The Effect of Ice-Phase Microphysics on Tropical Cyclones Simulated by the Lokal Modell

Thomas Frisius, Thomas Hasselbeck, Fritz Herbert

Goethe-Universität Frankfurt a. M., Theoretische Meteorologie

1 Introduction

It is known that the release of latent heat is essential for the growth and the longevity of tropical cyclones. Furthermore, it is necessary for the maintenance of storms that the formed condensate must be removed from the vortex area before it may be evaporated in subsaturated air. Therefore, the formation of precipitation and fallout are important processes in tropical cyclones. In most situations, the ice phase is incorporated in the dynamics of precipitation. Examples are the Bergeron-Findeisen process, autoconversion, or collection of cloud water by snow or graupel (riming). High resolution mesoscale models like the Lokal Modell (LM) take these cloud microphysical processes into account in their cloud parameterization schemes. The current version LM 3.14 simulates five categories of hydrometeors, namely cloud water, rain, cloud ice, snow and graupel. Therefore, the LM is a suitable model for the investigation of the ice phase dynamics in tropical cyclones.

Willoughby et al. (1984) and Lord et al. (1984) simulated the ice phase in tropical cyclones using an axisymmetric nonhydrostatic model with a cloud parameterization scheme for the five categories of hydrometeors mentioned above. They found that the existence of the ice phase forces downdrafts outside of the eyewall. These downdrafts are generated by the withdrawal of latent heat due to melting of falling graupel. Wang (2002) investigated the impact of the ice phase in a threedimensional nonhydrostatic model. He found a slight decrease of intensity due to the existence of ice. Furthermore, spiral bands in the tropical cyclone are forced by downdrafts which are produced by melting of graupel.

In the present study the effect of the ice phase on tropical cyclones is investigated within the LM. It turned out that the prognostic treatment of precipitating cloud constituents is crucial for the formation of spiral bands, especially, when the ice phase is present.

2 Description of experiments

A detailed description of the LM-configuration and initial state of the experiments is given by Frisius (2004). For all simulations the LM Version 3.14 is used in which the effects of spherical geometry are neglected (f-plane geometry). The lower boundary is a sea surface with constant temperature $T_s = 28°\mathrm{C}$. The model domain extends over a length of 1120 km in the zonal and meridional directions. The horizontal distance between two grid points amounts to 6.95 km so that the domain is divided in each horizontal direction into 161 grid points. In vertical direction the 35 levels of the operational LM version (see Steppeler et al. 2003) are adopted. The model uses no parameterization of convection processes since we believe that hurricane structures can be assigned to the meso-β-scale that cannot be represented properly when parameterization of convection is switched on.

Initially, a circular symmetric balanced cyclone is placed at the center of the model domain. The initial cyclone has a central pressure deficit of $\Delta p = 5\mathrm{hPa}$ and a characteristic radius of

r_0 =150 km. The initial temperature distribution only depends upon z and is characterized by a linear decrease with the lapse rate $\gamma = 0.0065$ km^{-1} below the tropopause lying at a height of $H = 10$ km. The initial relative humidity F is uniform and the pressure is calculated from the hydrostatic balance equation. The initial horizontal wind is given in accord with gradient wind balance.

The experiments are divided into two types. One type of experiments contains simulations using the traditional cloud parameterization scheme with diagnostic treatment of precipitation which is based on a column-equilibrium relation for the precipitation fluxes. A second type of experiments refers to simulations with the refined cloud parameterization scheme that is based on a prognostic treatment of the precipitation categories. This new cloud parameterization scheme is able to forecast five categories of hydrometeors (cloud water, rain, cloud ice, snow and graupel) with the possibility to switch off some categories.

Numerical experiments have been performed for

- cloud water only (NOPREC),
- cloud water and rain (WARMRAIN),
- cloud water, rain and snow (1CATICE),
- cloud water, rain, snow and cloud ice (2CATICE),
- all five categories (3CATICE) .

The shortcut in brackets denotes the name of the respective experiment. Note that the LM cannot simulate the 3CATICE experiment with diagnostic precipitation. The model simulates 144 hours of the hurricane development and the integration time step is 20 seconds.

3 Results

Figure 1 shows the evolution of maximum wind velocity at the lowest model level for all experiments. It comes apparent that in every model run the cyclone reaches hurricane intensity. However, there are considerable differences between the simulations with diagnostically and those with prognostically calculated precipitation. The diagnostic precipitation simulations with ice phase reaches category 4 on the Saffir-Simpson scale (up to 60m/s) while the WARMRAIN experiment reveals only a hurricane of category 1 and for short time periods category 2. The situations are reversed for simulations based on the prognostic precipitation scheme. The model-hurricane in the WARMRAIN experiment attains category 3 while in the experiments including the ice-phase the simulated hurricanes are at best category two hurricanes. The NOPREC experiment also exhibits the development of a tropical cyclone but its spinup takes longer. However, this case will not be discussed further since the structures of this simulated cyclone are rather unrealistic (no eye-formation and heap up of cloud water).

To see how these differences can possibly be explained it is useful to take a look at the horizontal distribution of the cloud elements which are shown as snapshots at $t = 108$ hours in Fig. 2. Obviously, the different cloud structures are related to the different intensities of the storms. The simulations 1CATICE and 2CATICE based on diagnostic precipitation only reveal a single closed eyewall with a marked wavenumber two undulation. In contrast the diagnostic WARMRAIN experiment exhibits the evolution of spiral bands and an incomplete eyewall. In all experiments with diagnostic precipitation the precipitation pattern is correlated with the cloud water pattern. This results from the column-equilibrium assumption of the diagnostic precipitation scheme in which the fallout of precipitation takes place at the

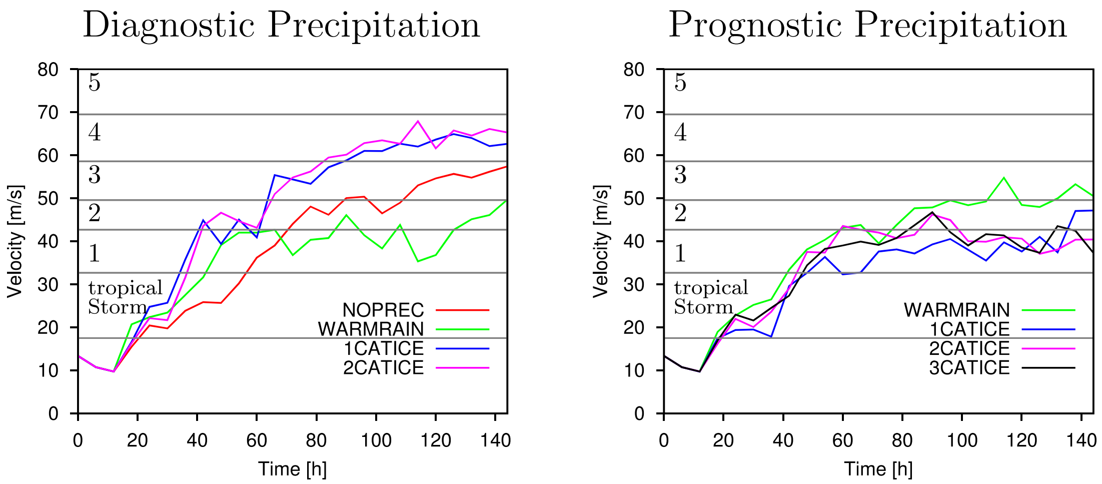


Figure 1: Maximum of wind at the lowest model level as a function of time for the various experiments. The left panel displays results for the cloud scheme with diagnostic precipitation and the right panel the results for the cloud scheme with prognostic precipitation. The thin horizontal lines bounds the areas of the Saffir-Simpson Hurricane scale which is divided into categories 1-5 (number on the left in the figure). The horizontal line at 17.5 m/s marks the minimum velocity of the tropical storm category.

same position where it is produced. The experiments 1CATICE and 2CATICE based on a prognostic precipitation do not show this correlation. The same is true for the 3CATICE experiment (not shown). With the prognostic scheme precipitable water can be advected to other locations. Especially, snow can spread out horizontally over large distance because the fall velocity is relvatively small. This may also be the reason why precipitation is still correlated with cloud water in the prognostic WARMRAIN simulation since slowly falling snow is not present. This can be verified in Fig. 3 where the various azimuthally averaged hydrometeor categories at $t = 108$ are displayed in a cross section for the experiments WARMRAIN, 1CATICE, 2CATICE and 3CATICE based on the prognostic precipitation scheme. Rain forms below the wide snow maximum in the experiments including the icephase while rain only falls close to the eyewall in the WARMRAIN experiment. Note that the amount of graupel is very small relative to the amount of snow. Therefore, graupel does not play an important role for the dynamics of the mature tropical cyclone of the 3CATICE simulation. The same is true for the cloud ice since the experiments 1CATICE and 2CATICE show quite similar results. Possibly cloud ice is only important for the initiation of snow production while the major snow production conversions are rather riming and depositional growth than autoconversion (for details of the ice-phase parameterization see Doms et.al., 2005).

It can be stated that the experiments showing only a single eyewall are associated with a larger storm intensity (maximum wind speed) than in the experiments showing cloud structures outside the eyewall. However, the physical reasons for these differences remain unclear so far. The results of the experiments with prognostic precipitation are in agreement with the findings of Wang (2002). He accentuates the advection of cold air into the boundary layer by downdrafts which limits the intensity of the storm. Figure 4 shows the downdraft velocity at z=1240m together with the equivalent potential temperature field for both 2CATICE experiments. Considerable qualitative differences can be seen. In the simulation with diagnostic precipitation downdrafts occur near the eyewall while with prognostic precipitation downdrafts appear far away from the storm center. Furthermore, the downdraft in the experiment with prognostic precipitation cools the boundary layer equivalent potential temperature up to 40 K below the ambient values. It can be expected that this cooling

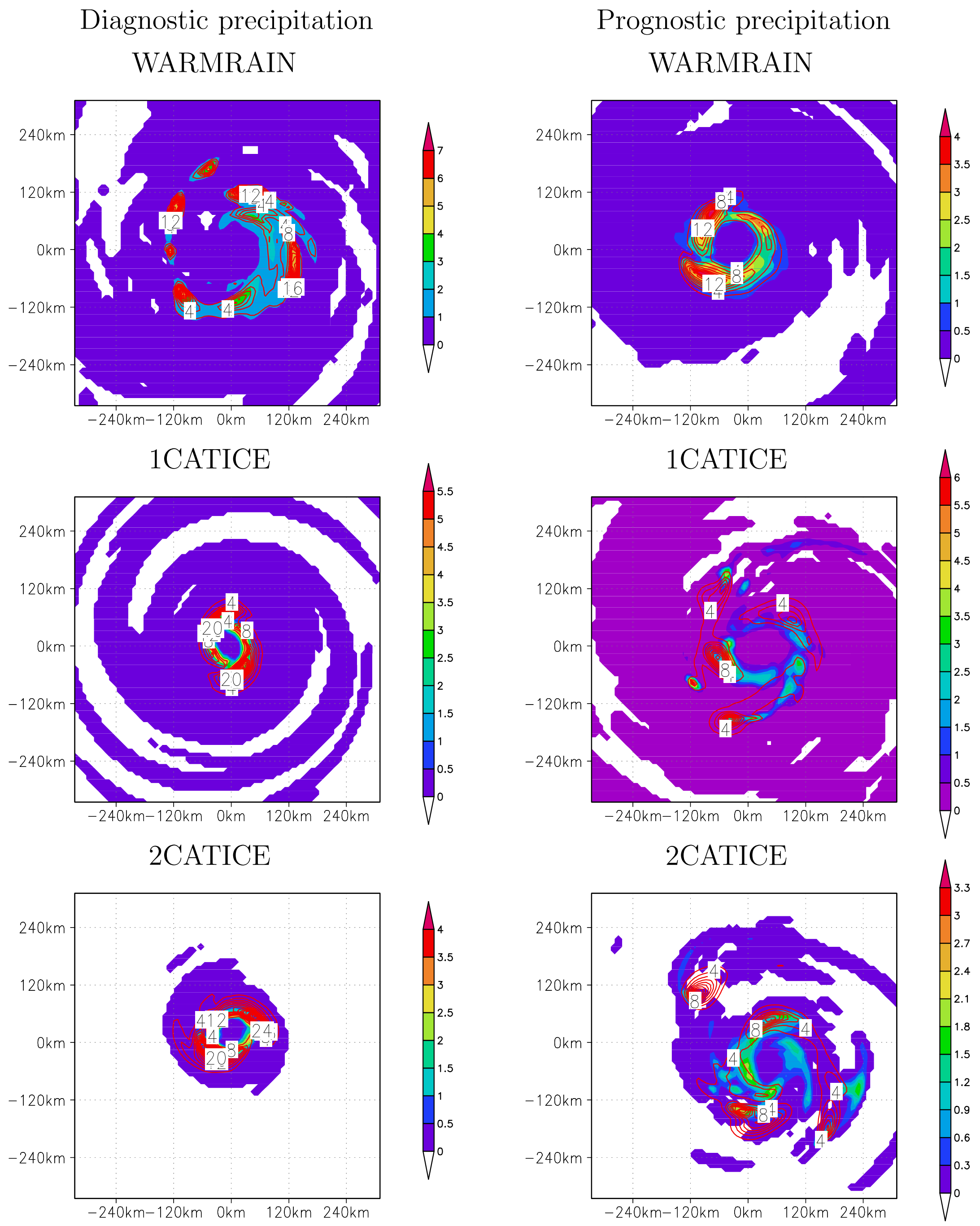


Figure 2: Snap-shots of the vertically integrated cloud water in kg/m^2 (coloured shadings) and vertically integrated precipitable water (red isolines, contour interval 2 kg/m^2) at $t = 108h$. The left (right) panel displays results for the cloud scheme with diagnostic (prognostic) precipitation.

effectively reduces the intensity of the storm since the boundary layer air ascends in the eyewall later on. There, it will release a smaller amount of latent heat than without this downdraft-induced cooling. Most downdrafts are associated with enhanced values of the vertically integrated melting rate (thick white isolines) suggesting that these downdrafts are indeed initiated by melting of snow. The same is true for the rain evaporation rate (not shown). Both processes contribute to a negative buoyancy of the air parcel. In the model experiment based on diagnostic treatment of precipitation no such downdrafts occur since the produced snow cannot be advected away from the eyewall due to the limitations of the

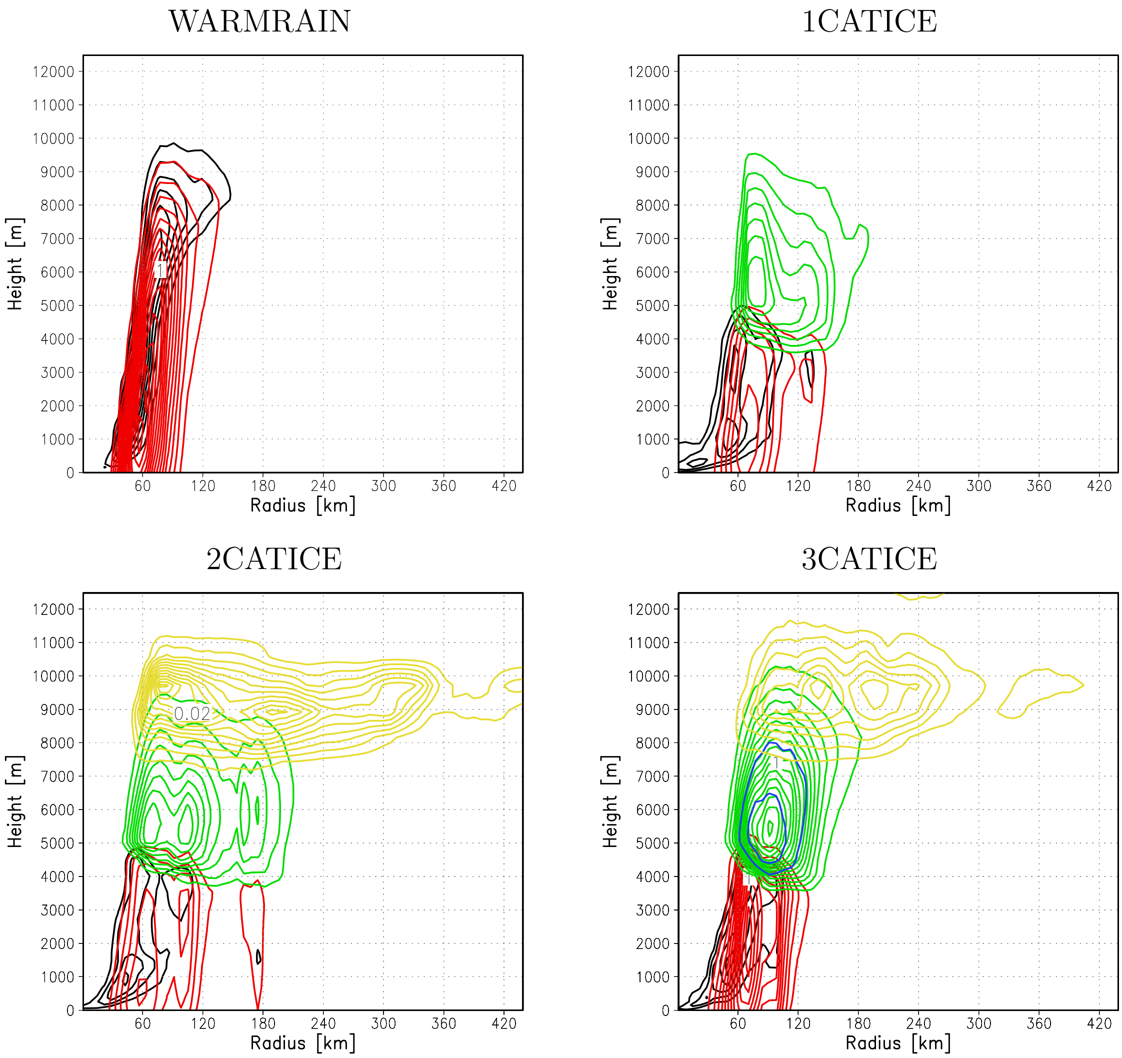
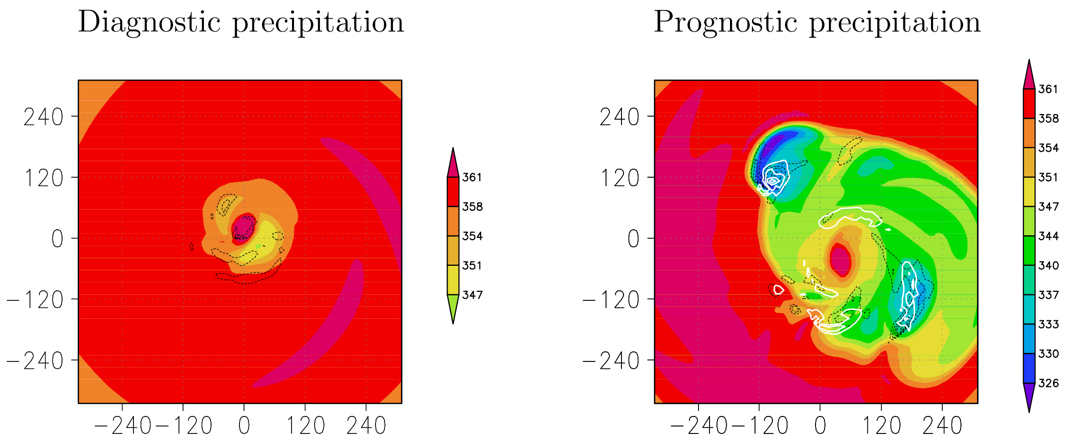


Figure 3: Azimuthal averages at $t = 180$h of cloud water content (black isolines, contour interval 0.1 g/kg), rain content (red isolines, contour interval 0.1 g/kg), snow content (green isolines, contour interval 0.1g/kg) cloud ice content (yellow isolines, contour interval 0.002g/kg) and graupel content (blue isolines, contour interval 0.1g/kg). Shown are the results of the experiments based on the prognostic treatment of precipitation.

diagnostic scheme.

4 Conclusion

This study reveals that the LM-simulation of tropical cyclones is very sensitive with respect to the details of the microphysical cloud parameterization scheme. The ice phase provides downdrafts due to melting of snow that reduces the intensity of the simulated storm. It seems that the diagnostic precipitation scheme is not capable in producing downdrafts by evaporation of rain and melting of snow. Therefore, no further convective cells are generated outside of the eyewall and no cooling of the boundary layer takes place. This leads to a higher storm intensity. Since cloud structures outside of the eyewall, for instance rainbands, are evident in real tropical cyclones (e. g. Anthes 1982) the cloud parameterization scheme with a prognostic treatment of precipitation is more suitable for tropical cyclone modeling than the old diagnostic scheme.



Diagnostic precipitation

Prognostic precipitation

Figure 4: Snapshot at t = 108hours showing equivalent potential temperature near the surface (coloured shadings) and downdraft velocity at z = 1240m (black dashed isolines, contour interval 0.2m/s). The thick white solid isolines in the right panel display contours of the vertically integrated melting rate. (contour interval 2kg/m^2/h). The left panel displays the 2CATICE experiment based on the diagnostic treatment of precipitation and the right panel the 2CATICE experiment based on the prognostic treatment of precipitation.

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