Time Scales of Hydrometeor Development Simulated in a Bin Microphysics Model Show the Marshall Palmer Parameterization is Consistent with Observations

G. J. Kooperman,[1] et al.[2]

Abstract. The resolution of global climate models (GCMs), and even many cloud-resolving models (CRMs), is not high enough to simulate the large range of spatiotemporal scales over which cloud processes occur. The very small-scale processes of cloud condensation nuclei activation, condensation, and collision-coalescence, are sub-grid and must be parameterized. The Marshall Palmer (MP) parameterization of hydrometeor size distribution is one such parameterization widely used in a range of model types including: CRMs, GCMs, and multi-scale modeling frameworks. The MP parameterization is evaluated here using a bin microphysics model, which simulates the evolution of the droplet size distribution in a rising air parcel under warm cloud conditions. The primary metric of evaluation is time scale; it is examined whether the time required to grow droplets from dry aerosol to rain is consistent with observed cloud lifetimes. It is shown that the hydrometeor concentration described by the MP parameterization develops in a realistic timeframe, but the size distribution is quite different from that developed in the bin microphysics model. These results are discussed in light of the limitations they imply for global-scale simulations.

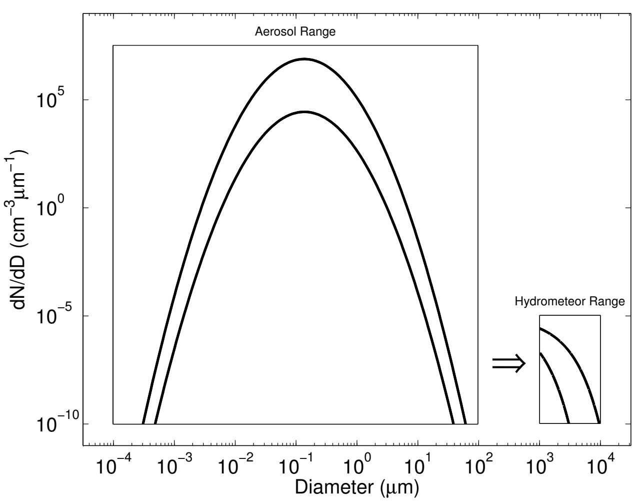

Figure 1. This figure shows the number concentration size distribution ranges for dry aerosols and hydrometeors. Both axes are in log scale indicating the large range over which these particles are spread. The aerosol range is from Hoppel et al. (1990) and the hydrometeor concentration has been calculated from the MP parameterization.

1. Introduction

Clouds currently represent one of the largest sources of uncertainty in climate science. How clouds will be affected by climate change and changes in anthropogenic aerosol is difficult to predict and is the topic of much debate (Solomon et al. 2007). How precipitation will be affected by these changes is even more uncertain and no conclusive results were presented in the 2007 IPCC report. Much of the discrepancies in model simulations of the global temperature trend presented by the IPCC are due to these uncertainties and deficits in understanding. This is because cloud processes occur on scales from micrometers to hundreds of kilometers and, given our current computational capacity, it is not possible to simulate all scales in a single model. Even in cloud-resolving models (CRMs), which run at 10 to 100 times the resolution of global climate models (GCMs), many processes including: cloud condensation nuclei (CCN) activation, condensation, and collision-coalescence, are sub-grid and must be parameterized. One parameterization used in GCMs, CRMs, and a combination multi-scale modeling framework (MMF), is the Marshall Palmer (MP) parameterization of hydrometeor size distribution. The MP parameterization is useful for all types of hydrometeors including rain, snow and graupel and its realism is evaluated here against a bin microphysics model, which simulates the evolution of the droplet size distribution in a rising air parcel under warm cloud conditions (only rain is evaluated here). It is examined whether the time required to grow droplets from dry aerosol to the MP calculated concentration of raindrops is consistent with observed cloud lifetimes. In addition to timeframe, we consider how well the MP size distribution matches the bin microphysics size distribution.

2. Background

2.1. Particle Growth

Particle growth in warm clouds, from suspended aerosol to precipitation, involves many complex processes including heterogeneous nucleation, diffusion, condensation, CCN activation, coagulation, and collision-coalescence (Seinfeld

[2]This work was completed by G. J. Kooperman as part of SIO217d term projects created and advised by Lynn Russell, using a model created by Grabowski and Wang (2009), with programming help from Piotr Flatau and writing help from anonymous reviewers. The submitted work is not yet suitable for citation. Please contact G. J. Kooperman, Scripps Institution of Oceanography, UC San Diego, 9500 Gilman Drive Dept. 0224, La Jolla, CA 92093-0224, gkooperm@ucsd.edu to receive an update on these results.

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and Pandis 2006). The main focus here is the evolution of the droplet number concentration and examining how well rooted the MP parameterization is in these physical processes. Particles transitioning from aerosols to rain droplets under go an enormous change in scale, as shown in Figure 1. The main process for transitioning the number concentration of aerosols to cloud droplets is CCN activation and growth by diffusion as defined by Köhler theory. The number of activated particles that grow into cloud droplets depends on the chemistry and size distribution of the particles, and the supersaturation of the surrounding environment (Seinfeld and Pandis 2006). The main process responsible for growing cloud droplets into rain droplets is collision-coalescence (Wang et al. 2006). In warm clouds, it is poorly understood how the observed rainfall rates develop as quickly as they do (Grabowski and Wang 2009). Here we use a model developed by Grabowski and Wang (2009) to simulate these processes in a rising air parcel. This model is described in detail below.

2.2. Marshall Palmer Parameterization

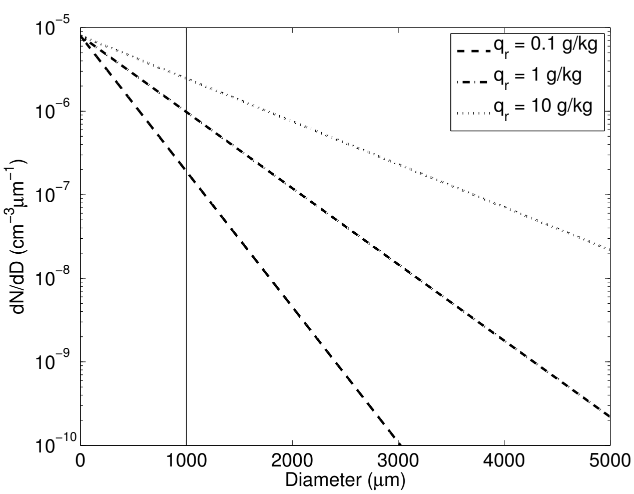

Figure 2. This figure shows the MP hydrometeor distribution as implemented in the MMF described below. It shows the change in number concentration as a function of hydrometeor diameter for three values of the rainwater mixing ratio q_r (Curic et al. 1997). It can be seen that the area under the curve and thus the total number concentration increases for increasing q_r. A cutoff line of 1 mm is shown, below this the parameterization does not match observation well (Marshall and Palmer 1948).

The MP parameterization was first introduced in 1948 and defines an empirical exponential hydrometeor size distribution, shown in Figure 2 (Marshall and Palmer 1948). The lines in Figure 2 follow the relationship:

$$\frac{dN}{dD} = N_0 e^{(-\Lambda D)}, \tag{1}$$

where Marshall and Palmer fit

$$\Lambda = 41 R^{-0.21} cm^{-1}, \tag{2}$$

and $N_0 = 0.08\ cm^{-4}$. D represents hydrometeor diameter, R represents rain rate, and N_0 is a y-intercept value. In its first introduction, shown here, the size distribution of rain droplets was defined as a function of rain rate and was shown to compare well to observations for rain rates ranging from 1 to 25 $mm\ hr^{-1}$. In more recent uses of the parameterization, the hydrometeor mixing ratio has become a more common input because it is a more regularly computed model variable (Curic et al. 1998; Khairoutdinov and Randall 2003). For each type of hydrometeor there is a constant y-intercept value that has been fit empirically to observations, we use the value for rain originally found by Marshall and Palmer (1948), which is discussed in detail below (Khairoutdinov and Randall 2003). While the simplicity of this distribution has made it widely used since it was first introduced, many other distributions, derived from general gamma or lognormal forms, are now used as well and are found to be more appropriate in cases where the droplet size relationship is more complex (Torres et al. 1994 and Williams et al. 2009).

2.3. Multi-Scale Modeling Framework

The motivation for this study comes from the use of the MP parameterization in an MMF developed by the Center for Multi-scale Modeling of Atmospheric Processes, however the results are applicable to many uses of the MP parameterization. This MMF approach uses a CRM nested in a host GCM to provide a link between small and large scale cloud processes. The resolution of most GCMs is on the order of hundreds of kilometers with bulk parameterizations replacing all microphysical processes. CRMs can be run on a range of spatial scales from hundreds to thousands of meters. In the implementation of the MMF considered in this study the CRM is the System for Atmospheric Modeling (SAM), which is nested in the Community Atmosphere Model, version three (CAM3). The SAM is implemented in two dimensions (zonal and height) with four kilometer grid spacing (Khairoutdinov et al. 2005). At this grid spacing all processes of particle growth are sub-grid and therefore parameterized. At each time step the model calculates the total water and partitions it into vapor, non-precipitating condensed water, and precipitating condensed water. The precipitating water mixing ratio is calculated using the Kessler formulation (Kessler 1995) and an assumed autoconversion threshold, after which it is further partitioned into rain, snow, or graupel (Khairoutdinov and Randall 2003). In the following analysis only warm cloud processes are considered, so it is assumed that all precipitation is in the form of rain.The hydrometeor distribution is then defined by the MP parameterization as a function of the rainwater mixing ratio and the local density of air (Marshall and Palmer 1948; Khairoutdinov and Randall 2003). In this study, we use the input values for the MP parameterization used in the SAM, but examine the results in light of any global-scale simulations.

3. Methods

In the MMF-SAM implementation, the MP parameterization is defined as a function of the local density of air and the rainwater mixing ratio and is given as

$$\frac{dN_r}{dD} = n_r(D_r) = N_{0r} exp(-\lambda_r D_r), \tag{3}$$

where

$$\lambda_r = \left(\frac{\pi \rho_r N_{0r}}{q_r \rho}\right)^{1/4}. \tag{4}$$

Both the rain water mixing ratio q_r and the local density of air ρ are dynamically adjusted with each time step, while the y-intercept parameter N_{0r} = 8 x $10^6\ m^{-4}$, the density of rain $\rho_r = 1000\ kg\ m^{-3}$, and the diameter of hydrometeors D_r (mm) are assumed constant (Khairoutdinov and Randall 2003). For simplicity, the density of air ρ in this study is assumed to be a reference density of 1.29 $kg\ m^{-3}$. The range of values chosen for q_r, from 0.1 to 10 $g\ kg^{-1}$, come from Curic et al. (1997) and represent values for a broad range of cloud types, $q_r = 1\ g\ kg^{-1}$ corresponds to a rain rate of 25 $mm\ hr^{-1}$ in the original form of the MP parameterization. Equation (3) can be integrated from 0 to infinity to give the total number concentration,

$$N_r = \frac{N_{0r}}{\lambda_r}. \quad (5)$$

Using values for the constants N_{0r}, ρ_r, and D_r from Khairoutdinov and Randall (2003), and the range of values of q_r, the range of N_r for rain is 2.1 to 6.8 x $10^{-3} cm^{-3}$; a result which is up to six orders of magnitude smaller than the number concentration range for cloud droplets given by Leaitch et al. (1992) as 20 to 1100 cm^{-3}.

In order to explore whether or not this difference in concentration is explainable by collision-coalescence processes a bin microphysics model developed by Grabowski and Wang (2009) is used to simulate the evolution of the droplet size distribution in a lifting air parcel. The model simulates a parcel of air rising adiabatically with a prescribed vertical velocity. As the parcel rises, the number of activated CCN is calculated using the Twomey (1959) equation

$$N_{CCN} = C_0(100S)^k, \quad (6)$$

where supersaturation S is given by

$$S = \frac{q_v}{q_s} - 1, \quad (7)$$

and q_s is defined by the Clausius Clapeyron equation as a function of pressure and temperature. C_0 and k are constants empirically fit to observations for a range of aerosol distributions and chemistries. Once the aerosol particles have been activated, they grow into cloud droplets by condensation. The supersaturation in this model reaches its maximum on the first time step, so no new aerosol particles are activated as time progresses. This is because, while q_s decreases with height and would tend to increase S, q_v decreases faster as water vapor is condensed out into liquid water on growing cloud droplets, so S decreases. The droplets then grow until they reach a size large enough to initiate efficient collision-coalescence. Once collision-coalescence begins the droplets reduce in number and increase their rate of growth quickly. Time evolution of this size distribution is shown in Figure 3.

The model includes both gravitational and turbulent collection kernels. The turbulent collection kernel is one approach to simulating warm cloud processes that has been shown to produce realistic rain initiation times (Grabowski and Wang 2009). For this study we used a prescribed vertical velocity of 1 m s^{-1}, which allows for direct comparison between time and height (i.e. 10 s corresponds to 10 m). We also ran the model for a variety of aerosol conditions including maritime, continental, equatorial Pacific, and polluted North Pacific (Grabowski and Wang 2009; Hegg and Hobbs 1992). The results of these four runs are shown in Table 1, and the results from the maritime run are plotted in Figure 3. The model was run until the concentration of droplets larger than one millimeter was approximately equal to the concentration given by the MP parameterization for $q_r = 0.2\ g\ kg^{-1}$. The results are discussed below.

4. Results and Discussion

From Table 1, it can be seen that the time required to grow droplets to the hydrometeor concentration of the MP parameterization increases as a function of activated CCN number concentration. This suppression of precipitation due to increased aerosol concentration is consistent with the second indirect effect (Seinfeld and Pandis 2006). The time scales for the four runs range from 1260 (21) to 1890 (31.5) seconds (minutes). The average lifetime of a cloud is 30 minutes (Plant 2009), indicating that the result shows a realistic timeframe for precipitation development. Therefore, given a natural range of aerosols and atmospheric conditions, it can be said that the hydrometeor concentration calculated by the MP parameterization would develop within the lifetime of a cloud. Had we chosen a reference $q_r > 0.2$ g kg^{-1}, the concentration of hydrometeors calculated by the MP parameterization would have been higher and would require more time to develop.

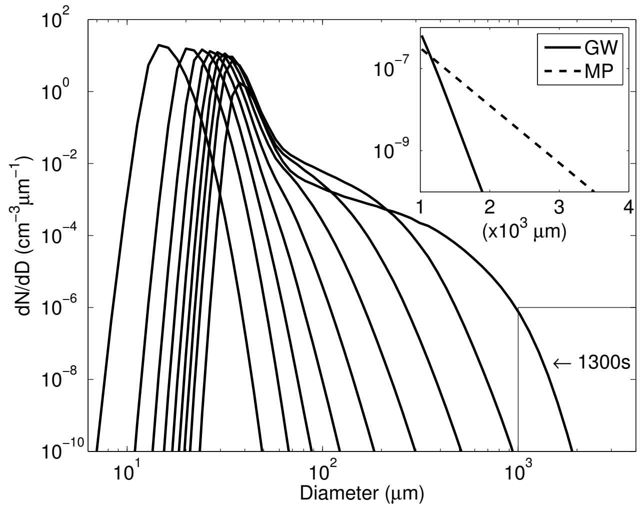

Figure 3. This figure shows the time evolution of the number concentration size distribution in the Grabowski and Wang (2009) model. The boxed section in the lower right hand corner of the figure shows the region considered to be hydrometeors (diameter > 1 mm). The small plot in the upper right hand corner of the figure shows a zoom in of the hydrometeor distribution when the concentration is equal to that of the MP parameterization, on a linear x axis. Shown here are the results from the maritime run, input values can be found in Table 1.

Table 1. This table shows the values used in the Twomey (1959) equation for four different aerosol conditions. SS_{max} is the supersaturation calculated by the Grabowski and Wang (2009) model on the first time step. CCN is the number of activated particles calculated on the first time step. And t_{rain} is the time required for the model to reach a hydrometeor concentration equal to that of the MP parameterization.

	Equatorial Pacific*	Maritime**	Polluted N. Pacific*	Continental**
C_0	100	120	400	1000
k	0.4	0.4	0.3	0.9
SS_{max} (%)	0.57	0.53	0.18	0.15
CCN (#)	80	93	387	479
t_{rain} (s)	1260	1300	1790	1890

*Hegg and Hobbs (1992), **Grabowski and Wang (2009)

From the small plot in the upper right hand corner of Figure 3, it can be seen that the number concentration size distribution of the MP parameterization is very different from that calculated by the Grabowski and Wang (2009) model (even though the concentrations are equal). The MP parameterization significantly over estimates the size of the hydrometeors, placing more in the larger size ranges. This results is consistent with MP comparisons to observations found by Joss and Gori (1978). In models this could impact how much of the resulting precipitation reaches the surface. The larger droplet sizes have a higher fall velocity and are more likely to reach the ground without evaporating, which could have an impact on the overall cloud lifetime and hydrologic cycle. Further, this result shows that the MP parameterization is likely to do a poor job in the simulation of drizzle. This is due to the fact that the over estimation of droplet size will result in a fast fall velocity of simulated raindrops.

So far we have compared the MP parameterization to a parcel model, but it is important to return to its intended use, as implemented in the MMF-SAM, which is to calculate the bulk microphysics of a four kilometer by four kilometer grid box (Khairoutdinov et al. 2005). Of the results presented above, the most significant concern, when scaling up to global simulations, is the resulting precipitation rate bias due to a disproportionate number of large droplets. DeMott et al. (2007) found that precipitation penetration into land, in a land-atmosphere coupled model, impacts the re-evaporation of this water as it is available as land surface water, which results in a feedback to the atmospheric water vapor content. Another area of concern is in the global radiative balance, which is significantly tied to the distribution of water (in both liquid and vapor form) in the atmosphere. Large droplets are more absorbent of long wave radiation than small droplets, which could give the global simulations a tendency to warm more than they should. However, an increase in precipitation reaching the surface without evaporating would reduce the water vapor content of the local atmosphere and have a cooling effect. The implications of effects like these should be considered in all global-scale studies involving the MP parameterization.

5. Conclusions

While there may be additional metrics by which to judge the MP parameterization in a global-scale model, the time scale and number concentration size distribution of droplets as evaluated here offers a revealing first look. The focus has been on the evolution of cloud droplets and hydrometeors through the growth processes of activation, condensation, and collision-coalescence. A bin microphysics model developed by Grabowski and Wang (2009) has been used to determine if the time required to transition from an observed aerosol concentration to the hydrometeor concentration given by the MP parameterization gives a realistic result. It has been shown that the hydrometeor concentration described by the MP parameterization develops in a realistic timeframe, but the size distribution is quite different from that developed in the bin microphysics model.

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