14.7 AXISYMMETRIC TROPICAL CYCLOGENESIS VIA A SINGLE CONVECTIVE RING

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1. INTRODUCTION

The mechanism of tropical cyclogenesis is not well understood. The first theories for tropical cyclogenesis start out from the idea that tropical cyclones result from the pre-existing convective instability of the tropical atmosphere (e. g. Charney and Eliassen 1964). In contrast to these theories Rotunno and Emanuel (1987) demonstrated with a numerical model that initial convective instability is not necessary for tropical cyclogenesis. They proposed the so-called WISHE (Wind Induced Sea Heat Exchange) mechanism where the feedback between evaporation and surface wind leads to growth of wind speed (see also Emanuel 1987).

Both theories have in common that many individual convection cells cooperate with the large scale flow to create a vortex. At the first sight the latter statement seems to contradict with the WISHE theory since convective instability is not necessary for vortex growth. But in this theory convection is assumed to act so fast that the atmosphere remains in a nearly neutral state. Hence, convection in the form of many individual cells is also an element of the WISHE theory.

The present study shows that tropical cyclogenesis may also take place when only a single convective ring is present. Some studies using numerical axisymmetric models reveal that the only significant updraft is the eyewall itself (e. g. Rotunno and Emanuel 1987). Of course this is not necessarily the case in the growth phase. Nevertheless, it will be demonstrated by a high-resolution axisymmetric model that indeed one single contracting convective ring can create a tropical cyclone vortex. The mechanism of this type of cyclogenesis is explained by a simple balanced vortex model based on the zero potential vorticity assumption.

2. MODEL DESCRIPTION AND INITIAL STATE

The axisymmetric numerical model solves the nonhydrostatic primitive equations. The prognostic equations are the momentum equations for the radial wind u, tangential wind v and vertical wind w, the mass continuity equations for the total density ρ and specific humidity q, and the thermodynamic equation for the potential temperature θ. The ideal gas law is used to determine the pressure variable Π (Exner function). It is simply assumed that condensed water immediately falls out as rain. The results were compared with simulations for which the model includes the cloud microphysical scheme of Kessler. A flux-gradient closure is used for the parameterization of turbulent fluxes. The turbulent exchange coefficient is set proportional to the deformation of the flow. The exchange coefficient for momentum is three times smaller than for the other variables. Turbulent fluxes at the surface are determined by bulk aerodynamic formulas. The drag coefficient for momentum takes the value C_D=0.001 while for temperature and moisture the value C_H=0.003 is used. Radiation is neglected and a constant Coriolis parameter f=5x10^{-5}s^{-1} is used. The model domain extends over a radial distance of 750km and a height of 15km. The distances between the grid points are 500m in the radial and 300m in the vertical direction.

Initially, a cyclone in gradient wind balance with maximum near surface tangential winds of 15m/s at a radius of 100km is placed in the model. The wind anomaly decays linearly with height and is zero at a height of 13km. The sea surface temperature is 28°C. The vertical temperature profile has a tropopause at 11km height and is initially slightly stable with respect to moist convection. However, latent surface heat fluxes rapidly produce CAPE at the radii where non-zero surface winds occur. The initial tropospheric relative humidity amounts to 75% in the troposphere and decreases above the tropopause.

3. RESULTS

Figure 1 shows the tangential wind at the lowest model level (z=150m) and the vertically integrated heating rate due to condensation as a function of radius and time. Note that this heating rate is proportional to the precipitation rate at the surface. The initial vortex decays until the first convective ring develops at t=40h. Afterwards, the convective ring exhibits amplitude oscillations and contracts while the vortex amplifies with maximum winds near the position of the ring. Later, the amplitude of the oscillations decreases and the ring broadens. Finally, the contraction of the ring stops at $r\approx$20km and the vortex seems to settle into a steady state with a maximum tangential wind of $v\approx$80m/s. At this time the convective ring can be interpreted as the eyewall of the tropical cyclone. The simulation has been repeated with the model that incorporates the Kessler cloud microphysical scheme. This simulation (not shown) reveals three episodes where a single convective ring intensifies the vortex

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and decays afterwards. The final ring develops the eyewall which is later replaced by another.

These model simulations show that tropical cyclogenesis can take place by the interaction of a single convective ring with a large-scale vortex. Although this scenario is probably not the one that comes about in real tropical cyclones it is nevertheless of interest since the mechanism of this idealized kind of cyclogenesis seems to be more lucid than in real cases.

Fig. 2 displays the same quantities as in Fig. 1 but the fields have been displayed as a function of potential radius

$$R = \left(r^2 + \frac{2}{f} vr \right)^{\frac{1}{2}} \qquad (1)$$

and time. It becomes clear that the radial extent of the convective ring is much larger in potential radius space. This results from the large absolute vorticity ζ near the updraft since $\partial R/\partial r \propto \zeta$. The maximum of heating and tangential wind only propagates slightly towards larger potential radii. Therefore, the angular momentum of the convective ring is almost conserved.

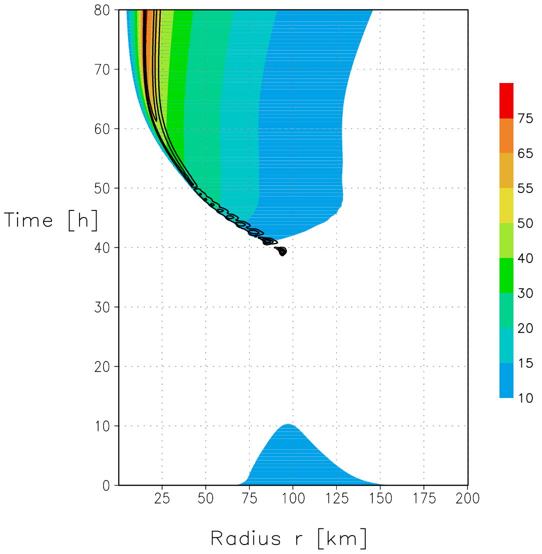

Figure 1: Tangential wind in m/s at the lowest model level z=150m (coloured shadings) and vertically integrated heating rate due to condensation (black isolines contour interval 50kW/m^2) as a function of radius and time.

4. CONTRACTION OF A CONVECTIVE RING IN A BALANCED MODEL

The simple axisymmetric balanced model is based on the zero potential vorticity assumption and has been described in detail by Frisius (2005). It is assumed that the free atmosphere is inviscid and that heating does not vary along angular momentum surfaces. In this case the potential vorticity remains zero if it vanishes initially. The thermal wind balance equation reads in potential radius coordinates

$$f^2 \frac{R^3}{r^3} \frac{\partial r}{\partial Z} = \Gamma \frac{\partial s^*}{\partial R}, \qquad (2)$$

where Z is the pseudo-height, Γ the vertical temperature gradient and s^* the saturated moist entropy. The assumption of zero potential vorticity implies $\partial s^*/\partial Z$=0. Therefore, the physical radius r becomes

$$r = \left(\frac{1}{r_b^{\,2}} + GZ \right)^{-\frac{1}{2}} \text{ where } G = \frac{2\Gamma}{f^2 R^3} \frac{\partial s^*}{\partial R}. \qquad (3)$$

The subindex b denotes that the variable is evaluated at the lower boundary of the model (Z=0).

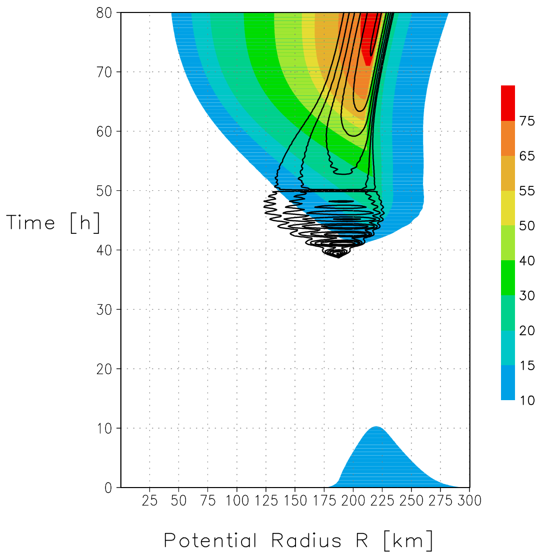

Figure 2: As in Fig. 1 but as a function of potential radius and time.

If no source of angular momentum is present in the free atmosphere, the mass inside of an angular momentum surface, namely

$$M = \pi \int_0^H r^2 \rho \, dZ \ , \qquad (4)$$

will be conserved. In (4) H denotes the height of the upper boundary. Inserting (3) into (4) and assuming ρ=const. (Boussinesq-Approximation) leads to:

$$r_b = \left(\frac{\exp(MG/\pi\rho) - 1}{GH} \right)^{\frac{1}{2}} \ . \qquad (5)$$

It is possible to deduce the surface tangential wind velocity v_b from (5) using the relation (1). If potential vorticity is zero the prognostic equation for saturated moist entropy reads

$$\frac{\partial s^*}{\partial T} = Q \quad , \tag{6}$$

where Q is the source for saturated moist entropy. The derivative $\partial/\partial T$ denotes the time derivative at a fixed potential radius. The entropy s^* results from (6) for a known entropy source Q and the result can be used in (5) to determine the radius at the surface.

To represent a convective ring a narrow heating profile of the form $Q=Q_0 \exp(-(R-R_0)^2/\Delta R^2)$ has been prescribed, where $Q_0=10^{-4}$ W/kgK, R_0=200km and ΔR=25km. The initial vortex is barotropic with a maximum tangential wind of 10m/s at $R=R_0$. The time evolution of the surface tangential wind of the analytical solution is displayed in Fig. 3. Obviously, the convective heating produces anticyclonic winds inside of R_0 and cyclonic winds outside of R_0. Furthermore, anticyclonic winds predominate. Therefore, this solution has nothing in common with the numerical solution discussed in section 3. The reason stems from the fact that the balanced model lacks one important process so far, namely, horizontal momentum diffusion. This becomes evident, when one tries to transform the solution to physical radius coordinates which is not possible because of a frontal collapse near R= R_0. Therefore, this solution is unphysical.

The results of a numerical solution of the balanced model including horizontal diffusion as described by Frisius (2005) are presented in Fig. 4. Horizontal diffusion is only applied at the lower boundary. Therefore, a frontal collapse can still appear at the upper boundary. It can be seen in the figure that only cyclonic winds are generated and that amplification is accompanied with a decrease of the radius of maximum wind. Hence, this solution agrees much better with that of the primitive equation model. How can these results be explained? The horizontal diffusion term for tangential wind is given by:

$$D_v = k\frac{\partial^2 v}{\partial r^2} + k\frac{\partial}{\partial r}\left(\frac{v}{r}\right) \quad , \tag{7}$$

where k denotes a diffusion coefficient. The second term on the right hand side of this equation leads to a positive tangential wind tendency around the centre of the convective ring. Therefore, anticyclonic winds decay while cyclonic winds increase. This term stems from the metric of the cylindrical coordinates and ensures global angular momentum conservation. Consequently, this effect would not appear in slab symmetric phenomena as, e.g., in a straight squall line where both signs of along-front winds are equally damped by diffusion.

The additional inclusion of horizontal diffusion at the upper boundary leads to the formation of a secondary wind maximum inside of the convective ring (not shown). An upper boundary front is found at the potential radius of this secondary wind maximum. This unrealistic feature possibly stems from the exclusion of adiabatic warming by dry downdrafts in the model. This effect could reduce the temperature gradient inside of the ring and dampen the upper boundary cyclonic wind maximum that is associated with the front.

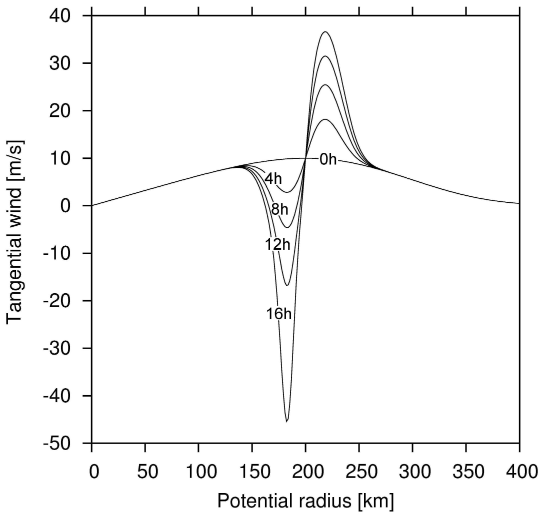

Figure 3: Tangential surface wind in m/s as a function of potential radius for several time points. Shown are the results obtained from the analytical solution (5).

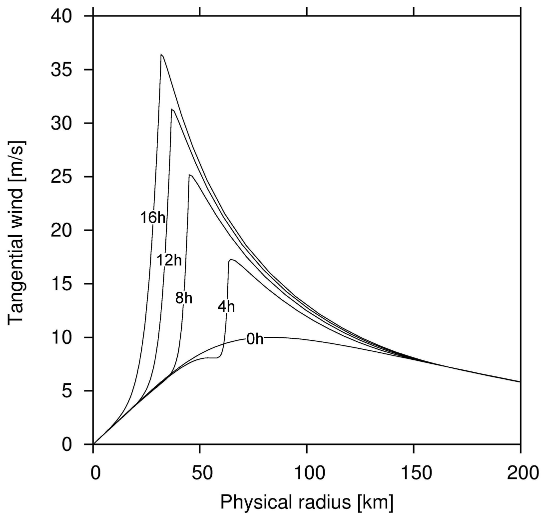

Figure 4: Tangential surface wind in m/s as a function of physical radius for several time points. Shown are the results from a numerical solution of the balanced model including horizontal diffusion.

5. DISCUSSION

It has been demonstrated with an axisymmetric nonhydrostatic model that a single convective ring can generate a tropical cyclone vortex. This result could be explained by a simple balanced vortex model based on the assumption of zero potential vorticity. An important key process is horizontal angular momentum diffusion which is necessary to avoid a frontal collapse and to contract the convective ring. However, to fully understand the cooperation between the convective ring and the vortex it is still necessary to find out the reasons for the maintenance of the convective ring. It can be expected that surface fluxes of water vapour at sufficiently large wind speeds are crucial for the maintenance.

6. ACKNOWLEDGMENTS

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