COMPARISON OF CIRRUS CLOUD MODELS:
A PROJECT OF THE GEWEX CLOUD SYSTEM STUDY (GCSS)
WORKING GROUP ON CIRRUS CLOUD SYSTEMS

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1. INTRODUCTION

The GEWEX Cloud System Study (GCSS, GEWEX is the Global Energy and Water Cycle Experiment) is a community activity aiming to promote development of improved cloud parameterizations for application in the large-scale general circulation models (GCMs) used for climate research and for numerical weather prediction (Browning et al., 1994). The GCSS strategy is founded upon the use of cloud-system models (CSMs). These are "process" models with sufficient spatial and temporal resolution to represent individual cloud elements, but spanning a wide range of space and time scales to enable statistical analysis of simulated cloud systems. GCSS also employs single-column versions of the parametric cloud models (SCMs) used in GCMs. GCSS has working groups on boundary-layer clouds, cirrus clouds, extratropical layer cloud systems, precipitating deep convective cloud systems, and polar clouds.

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Central to the GCSS strategy is the conduct of model comparison projects. These systematic comparisons document the performance of state-of-the-art models, detect problems with specific models, and identify fundamental issues resulting in significant inter-model differences, such as the approach to representing a specific process. Comparison to field observations, especially in a case study mode, is another cornerstone of the GCSS approach. The concept is that these activities will serve to markedly accelerate community-wide improvements in CSMs, as well as to provide better focus for planned field experiments in terms of key science issues related to the modeling of cloud systems. CSMs are quite well matched, in terms of scales and resolved physical processes, for such comparisons with observations. Moreover, when sufficient confidence is established in the models via validation versus field measurements, CSMs can serve as highly useful research platforms for the development of concepts and approaches to cloud parameterization because they do resolve the physical processes operating in cloud systems to a much greater extent than SCMs. While some processes must still be parameterized in CSMs, such

parameterizations are more focused, in terms of the represented physical process, and better correspond to the scales at which such processes actually operate.

2. IDEALIZED CIRRUS MODEL COMPARISON

The GCSS Working Group on Cirrus Cloud Systems (WG2) is conducting an Idealized Cirrus Model Comparison Project where cirrus cloud simulations by a variety of cloud models are compared for a series of idealized situations with relatively simple initial conditions and forcing. *Preliminary* results of this activity are reported herein. A second WG2 project, Cirrus Parcel Model Comparison, is reported in a companion paper in this volume (Lin et al., 2000). In the present project, results were submitted from 16 distinct models, including 3-dimensional large eddy simulation (LES) models, 2-dimensional cloud-resolving models (CRMs), and SCMs. The microphysical components of the models range from single-moment bulk (relative humidity) schemes to sophisticated size-resolved (bin) treatments where ice crystal growth is explicitly calculated. Radiative processes are also included in the physics package of each model and are similarly varied.

The baseline simulations include nighttime "warm" cirrus and "cold" cirrus cases where cloud top initially occurs at about −47°C and −66°C, respectively. The cloud is generated in an ice supersaturated layer about 1 km in depth (120% in 0.5 km layer) with a neutral ice pseudoadiabatic thermal stratification (Fig. 1).
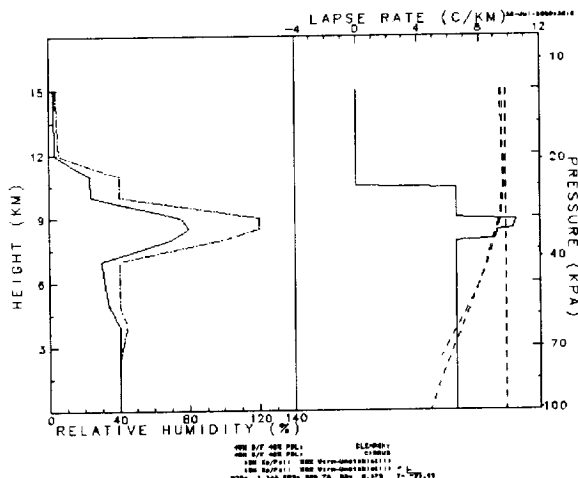
standards, where the tropopause occurs more than 1 km above the nominal cirrus layer in the "warm" and "cold" cirrus cases, i.e., at -56°C at 10.5 km and -75.5°C at 15.5 km, respectively.

Continuing cloud formation is forced via an imposed diabatic cooling representing a 3 cm s^{-1} uplift over a 4-hour time span followed by a 2-hour dissipation stage with no imposed "ascent" cooling. Variations of the baseline cases include no-radiation and stable-thermal-stratification cases.

The time-dependent behavior of the vertically-integrated and horizontally-averaged ice water path (IWP) are shown in Fig. 2 for the "warm" (lower panel) and "cold" (upper panel) cirrus comparisons (neutral stratification, infrared only). This is the grossest measure of model response to the prescribed conditions.
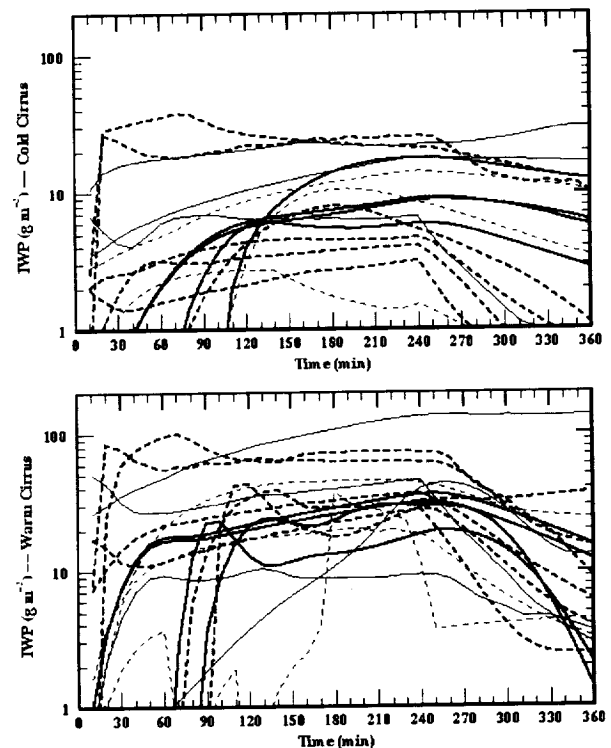
IWP — C/WNir

Figure 2: Time-dependent behavior of IWP (g m^{-2}) in simulations of "cold" (upper panel) and "warm" (lower panel) cirrus clouds with 16 cloud models -- see text for detailed description and explanation.

Figure 1: Relative humidity, relative humidity with respect to pure ice, and temperature lapse rate profiles for the "warm" cirrus case. Reference lapse rates corresponding to neutral stratification for ice pseudoadiabatic and dry adiabatic processes are also shown. Profile shape is similar for the "cold" cirrus case.

Away from cloud forming region, ambient conditions correspond to the Spring/Fall 45°N and Summer 30°N

Results are shown for 16 models including 3 SCMs. Specific models are not identified here. Though somewhat arbitrary, the results are distinguished in terms of model heritage and design. Results from models built primarily to be cirrus models or with a strong cirrus heritage are shown by the heavy dashed or heavy solid lines. The heavy dashed lines denoted results from models with a bulk treatment of cloud microphysics

while the heavy solid lines indicate results from models with highly detailed bin treatments of cirrus cloud microphysical development. Thin dashed lines correspond to results from SCMs and the thin solid lines indicate models originally developed to treat deep convective cloud systems.

It is immediately obvious that a wide range of model response is found even in IWP (factor of 10). Focusing on the "cold" cirrus comparison, two significant groupings are evident. The bulk microphysics "cirrus heritage" models tend to behave in a similar manner. The "bin" models also group. The results from SCMs and models with a deep convection heritage yield results roughly spanning the range of the others. We will focus here on the cirrus heritage models.

Cloud formation is delayed in the bin models relative to the bulk models. All models employed an initial random field of weak thermal perturbations (0.02°C maximum). Thus, while the bulk models immediately respond to supersaturated conditions, the bin models wait until local conditions achieve sufficient relative humidity (up to 140% or more), via circulation, to trigger nucleation (Lin et al., 2000).

However, larger IWP is achieved in the bin models and is better maintained after the "ascent" forcing is turned off at 240 minutes. IWP is dissipated much more rapidly in the bulk models after this time. Even within these groups, differences amount to better than a factor of 2 at 240 minutes and are significantly greater at later times in the cold cirrus comparison. Results are more confused in the warm cirrus case where the overall spread is less (120-240 min.) and IWP declines precipitously after 240 minutes in most models. It should be noted that observations of "warm" cirrus have been much more plentiful than for cirrus at very cold temperatures and may be partly responsible for the greater convergence of results in the warm case.

Shown in Fig. 3 is a measure of circulation intensity within the cloud layers for the bulk and bin cirrus heritage models. Note that the simulations begin from a resting state. Focusing again on the cold cirrus case (top panel), two groups are again apparent. The models yielding the most dynamically energetic simulations of the cirrus heritage modles are the bin models. The bulk models produce significantly less intense circulation. Clearly, the two classes of models exhibit fundamentally different behavior for the cold cirrus case. As with IWP, the distinction is less clear for the warm cirrus case.

Another gross measure of model response is the location of cloud top and base. Shown in Fig. 4 are the locations of cloud top and cloud base, and the cloud thickness at 240 minutes in the cold cirrus simulations. These altitudes are determined by applying a suitable threshold to the horizontally-averaged ice water content profile where the same threshold is used for all the models. A range of more than 1 km is found in the
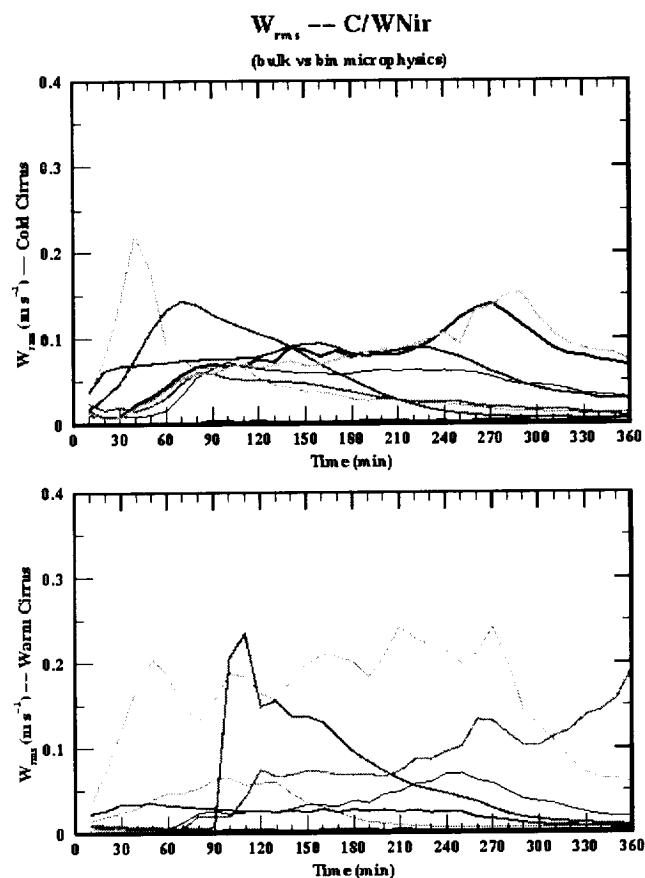

Figure 3: Time-dependent behavior of root mean square vertical velocity in the cloud forming region during simulations of cold (upper panel) and "warm" (lower panel) cirrus clouds by "cirrus heritage" models. See text for further explanation.

location of cloud top. Cloud base varies by more than 2 km among the models while cloud thickness ranges from 1.5 km to more than 4 km. This is a remarkable degree of inter-model difference.

To first order, these fundamental differences can be traced to differences in the size distribution of the ice crystal population represented in the two different classes of models. The bin models tend to have smaller, and consequently much more numerous, ice crystals while the bulk model are dominated by larger crystals, whether explicit or assumed. The primary effect of the differences in ice crystal size distribution is on the diagnosis of ice water fall speed. This was explicitly confirmed via calculations of an effective ice water fall speed integrated across the particle spectrum done within the bin models as part of this comparison project (not so easy a task). As noted by Starr and Cox (1985b), the ice water fallout process has a dominant effect on the vertical distribution of ice water and on the intensity of circulation within cirrus clouds. In the bin models, cloud top tends to grow upward while it is relatively static in

the bulk models. Correspondingly, the ice water content profiles are peaked more toward cloud top in the bin model simulations while the bulk models exhibit peak ice water content at a level below the middle of the cloud, much as seen in Starr and Cox (1985a). The downward extension of cloud base is enhanced in models with larger ice crystals.

As stated above, the relative agreement found in the warm cirrus case may be partly attributed to the availability of observations of "warm" cirrus clouds. Moreover, it should be noted that for homogeneous nucleation processes, disagreements among parcel models, from which the microphysical treatments in multi-dimensional bin models are derived, are significantly enhanced in the cold regime (Lin et al., 2000). The same ambient aerosol populations used in the WG2 Cirrus Parcel Model Comparison Project was also used here by the models requiring this information.

An additional set of experiments was performed in which the ice water fall speed was set to fixed values for all crystals, irregardless or size or habit. Values of 20 cm s^{-1} and 60 cm s^{-1} were used. The intent was to trick the bin models into behaving like the bulk models and vice versa, i.e., these values are roughly representative of the effective ice water fall speeds found in these model classes, respectively. The results largely confirmed the present interpretation. Tests of radiative impact (present versus no radiation simulations) revealed a consistent effect but not one that alters the present conclusion, i.e., relative to present simulation by each model, the no-radiation simulation produced similar relative changes.

3. CONCLUSIONS

While the present results may at first appear discouraging, they can also be seen to indicate that significant progress can be made in the very near future. The disagreements are substantial. Present observational capabilities, including recent advances in measurement of small ice crystal populations, should be able to adequately resolve the shape of the ice water content profile and the overall ice water path. The result that internal cloud dynamical intensity is highly correlated with ice crystal size distribution allows an additional confirming test that is within present measurement capability. Observations of bulk ice water fall speed are also now being derived from mm-wavelength Doppler radar. Further information about GCSS WG2 and its projects may be found at the GCSS WG2 webpage: http://eos913c.gsfc.nasa.gov/gcss_wg2/

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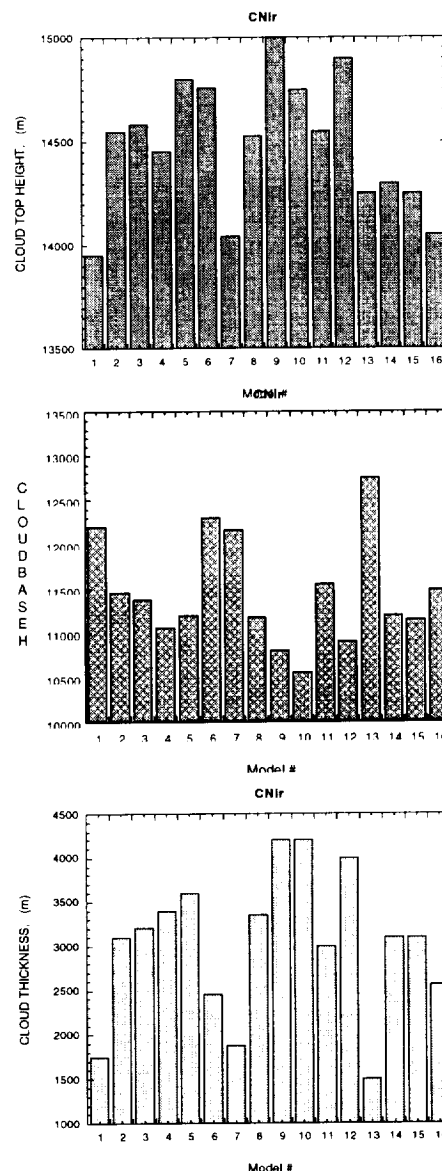
Figure 4: Distribution of cloud top (upper), cloud base (lower) locations, and corresponding cloud thickness for simulations of cold cirrus case. See text for discussion.