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Dynamic instabilities of hurricane-like vortices in dry experiments

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1. Introduction

Asymmetries caused by internal vortex dynamics are thought to be the main mechanism that produces the frequently observed polygonal eyewalls and meso-vortices in hurricane core regions (Montgomery and Kallenbach, 1997; Schubert et al., 1999). It has been shown that these asymmetries can also change hurricane intensity. Many previous studies have illustrated that vortex Rossby waves and barotropic instability can be responsible for some of these internal dynamic processes.

A hurricane, however, has available potential energy because it is a rapidly rotating system with a warm core structure. Hence, under certain conditions this available potential energy can be released, changing the structure and intensity of a hurricane. Baroclinic energy conversion is the energy conversion between the available potential energy and the eddy kinetic energy, while baroclinic instability is defined as the exponential growth of eddies produced by the baroclinic process. This study investigates the existence of baroclinic and barotropic instabilities in a hurricane core region and their impact on the hurricane structure and intensity using numerical simulations of dry idealized hurricane-like vortices.

2. Methodology

A set of numerical simulations of hurricane-like idealized vortices are performed using Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version 5 (PSU/NCAR MM5). In order to focus on internal vortex processes only, all external forcings, such as environmental wind and the beta effect, are removed. In addition, both moist and boundary layer processes are eliminated from the simulations to keep the vortices near a steady state.

Three axisymmetric, quasi-steady-state vortices are designed based on the results of a full-physics simulation of hurricane Floyd (1999). The control vortex is an axisymmetric version of Floyd. The experimental two vortices were created by altering the balanced temperature and wind fields. One experimental vortex (EXP-1), the radial gradients of temperature are increased, and the other vortex (EXP-2) are designed to have the maximum potential vorticity in the eyewall (EXP-2). The plan views of relative vorticity of these three vortices at the height of 4km are shown in Fig. 1. The EXP-1 vortex is designed to satisfy the necessary condition of baroclinic instability, such that the radial gradient of potential vorticity is opposite on the different vertical levels at least once. The EXP-2 vortex satisfies the necessary condition of barotropic instability, which is that the radial gradient of potential vorticity at a certain vertical level changes sign at least once.

To check the stability of the vortices, all the vortices are slightly perturbed by small perturbations with magnitudes that are about 3-order smaller than that of the mean vortices. The usage of small perturbations makes the problem linear, because the interactions between the perturbations become negligible. The time evolutions of the perturbations are analyzed to examine whether a vortex is stable or not. If a vortex turns out to be unstable with respect to a small perturbation, the energy source of a perturbation is calculated to identify the type of instability.

3. Results

The kinetic energy of the perturbations of EXP-1 and EXP-2 grow with time, while that of the control vortex decreases (Fig. 2). The energy sources of the growing perturbations of EXP-1 and EXP-2 vortices are obtained from the eddy energy equation in cylindrical coordinates.

$$\frac{d}{dt}\int (EE)dV = -\int r\overline{u'v'}\,\frac{\partial\overline{\omega}}{\partial r}dV - \int \left(\frac{g}{\overline{\theta}N_o}\right)^2 \overline{u'\theta'}\,\frac{\partial\overline{\theta}}{\partial r}dV$$

Where EE is perturbation energy, the sum of eddy available potential and kinetic energy. Radial and azimuthal velocity are denoted by u and v, while $\overline{\omega}$ ($\equiv \frac{\overline{v}}{r}$) is the azimuthal mean angular velocity. Other variables are conventional. The first term on the left hand side of Eq (1) represents barotropic energy conversion, while the second term represents baroclinic energy conversion. As expected, the energy for the growth of perturbations in the EXP-1 vortex results primarily from baroclinic energy conversion, and that of the EXP-2 vortex is mainly from barotropic energy conversion. Therefore, the EXP-1 vortex can be regarded as a baroclinically unstable vortex, while the EXP-2 vortex is barotropically unstable. Since structures similar to these two unstable vortices are frequently in nature, there is high possibility that barotropic and baroclinic instability both play significant roles in the dynamics of the hurricane core region.

To examine the effects of the instabilities on hurricane intensity, the energy flows of perturbations of both unstable vortices are analyzed (Fig. 3). The energy diagram shows that the perturbation of the EXP-1 vortex gain energy from available potential energy of the primary vortex. Then, a small portion of the perturbation energy converts to the azimuthal mean kinetic energy of the primary vortex through an axisymmetrization process. On the other hand, the perturbation of the EXP-2 vortex gains most of its energy from the azimuthal mean kinetic energy

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of the primary vortex, with smaller amounts of energy gained from the mean available potential energy. Therefore, baroclinic instability process intensifies the kinetic energy of the mean vortex, whereas barotropic energy weakens the mean vortex.

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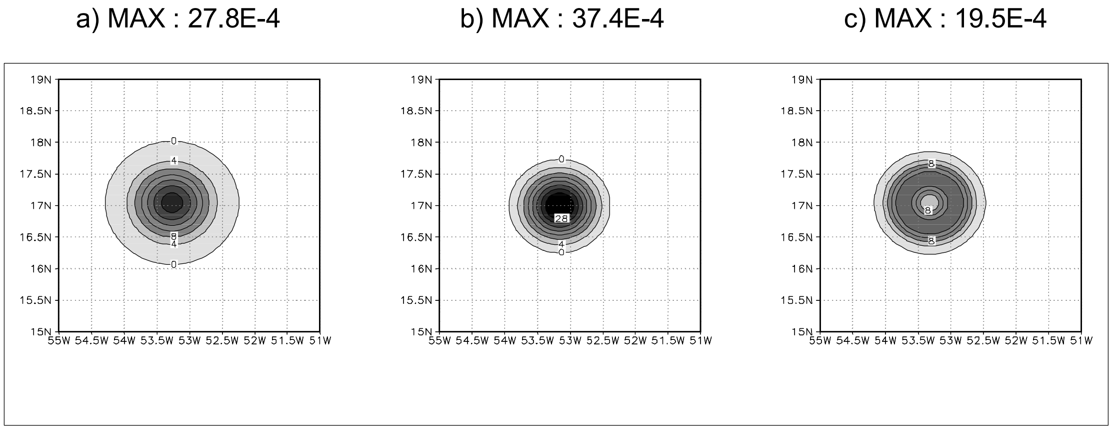
a) MAX : 27.8E-4 b) MAX : 37.4E-4 c) MAX : 19.5E-4

Fig. 1. Plan views of the relative vorticity of a) the control, b) EXP-1, and c) EXP-3 vortices at a height of 4km. The contour interval of perturbation is 4.0E-4. The maximum values are denoted in the pictures.

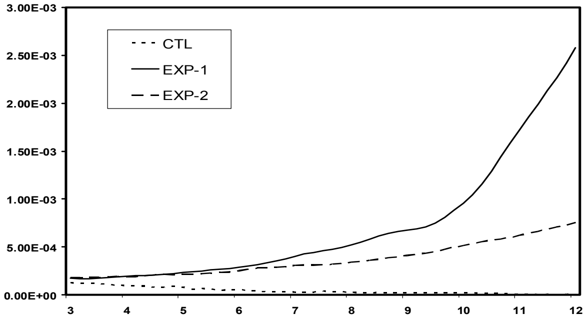

Fig. 2. Time series of the perturbation kinetic energy of the control, EXP-1, and EXP-2 vortices. The perturbation kinetic energy is integrated from the surface to the top of the model and from 10km to 120km radius

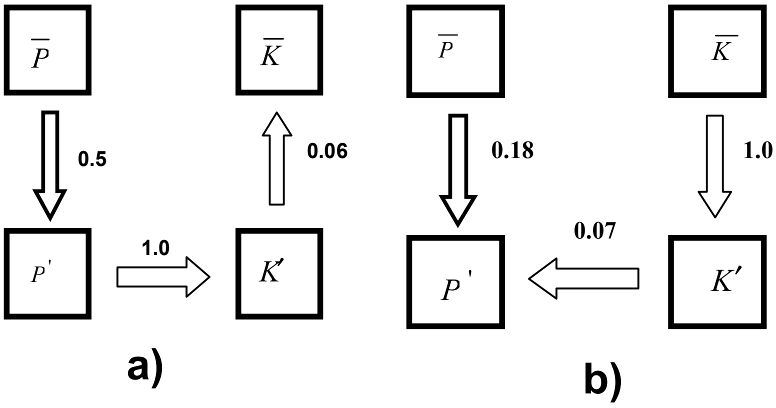

Fig. 3. Energy diagram for a) EXP-1 vortex, and b) EXP-2 vortex. $\overline{P}$,P' represent azimuthal mean available potential energy and perturbation available potential energy, respectively. $\overline{K}$,K' are azimuthal mean kinetic energy and perturbation kinetic energy, respectively. The energy transfer values are normalized to have one as a maximum value.