High Resolution Modeling of Cloud Fields at the TWP Site with MM5

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Introduction

The advent of powerful computers has enabled atmospheric scientists to run weather forecast and climate models at ever increasing resolutions. Of particular interest are limited area models with high temporal and spatial resolution that can be run affordably on workstations. These models, initialized and forced at the boundaries with data from large-scale models with coarse resolution, resolve fine-scale features in the interior, a process generally known as dynamical downscaling (e.g., Murphy 1999). However, the success of a high-resolution simulation depends on a number of factors such as the coupling at the boundaries or the representation of physical processes. These processes are treated differently at different resolutions; convection, for example, is parameterized at coarse resolution but cumulus clouds are explicitly resolved at finer scales. Furthermore, the values of model parameters may be optimal at certain scales but inappropriate at others. The selection of the right combination of parameterizations is therefore a difficult task in complex numerical models of the atmosphere.

Our main objective in this paper is to study the capabilities of the Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) mesoscale model (MM5) for regional climate simulations. We are also interested in the generation of realistic three-dimensional (3-D) distributions of clouds for separate studies with a 3-D radiative transfer model. The comparison of simulations and data collected at the Atmospheric Radiation Measurement (ARM) Tropical Western Pacific (TWP) site during the Intensive Operational Period (IOP) Nauru99 allows us to estimate the skills of MM5. In addition to traditional comparisons of mesoscale models that concentrate on the skills for precipitation or 2-m temperature, we will also study the distribution of radiatively important components of the atmosphere-like clouds. In a first stage, comparisons are restricted to data from the Nauru site, but they can later be extended to include data from shipborne instruments operated during Nauru99.

Model Setup

The PSU/NCAR mesoscale model MM5 is a non-hydrostatic limited area nested grid model used for operational weather forecasting and research purposes. The main characteristics of MM5 are described in Grell et al. (1995). For this study, we use the most recent version 3.3 of the model. The setup of the model and the selected major parameterization are listed in Table 1. The three domains are centered in

Table 1. Model setup.

	Domain 1	Domain 2	Domain 3
Grid Size	44×44	64×64	115×115
Resolution	27 km	9 km	3 km
Time Step	90 s	30 s	10 s
Convection	Grell (1993)	Explicit	Explicit
Boundary Layer	MRF (Hong and Pan 1996)		
Microphysics	Schultz (1995) / Reisner et al. (1998) / GSFC (Tao and Simpson 1993)		
Radiation	CCM2 (Kiehl et al. 1994), updated every 30 minutes		
Vertical Setup	σ-coordinate system, 23 layers, rigid lid at 50 hPa		

CCM2 = Version 2 of the NCAR Community Climate Model.

GSFC = Goddard Space Flight Center.

MRF = Medium-Range Forecast Model.

the vicinity of the TWP site at Nauru with the largest domain covering roughly 5°×5°. They are nested in a two-way mode so that information is passed from the coarse to the fine as well as from the fine to the coarse domains. Three different microphysical schemes have been tested (Table 1), but for each run the microphysics were the same in all domains. All of the microphysical schemes deal explicitly with five different water species in addition to water vapor: cloud water, rain, cloud ice, snow, and graupel. The model is initialized at 00Z on June 15, 1999, and each simulation extends over 10 days. All statistical quantities are evaluated over the last 9 days only to allow the model to spin-up. To explore the effects of fine resolution, the model was run with all three or with only the 27-km and 9-km domains. Initial and boundary conditions are taken from National Center of Environmental Prediction (NCEP) reanalysis with boundary conditions updated every 6 hours. The results are saved every 3 hours for domains 1 and 2 and every hour for domain 3. Vertical profiles are extracted from these saved results in the nearest gridpoint relative to Nauru.

Comparison Against Satellite Observations

The model results of the 27-km domain are compared against Geostationary Meteorological Satellite (GMS)-5 images, where the 5-km satellite images have been resampled at 25 km. The cloud cover of MM5 is defined as the fraction of gridpoints where cloud water exceeds 5 g/m^2. The GMS visible albedo is converted to cloud cover by dividing all pixels with albedo exceeding 20% by the total number of pixels in the area under consideration. Figure 1 compares the cloud cover of the model against satellite observation. Agreement is poor if the cloud cover of GMS is evaluated in an area of equal size as the model's domain 1. This is not too surprising because the area covered by domain 1 is comparable to the scale of cloud systems in the Western Pacific and the cloud cover is highly sensitive to the location of the domain. A slight displacement of the boundary can have a large effect upon the derived

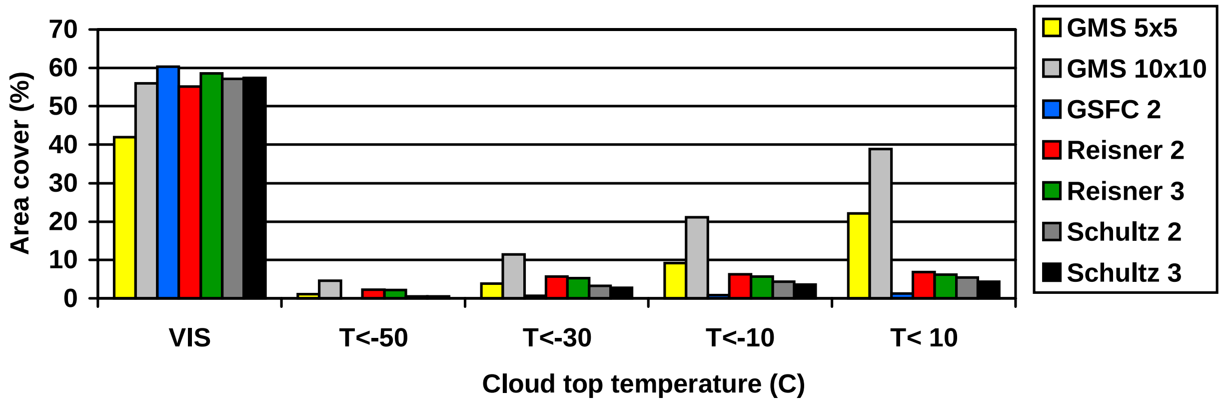

Figure 1. Cloud cover comparison between MM5 in domain 1 and GMS-5, visible and infrared (IR) channels. GMS cloudiness is evaluated in 5°×5° and 10°×10° domains. The different model runs are identified by their microphysical scheme, the number denotes the number of domains used in the simulation, for example, "Schultz 2" is a run with Schultz' microphysics with the 27-km and 9-km domains.

cloud cover. A better agreement is achieved if the area of the satellite image is extended to cover about four times the size of domain 1. The larger area is more representative for climatological values at the cost of reduced variability.

A disadvantage of the comparison with the visible GMS channel is the restriction to daylight hours. Using the 10.8-μm IR channel provides information about the brightness temperature that can be compared to the temperature of the uppermost cloud layer. Figure 1 compares the fraction of pixels with a cloud top temperature below a given threshold. The area with lower brightness temperatures is consistently smaller in MM5 than in the satellite image. We can conclude that the model underestimates the cloud altitude, the occurrence of high clouds, or both from the fact that visible cloud cover of MM5 is in fair agreement with observations and the brightness temperature is too high. However, these results have to be taken cautiously as satellite images and MM5 fields are snapshots with at least 3 hours between two consecutive images, providing a very small amount of data for statistical comparison over the 10-day integration period. Furthermore, the limited size of the model domain does impose some restrictions on the finding.

Comparison Against Upper Air Observations

The frequency of radio soundings from Nauru was 6 hours during the first 7 days of integration and 3 hours thereafter. These upper air observations (BBSS) were compared against profiles extracted from MM5 at the nearest gridpoint approximately 30 minutes after the radiosonde has been released. Note that the location of the nearest gridpoint is different for the 3-km and the 9-km domain. No correction has been applied for the ascending time and the lateral drift of the sonde. In order to compare model against soundings, the observational data was averaged across each model layer. The difference between these observational profiles and the simulation is shown in Figure 2. It seems that neither the different microphysical schemes nor the variation of the resolution have much impact on results. There are, however, a few systematic differences between model results and observation. The model generally

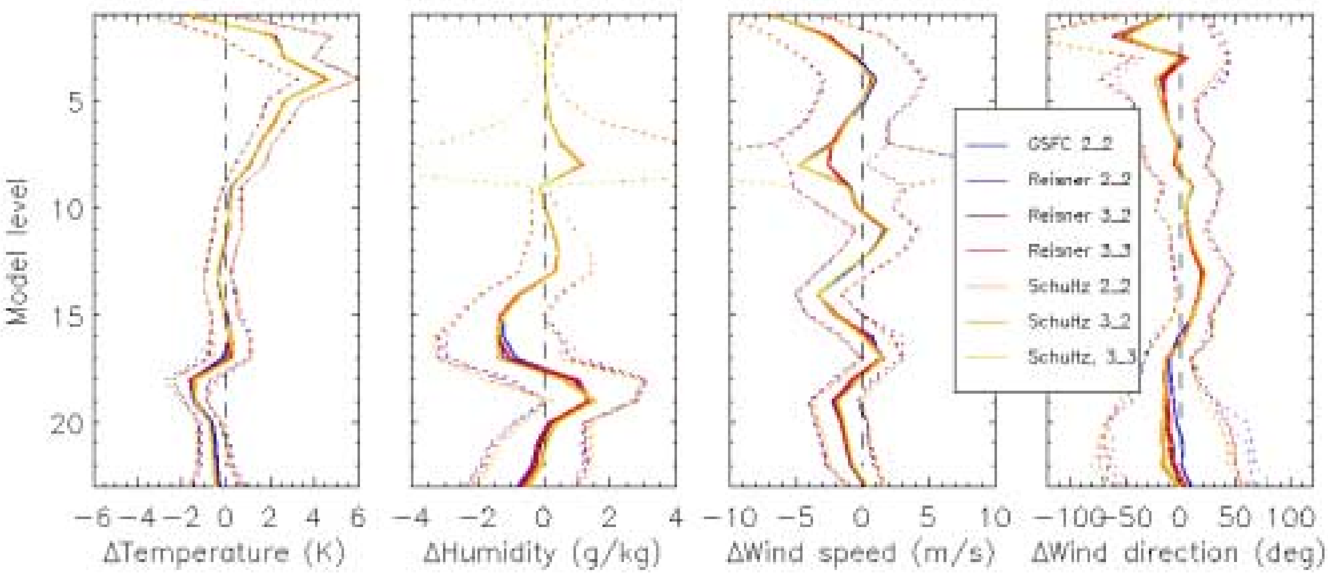

Figure 2. Averaged difference between MM5 profile in nearest gridpoint and the radiosounding (BBSS) from Nauru. The different runs are identified by the name of the microphysical scheme, followed by the number of domains in the simulation and the resolution at which the variable is evaluated; for example, "Schultz 3_2" is a run with the Schultz scheme and all three domains but the variable is evaluated on the 9-km grid.

overestimates the tropopause temperature and underestimates the temperature at the top of the boundary layer. Furthermore, there seems to be a slight excess of humidity in the upper part of the boundary layer just adjacent to a too dry region in the lower troposphere. It is possible that this finding is related to the underestimated cloud altitude—a possible explanation would be a too weak transport across the boundary layer top. The wind is in fair agreement with observational data even though the difference of the wind speed fluctuates throughout the atmosphere, but nowhere does the mean difference exceed 4 m/s except in the vicinity of the tropopause. The wind direction is well modeled on the average, but the standard deviation is high in the boundary layer.

Comparison Against Surface Observations

Observations of pressure, temperature, and humidity at Nauru (SMET) are compared against model results at the nearest gridpoint (Figure 3). The simulated surface (SFC) pressure does exceed the observed, but it shows similar 12-hour fluctuations although the amplitude is not large enough in the model. The SFC temperature of MM5 is obtained by adjusting adiabatically the temperature from the middle of the lowest layer (approximately 35 m above ground) to SFC pressure. Figure 3 illustrates that the average SFC temperature is fairly well reproduced while the diurnal variation is largely under-estimated by the model. Part of this may be due to the method of computing SFC temperature from the air temperature alone, not taking into account the effects from ground heating or cooling. Another explanation may be the prescribed SST that largely determines the temperature of the lowest model layer. In general, there is little difference in SFC temperature between the various model configurations

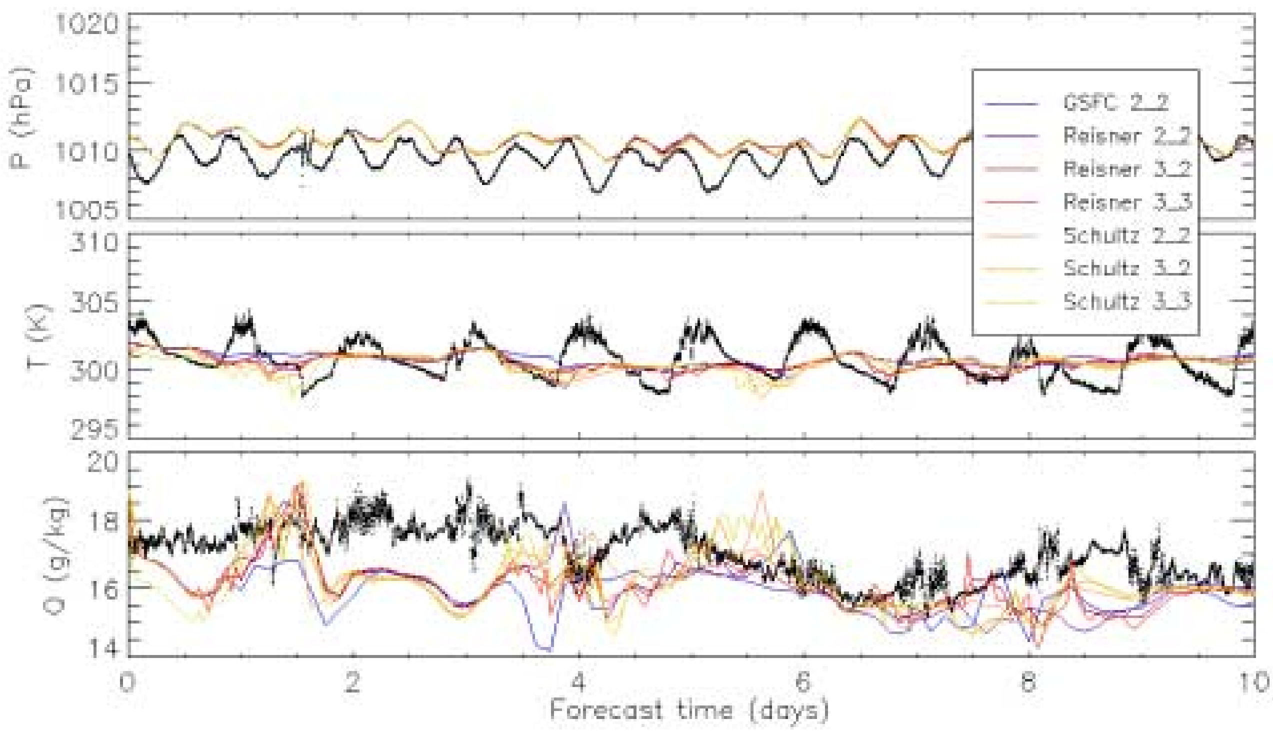

Figure 3. Time series of SFC observations (black dots) and MM5 variables at nearest gridpoint, same naming convention as in Figure 2.

except for nights during which some of the runs are colder. However, the model runs whose SFC temperature is colder during the night are not always the same and the different model configurations do not lead to systematic differences.

Differences in humidity between MM5 and observation become apparent in Figure 3. The simulated specific humidity of the lowest layer is compared to the specific humidity derived from reported SFC air and water vapor pressure. The observations show a relatively high level of humidity in the beginning, followed by a dry period culminating during day 7 of the integration and a slightly wetter phase thereafter. The observed specific humidity is not characterized by a diurnal cycle, instead, the time-scale of the strongest fluctuation is several days. MM5, on the other hand, seems to linger around a more or less constant humidity level, interrupted only for isolated periods of about 24 hours in length with increased humidity. The transition from a humid state in the beginning to a drier state later in the integration is not captured at all by the model. Unlike in the case of temperature and pressure, the differences between model configurations has a larger impact on the specific humidity of the lowest layer, but these differences do not seem to be systematic in nature.

The average values and variances of SFC pressure, temperature, and specific humidity are listed in Table 2 and support the notion that MM5 captures the mean values of pressure and temperature reasonably well but underestimates their variability. In contrast, the mean humidity is slightly too low in the model but its variability is reasonable. The humidity bias is certainly related to the fact that the

Table 2. Observations from SMET and model results of surface variables at Nauru; the first number is the mean value followed by the variance. The same naming convention as in Figure 2 is used.

	Pressure (hPa)		Temperature (K)		Specific Humidity (g/kg)	
Obs	1009.5	99.9	300.7	1.9	17.0	6.4E-4
GSFC 2_2	1010.6	45.9	300.7	0.2	15.9	4.4E-4
Reisner 2_2	1010.6	46.0	300.5	0.2	16.0	7.0E-4
Reisner 3_2	1010.6	46.8	300.4	0.3	16.1	4.9E-4
Reisner 3_3	1010.6	37.9	300.4	0.3	16.1	5.5E-4
Schultz 2_2	1010.6	44.9	300.5	0.4	16.2	7.2E-4
Schultz 3_2	1010.6	46.7	300.4	0.4	16.2	7.1E-4
Schultz 3_3	1010.6	39.1	300.3	0.5	16.2	8.7E-4

model humidity is representative for the lowest layer (70 m) while the observation is from the SFC. However, this cannot explain the absence of the variation with a multi-day timescale in the model.

Besides comparing standard meteorological variables, we take advantage of some of the additional observations collected by the Atmospheric Radiation and Cloud Station (ARCS-2) in Nauru. The microwave radiometer (MWR) provides information about vertically integrated humidity (Q_{tot}) and cloud water (LWP). Radiometers measure broadband downwelling shortwave (SW) and longwave (LW) radiation (SKYRAD) that can be compared to the output of the radiation scheme in MM5. Finally, information about clouds is derived from Vaisala ceilometer data (VCEIL). The cloud frequency is computed as the fraction of data points with lowest cloud base reported between 0 km and 10 km. The mean cloud base altitude is then found by averaging the observed cloud base in these points. The time-averaged values of all these variables together with their respective counterparts from the various model runs are listed in Table 3. MM5 underestimates Q_{tot} irrespective of the microphysical scheme employed, but the inter-model differences are small. In contrast, cloud water varies widely depending on the microphysics, but all values are still lower than the observed average. This large spread between models manifests itself also in the differences in cloud base. The different micro-physical schemes control not only where and when clouds form but, equally important, how they disappear by either generating precipitation or evaporating. These processes affect the distribution of humidity and the subsequent formation of new clouds. This feedback between humidity and clouds accentuates the difference between the various microphysical schemes that only become apparent in longer model runs. Despite the differences in cloud water and base altitude, the modeled frequency of cloud occurrence is similar to observations. The lowest cloudiness is found when the model is evaluated in the 3-km domain. In both runs with a 3-km domain, the frequency of clouds gets considerably higher if evaluated on the 9-km grid instead. One may conclude that cloudiness is strongly affected by the horizontal resolution of the model, and a more thorough exploration of cloudiness and its definition is required.

Table 3. As Table 2 but for observations with MWR (Q_{tot} and LWP), SKYRAD (SW_{down} and LW_{down}), and VCEIL (cloud base and frequency of occurrence); only the mean values are listed. The average cloud base altitude has been calculated for cloudy conditions only, see text.

	Q_{tot} (kg/m^2)	LWP (g/m^2)	SW_{down} (W/m^2)	LW_{down} (W/m^2)	Cloud Base (m)	Cloud Frequency (%)
Obs	47.7	140.2	212.8	415.1	1350	27
GSFC 2_2	43.4	63.4	263.2	409.8	1078	38
Reisner 2_2	43.2	43.2	237.7	419.5	905	36
Reisner 3_2	43.2	23.3	280.9	409.8	839	39
Reisner 3_3	43.2	23.6	269.0	411.4	671	22
Schultz 2_2	43.2	38.7	213.7	420.5	811	37
Schultz 3_2	42.9	14.3	257.6	411.7	751	37
Schultz 3_3	42.9	11.9	242.3	401.1	822	16

The differences in humidity and cloud water have an impact on the radiation. The model overestimates SW reaching the ground while LW agrees more favorably. The excess SW radiation is possibly linked to the generally underestimated cloud water amount, but further analysis is required.

Conclusions and Outlook

MM5 simulates the mean state of the atmosphere reasonably well, but fails to reproduce the observed variability. Further investigation is necessary to determine whether this is due to the prescribed SST or whether the limited domain size ties the interior of the domain too tightly to the prescribed boundaries. Another issue is how suitable the employed parameterizations are at the scales used for the present simulations. Re-tuning some of the parameters (or even replacing some of the parameterizations) may be required to properly represent some sub-grid scale processes. The different microphysical parameterizations did not change the general behavior of the model simulation in what concerns pressure, temperature, and even cloud cover, but it affected the distribution of cloud water and radiation.

Despite the fair agreement in visible cloud cover between MM5 and observation, model-predicted cloud top temperatures are too high, and thus, the cloud tops are probably too low. This finding is in agreement with the too low cloud base altitude in comparison with ceilometer observations. It is possible that the boundary layer scheme is responsible for a pile-up of water vapor in the boundary layer that results in too many low and not enough middle and high clouds. A clearer picture of MM5's skills to represent clouds will emerge once the comparison is extended to include the millimeter cloud radar (MMCR) and micropulse lidar (MPL).

Adding finer domains in the interior, even with two-way nesting, has only a minor impact on pressure, temperature, and humidity. The addition of finer domains does not notably improve the model's skills. As stated above, this may be related to the choice of parameterizations. Careful modifications may improve the model performance with high resolution interior domains.

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