P3.5 Kinetic Energy Efficiencies of Idealized Developing Tropical Cyclones

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1. Introduction

Forecast skill for tropical cyclone intensification remains relatively poor. Part of the problem results from gaps in our understanding of the basic internal dynamics of tropical cyclones. It is our hope that a better physical understanding of the effects that the structure of a cyclone has on its own intensification will eventually lead to improvements in intensity prediction. In this study, we use a linear model to investigate the intensification of an idealized, symmetric, hurricane-like vortex. A stable, balanced vortex is initialized from a mean tropical sounding and a vorticity profile chosen to provide a specified radius of maximum winds and maximum tangential velocity. A small temperature perturbation is then introduced into the vortex, and the vortex is allowed to evolve until it again reaches a balanced state. We define the Kinetic Energy Efficiency (KEE) to be the change in the kinetic energy of the symmetric wind field per unit heating associated with the initial perturbation. This process is repeated for perturbations introduced separately into each point in the (r,z) plane, thus showing how intensification varies with the location of heating. Many calculations were performed to determine the sensitivity of KEE to various parameters that characterize the vortex. These parameters include radius of maximum wind (RMW), maximum wind speed, latitude, and the type of vorticity profile. Calculations were performed for both Gaussian and modified Rankine vorticity profiles. Shown in Figure 1 are examples of the radial structure of the vortices which we used.

2. Model

Our methods are similar to those of Schubert and Hack (1982), Shapiro and Willoughby (1982), and Hack and Schubert (1986), but extended to allow for time-evolving, nonhydrostatic dynamics of perturbations to balanced vortices. We use the linear model developed by Nolan and Montgomery (2002) and Nolan and Grasso (2003), now known as Three Dimensional Vortex Perturbation Analysis and Simulation (3DVPAS). Here, we consider only symmetric perturbations generated by symmetric heating.

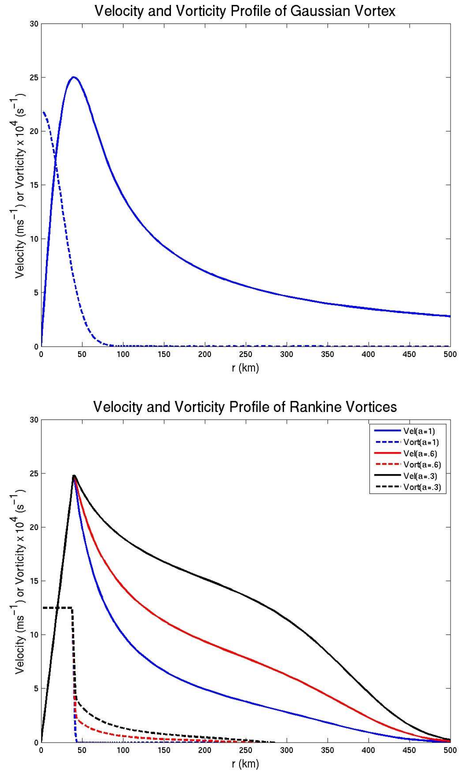

Figure 1: Vorticity and velocity profiles of Gaussian (top) and modified Rankine (bottom) vortices.

3. Kinetic Energy Efficiency

When an unbalanced heating perturbation is introduced into a balanced vortex, the vortex undergoes an adjustment process whereby it attains a new state of gradient and hydrostatic balance. A portion of the heat energy is immediately realized as Available Potential Energy (APE), which is in turn rapidly converted to Kinetic Energy (KE). Oscillations in APE and KE occur in an initial period of unsteady dynamics. The adjustment process is essentially complete within a few hours. Figure 2 shows an example of the time evolution of this adjustment to balance.

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There are a number of physically meaningful measures of the efficiency of intensification, including surface pressure fall and the increase in V at the RMW. Unfortunately, the spatial distribution of these parameters with regards to the location of the heat bubble are not physically realistic. For example, the surface pressure fall is always maximized by heating at the center and near the surface, where significant latent heat release is unlikely to be found. Therefore, we define Kinetic Energy Efficiency (KEE) to be the change in kinetic energy of the vortex per unit heating. Shown in Figure 3 is a typical plot of the distribution of KEE. Note the relatively small magnitude of KEE; very little of the heat added is converted to the kinetic energy of the vortex, even under the most favorable circumstances. KEE is maximized at the center, but is also smoothly distributed over regions where significant heating would be expected to occur. Efficiency is generally a maximum at and just above the center of the warm core.

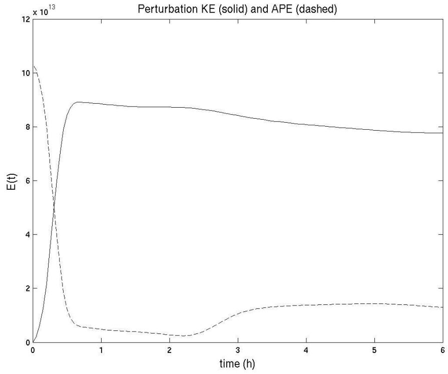

Figure 2: KE and APE as a function of time after an instantaneous heating perturbation is introduced to the vortex.

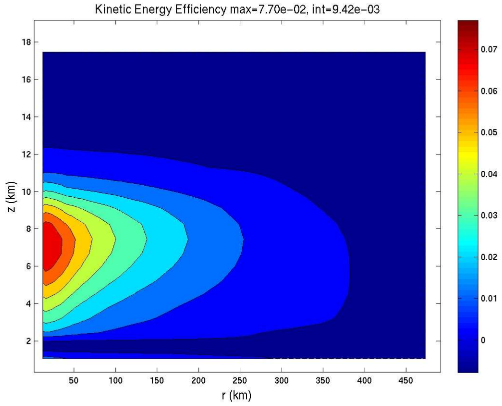

Figure 3: An example of Kinetic Energy Efficiency as a function of radius and height.

4. Sensitivity of KEE to Vortex Structure

In order to quantify the variation of efficiency with structure, it is desirable to define a single parameter that is representative of the efficiency of a real tropical cyclone subject to heating in and around the RMW. We defined Mean KEE as the KEE averaged over the volume between .5*RMW and 1.5*RMW, from 2-12km above the surface. Figure 4 shows plots of the sensitivity of KEE to vortex structure. For both Gaussian and modified Rankine vortices, V_{MAX} is by far the most important parameter, with an approximate 8-fold increase of KEE as wind speed is increased from 10 to 40m/s. The relationship is approximately linear. KEE increases with increasing latitude (Coriolis parameter). The absolute increase is larger for a stronger vortex. However, KEE increases by a greater percentage for the weaker vortex. The effect is approximately linear with the sine of the latitude. For Gaussian vortices, KEE generally increases with increasing RMW, but appears to level off at large RMW. In contrast, for modified Rankine vortices, KEE generally decreases with increasing RMW, at a rate dependent on the value of ‘a’ (the decay parameter for the velocity profile outside of the RMW, where V is proportional to $1/r^a$). It is more sensitive for small ‘a’. The efficiency of a pure Rankine vortex has very little (if any) dependence on RMW. The efficiencies of modified Rankine vortices are also quite dependent on the value of ‘a’ itself. Efficiency decreases with increasing values of ‘a’. For V_{MAX} = 15m/s, KEE is more than twice as large for a = .1 as it is for a pure Rankine vortex. At 30m/s, the difference is even greater, about a factor of 3. Since RMW, V_{MAX}, and the vorticity profile inside the RMW are all held constant, this demonstrates a profound sensitivity of KEE to the vorticity profile in the outer core and beyond.

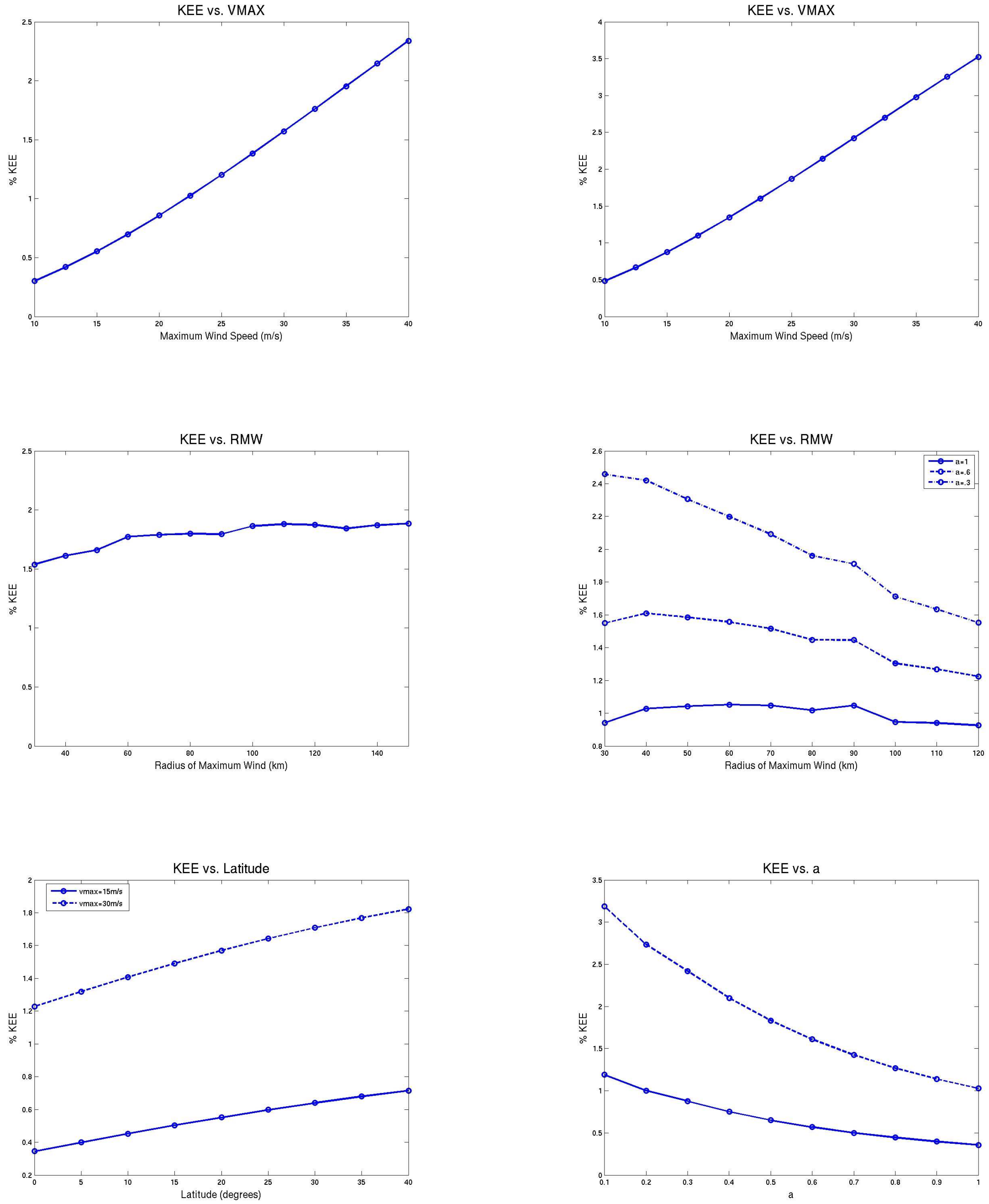

Figure 4: Kinetic Energy Efficiency as a function of V_{max} , latitude and RMW for a Gaussian vortex (above left), and V_{max}, RMW, and ‘a’ for a Rankine vortex (above right).

5. Summary

The goal of this study is to investigate the influence that the internal structure of a hurricane-like vortex has on its own intensification. Specifically, we have quantified the amount of kinetic energy which is retained by a vortex following the introduction of a given heat perturbation, and determined how this efficiency systematically varied with vortex structure. Significant conclusions are the following:

The final balanced response of a vortex following a symmetric heating perturbation centered at the RMW is a strengthening and broadening of the warm core. Since the maximum temperature change occurs between the center and the RMW, this is where the maximum pressure falls occur, tightening the gradient, and increasing the maximum windspeed.

Latent heat release would be theoretically most effective if it occurred at the center of the vortex and at and somewhat above the height of the warm core center. This is the region where inertial (static) stability is greatest (smallest).

Stronger vortices are much more efficient than weaker ones, in agreement with previous studies. For every 10 m/s increase in windspeed, efficiency increases by 0.7-1%. While that may seem small, it means that a 40 m/s vortex is about 7 or 8 times more efficient than a 10 m/s vortex.

Vortices at higher latitudes are significantly more efficient due to their increased inertial stability.

The effect of RMW appears to depend on the radial profile of vorticity outside the RMW, with a positive trend with increasing RMW for Gaussian vortices, little to no effect for a pure Rankine vortex, and a strongly negative trend for modified Rankine vortices with broad wind fields.

The efficiencies of modified Rankine vortices are very sensitive to the decay rate of the tangential wind beyond the RMW. Vortices with very slowly decaying winds (a = 0.1) can be 3 times more efficient than a pure Rankine vortex. This implies that the intensification rates of real tropical cyclones may be highly dependent on the structure of the wind field outside of the core.

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