Numerical Simulation of Tropical Cyclogenesis with the Lokal-Modell

THOMAS FRISIUS

Atmosphärische Wissenschaften
Institut für Meteorologie und Geophysik
der Universität Frankfurt a. M.

1 Introduction

Tropical cyclones are mesoscale phenomena. The inner structure of a tropical cyclone consists of an eye with warm dry air surrounded by an eyewall where a large amount of condensation takes place due to strong vertical motion. These structures can be assigned to the meso-β-scale. Therefore, the nonhydrostatic limited-area model "Lokal-Modell" (LM) of the German Weather Service would be an appropriate model for simulating the inner core of a tropical cyclone. However, convective clouds are also incorporated in such a storm, especially in the growth stage. Hence, convection must be parameterized or resolved explicitly. The use of a convective parameterization does not appear suitable since there is only a small gap between the scale of an individual convection cell and the scale of the tropical cyclone core. On the other hand the operational version of the LM uses a standard resolution of 6.95 km that is somewhat too coarse for simulating individual convective cells. However, other modelling studies of tropical cyclogenesis work with similar resolutions and found a reasonable reproduction of tropical cyclone structures (e. g. Liu et al. 1997 and Wang 2001). Therefore, it is not meaningless to attempt simulations of tropical cyclogenesis using the LM without a convective parameterization.

This study presents results of idealized tropical cyclone simulations in order to see how well the genesis event and the storm structures can be described with the LM. Furthermore, the sensitivity of the storm development to the use of a convective parameterization and various parameters is studied.

2 Description of Experiments

For all simulations the LM version 2.12 is used in which the effects of spherical geometry are neglected (f-plane geometry). The lower boundary is a sea surface with the constant temperature T_s. The experiments do not include effects of radiation. The model domain extends over a length of 1120 km in the zonal and in the meridional direction. The horizontal distance between two grid points amounts to 6.95 km so that each horizontal direction is divided into 161 grid points. In the vertical direction the 35 levels of the operational LM version (see Steppeler et al. 2003) are adopted. Near the lateral boundaries all variables are damped toward a horizontally uniform and motionless state with the Davies relaxation technique (Davies 1976). As in the operational LM version a four-category parameterization scheme for cloud microphysical processes is applied. The four categories of water are water vapor, cloud water, rain and snow. Turbulent exchange is parameterized with the operational scheme (see Steppeler et al. 2003).

Initially, a circular symmetric balanced cyclone is placed at the center of the model domain. The pressure p of this cyclone is prescribed by:

$$p(r,z) = p_0(z)\left(1+\frac{\Delta p}{1000\mathrm{hPa}}\right)^{-\exp(-r^2/r_0^2)}, \tag{1}$$

where r denotes the distance from the center of the domain, z the height, $p_0(z)$ the pressure of the environment and r_0 a radius that determines the horizontal scale of the cyclone. The parameter Δp roughly measures the initial surface pressure difference between the center and the environment.

The initial temperature distribution only depends upon z and is given by:

$$T(z) = \begin{cases} T_s - \gamma z & z < H \\ T_s - \gamma H & z \geq H \end{cases}, \tag{2}$$

where $H = 10000$ m is the height of the tropopause and $\gamma = 0.0065$ Km^{-1} the lapse rate. The initial relative humidity F is uniform and the pressure $p_0(z)$ is calculated from the hydrostatic balance equation using $p_0(0) = 1000$ hPa. The initial horizontal wind is in gradient wind balance.

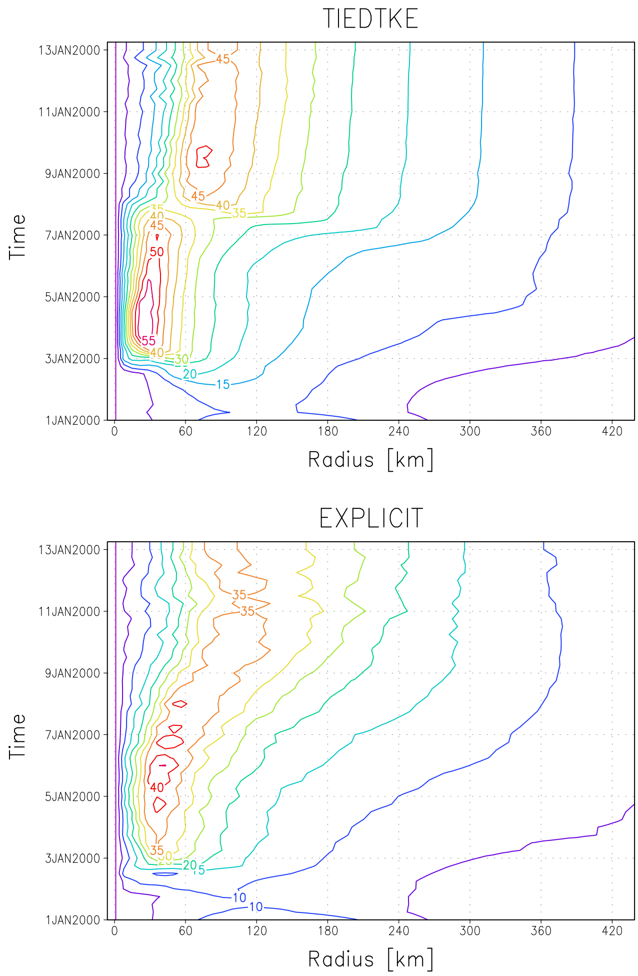

Figure 1: : Radius-time plot of the azimuthally averaged tangential wind at the lowest model level for the Tiedtke (upper panel) and Explicit (lower panel) run (contour interval 5m/s).

The parameters Δp, T_s and F are varied in the sensitivity experiments. For the reference runs the parameters are prescribed by Δp =5 hPa, r_0=150 km, T_s = 28°C, F = 0.7, $f = 0.729 \times 10^{-4}$ s^{-1}. Two categories of experiments are performed. In the first category the LM adopts the Tiedtke mass flux scheme for the parameterization of convection (Tiedtke 1989). In the second category convection is simulated explicitly without parameterization.

3 Reference experiment

In this section the results of the reference runs are presented. Fig. 1 shows the evolution of the azimuthal mean tangential wind at the lowest model level as a function of time and radius for both experiments. The azimuthal average has been applied with respect to the location of the minimum surface pressure. It can be seen that the initial wind increases and the radius of maximum wind shrinks until a mesoscale cyclone with hurricane force winds establishes. Compared to the explicit run the experiment with the Tiedtke closure reveals stronger maximum winds at a smaller radius. The magnitude and radius of maximum wind lie within the range observed in real tropical cyclones (e. g. Holland 1980). In the Tiedtke run the radius of maximum wind changes abruptly after 7 days due to the formation of a secondary wind maximum that replaces the inner one. Such a replacement has also been observed in real hurricanes (Willoughby et al. 1982) and in numerical simulations (Tenerelly and Chen 2002). In the explicit run the radius of maximum wind moves rather gradually outward. This seems to be related to asymmetries from the circular symmetry in the explicit run where spiral bands instead of convective rings induce the migration of the inner eyewall.

This suspicion is supported by Fig. 2 where snapshots of the vertically averaged temperature and vertical wind fields are displayed at t = 108 hours (the vertical average ranges from the surface to z =10000m). Obviously, the vertical wind pattern exhibits a ring-like eyewall in the Tiedtke run. In contrast, the explicit run reveals a spiral band rather than a closed eyewall. The temperature fields are in both cases nearly axisymmetric with a maximum at the storm center. The maximum of the temperature anomaly amounts to 12°C in the Tiedtke run and 9°C in the explicit run. Such magnitudes also arise in observed tropical cyclones

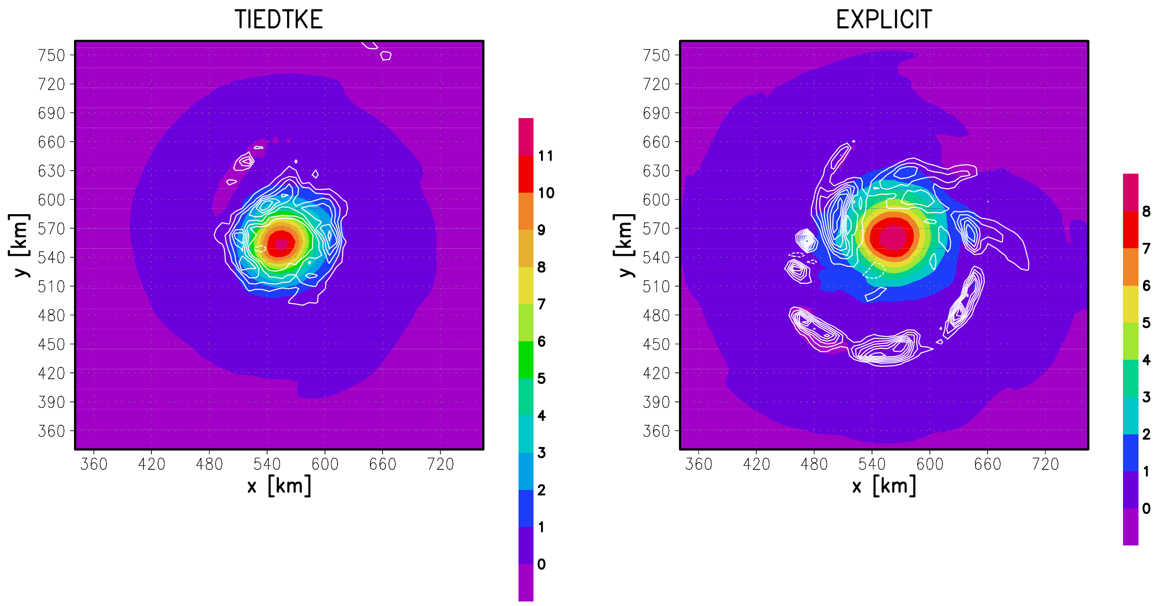

Figure 2: Snap-shot of the vertically averaged vertical wind (white isolines, contour interval 0.2m/s) and temperature (coloured shadings, in °C) at t = 108hours. Negative isolines are dashed.

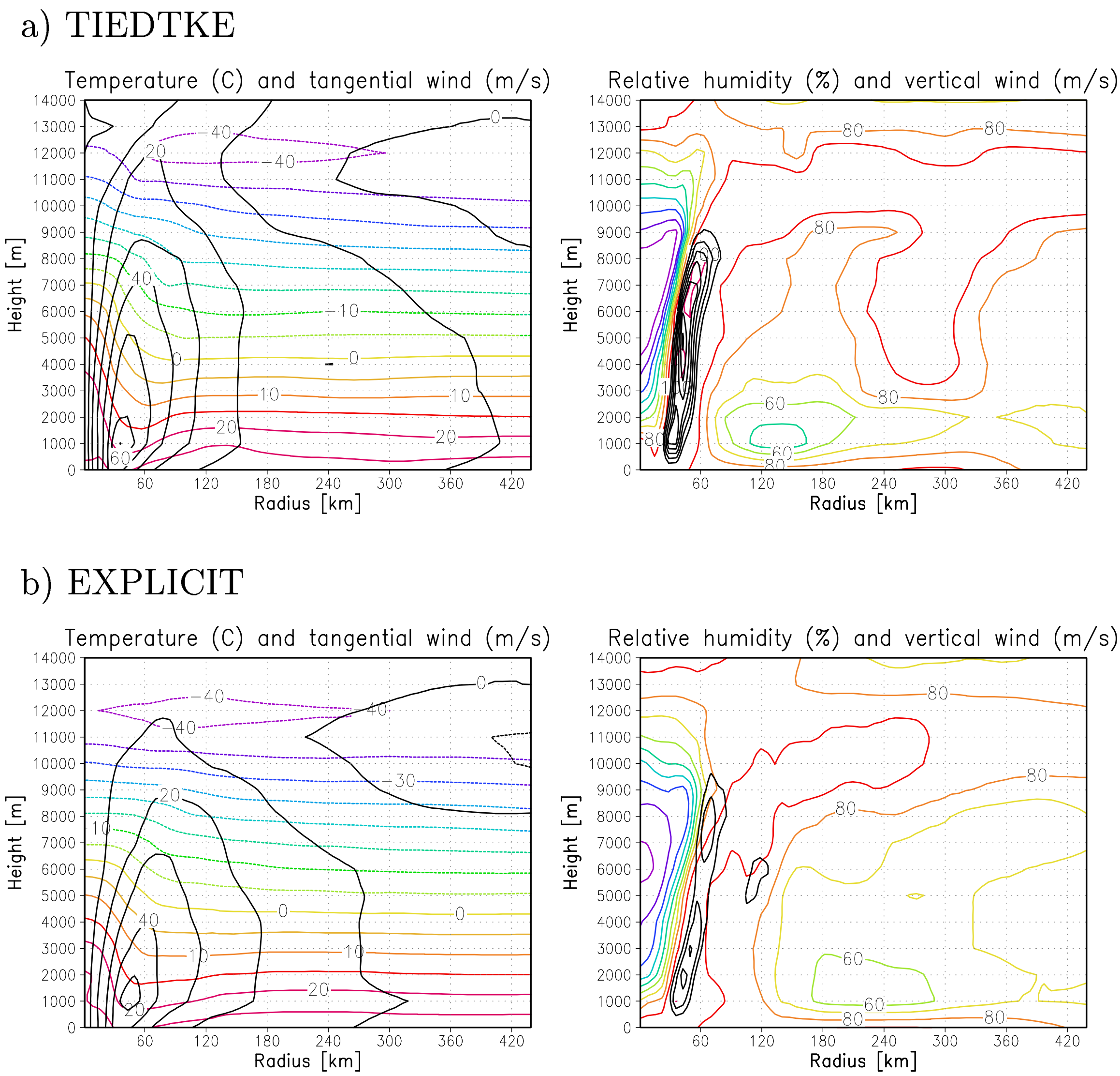

Figure 3: Azimuthal average of temperature (coloured isolines, left panel, contour interval 5°C), tangential wind (black isolines, left panel, contour interval 10m/s), relative humidity (coloured isolines, right panel, contour interval 10%), and vertical wind (black isolines, right panel, contour interval 0.2m/s) at t =108 hours for a) the Tiedtke run and b) the explicit run. Negative isolines are dashed.

(e. g. Anthes 1982). The center of the tropical cyclone moves only slightly and randomly in the horizontal plane. This result seems to be related to the simple f-plane geometry where no propagation of circular symmetric vortices occurs. The cyclone movement is a bit more pronounced in the explicit run than in the Tiedtke run.

Fig. 3 displays azimuthal averages of temperature, tangential wind, relative humidity and vertical velocity at t =108 hours. In both cases the cyclone has a warm and dry eye where the relative humidity is below 10%. This low value stems from adiabatic warming caused by the downward motion in the eye. Liu et al. (1997) also found such low values in their numerical simulations. The maximum of tangential wind appears at a height of z = 1000 m and inside of 50 km radius. The wind decreases with increasing height with an outward slope of the wind maximum. This can be understood by the thermal wind balance since the isotherms indicate a temperature front that also slopes outward with increasing height. The

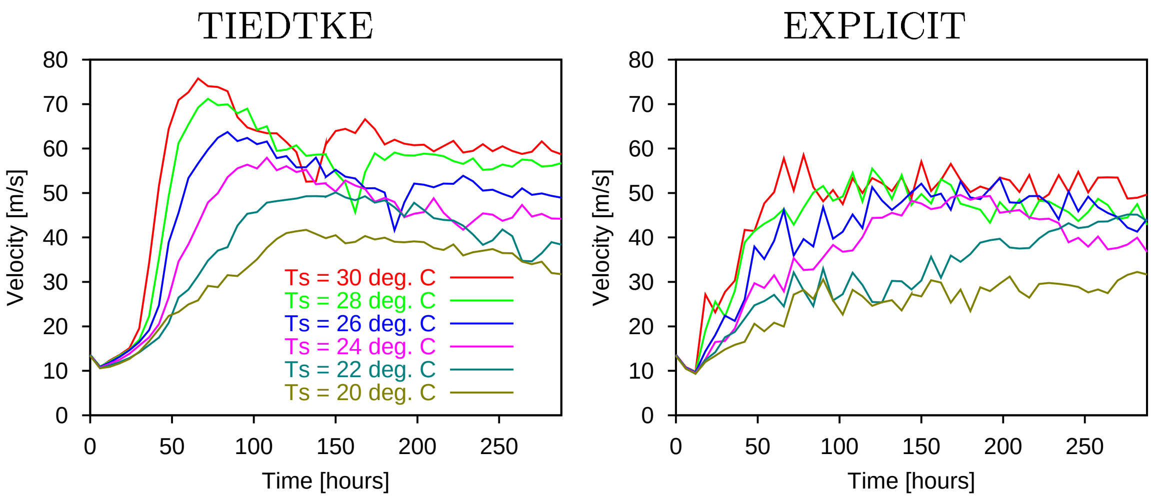

Figure 4: Maximum of wind at the lowest model level as a function of time for various sea surface temperatures. The left panel displays results for the Tiedtke runs and the right panel those for the explicit runs.

vertical wind has a maximum near the radius of maximum wind. Another maximum is seen in the explicit run which is associated with the spiral band detected in Fig. 2. Note that a substantial amount of the vertical velocity amplitude vanishes due to azimuthal averaging. In summary the basic structure of the azimuthally averaged cyclone in the Tiedtke run resembles that of the explicit run. However, the simulated cyclone of the explicit run has a larger eye and less strong tangential and vertical winds in the azimuthal mean.

4 Sensitivity to surface temperature, initial amplitude and humidity

In this section the sensitivity of tropical cyclogenesis to some model parameters is described. Fig. 4 displays the development of the maximum wind at the lowest model level for various surface temperatures. The maximum wind may be interpreted as a storm intensity. Obviously, the growth rate and the maximum storm intensity increases with increasing surface temperature in the Tiedtke experiments. This result coincides with the observational fact that tropical cyclones only occur over warm ocean surfaces. However, the LM with the Tiedtke closure exhibits the development of a cyclone with hurricane force winds even for $T_s = 20°$C. In nature, tropical cyclogenesis is only observed for temperatures larger than 26.5°C. A gradual increase of maximum storm intensity to increasing surface temperature is not obvious in the explicit simulations. Until 150 hours the winds remain slightly below the lower limit of a hurricane (32.7 m/s) for $T_s = 20°$C and $T_s = 22°$C while the other simulations reveal the development of a tropical cyclone with strong surface winds of about 50 m/s. Until this time there seems to exist a threshold between 22°C and 24°C for the development of a hurricane. Later on, however, the vortex for $T_s = 22°$C also attains hurricane strength.

Fig. 5 shows the response to the initial vortex amplitude that is controlled by the parameter Δp. It is seen that the initial vortex amplitude acts to accelerate the development while the maximum storm intensity is relatively unaffected. In one case (explicit run with $\Delta P = 1$hPa) no growth takes place at all. This can be explained by the missing ability of the initial cyclone to lift the air to the level of condensation. Indeed, condensation does not take place in this simulation. In contrast, the Tiedtke convection scheme can cause condensation even when no air parcel reaches the level of condensation.

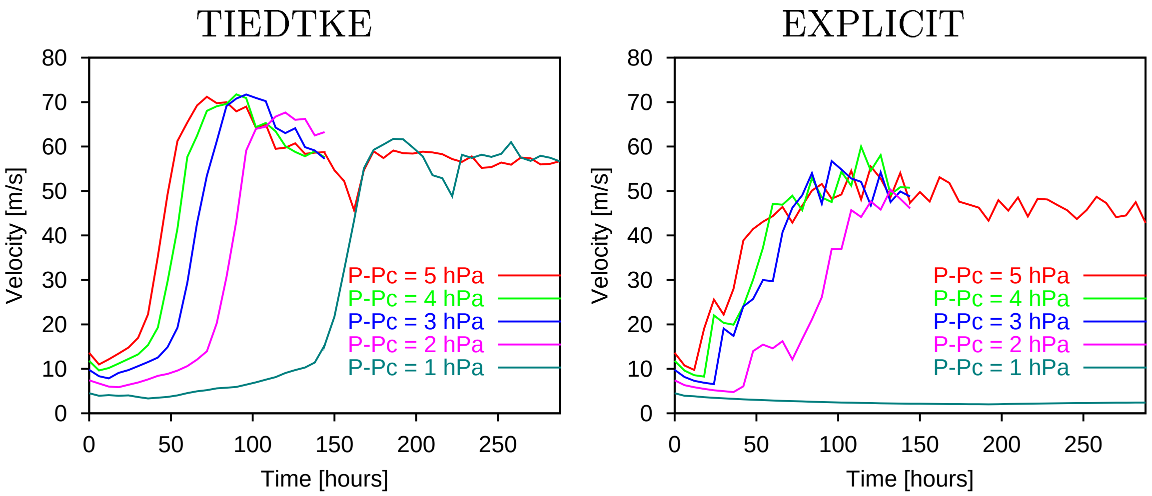

Figure 5: As in Fig. 4 but for various values of the initial surface pressure difference between vortex center and environment.

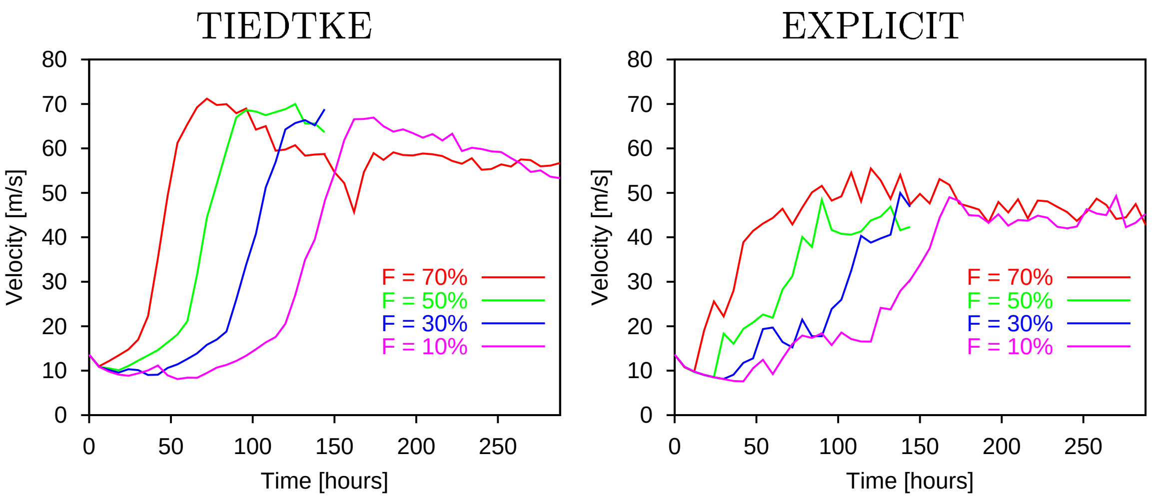

Figure 6: As in Fig. 4 but for various values of the initial relative humidity.

Fig. 6 displays the sensitivity of the development to initial relative humidity. A decrease in initial relative humidity leads to a delay of the development and again, the maximum intensity does not depend upon the varied parameter. Even in the very dry case of 10% initial relative humidity the model exhibits the development of a tropical cyclone. This fact can be explained by the evaporation from the sea surface that causes convective destabilization sooner or later.

5 Conclusion

The experiments reveal the ability of the LM to simulate the evolution and structures of a tropical cyclone realistically. The simulated mature cyclone has a warm and dry core which is surrounded by an eyewall with intense vertical motion. Asymmetries from the circular symmetry like spiral bands are more pronounced in the simulation with explicit convection than in the corresponding simulation involving the Tiedtke mass flux scheme. The intensity of the storm simulated with the Tiedtke closure is somewhat larger than without parameterization. Possibly, this can be explained by the larger degree of circular symmetry leading to a better efficiency in converting the latent heat release to kinetic energy. Indeed, the maximum potential intensity theory for tropical cyclones (Emanuel 1995) is based on the assumption of axisymmety. Further experiments show that the maximum storm intensity increases with increasing surface temperature while it is relatively insensitive to the initial vortex strength and humidity except for one case in which condensation does not take place. On the other hand the development is accelerated with increasing initial strength and humidity. A threshold behaviour with respect to the surface temperature is only indicated in the explicit simulation results. However, the threshold value still seems to be too low when compared to statistics of observed tropical cyclones. In summary, it can be stated that the LM simulates the tropical cyclones somewhat more reasonably when no parameterization of convection is used. Possibly, a higher horizontal resolution may lead to more realistic results.

At a surface temperature of 28°C the occurrence of condensation and convective instability seems to be the only criterion for the development of a tropical cyclone in the idealized experiments presented here. In the real atmosphere, the criterions for the development are much more restrictive (see McBride and Zehr 1981). It is not clear so far wether this disagreement results from the unrealistic high degree of idealization in the experiments or from the weakness of the LM to forecast a non-developing tropical depression. This question remains as a prospect for future research.

Acknowledgments

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