J2.9 THE IMPACT OF CONTROVERSIAL SMALL ICE CRYSTALS ON GCM SIMULATIONS

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1. COMPARISON OF MID-LATITUDE AND TROPICAL ANVIL SIZE DISTRIBUTION SCHEMES

There is growing evidence that the concentrations of small ice crystals (D < 70 μm) exceed peak concentrations of larger crystals by orders of magnitude, resulting in bimodal size spectra. There is also evidence that the Forward Scattering Spectrometer Probe (FSSP) may, in spite of its limitations, render reasonable estimates of ice particle concentration under glaciated conditions (e.g. Ivanova et al. 2001). This topic remains controversial due to the phenomena of larger ice crystals shattering at the FSSP inlet. Two size distribution (SD) schemes have recently been developed for cirrus clouds that incorporate FSSP measurements; a scheme for mid-latitude cirrus (Ivanova et al. 2001) and a scheme for tropical anvil cirrus based on CEPEX data provided by Greg McFarquhar (Ivanova 2004). Examples of the SD schemes for mid-latitude and tropical anvil cirrus clouds are shown in Figs. 1 and 2. The key difference is that for the tropical anvil scheme, the small mode increases in amplitude with decreasing temperature T, while the opposite occurs for the mid-latitude scheme. This behavior produces dramatic differences at cold temperatures (T < -55 ^{o}C) in the radiative properties of tropical anvil and mid-latitude cirrus clouds, as shown in Figs. 3-4. Since the small mode dominates the SD projected area at cold temperatures in tropical anvil cirrus but not in mid-latitude cirrus, their radiative properties are quite different at cold temperatures.

2. GCM EXPERIMENTS

A GCM experiment was conducted to investigate how GCM performance was influenced by the choice of the ice particle SD scheme. Using the Community Atmospheric Model (CAM), an Atmosphere GCM based at NCAR, a one year simulation (not including the spin-up time) was run using only the tropical anvil SD scheme, and another one year simulation was run using only the mid-latitude SD scheme. These will be referred to as the tropical and mid-latitude simulations.

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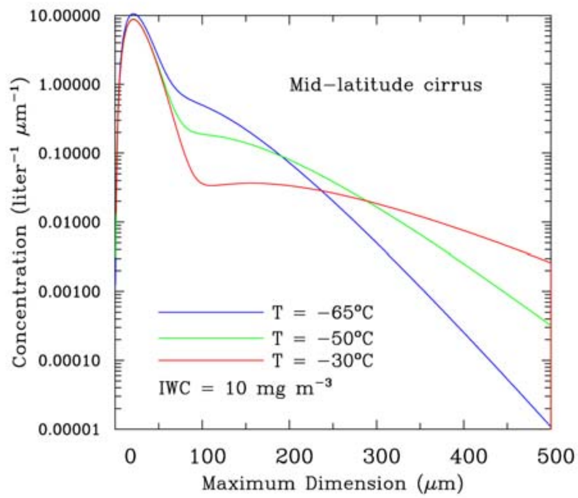


Figure 1. Examples of SDs from the mid-latitude cirrus scheme, which are diagnosed as a function of temperature and ice water content (IWC).

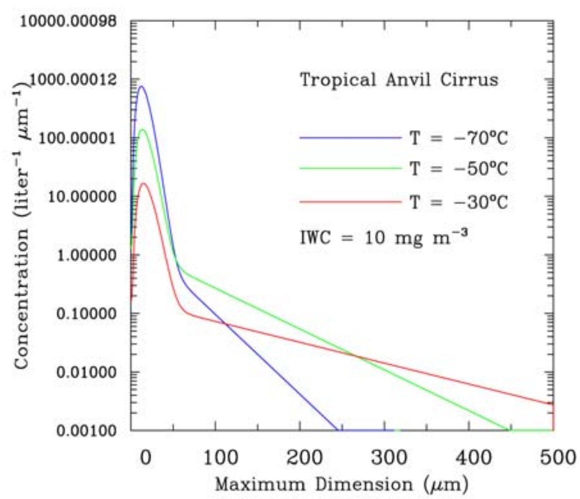


Figure 2. Same as Figure 1, except for the tropical anvil SD scheme.

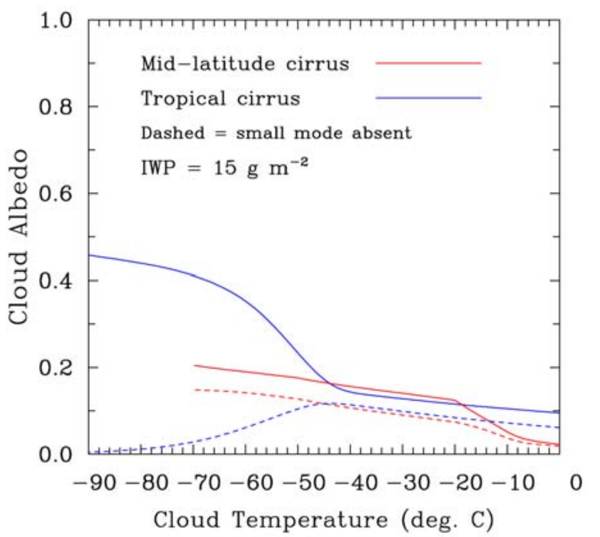


Figure 3. Albedo differences between mid-latitude and tropical anvil cirrus clouds having the same ice water path (IWP). Note the contribution of the small crystal mode (dashed curves are for the large mode only; solid curves are for the complete SD).

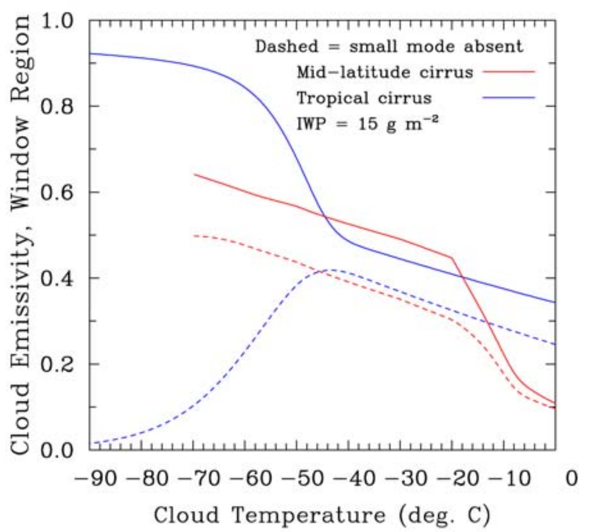


Figure 4. Same as Fig. 3 except for cloud emissivity differences.

To properly evaluate the impact of a SD scheme, reasonably accurate estimates of the mass sedimentation rate for the SD must be obtained. The treatment of ice particle terminal velocities (v_t) are based on Mitchell (1996) and Mitchell and Heymsfield (2005), where projected area- and mass-dimensional power laws are used to calculate v_t for any ice particle shape. The methodology for determining ice mass sedimentation rates is given in Ivanova et al. (2001), which is based on the median mass dimension of each SD mode and the ice crystal shape. Predicted and observed v_t values differ by less than 20%. The ice crystal shape recipes assumed for mid-latitude and tropical anvil cirrus were recommended by Paul Lawson (personal communication). Bullet rosette crystals dominated in mid-latitude cirrus while planar polycrystals dominated in tropical anvil cirrus.

SD sedimentation rates predicted for the mid-latitude and tropical SD schemes are shown in Fig. 5. Also shown are the sedimentation rates currently used in the CAM. The different behavior of the mid-latitude and tropical anvil SD schemes is responsible for these sedimentation rate differences in Fig. 5. The amplitude of the small crystal mode increases with decreasing temperature in tropical cirrus, whereas the opposite occurs in mid-latitude cirrus.

Ice cloud optical properties were treated using the Modified Anomalous Diffraction Approximation, or MADA (Mitchell et al. 2006), with asymmetry parameters calculated in terms of wavelength, ice particle size and shape as described in Mitchell et. al. (1996) and McFarquhar et al. (2006). In addition to its accuracy, MADA is formulated in terms of the projected area- and mass-dimensional power laws for ice crystals and the SD parameters for each mode of the bimodal distribution. It thus couples smoothly with the SD and ice sedimentation schemes. In this way the processes interrelating the SD, the sedimentation rates and optical properties are all self-consistent.

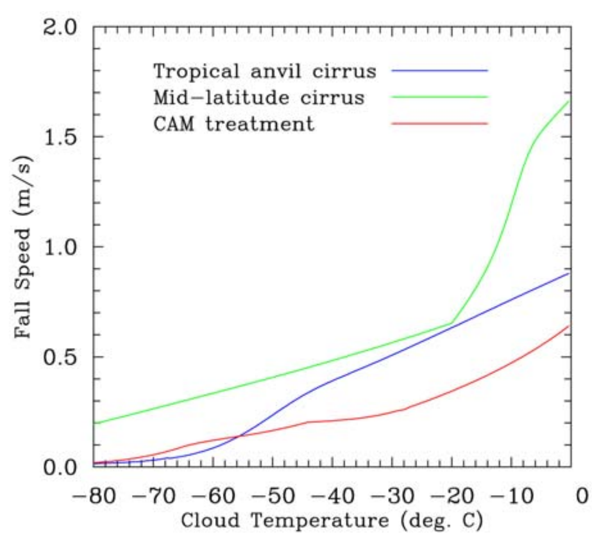


Figure 5. Comparison of ice mass sedimentation rates for tropical anvil and mid-latitude cirrus clouds, and the sedimentation rates currently predicted by the CAM.

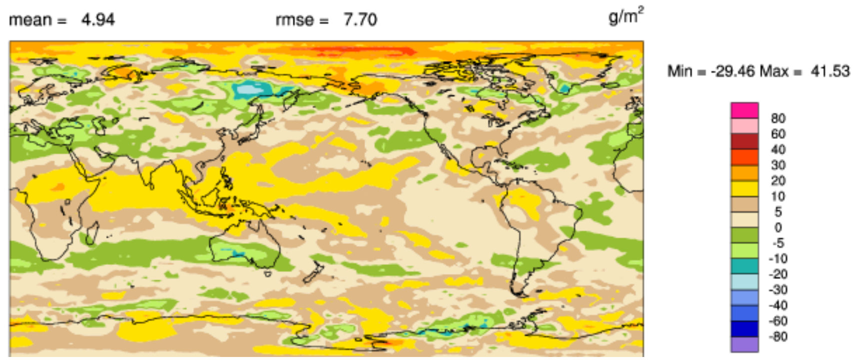


Figure 6. The annual average in-cloud IWP for the tropical SD run minus the mean in-cloud IWP for the mid-latitude SD run.

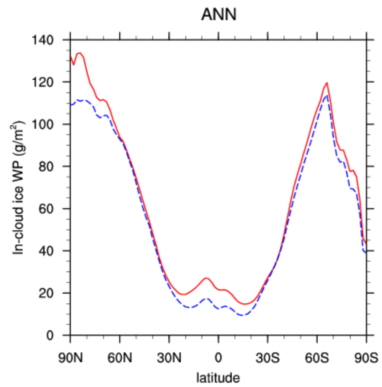


Figure 7. Zonal mean IWP for the tropical (red) and mid-latitude (blue) simulations.

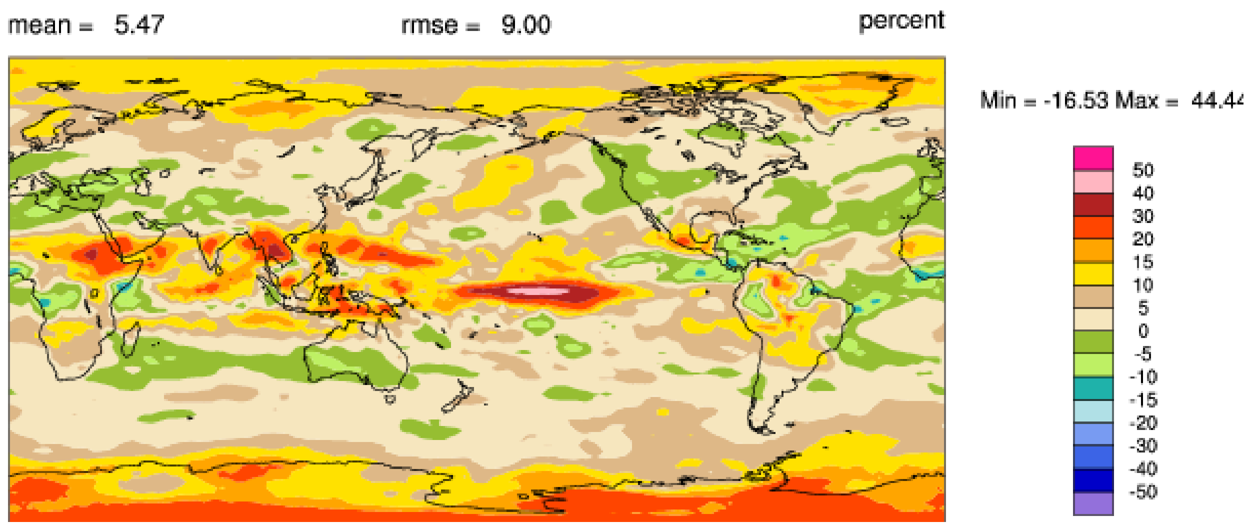


Figure 8. Annual average cirrus cloud coverage for the tropical SD simulation minus that for the mid-latitude SD simulation, shown as percent difference.

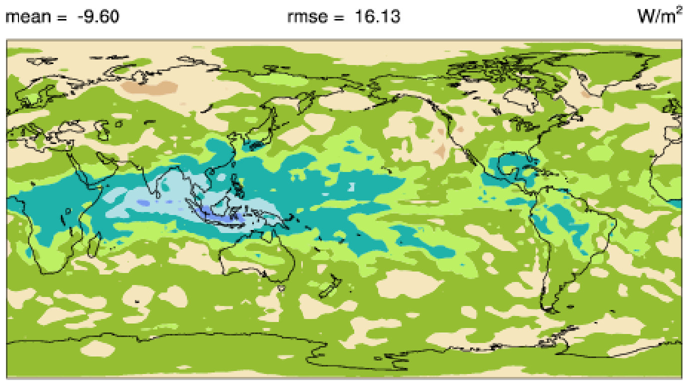
2.1 In-cloud ice water path and cirrus cloud coverage

Figure 6 shows the in-cloud IWP for the tropical SD run minus the in-cloud IWP for the mid-latitude SD run. It is seen that in the tropical regions, where deep convection is common, the IWP is about 5-20 g m^{-2} higher in the tropical SD simulation. Since IWPs for the mid-latitude SD simulation were typically 10-15 g m^{-2} in the tropics, this represents an IWP increase of roughly 60% in this region due to lower fall velocities, as evident in Fig. 7. In the mid-latitudes, where temperatures in the upper troposphere are warmer relative to the tropics, the two SD schemes exhibit similar behavior, and IWP differences are much less.

The differences in sedimentation rates between the mid-latitude and tropical anvil SD simulations also produced changes in cirrus cloud coverage. This is shown in Fig.8, which shows that cirrus cloud coverage increases when the tropical anvil SD is used, especially in the tropics where the small mode of the SD can dominate. Zonal annual averages (not shown) indicate that for the tropical SD simulation, cirrus coverage increased in the tropics by 7-12% relative to the mid-latitude SD simulation. This is due to lower sedimentation rates that result in longer cloud lifetimes.

2.2 Impact on cloud radiative forcing

Figures 9 and 11 show differences between the two simulations in terms of shortwave cloud forcing (SWCF) and longwave cloud forcing (LWCF), respectively, at the top of the modeled atmosphere. Annual zonal means (Fig. 10 and 12) indicate the tropical SD simulation



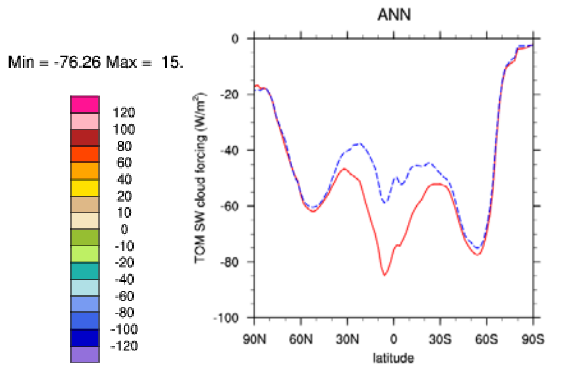
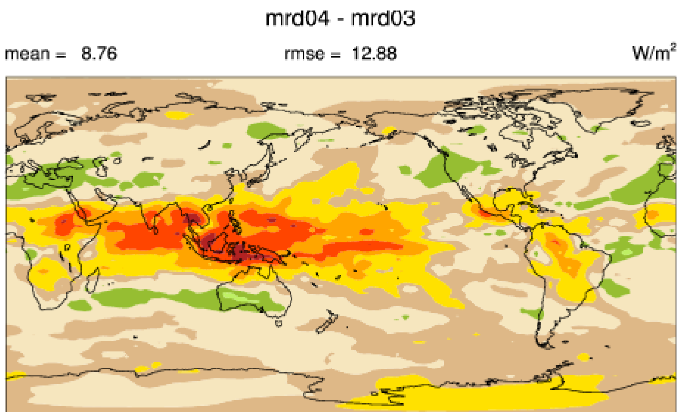


Figure 9. SWCF for the tropical anvil SD run minus SWCF for the mid-latitude SD run.

Figure 10. Zonal mean SWCF for the tropical (red) and mid-latitude (blue) SD CAM runs.



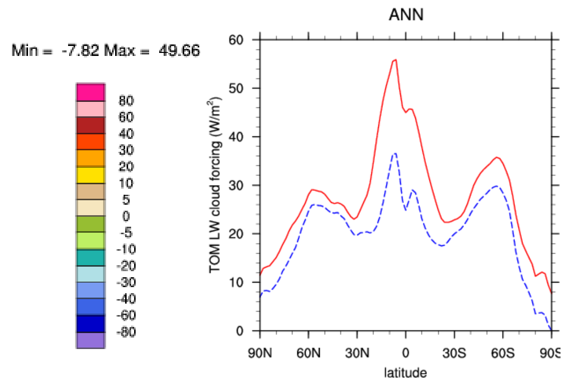


Figure 11. LWCF for the tropical anvil SD run minus LWCF for the mid-latitude SD run.

Figure 12. Zonal mean LWCF for the tropical (red) and mid-latitude (blue) CAM runs.

yielded SWCF up to –25 W m^{-2} stronger and LWCF up to 20 W m^{-2} stronger relative to the mid-latitude simulation. For this CAM experiment, the tropical anvil SD simulation has a net cooling effect in the tropics of about 5 W m^{-2} relative to the mid-latitude run. This is comparable to the net warming directly induced by greenhouse gases in this region. Both the magnitude of these cloud forcing differences and their net effect indicate that the feedback effect of cirrus clouds in response to atmospheric warming by greenhouse gases will be sensitive to the type of SD scheme used in a GCM. This may be a general result applicable to all GCMs that contain realistic coupled parameterizations of ice cloud microphysics and radiation.

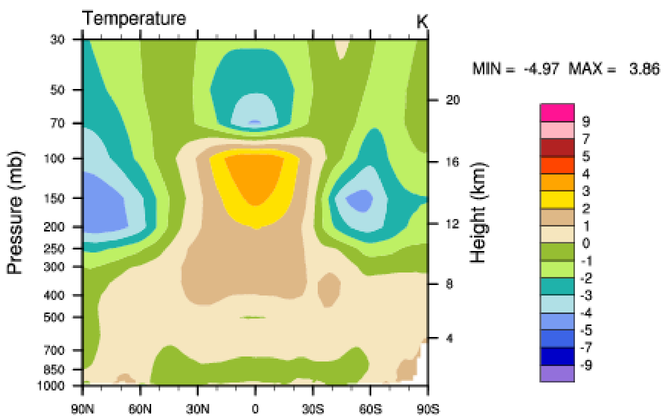


Figure 13. Temperature differences between tropical anvil and mid-latitude SD simulations.

2.3 Impact on upper troposphere heating rates and temperature

The SW heating rate increases in the tropical run relative to the mid-latitude run range from about 0.05 to 0.15 K/day, while the LW heating rate increases (i.e. reduction in LW cooling rates) range from about 0.1 to

0.25 K/day (not shown). These heating rate increases combine to produce a temperature increase reaching about 3.5 K in the tropical upper troposphere, relative to the mid-latitude SD run, as shown in Fig. 13. This is a dramatic temperature increase and sensitivity for a region that can strongly influence deep convection and the general circulation. The region of this temperature increase is under-predicted with respect to temperature by some GCMs, and is known as a “cold bias”. These results suggest such a cold bias may be remedied by an appropriate choice of the SD scheme.

The sensitivity of the CAM cloud forcing and temperature to the SD scheme used results from (1) the direct radiative effect of the SD as described in Figs. 3-4 and (2) the dependence of sedimentation rates on the SD, which affects the IWP and cloud coverage.

3. REFERENCES

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