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THE INTERACTION OF A TROPICAL-CYCLONE-LIKE VORTEX AND A FRONT IN A BAROTROPIC MODEL

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1. INTRODUCTION

During extratropical transition a tropical cyclone approaches the mid-latitude westerlies and thus moves into an environment with strong horizontal temperature gradients at the surface and on the tropopause. In this paper we consider how such horizontal temperature gradients might influence the motion of a tropical cyclone.

Previous studies have shown that much of the dynamics of tropical cyclone motion can be captured by a barotropic model. Bretherton (1966) showed that a horizontal temperature gradient at a boundary is equivalent to a horizontal potential vorticity gradient concentrated at the boundary. Thus the closest analogy to a front in a barotropic model is a strong horizontal vorticity gradient. We wish to consider the case in which a vortex in the Northern Hemisphere approaches an east-west oriented baroclinic zone from the south. There is warm air to the south of the baroclinic zone and cold air to the north. The surface baroclinic zone can be represented in a barotropic model by high vorticity to the south and low vorticity to the north. The baroclinic zone on the tropopause corresponds to low vorticity to the south and high vorticity to the north. In this paper we show two calculations, one representing a surface cold front, the other a tropopause cold front.

2. MODEL AND INITIAL CONDITIONS

A semi-Lagrangian finite difference model is used to solve the nondivergent barotropic vorticity equation in Cartesian coordinates (x,y) on an *f*-plane. The implicit, second order, time discretisation is given by:

$$\zeta(\mathbf{x},t)=\zeta(\mathbf{x}_d,t-dt),$$

where ζ is the vertical component of relative vorticity, $\mathbf{x}=(x,y)$, t is time and dt the time step. The 'departure' point $\mathbf{x}_d$ is defined by:

$$\mathbf{x}_d=\mathbf{x}-\frac{dt}{2}\left(\mathbf{u}(\mathbf{x},t)+\mathbf{u}(\mathbf{x}_d,t-dt)\right).$$

The horizontal velocity vector, **u,** and the streamfunction, ψ, are given by:

$$\mathbf{u}=\left(-\psi_y,\psi_x\right),\qquad \nabla^2\psi=\zeta\ .$$

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The standard second order 5-point discretisation is used for the Laplacian, and centred differences for horizontal gradients. Cubic splines are used to interpolate ζ and **u**, with damping on the coefficients (to ensure numerical stability) which is comparable to a ∇^4 damping on the vorticity field.

The numerical domain is an 1800 km square box, with periodic boundary conditions. The fields are held on a 512 x 512 mesh, so that the grid spacing is about 3.5 km. A timestep of 2500 seconds is used.

The vorticity profile of the vortex is Gaussian and the front is a vorticity discontinuity (smoothed over a few gridpoints). The vortex is initially located 250 km south of the front. The results of two experiments are shown here. The first represents a surface cold front, with a vortex strength of $10^{-4}\,s^{-1}$ and a vorticity front of strength $\Delta\zeta=-4\,x\,10^{-5}\,s^{-1}$. The second represents a tropopause cold front with a vortex strength of $2\,x\,10^{-4}\,s^{-1}$ and a vorticity front of strength $\Delta\zeta=2\,x\,10^{-5}\,s^{-1}$. The vorticity fronts can be related to surface temperature fronts using the velocity scale (U^*) associated with the latter which is (Juckes, 1995):

$$\Delta\zeta\approx\frac{U^*}{L}=\frac{\alpha g\Delta\theta}{\pi\theta_{00}NL}$$

where g =10 $m\,s^{-2}$ is the acceleration due to gravity, $N=10^{-2}\,s^{-1}$ the Brunt-Väisälä frequency, θ_{00} = 300 K a reference potential temperature, and L = 1000 km the scale of frontal waves. α = -1 for the surface and α = 1/2 for the tropopause (assuming the Brunt-Väisälä frequency increases by a factor of two across the tropopause). This implies $\Delta\theta\approx$ 20 K for the fronts in these experiments.

3. RESULTS

Figure 1 shows a calculation for the case where the tropical-cyclone-like vortex is located to the south of a 'surface cold front' with high vorticity to the south of the front and low vorticity to the north. The cyclonic circulation of the vortex interacts with the front so that low vorticity is advected southwards to the west of the vortex and high vorticity is advected northwards to the east of the vortex. Thus an anticyclonic circulation develops to the northwest of the vortex and a cyclonic circulation to the northeast. There is a northerly component of flow across the centre of the vortex associated with these circulations so that the vortex moves away from the front.

The environmental flow near the front is horizontally sheared and distorts the vortex. After about 22 h the vortex has an elliptic shape (Fig. 1b). After this time vorticity filaments develop and the inner part of the vortex becomes more axisymmetric in the manner described by Melander et al. (1987).

Figure 2 shows a calculation for a vortex located to the south of a 'tropopause cold front' with low vorticity to the south of the front and high vorticity to the north. In this case the interaction of the vortex with the front leads to a southerly component of flow across the centre of the vortex. The vortex moves towards the front and eventually becomes wrapped up in the front. As in the previous case the vortex is distorted by the horizontally-sheared flow, becomes elliptic in shape and then axisymmetrizes.

4. SUMMARY

Calculations with a barotropic model show that a vortex will induce a wave on a front. The phase relation between the vortex and the wave is such that the vortex tends to be forced away from a surface cold front and attracted towards a tropopause cold front. Thus as a tropical cyclone approaches a deep baroclinic zone we might expect the lower part of the tropical cyclone to move away from the baroclinic zone and the upper part towards the baroclinic zone so that the tropical cyclone develops a vertical tilt. The three-dimensional interaction of a tropical cyclone and a front will be investigated in a future study.

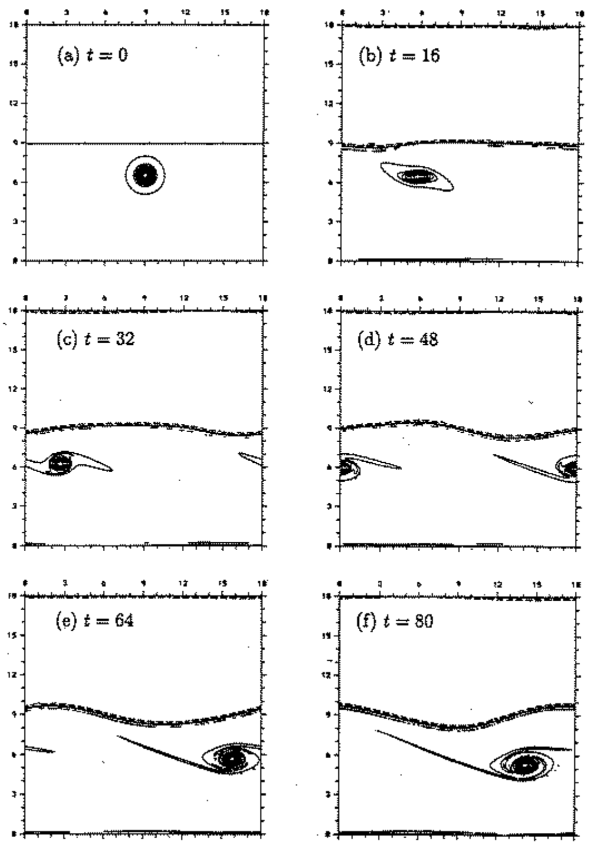

Figure 1: Evolution of relative vorticity for the interaction of a vortex with a "surface cold front". The units are non-dimensionalised on 100 km and 5000 seconds.

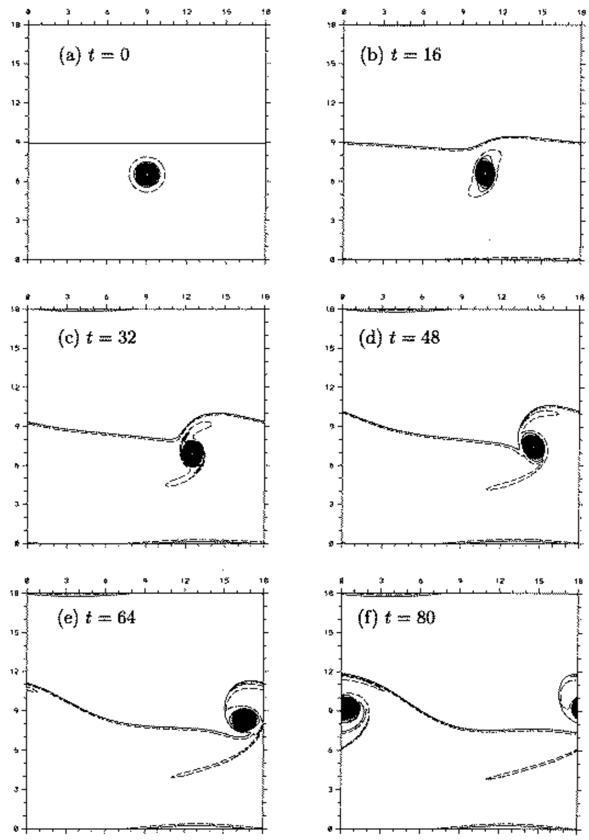

Figure 2: As Fig. 1 for the interaction of a vortex with a "tropopause cold front".

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