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Few editorial changes – typos. It would have helped the reader if a table of relative CPU times for the various schemes were included. I think this info is out there. Purpose = quantify things.

Great job.

CUMULUS PARAMETERIZATIONS IN THE MM5 AT AIR FORCE WEATHER AGENCY: A RECOMMENDATION

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I. ABSTRACT

Currently, the Air Force Weather Agency (AFWA) supports operational weather units in the U.S. Department of Defense (DoD) with one of the very latest Numerical Weather Prediction (NWP) models, the Mesoscale Model Version 5 (MM5), which was developed jointly by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) in Boulder, CO. AFWA provides this support around the world by running the MM5 over several geographic domains. The MM5 is capable of depicting each meteorological regime with greater accuracy by incorporating updates to the model physics that are more appropriately tailored to each specific region. It is the purpose of this paper to explore the choices for cumulus parameterizations in the implementation of MM5 as it is being executed at AFWA. The paper will explore an overview of the AFWA MM5 variant first, then will proceed to explore the available cumulus parameterization options. Finally, a recommendation will be made towards the specific cumulus parameterizations that AFWA ought to use in the MM5 in each geographic region.

II. INTRODUCTION

MM5 is The Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model, Version 5. It is a very mature mesoscale forecast model, as it has been progressively developed and improved for nearly 20 years. It is still undergoing development today at universities, U.S. Government laboratories, and private companies worldwide.

MM5 is a numerical weather prediction model, loosely similar to the LFM, Eta, NGM, and other regional-scale models. MM5 runs at finer resolutions than models you may be accustomed to using. Because of the increased resolution, output from MM5 will depict mesoscale features that are not seen in either global scale models (e.g., AVN and NOGAPS) or larger scale regional models (e.g., NGM and ETA).

– not really. I am accustomed to cloud models with grids <300m

MM5 is the Air Force Weather 's (AFW) operational fine-scale meteorological model of choice. At AFWA, MM5 was declared operational on 28 October 1997, in conjunction with the first Initial Operational Capability (IOC-1) of the Global Theater Weather Analysis and Prediction System (GTWAPS) program. MM5 is run operationally for the following theaters at AFWA: Alaska (36/12 km resolution), Central America (36/12 km resolution), Europe (36/12 km resolution), Southwest Asia (36/12 km resolution), CONUS (36/12 km resolution), Pacific (36/12 km resolution), Diego Garcia (36 km resolution), and Africa (36 km resolution).

MM5 is also used operationally and semi-operationally at several institutions worldwide.

Information about the MM5

The run-time configuration of MM5 at AFWA is likely to be different from the run-time configuration of MM5 at other institutions. The physics packages (which determine how the model treats things like convective precipitation, solar radiation, boundary layer structure, and cloud moisture phase changes) in MM5 are redefinable (by the modelers at AFWA Offutt AFB) with several choices available. For example, the physics packages implemented in the AFWA MM5 forecast for the Alaska region may differ from the physics packages in the MM5 forecast generated by the University of Alaska for the same region. In fact, AFWA's MM5 forecasts for one region may include different physics packages than AFWA's MM5 forecasts for another region (e.g. tropical vs. mid-latitude regions).

Due to the choices available for MM5 configurations, it is difficult to make wide sweeping generalized statements about MM5's ability to forecast various parameters, e.g., the speed of fronts, the development of lee cyclogenesis, the intensity of convection, the amount of precipitation, or the accuracy of the forecast low temperatures. Several factors contribute to MM5's ability to make a good forecast. Of greatest importance is AFWA's ability to generate the best initial conditions and lateral boundary conditions possible. AFWA is pursuing various methods of initialization to include surface and upper air observations, wind profilers, and satellite data.

The information flow in the AFWA MM5 forecast pipeline is depicted in the simple schematic (Figure 1) below. Items in dotted lines are not part of the current system; they are projected to be part of the pipeline in the future. Not all of the processing in the MM5 forecast pipeline is shown in the schematic.

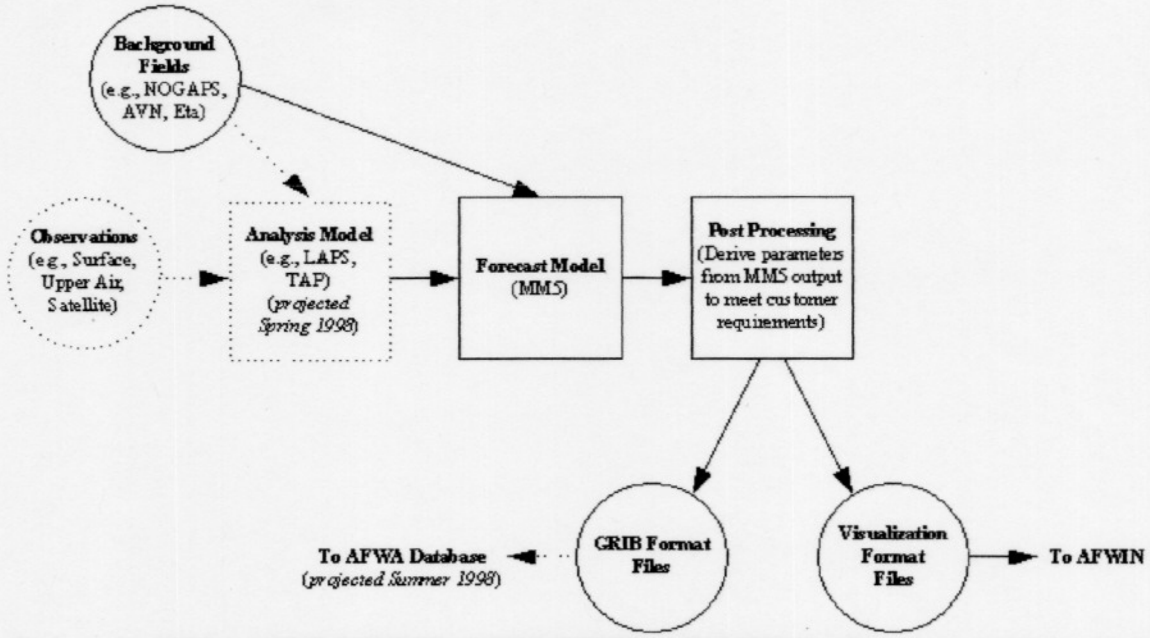

Figure 1: AFWA MM5 MODEL EXECUTION PROCESS. (Courtesy AFWA, 1997)

Currently at AFWA, MM5 is initialized from the previous run of another larger-scale model (e.g., NOGAPS, AVN, Eta). That means there are no observations that are directly analyzed for the AFWA MM5 initial state. The initial conditions for MM5 largely reflect the "goodness" of the 6-hour or 12-hour larger-scale model forecast from the previous cycle, with very little "correction" to the "current" state of the atmosphere. If the larger-scale model is handling the state of the atmosphere well, it will be reflected in the MM5 forecast, and vice versa.

What is this called? There is a name for it.

As shown in the dotted lines in the schematic, there are plans to incorporate observations into the initial state of MM5 via an analysis model in Spring 1998. These observations will make the MM5 initial conditions more representative of the "current" state of the atmosphere. Initially, surface observations and soundings will be used by the analysis model. In subsequent months and as technology permits, the observations will be expanded to include satellite-derived information, pilot reports, wind profilers, radar, and other observations that are stored in the database at AFWA.

Presently, the MM5 00 hour cloud moisture fields are initialized to zero (no moisture). Hence, MM5 does not have any clouds at the beginning of the forecast, which is a standard procedure for static initialization of many regional models. Like other regional models, MM5 needs time to "spin-up" the clouds. For this reason, early forecasts of clouds (e.g., before 12 hours) will depict fewer clouds than the satellite imagery. AFWA is currently testing modifications to the modeling system to improve the early-hour cloud forecasts.

At AFWA, objective and subjective verification of MM5 occurs on a daily basis. By comparing the model with surface and upper-air observations, root-mean-square errors (RMSE) and bias scores are automatically computed at the surface and five mandatory levels for a handful of variables at the synoptic valid times (00Z and 12Z). Statistics compiled since Spring 1997 indicate the AFWA MM5 forecasts tend to show an improvement over the AFWA RWM forecasts for the same areas (Note: the "*RWM*" was the "*Relocatable Window Model*". This was the previous regional NWP model run at AFWA). The AFWA MM5 forecasts are also compared to satellite images to assess overall storm placement and development of smaller-scale features (e.g., squall lines) that would not necessarily be reflected in the synoptic observations.

III. THE MM5 AT AFWA: CURRENT CONFIGURATION

AFWA MM5 Model Physics Configuration

What is a parameterization? Although fine-scale numerical weather prediction models like the PSU/NCAR MM5 are able to resolve mesoscale features that global models like AVN and NOGAPS cannot, there are still many phenomena that are still too small for the model to explicitly resolve. Examples of these "sub-gridscale" processes are the mixing of heat, moisture, and momentum within the lowest few kilometers of the atmosphere, and the microphysical processes that lead to the formation of precipitation. A parameterization is a set of rules, based on either physical/dynamical principles or empirical rules, which are used to handle the sub-gridscale processes. The MM5 - as executed at AFWA Offutt - currently uses the following parameterizations in all of the MM5 Windows:

- Grell Cumulus Parameterization
- Blackadar Planetary Boundary Layer Model
- Reisner Mixed-Phase Explicit Moisture Microphysics
- Dudhia Cloud Radiation
- Blackadar Force/Restore method for Ground Temperature

As MM5 continues to develop a "track record" in different theaters around the world, AFWA may choose to use different parameterizations for different theaters, for example, in a tropical theater vs. a polar theater. ***Right now, though, these settings are used for ALL windows / domains for MM5 at AFWA, without regard to regional consideration.*** The fact that the same parameterizations are used in all windows forms the basis for this motivation paper in the first place. Figure 2 below shows the different coverages of the AFWA MM5 domains throughout the world. As you can see clearly, AFWA is

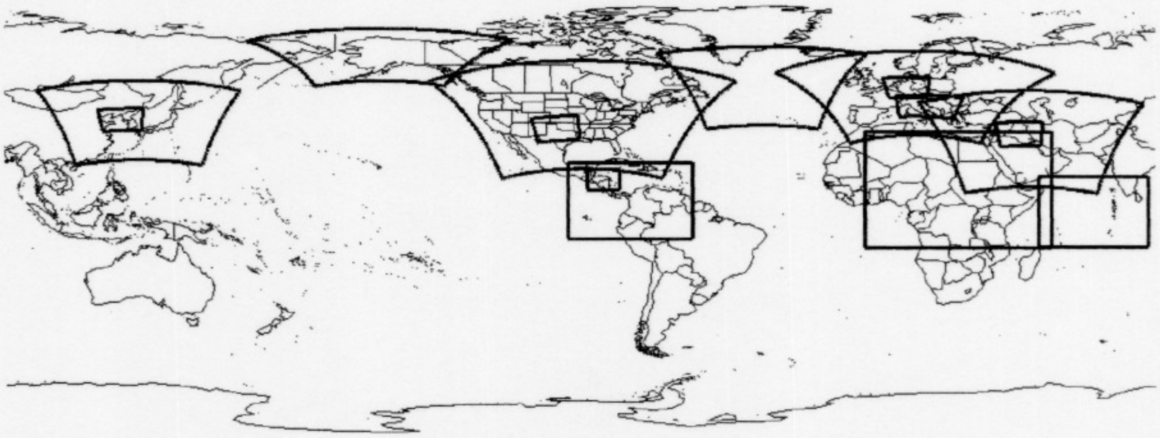

Figure 2: MM5 DOMAIN COVERAGE THROUGHOUT THE WORLD (Courtesy AFWA, 1998). Note: very little oceanic coverage.

running MM5 over a significant proportion of the land surfaces world. Let us then consider – very briefly – the nature of each of these selected parameterizations to get a more comprehensive look at the MM5 as it is run at AFWA, and then we will later shift our focus towards the cumulus parameterization.

Grell Cumulus Parameterization

Why do we need a cumulus parameterization? At scales of 5-10 kilometers, individual thunderstorms are typically too small to be fully resolved on AFWA's 36 and 12 km MM5 grids. This parameterization accounts for sub-gridscale convection (updrafts) and compensating resolved-scale subsidence with appropriate heating and phase change processes *within the air column*. It was developed for grid sizes of 10-30 km, so when we occasionally run a 4 km window, we don't use any cumulus parameterization. We let the model's equations handle convection explicitly.

Blackadar Planetary Boundary Layer Model

The Blackadar PBL model parameterizes the mixture of heat, moisture, and momentum within the lowest few kilometers of the atmosphere. It determines the vertical extent and intensity of mixing based upon the stability of the lowest model layer (around 35 m). When this layer is stable the intensity of mixing is determined by the magnitude of the Richardson number. When the layer is unstable, the vertical extent and intensity of mixing are determined by the lapse rate within the convective boundary layer and sensible heat flux near the ground.

Reisner Mixed-Phase Explicit Moisture Microphysics

In this parameterization, cloud and rainwater fields and ice phase processes are predicted explicitly. The inclusion of supercooled water allows for slow melting of snow. No graupel or riming processes are calculated.

Dudhia Cloud Radiation

This parameterization provides solar and infrared fluxes at the ground and atmospheric temperature tendencies resulting from radiative processes. It is sophisticated enough to account for longwave and shortwave interactions with resolved cloud water and ice as well as clear-air.

Blackadar Force/Restore method for Ground Temperature

This uses two soil layers. The upper layer's temperature is based on an energy budget and its depth is assumed to represent the typical depth of diurnal temperature variations (around 10-20 cm). The lower layer temperature remains constant.

MM5 Boundary Conditions (BC)

The MM5 uses relaxation-inflow/outflow BC which allow larger scale migratory features to propagate into the Mesoscale domain. Also, migratory features on the Mesoscale grid are allowed to flow through the boundary, thereby avoiding reflection and noise.

RELAXATION: The boundaries are handled over a 3D frame, five gridpoints wide, extending from the surface to the model top. The extreme outer row/column take on the full value and tendency of the larger scale model used to drive the MM5 boundaries. Over the remainder of the frame, the weighting factor for the larger scale value decreases while the weighting factor for the Mesoscale values increase. This provides a smooth blending of the larger scale and mesoscale features in the frame region. For the 36km domain, the frame is 144 km wide.

INFLOW BOUNDARY: On an inflow boundary, i.e. wind blowing into the domain, *moisture variables are set to 0.0 and other variables are a weighted combination of larger scale model values (AVN, NOGAPS, etc.) and the MM5 value at that grid point.* This is the reason you may see well developed cloud systems near the frame of an inflow boundary but not on the inflow boundary.

OUTFLOW BOUNDARY: On an outflow boundary the same weighting factors are applied with the following exception. All variables on a penultimate row/column are copied to the ultimate row/column so that a zero gradient condition exists.

TIMING: MM5 BC are derived from Larger scale models (AVN, NOGAPS, etc.) and made available to the MM5 grid on a 3 hourly basis. Hence, there are large scale boundary values at each 3 hour point, and tendencies are computed via linear rate of change over the three hour period.

BOTTOM LINE: These BC are much better than we've used here in the past. *Remember that near the edge of the grid, you have a blending of synoptic and mesoscale features, so you shouldn't expect to see true mesoscale development in these regions.* For your information, the European 36 km grid is 96 grid points in the north-south direction, and 120 in the east west. As you view your products, the boundary frame only encroaches on 5% of the grid.

IV. MORE ON THE GRELL PARAMETERIZATION

The Grell parameterization is given first in this discussion since it is the only cloud parameterization used in AFWA's implementation of MM5. The diagram below (figure 3) demonstrates the type of cumulus convection to be discussed.

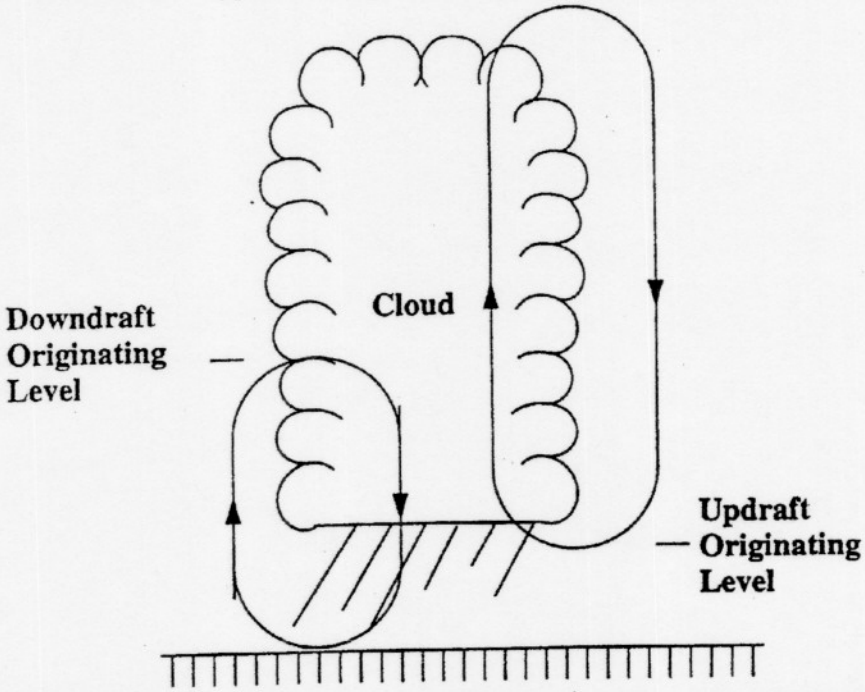

Figure 3: CONCEPTUAL MODEL OF CONVECTION PARAMETERIZED IN THE GRELL SCHEME (Courtesy Grell et al, 1995).

The Grell scheme (1993) is a very simple scheme in which clouds are depicted as two steady state circulations, caused by an updraft and downdraft. No direct mixing takes place between the cloudy air and the drier environmental air, except at the top and bottom of the cloud / circulations. So, no entrainment or detrainment is permitted with height, and the mass flux in constant with height. The conditions at the originating levels are given by the environment. In this scheme, no cloud water is assumed to exist, but is all converted ~~the~~ to rain with perfect efficiency. Physically, for both the updraft and the downdraft, the scheme allows for maximum buoyancy. Here, the cloud base is not limited to the boundary layer, but can be anywhere in the troposphere.

The Grell scheme provides a feedback into the larger scale equations of the model entirely through compensating mass fluxes and detrainment through cloud top and bottom.

The problems with the Grell scheme are apparent: There is no direct mixing (entrainment / detrainment) of dry environmental air into / out of the cloud at various heights, but only at the cloud top and bottom. There are only vertically stacked clouds. This assumption can be valid under only certain real-life atmospheric conditions. The tropical regimes often have clouds that behave thus, and such cloud behavior is sometimes observed in northern hemisphere summertime. Otherwise, this basic model will breakdown rather quickly in most other meteorological situations. Furthermore, this scheme tends to take all available moisture and precipitate it as rain completely. Clearly clouds do not actually do this in real life.

Because this scheme is mathematically much simpler than most others, it was implemented at AFWA to reduce the computer run time for the MM5. Other schemes tend to be more computationally expensive.

V. OTHER OPTIONS AVAILABLE IN MM5 FOR CUMULUS PARAMETERIZATION

The MM5 has a variety of way to treat precipitation physics. These methods are divided into two groups: the explicit and implicit. Explicit schemes treat precipitation physics that are resolved at the model grid scale, whereas implicit schemes deal with non-precipitation physics. MM5 also allows for "dry" runs, where moisture is treated as a passive variable. Here, no schemes are applied. Another version of this is the "fake" dry run, in which Latent heat considerations are included.

Here, we will focus on the explicit and implicit schemes. We will only discuss these at a high level, concentrating on the assumptions that underlie these schemes. We will consider first the implicit schemes, on which we have already discussed one: the Grell parameterization. The other three are the Anthes - Kuo Scheme, the modified Arakawa-Schubert scheme, and the Kain-Fritsch Scheme. Then, we will briefly discuss the explicit treatment of clouds in MM5.

A. The Anthes - Kuo Scheme

The Anthes - Kuo (AK) Scheme uses the column integrated moisture convergence (called "M") to determine where convection will occur and how intense it will be. Convection is initiated when conditional instability exists (according to conventional parcel theory) and "M" exceeds a threshhod value in the column. The moisture convergence does two things: (1) it moistens the cloud, and (2) it develops convective precipitation rates ("PR") as given by:

units?

$$\mathbf{PR = (1 - b)\, M}$$

units

where b = 2 (1 - ***RH***), and ***RH*** is the average Relative humidity in the column. The original version of the AK scheme did not include any consideration of the effects of convective downdrafts. This last item is perhaps its greatest weakness.

Feedback into the larger scale equations, which is the vertical distribution of heating and moistening, takes place through the help of normalized profiles of convective heating, moistening, and through a vertical eddy flux divergence of water vapor associated with cumulus convection. These profiles were determined by Anthes et al (1987) and were based on budget studies of the atmosphere. They are simplistic treatments of the atmosphere.

B. The Modified Arakawa-Schubert scheme

The Modified Arakawa-Schubert (AS) scheme was developed by Grell (1991 and 1993), who took advantage of the AS scheme to add a parameterization of moist convective downdrafts. The most impressive aspect of the AS scheme, in my opinion, is the fact that this scheme actually takes into account the entrainment of mass flux (of dry air) into a cloud throughout the vertical column. The AS scheme literally calculates a "fractional entrainment rate" called μ, given below:

$$\mu = \{1/m(z)\} \{ dm(z)/dz \}$$

where "m" is mass and "z" is height. In the earlier version of the AS scheme, μ was also literally used as the parameter that actually characterized the cloud; later, an option was included such that cloud top detrainment level could be used instead. The first option, μ, is best used when the grid spacing is course (~30km), whereas the second option is best used when the model resolution is finer (~4-10 km).

now much so.

The AS scheme tends to be more computationally expensive, thus AFWA choose not to use it.

A table showing relative CPU times with the various schemes would be helpful and appropriate

C. The Kain-Fritsch Scheme

The Kain-Fritsch Scheme (KF) takes advantage of the Convective Available Potential Energy (CAPE) to parameterize the cloud. CAPE, also known as the Potential Buoyant Energy, is the work done per unit mass on the environment by a buoyant parcel of air as it rises from the Level of Free Convection (LFC) to the Equilibrium Level (EL), and it depends on Potential Temperature of the parcel and of the environment. The

CAPE is determined at a grid point. Once the convection is triggered, CAPE is assumed to be removed in a grid column within an advective time period. The KF scheme utilizes an improved cloud model which is mass conservative, allows cloud-environment interaction, includes parameterized convective downdrafts, and it has a detailed representation of cloud physics, which includes entrainment and detrainment at the cloud edge. Convective precipitation rates (PR) are computed through:

$$PR=E\ S$$

where "E" is the precipitation efficiency, and "S" is the sum of the vertical fluxes of vapor and liquid at about 150mb above the Lifting Condensation Level (LCL).

The KF scheme is clearly the most realistic scheme presented thus far. It is more computationally expensive than the Grell, but only slightly quantify more. typically Recent conversation between the author and AFWA modeling experts revealed that the increase in processing time is only moderate. - quantify It is suspected that with anticipated upgrades to the AFWA computing network (the so called 'silver nodes'), we could go to the KF scheme, increasing MM5's ability to parameterize clouds. Further, recent informal studies have been conducted at AFWA, comparing the KF and other schemes, such as the Grell and AK, to observed weather. Visualizations of MM5 cloud water, when compared to satellite imagery have revealed - via strictly subjective analysis – that the KF is superior to the Grell over most of the AFWA MM5 36km domains and most 12 km domains.

I recall you gave this in the talk but these would be helpful in the paper, as well, for the reader

D. Explicit treatment of resolvable scale precipitation processes

The MM5 has the ability to use explicit schemes to resolve precipitation Processes, as mentioned earlier. This explicit scheme is usually done only at fine scales (as per conversation with AFWA modelers, 4-10 km seems to be the accepted breaking point between explicit and implicit scheme usage). The implicit schemes tend (though not always) to remove supersaturation as precipitation and then add latent heat changes to the thermodynamic equations. More detailed schemes will directly handle cloud water, rain water, ice, and snow.

The MM5 can treat explicitly the following processes at the finer scales: Condensation of water vapor into cloud, Condensation of cloud water into ice, accretion Cloud by rain, Conversion of cloud water to rain, Conversion of ice to snow, evaporation of rain, and sublimation of snow. MM5 will also handle the initiation of ice crystals, and the sublimation/deposition of cloud ice. Figure 4 below provides a schematic of these processes.

It is in the explicit cloud physics that we find direct use of the drop size Distributions discussed in the classic book(s)? by Pruppacher and Klett (1978). The MM5 is specifically trained to use the Marshall Palmer distribution. This assumption is reasonably valid over the continental US and other mid-latitude regimes, but this could fine tuned with relative ease by simply changing the empirical constants which are used to relate precipitation drop size to fall velocity. Much work has been done in this arena. The work of Fujiwara (1965) provides good insight over Miami, which could be used for the AFWA Central American window. The work of Blanchard (1953) gives good information over Hawaii., and many others have contributed to this effort over many vastly different regions of the world. A word of caution is necessary here, though: often, these studies were done in regions where there are very complicated interactions between the air flow and land / orographic features. Careful consideration is needed when a change is made to these constants, and what scale / resolution is intended for use.

good point

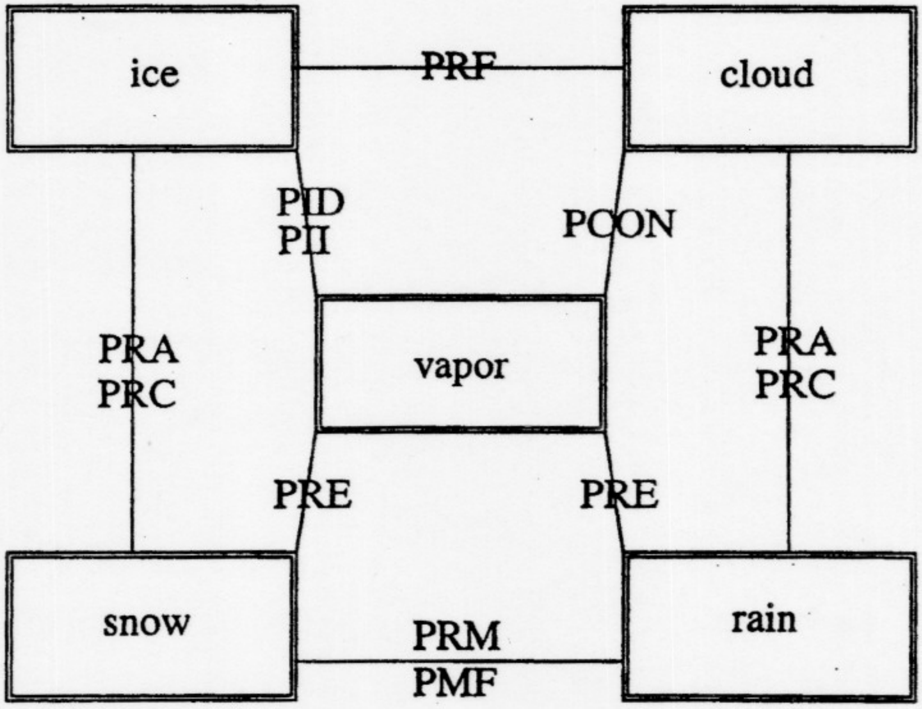

Figure 4 **Box diagram illustrating the processes in the moisture scheme for ice (crystals), cloud(liquid), snow and rain. PCON, condensation/evaporation of cloud; PRA, accretion; PRC, conversion; PID, deposition onto ice crystals; PRE, evaporation for rain and deposition/sublimation for snow; PMF, melting/freezing due to advection; PII, initiation of ice crystals; and PRM, melting of snow due to fall.** ***(Taken from Grell et al, 1995)***

VI. RECOMMENDATIONS / CONCLUSIONS

Briefly, the final recommendation is to press ahead with using the Kain-Fritsch Parameterization in the MM5, rather than the Grell for both the 36 km and 12 km windows . The Grell scheme, while computationally less expensive, is not going to reflect real cumulus development as accurately as the KF. The KF incorporates more of the real interactions that actual cumulus experience.

work well for most AFWA domains, but in the tropics, there are potentially more accurate distributions that can be considered, and should be studied.

VII.CREDITS

Much of sections II and III on the MM5 at AFWA was originally developed via a joint effort between the author and a number of the NWP experts at AFWA, in the Weather Models Section (Office code DNXM). This material can be found in its original form on the internet at the following site:

ftp://ws-ftp1.afwa.af.mil/pub/aboutmm5/index.html