Final Technical Report

Title: Improving Cloud and Precipitation Physics in a Seamless Regional-Global Climate Model
Project ID 0015329
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Summary

The objective of this project was to improve numerical simulation and forecasting of regional climate by incorporating recent advances in the understanding and modeling of atmospheric aerosols, clouds, and precipitation mechanisms in an advanced regional-global numerical model. We utilized the Ocean-Land-Atmosphere Model (OLAM), which is a global model that is partly derived from the Regional Atmospheric Modeling System (RAMS). OLAM's global grid can be configured with a high resolution locally-refined region that provides seamless two-way communication between global and regional scales of motion. The full interaction between regional and global climate is a major improvement in accuracy and applicability over conventional regional climate models (RCMs) that are one-way nested within global climate models (GCMs). When OLAM is applied as a RCM, most computational effort is concentrated in its high-resolution region, and the lower-resolution remainder of its global domain adds relatively minor computational cost while providing significant benefits.

In the first phase of the project, significant upgrades to RAMS that had been made over the preceding several years, including the introduction of aerosols as prognostic fields, radiative effects of aerosols, representation of aerosol sources and formation, and the impact of aerosols on clouds and precipitating systems were transferred into OLAM. These mechanisms had been extensively studied and verified in RAMS, and the multiple effects of aerosols had been shown to significantly impact climate. A unique feature of the RAMS microphysics model is that, while being a bulk scheme, droplet collection, sedimentation, ice particle riming, vapor deposition growth, and cloud droplet nucleation are all simulated with the assistance of numerical integrations over size bins, similar to the type of computations that are performed in a full bin microphysics model. The bin computations more accurately represent nonlinearities that are inherent in the physical processes and make unnecessary some approximations that are unavoidable in traditional bulk microphysics methods. However, the bin computations are computationally expensive, so a method was developed where all bin computations are performed *a priori* and used to develop lookup tables for each of the physical processes.

During model simulations, the table values are accessed, often using interpolation over multiple parameter dimensions, so that no bin computations are actually performed at the time of the model integration.

While OLAM microphysics already utilized the bin lookup table method for some processes, this was expanded based on the new developments in RAMS. In the course of upgrading OLAM microphysics for this project, we also expanded the bin computation approach beyond its level of development in RAMS by bringing all forms of collision between hydrometeors under the umbrella of the stochastic collection equation with size-dependent collision efficiency. Most significantly, this included collisions between cloud droplets and ice (riming), cloud droplets with cloud droplets (often called “autoconversion” in parameterizations), cloud droplets with the newly-added “drizzle” category, which in the model is defined as an intermediate size of prognosed liquid water between cloud and rain drops, drizzle to drizzle collisions, and both cloud to rain and drizzle to rain collisions. Numerical integration over 2-dimensional bin space of each of these collision types further improves accuracy while still retaining the computational efficiency typical of bulk microphysics models.

RAMS microphysics lookup tables for activation of cloud condensation nuclei (CCN), giant CCN (GCCN), and ice nuclei (IN) were implemented in OLAM for this project, enabling OLAM to simulate the impact of prognosed aerosols on microphysical processes. Initially, aerosol chemistry was assumed to be ammonium sulfate or sodium chloride, but subsequently we began implementation of a much more general approach that accommodates a superposition of many aerosol species and represents their competition for water vapor during the nucleation process using the bin approach. This effort was not originally proposed, but in the course of the project was realized to be superior to our original method. This approach will be completed subsequently to this project.

One additional technical development that was performed in the first phase of this project was to restructure the OLAM microphysics model so that it could store a time series of every hydrometeor property, including mass, temperature, and number concentration, as well as its conversion rate to or from other forms of water for each individual microphysical process each timestep of a simulation. Given that this constitutes an enormous amount of information, it was configured for only a single atmospheric volume (e.g. a single grid cell) and intended for situations where that volume is simulated as a Lagrangian parcel. Time-series plots of each of these quantities, numbering over 200, provide an invaluable tool for testing and evaluating the microphysics model.

In the second phase of the project, we completed OLAM simulations for two field experiment cases. The first case corresponds to The Tropical Warm Pool—International Cloud Experiment (TWP-ICE), which was conducted in January–February 2006 in Darwin during the northern

Australian monsoon season by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement Program (ARM) and the Australian Bureau of Meteorology (BOM). The second case corresponds to a wintertime orographic mixed-phase cloud that occured 11-12 Feb 2007 in Colorado, which was documented in a previous study (Saleeby et al., 2009). These contrasting cases were selected to test the upgraded CSU bulk microphysics parameterization, which was installed in OLAM as the first phase of this project, in diverse environments. Based on these simulations, we prepared a draft paper for publication entitled "Evaluation of Tropical and Wintertime Orographic Precipitation in an Upgraded Bulk Microphysics Scheme" (see separate attachment). However, while discussing and further analyzing these results, we determined that both simulations should be re-run with the highest resolution region of the variable-resolution OLAM grid expanded to larger geographic area. In particular for the tropical convection regime of the TWP-ICE experiment, we considered it especially important that convective systems be able to initiate and progress through all stages of development while residing entirely within the most refined region of the grid. Through this choice, the tropical convective systems would be governed by resolved dynamics and the upgraded bulk microphysics parameterization, with no contribution from sub-grid convective parameterization. We thus postponed completion of the paper pending the new simulation results and analysis.

During these efforts under separate funding, we completed major improvements of the OLAM model. Most significant among these was the implementation of a hexagonal grid option, where previously only a triangular mesh was available. Numerous tests demonstrated that the hexagon grid (and the specific numerical discretization methods that accompany it) performs better than the triangle grid, and we began using hexagonal grid cells for virtually every application. Accordingly, we made the decision that although the original simulations for this project were performed with the triangular mesh, re-runs of both cases would employ the hexagonal grid, in addition to being at higher resolution.

Simulations of the TWP-ICE case were carried out on the hexagonal grid using a grid cell size of 100 km over most of the globe. Resolution was progressively doubled at radial distances of 3000, 2000, 1000, 800, 600, and 400 km from the TWP_ICE field experiment site, culminating in a grid spacing of 1.6 km over a circular area 800 km in diameter and centered on the site. Convective parameterization was activated in the coarsest resolution regions of the grid with grid cell sizes of 100, 50, 25, and 12.5 km, while it was switched off in the regions with 6.4, 3.2, and 1.6 km grid cell sizes. Selective use of convective parameterization is standard practice in nested grid models whose grids transition between areas that resolve convection to those that do not. It is well known that grid spacings of 5 or 10 km are too coarse to adequately resolve convective updrafts and too fine to fit the conceptual models on which the parameterizations are based. Therefore, the portions of the OLAM grid whose resolution is in that range do not have adequate representation of convection, and the choice of whether or not to activate convective parameterization there is challenging. In a simulation like the TWP-ICE case, this shortcoming can be mitigated by making the 1.6 km grid region very much larger than the focus region (the field site) so that the intermediate-sized grid cells are less influential on the results there. This is one of the main reasons for choosing the large extent of this region.

Figure 1 shows accumulated precipitation over a 24-hour period ending at 00 UTC on 19 January 2006 for a 2000 km x 2000 km area that is centered on the field site. It is immediately apparent that the precipitation amount and distribution pattern changes between the inner region where convective parameterization is switched off, that is, within a radius of 800 km of the center of the plot, and the outer region where convective parameterization is allowed to operate. In the inner region, narrow bands of higher precipitation are interspersed with paths that received much less precipitation or none at all. The precipitation bands were produced by convective cells that moved toward the east-southeast, and these systems were reasonably well resolved on the model grid, as seen in Figure 2 which zooms in on the center of the region depicted in Figure 1 and adds a grid overlay. Outside the radius of 800 km, precipitation is sharply higher. It is evident that the convective parameterization is a much more active producer of precipitation than the microphysics parameterization with well resolved convective dynamics. Figures 3 and 4 show individual contributions from convective parameterization and microphysics to the total precipitation shown in Figure 1. Precipitation from convective parameterization is especially heavy on the southeastern side of the central region, which is immediately downwind of the region where only microphysics is producing precipitation. The convective parameterization, being tuned to treat that environment as more highly convective than the model's own resolved dynamics and microphysics machinery, abruptly extracts more moisture from the air. By the same mechanism, the western and northwestern side of the 800 km radius circle are upwind, and air passes first through the zone where convective parameterization is allowed to operate and then into the central high resolution part of the grid where parameterized convection is switched off. The parameterization upwind has been excessive in its removal of moisture and convective energy from the air, leading to a rain shadow in the inner region, as seen in both Figures 1 and 3, and the rain shadow extends for hundreds of kilometers downwind toward the center of the plot.

The rain shadow effect is particularly troubling because it is a purely numerical artifact caused by a mismatch in the behavior of parameterized and resolved convection in the model. Even though we configured a convection-resolving region of the grid that was far larger than the TWP-ICE field site and large enough to accommodate convective systems through their life cycles, the presence of the convective parameterization hundreds of kilometers away was projected much closer to the site. We considered this phenomenon to be highly important, not only for its impact on this project, but to modeling by the community in general because grid nesting or variable-resolution grids that transition from grid-resolved to parameterized convection are very commonly used. We therefore chose to temporarily divert our efforts to further investigating this problem and finding remedies to correct it, or to at least reduce its severity.

To that end, we implemented 4 convective parameterizations in OLAM (commonly named Grell, Grell-Freitas, Tiedtke, and Emanuel), and tested and compared them alongside the Kain-Fritsch parameterization that was already in OLAM and was used for the simulations described above. The comparisons showed that the Kain-Fritsch parameterization was one of the most active, and the Tiedtke parameterization was the least active for most environments. This difference is illustrated for the TWP-ICE simulation by comparing Figures 1, 3, and 4 with their counterparts, Figures 5, 6, and 7, which were produced using the Tiedtke convective parameterization. Convective precipitation is much less with Tiedtke (Figure 6; notice the nonlinear precipitation scale) and the rain shadow effect is much weaker and less extensive (Figures 5 and 7). In addition, precipitation amounts are generally higher in the southeastern quarter of the inner 800 km diameter circle, showing that the difference in activity of the convective parameterizations has an impact hundreds of kilometers downwind.

While comparing convective parameterizations for the TWP-ICE experiment, we also evaluated them in lower resolution simulations that required convective parameterization to be used in all grid cells. Most of these cases were run for 6-year periods to examine mean global precipitation patterns and compare them against GPCP precipitation climatology. We found that while the Tiedtke scheme performed the best for the TWP-ICE case, it was not the best overall globally. Its main advantage for TWP-ICE is that it is about equally responsive to convectively-unstable environments as resolved dynamics and microphysics, so it is more suitable than other schemes for variable resolution grids where it can be selectively turned off in high resolution regions. We also compared two different PBL turbulence parameterizations with each of the convective parameterizations, with very significant differences found in precipitation patterns. The interaction between PBL and convective parameterizations proved to be highly important, particularly because convective parameterizations are highly sensitive to conditions in the PBL.

Besides comparing precipitation results for the different convective and PBL turbulence parameterizations, we examined surface and top-of-atmosphere radiative fluxes in each case, finding that some of them, particularly shortwave fluxes, are sensitive to choice of parameterization. Comparison with CERES radiative flux climatologies has helped to evaluate each parameterization. The microphysics upgrades applied in the first phase of this project included radiative properties of the newly-added prognostic aerosols and the drizzle hydrometeor category, and these properties were initially applied to the Harrington radiation scheme used in both RAMS and OLAM. During the later phase of this project, we implemented the more sophisticated RRTMg radiation parameterization in OLAM while applying the same radiative properties from the microphysics model. Examination of precipitation, radiation, and other results was then extended to comparisons between Harrington and RRTMg parameterizations, with the general conclusion that RRTMg gives more accurate results for most fields in most cases.

As we are submitting this final report, we are preparing a highly-revised version of our original manuscript for publication. In addition, we are preparing a second paper that summarizes our investigation of the rain shadow effect and other numerical problems that arise when variable-resolution model grids, though highly useful tools, transition from convection resolving regions to coarser resolution where convection must be parameterized as a sub-grid scale phenomenon. Unfortunately, the diversion of this research project into the investigation of convection issues and the comparison of convective and PBL schemes has delayed preparation of these publications, but as we argued above, this is a highly important topic that we believed needed to be investigated and better understood before proceeding with the simulations. It was clear that the rain shadow effect was a numerical artifact that was impacting the model solution. Copies of these papers will be appended to this report at the time they are submitted for publication.

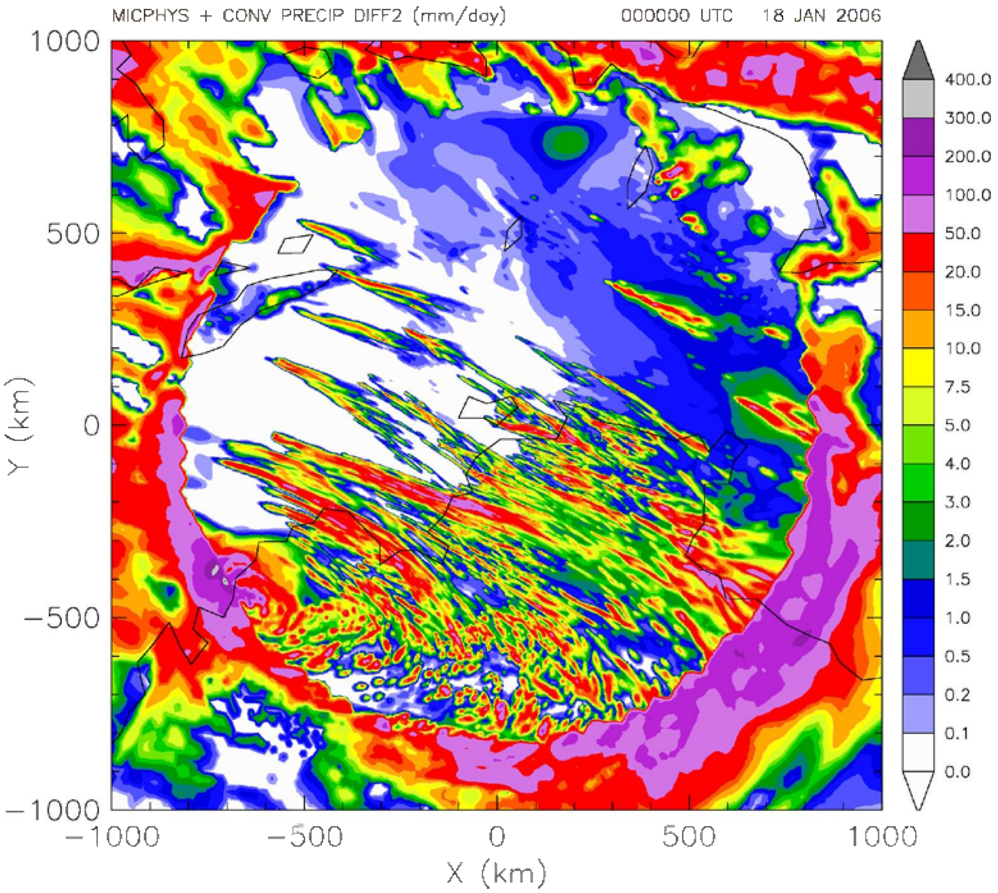

Figure 1. Combined microphysics and convective precipitation with Kain-Fritsch parameterization.

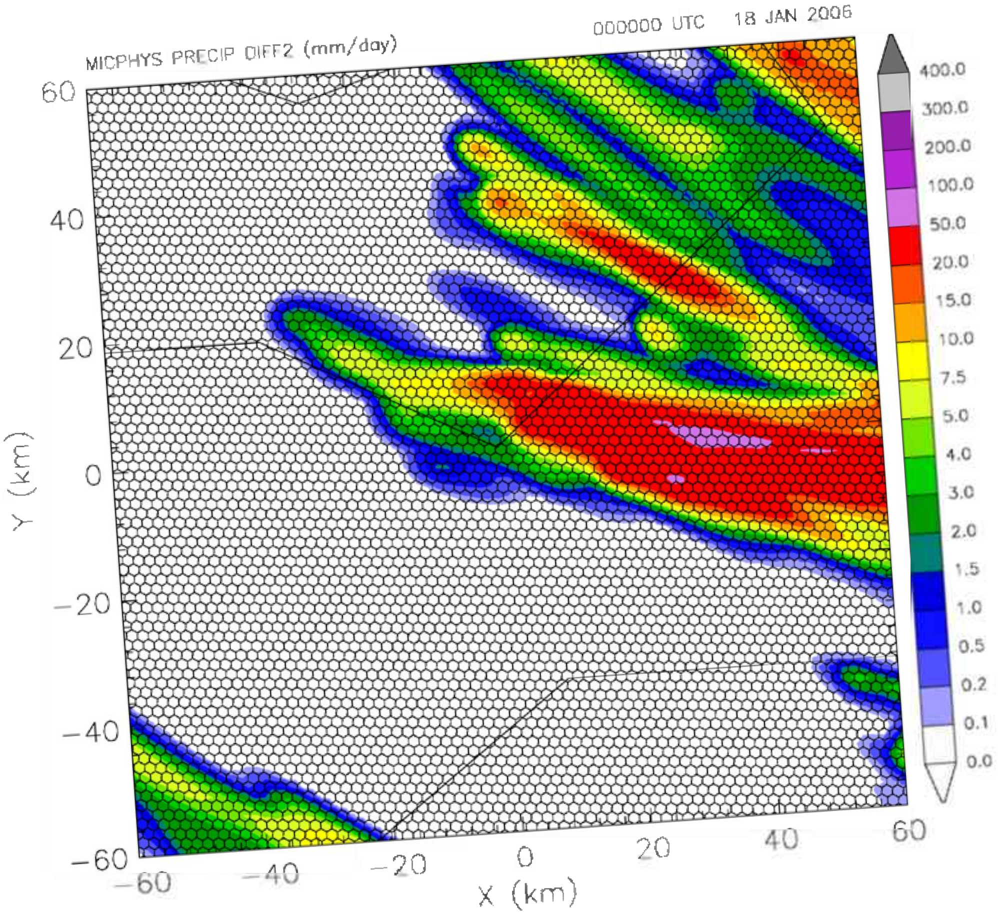

Figure 2. Microphysics precipitation with Kain-Fritsch parameterization used outside region shown.

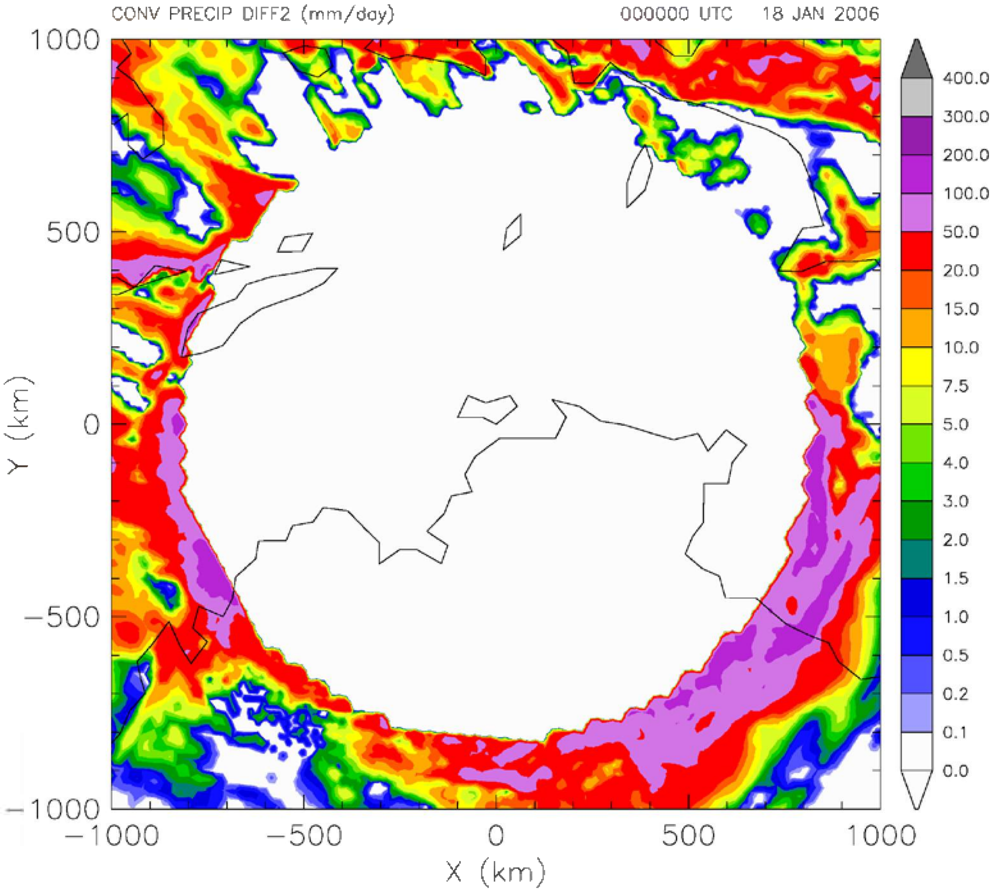

Figure 3. Convective-only component of precipitation with Kain-Fritsch parameterization.

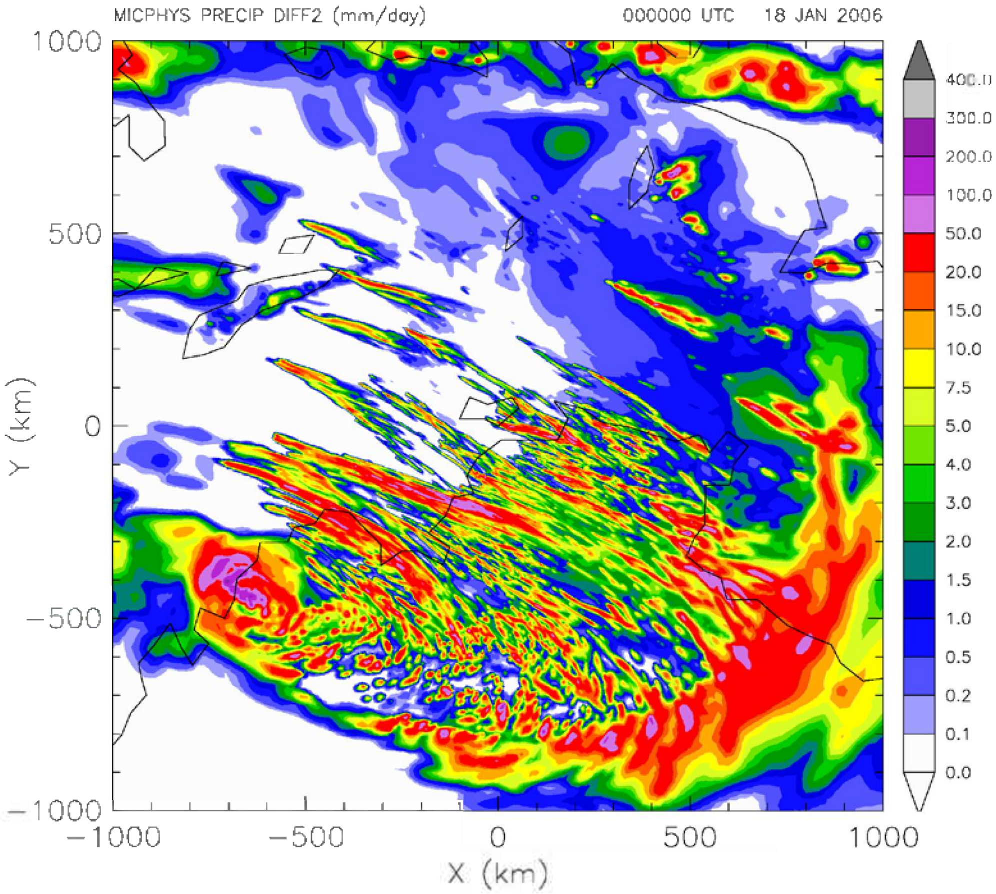

Figure 4. Microphysics-only component of precipitation with Kain-Fritsch parameterization.

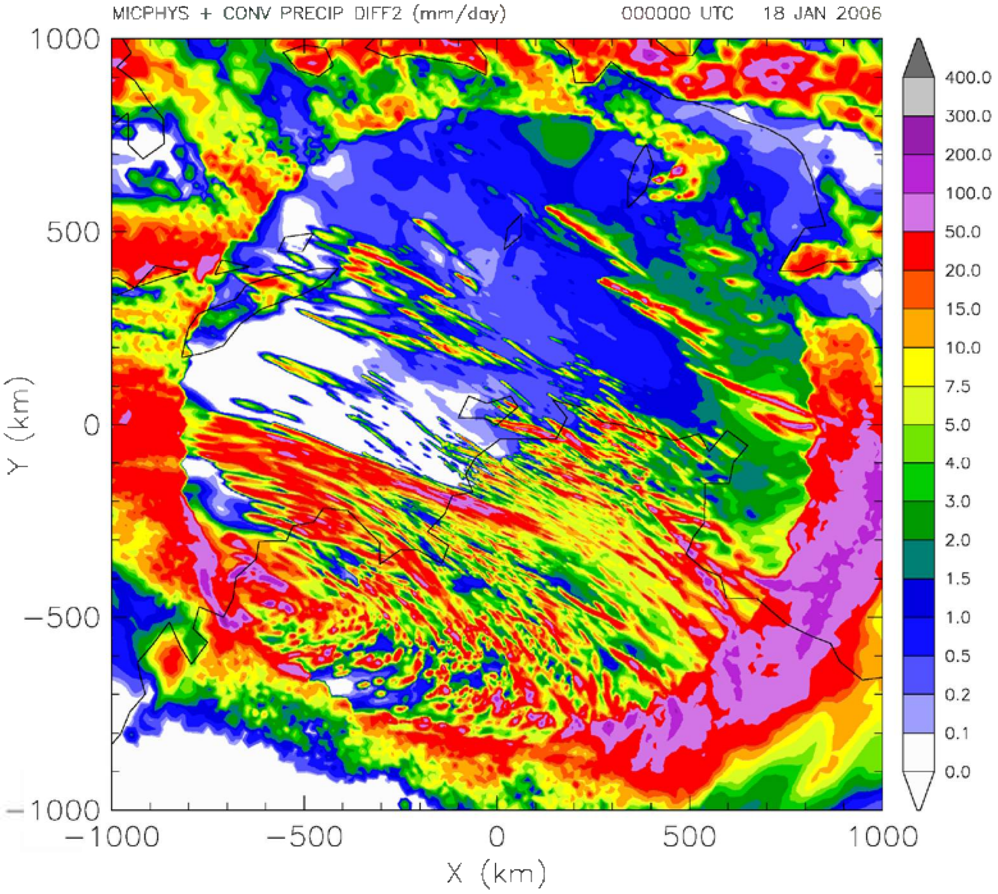

Figure 5. Combined microphysics and convective precipitation with Tiedtke parameterization.

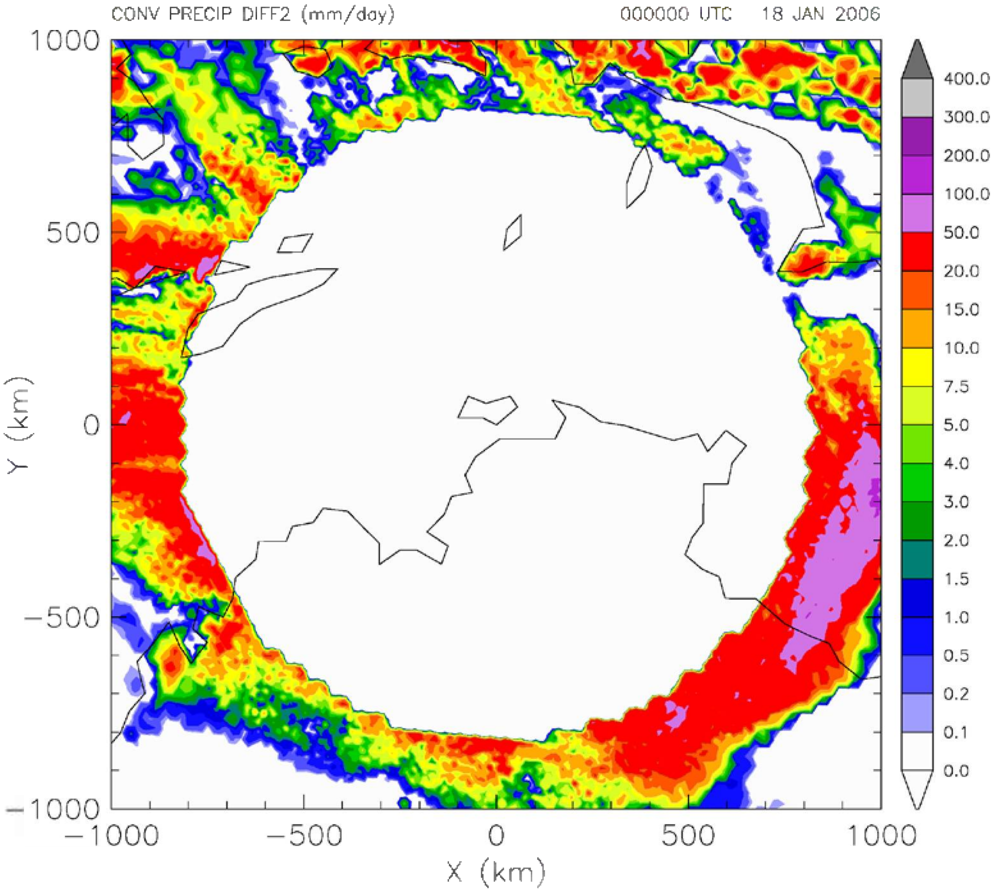

Figure 6. Convective-only component of precipitation with Tiedtke parameterization.

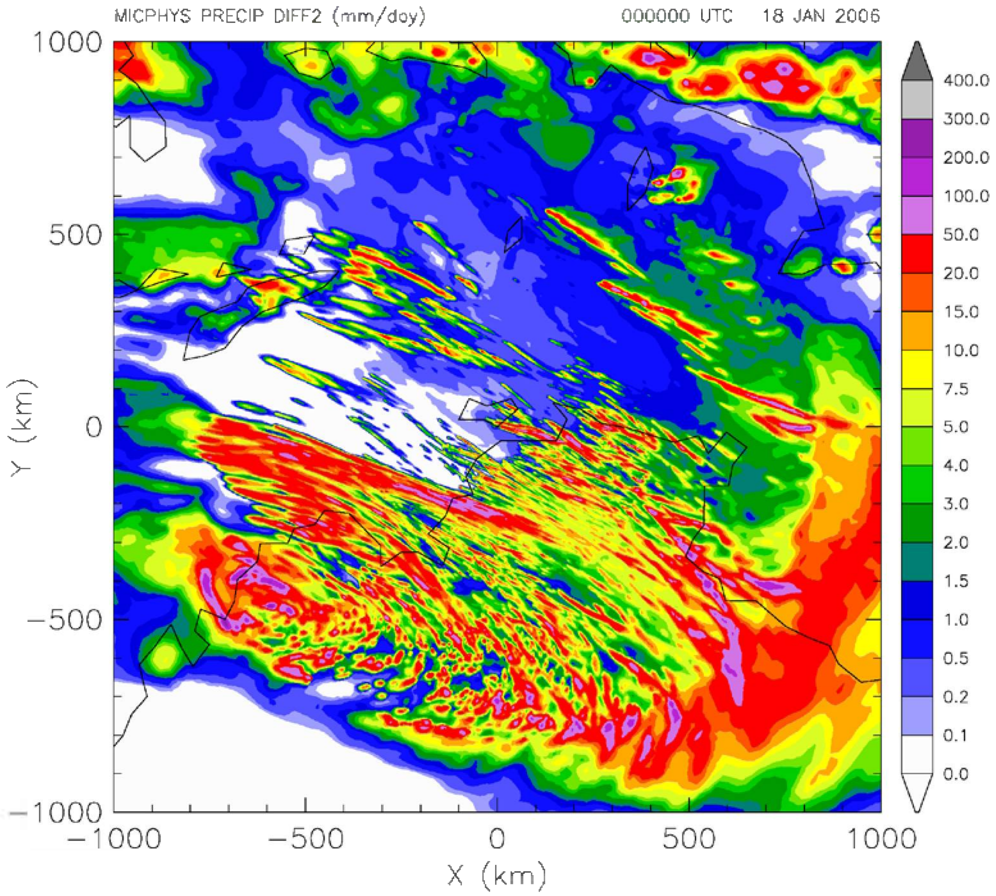

Figure 7. Microphysics-only component of precipitation with Tiedtke parameterization.