11D.2 RAPID FILAMENTATION ZONES IN INTENSE TROPICAL CYCLONES

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1. INTRODUCTION

An "echo-free" moat, a lull in convection outside a tropical cyclone (TC) eye wall, typically appears in intense TCs. Doppler radar data presented in Dodge et al. (1999) shows, although there is weak stratiform precipitation in the moat there is generally subsidence below bright bands at 5 km. As another indicator of subsidence, flight-level radial profiles (e.g., Fig. 1) often show elevated temperature and lower dewpoint in such regions. Another important factor contributing to the moat is dynamical in nature; namely, intense radial shear in the tangential winds filaments vorticity and convective elements in the moat. To decide whether convection can exist outside a TC inner-core, a practical time scale for filamentation is defined for typical vorticity profiles in intense TCs.

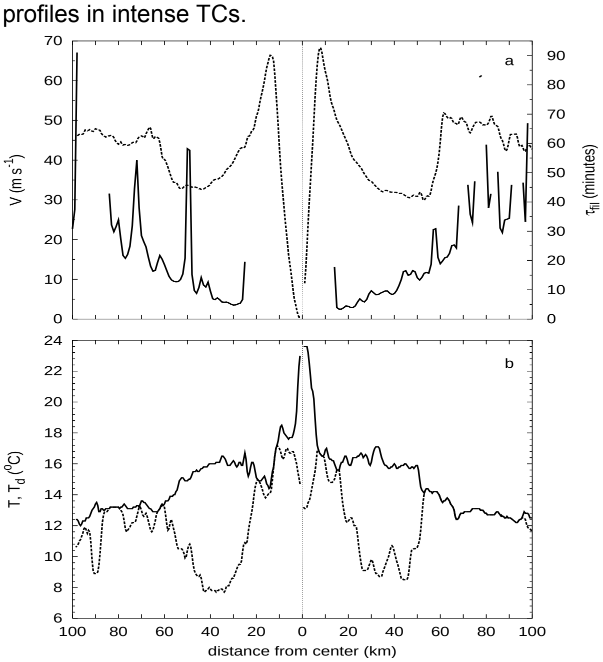

Fig. 1. (a) Flight-level tangential wind (dashed line) and filamentation time, as computed from (4) for a 700 hPa flight track through Hurricane Gilbert; (b) corresponding temperature and dewpoint temperature along the same flight track.

2. BASIC CONCEPTS

With the assumptions of inviscid, nondivergent barotropic flow on the *f*-plane, the Navier-Stokes equations can be written as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial(\psi,\zeta)}{\partial(x,y)} = 0, \qquad (1)$$

and

$$\zeta = \nabla^2 \psi , \qquad (2)$$

where ζ is the relative vorticity, $\partial(:,:)/\partial(x,y)$ is the Jacobian operator, and ψ is the streamfunction for the nondivergent flow. Define the rates of strain S_1 and S_2, where

$$S_1 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \text{ and } S_2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \qquad (3)$$

are twice the stretching and shearing deformation. In a TC, ζ^2 and $S_1^2 + S_2^2$ can usually be considered constant along a trajectory, since the azimuthal wind is much larger than the radial wind and the flow is nearly axisymmetric. It is well-known (Weiss 1991) that if $\zeta^2 > S_1^2 + S_2^2$ the flow is rotation-dominated and coherent structures can survive. On the other hand, if $\zeta^2 < S_1^2 + S_2^2$ the flow is strain-dominated and vorticity is strained into thin layers with large gradients of vorticity. In such regions, a filamentation time $\tau_{fil}(x,y)$ can be defined

$$\tau_{fil}(x,y) = 2\left(S_1^2 + S_2^2 - \zeta^2\right)^{-\frac{1}{2}}. \qquad (4)$$

The hypothesis we consider is that convective clouds become highly distorted and suppressed in regions where the filamentation time τ_{fil} is less than the timescale for deep, moist convective overturning τ_{conv}. A reasonable value for τ_{conv} is 30 minutes since a typical updraft velocity is 8 m s^{-1} and the cloud depth typically extends from the top of the boundary layer (600 m) to the anvil level (15 km). For an operational definition, it is useful to define a rapid filamentation zone as a region in which $\tau_{fil} < \tau_{conv}$.

To show how rapid filamentation zones evolve during the life cycle of a TC, let us consider a simple example of a Gaussian vortex such that the tangential wind profile, defined now in polar coordinates with *r* the radius and θ the azimuthal angle, is

$$v_\theta = \frac{\Gamma}{2\pi r}\left(1 - e^{-r^2/b^2}\right), \qquad (5)$$

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where the constant Γ is the circulation at large radii and b is the e-folding distance of the vorticity distribution. The maximum tangential wind occurs at $r_{\text{max}} \cong 1.121\, b$ and has the value $v_\theta(r_{\text{max}}) \cong 0.638\ \Gamma/(2\pi b)$. Following (4), the filamentation time is

$$\tau_{fil} = \frac{2\pi b^2}{\Gamma}\left(\frac{r}{b}\right)^2\left(1 - e^{-r^2/b^2}\right)^{-\frac{1}{2}} \times$$

$$\left[1 - \left(1 + \frac{2r^2}{b^2}\right)e^{-r^2/b^2}\right]^{-\frac{1}{2}} \quad \text{for} \quad \frac{\partial v_\theta}{\partial r} < 0. \qquad (6)$$

With the choice $\Gamma/(2\pi) = 7.5 \times 10^5\ \text{m}^2\ \text{s}^{-1}$, Fig. 2 provides $v_\theta(r)$ and $\tau_{\text{fil}}(r)$ for various values of b. The values of b represent a tropical storm (b = 20 km) and category 1 through 5 (Saffir-Simpson scale) TCs (i.e., b = 13.0, 10.2, 8.5, 7.4, 6.3 km, respectively). Decreasing b increases the maximum tangential wind and decreases the radius of maximum wind. The sequence of curves in Fig. 1 can be interpreted as typical profiles that occur during intensification from a tropical storm to a category 5 TC. As r approaches the radius of maximum wind from the right, the filamentation time approaches infinity for each value of b. As r increases, all curves asymptotically approach one another and increase as r^2. The $\tau_{\text{fil}}(r)$ curve for the tropical storm lies above τ_{conv}. However, as the idealized Gaussian cyclone becomes stronger, the filamentation timescale dips well below τ_{conv} and the region affected by such strain-dominated flow grows. In the rapid filamentation zone we expect that any patches of anomalous vorticity are quickly filamented into arbitrarily thin strips, which are ultimately lost to diffusion.

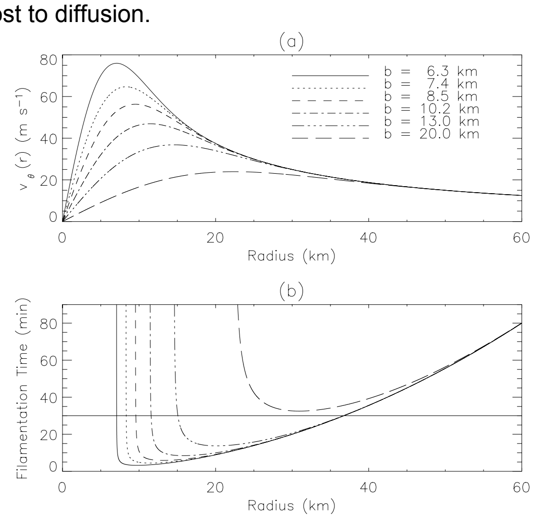

Fig. 2. (a) Radial profiles of $v_\theta(r)$ as given by (5) for six different values of the parameter b. (b) Corresponding radial profiles of $\tau_{\text{fil}}(r)$ as given by (2). The filamentation times are only plotted where $S_1^2 + S_2^2 - \zeta^2 > 0$.

3. NUMERICAL SIMULATIONS

Equations (1) and (2) can be numerically integrated to illuminate the process of filamentation in intense vortices. We obtain solutions through a double Fourier pseudospectral model. Time integration is carried out through a standard fourth-order Runge-Kutta scheme. Furthermore, vorticity diffusion is affixed to our system of equations in the form $\nu \nabla^2 \zeta$, where ν is the constant viscosity coefficient.

One set of experiments places a Gaussian vortex of (2.5) with various values of b on top of a stirred vorticity of much weaker amplitude, but biased toward cyclonic vorticity. Most random vorticity elements have a scale between 20 and 40 km with amplitudes of $1.5 \times 10^{-5}\ \text{s}^{-1}$. These random vorticity elements can be viewed as the result of vorticity generation by small groups of irregularly spaced cumulonimbus clouds. These experiments are performed with 1024 x 1024 equally spaced collocation points on a doubly periodic domain of size 600 km x 600 km. The model is run with a de-aliased calculation of the quadratic nonlinear terms, resulting in 340 x 340 Fourier modes. The wavelength of the highest Fourier mode is 1.76 km. A time step of 5 s is used in these experiments and a viscosity ν = 20 $\text{m}^2\ \text{s}^{-1}$ is chosen to yield a 1/e damping time of 1.1 h for all modes having total wavenumber 340. Such experiments show that category 5 TCs rapidly filament ambient vorticity elements in a few minutes in the vicinity of the core vortex, whereas tropical storms have only slightly deformed the elements in one half hour. In the nondivergent barotropic system, strain-dominated flow is the reason for the formation of a moat.

Various other unforced experiments with the numerical model are performed. It is found that rapid filamentation plays a governing role in binary vortex interactions when a vortex is strained-out into a concentric ring of vorticity around a stronger vortex. In addition to rapid filamentation in the moat, when a secondary eyewall exists in a TC, rapid filamentation zones can form outside this secondary eye. Vortex crystal experiments are also carried out. In these cases, rapid filamentation zones occur in a circular region at a radius smaller than the initial barotropically unstable ring of vorticity, but mesovortices in this region maintain themselves since the vorticity dominates strain within each mesovortex.

4. REFERENCES

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