Nonhydrostatic, three-dimensional perturbations to balanced, hurricane-like vortices. Part I: Linearized formulation, stability, and evolution

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Abstract

In this paper, the first of two parts, the dynamics of linearized perturbations to hurricane-like vortices are studied. Unlike previous studies, which are essentially two-dimensional or assume that the perturbations are quasi-balanced, the perturbations are fully three-dimensional and nonhydrostatic. The vortices used as basic states are also three-dimensional (though axisymmetric), with wind fields modeled closely after observations of hurricanes and tropical storms, and are initially in hydrostatic and gradient wind balance. The equations of motion, computational methods for solving them, and methods for generating the basic-state hurricane-like vortices are presented. In particular, three basic states are studied: a vortex modeled after an intense (category 3) hurricane, a moderate (category 1) hurricane, and a weak tropical storm. The stability of each vortex is considered. The category 3 vortex is found to be rather unstable, with its fastest growing mode occurring for azimuthal wavenumber three with an e-folding time of approximately 1 h. The category 1 vortex is less unstable, as its most unstable mode occurs for wavenumber two with an e-folding time of 5 h. In both cases, these unstable modes are found to be close analogs of their strictly two-dimensional counterparts, and essentially barotropic in nature. The tropical storm-like vortex is found to be stable for all azimuthal wavenumbers. For this vortex, the evolution of purely thermal, unbalanced perturbations in the vortex environment are studied; such disturbances might be the result of asymmetric bursts of convection in the vicinity of the vortex, which are typical for developing storms. The evolution of these perturbations goes through two phases. First, there is substantial gravity wave radiation and rapid adjustment to quasi-gradient wind balance. In the second phase, the quasi-balanced perturbations are axisymmetrized by the shear of the basic-state vortex, and cause localized accelerations of the symmetric vortex via eddy momentum and heat fluxes. The full response of the symmetric vortex and comparisons to fully nonlinear simulations are the topics of the second part.

Full Text

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1. Introduction

Successful forecasting of the tracks and intensities of tropical cyclones remains one of the most difficult and exciting challenges in meteorology. While track forecasts have improved steadily in recent years (McAdie and Lawrence 2000), intensity forecasts have also improved but not nearly as much (DeMaria and Kaplan 1999). The relationship between hurricane intensity and environmental parameters such as sea surface temperature and environmental soundings remains a topic of active debate (Emanuel 1989, 1997; Holland 1997; Gray 1997; Camp and Montgomery 2001). Furthermore, even the most successful hurricane forecast models (e.g., Kurihara et al. 1998) do not fully resolve inner-core features such as the eyewall and the eye, the structures of which are critical to all intensity theories.

While the hurricane is primarily regarded as an axisymmetric vortex (Anthes 1982; Ooyama 1982), there is substantial evidence that asymmetric dynamics play an important role in both track and intensity changes.

Asymmetries of azimuthal wavenumber one, caused by interactions with the environment, asymmetric convection, and the planetary beta effect, have long been considered crucial in understanding and predicting the tracks of tropical cyclones (Fiorino and Elsberry 1989; Willoughby 1992, 1994; Smith and Weber 1993; Montgomery et al. 1999). Recently, a wavenumber-one instability inherent to the inner cores of hurricane-like vortices has been identified as the likely cause for the frequently observed small-amplitude trochoidal wobble of hurricane tracks (Nolan and Montgomery 2000; Nolan et al. 2001). The growth of asymmetries inside the hurricane eyewall has been hypothesized as the cause for the polygonal eyewalls occasionally observed with radar (Lewis and Hawkins 1982; Muramatsu 1986), and also the appearance of smaller, more intense vortices (mesovortices) inside the eyewall itself (Black and Marks 1991; Hasler et al. 1997), which are perhaps analogous to the multiple vortex phenomenon in tornadoes (Fujita 1971; Lewellen et al. 1997). Knaff et al. (2002) have suggested that such disturbances are responsible for rapid reorganizations of the inner-core structure occasionally observed in hurricanes. Innercore asymmetries and the mixing associated with them are becoming more and more frequently observed, due to the ever-increasing resolution of both observational techniques (Kuo et al. 1999; Reasor et al. 2000; Kossin and Eastin 2001; Daida and Barnes 2000) and numerical simulations (Liu et al. 1997, 1999; Braun et al. 2000; Braun and Tau 2000; Fulton 2001; Chen and Yau 2001; Wang 2002a,b).

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