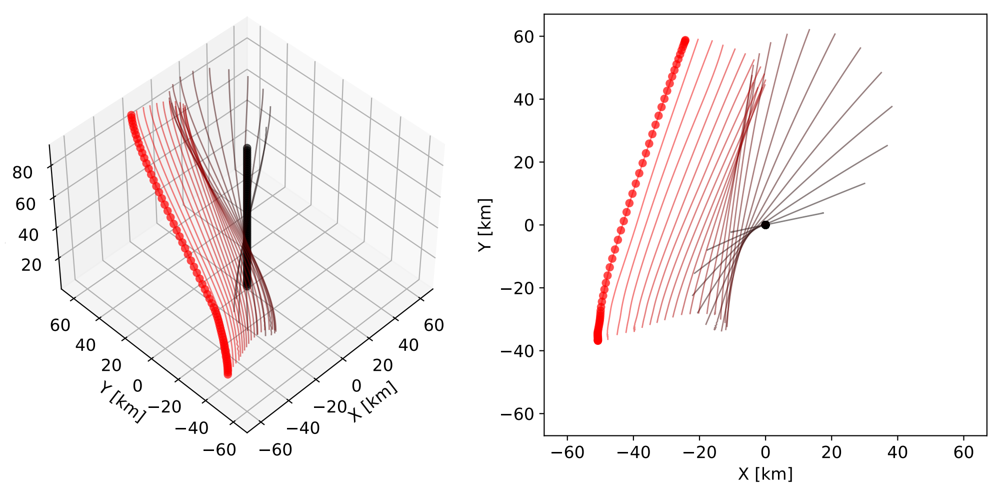

Figure 3: Combined effects of shear and symmetric-asymmetric diabatic heat release over 10 days. After ~ 5 days the tilt orientation remains stationary relative to shear (in x-direction).