SIO 217A: ROAST Project 2014

Radiative Cloud Study

Mid-Latitude Cirrus Thinning and Thickening: A Radiative Sensitivity Study

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1. INTRODUCTION

Global average surface air temperature (SAT) has been significantly increasing since the industrial revolution [*Trenberth et al.,* 2007]. This has led the scientific community to focus their efforts on understanding how and why climate will be impacted by such a change. Additionally, considerable resources have been dedicated to geoengineering the large-scale climate to reduce global warming. Solar radiation management is widely considered by the Intergovernmental Panel on Climate Change as a viable option.

Solar radiation management attempts to manipulate the amount of solar radiation incident on the Earth's surface to manage global average SAT. Large amounts of absorption at the surface of shortwave radiation will increase SATs. In turn this will increase outgoing longwave radiation emitted by the Earth, which will cause higher absorption of greenhouse gases. These gases will re-emit in all directions thereby further increasing the amount of longwave radiation absorbed at the surface. Proposed efforts to manage the amount of incoming solar radiation range from increasing cloud albedos [*Latham*, 2002] to obstructing solar radiation with space-based mirrors [*Bewick et al.*, 2012]. In the context of manipulating cloud albedo, special consideration has been given to cirrus clouds.

Cirrus clouds are mainly composed of ice crystals and have temperatures ranging from ~185K-210K. Such clouds tend to be found between 8-20km with an average cloud depth of 4.5km [*Orikasa et al.*, 2013]. Due to the large concentration of ice crystals found in cirrus clouds, the optical and radiative properties are non-trivial as they depend on the size, shape, and orientation of ice crystals. In general, cirrus clouds have high albedo and are effective at reflecting shortwave radiation, which acts as cooling effect on climate. Ice-crystals can also be strong absorbers of longwave radiation and therefore act as a warming effect on climate. Thus, geoengineering research has been aimed at maximizing the albedo of cirrus clouds while reducing the relative amount of longwave radiation absorbed. In this project, we use observed ice-crystal particle size distributions in a mid-latitude cirrus cloud in an attempt to find this "goldilocks zone" and improve our understanding of the relative role cirrus clouds play in the climate system.

2. METHODS: MODEL, OBSERVATIONAL DATA, & ASSUMPTIONS

The number concentrations of the ice crystals reported by [*Orikasa et al.*, 2013] come from a series of 37 mid-latitude cirrus ballooning experiments from the periods of 1994 to 2007. The ice crystal imaging system on board the balloons payload is the hydrometeor videosonde or HYVIS. The HYVIS instrument is capable of measuring ice crystals with radii of 10μm to 200μm with uncertainties of a factor of 3 from 10-30μm and of a factor of 2 above 30μm.

The data of the HYVIS instrument is given on a scatter plot of the number concentration, in units of $m^{-3}\mu m^{-1}$, versus the maximum dimension, in units of μm. Since the number concentration is normalized by the bin size of the ice crystal sizes, it is required to multiply the concentration by the bin size to get the true concentrations [e.g., *Seinfeld and Pandis*, 2006]. The maximum dimension quantity is used in place of radius because ice crystals are non-spherical.

However, due to the enormous level of added complexity in determining the radiative properties of the actual shape of ice crystals, for the purpose of this study we are assuming ice crystals to completely spherical and the maximum dimension to be the radius.

Given the particle size distribution the ice water path and effective radius can be determined by a series of intermediate steps. From here, the optical depth can be calculated. For brevity we do not show the equations describing ice water path, effective radius, or optical depth. The full derivations can be found in *Thermodynamics of Atmospheres and Oceans*, [1999]. Upon calculating the optical depth of the cirrus cloud, the shortwave absorptivity can be calculated using the methods presented by [*Ramaswamy et al.*, 1989]. It is important to constrain shortwave absorptivity because it can be used as an intermediate step to calculated reflectivity. If absorptivity (A) and transmissivity (T) are known then reflectivity (R) is:

$$R = 1 - A - T \tag{1}$$

where,

$$T = e^{-\tau * \sec Z} \tag{2}$$

and

$$A(\mu,\tau) = 0.5(0.346 + 0.234F_1 - 0.076F_2 + 0.014F_3) + K_2(0.267 + 0.048F_1 - 0.012F_2 - 0.006F_3) + K_3(-0.006 - 0.005F_1 + 0.005F_2 - 0.005F_3) \tag{3}$$

where,

$\mu = \cos(z)$, z = zenith angle; $F_1 = 0.1\tau - 1$;
τ = optical depth; $F_2 = 2F_1^2 - 1$;
$K_2 = (2\mu - 1.01)/0.99$; $F_3 = 4F_1^3 - 3F_1$;
$K_3 = (2K_2^2 - 1)$;

It is important to note that this absorptivity is defined for a specific optical depth range of $0.5 < \tau < 20$. The values for the incoming shortwave radiation and the outgoing longwave radiation were derived for a latitude of 45°. The shortwave mid-latitude solar radiance is given approximately by,

$$F_{short} \approx 0.42 * S_0 * \sin(45^\circ) \approx 400 \text{ W/m}^2 \tag{4}$$

where,

$$S_0 = 1360 \text{ W/m}^2 \text{ (Solar constant)} \tag{5}$$

Equation 4 is evident as about 42% of incoming solar spectrum is in the shortwave. Therefore, we only take into account 42% of the total incident solar radiation at 45° latitude. The longwave radiance value used is 230 W/m^2, which comes from the NOAA climatological table of outgoing longwave radiation (OLR). The troposphere contains nearly 100% of the water vapor found in the atmosphere. Further, water vapor has been shown to be the primary absorber of OLR (REFERENCE). Therefore, full atmosphere OLR can be estimated by measuring OLR out of the top of the troposphere. Cirrus clouds are predominantly found near or above the

tropopause. As a result, the incoming longwave radiation measured at the bottom of a cirrus cloud can be used as an approximation for full atmosphere OLR.

We then were able to scale the relative particle size concentration and begin our sensitivity tests. Each scaling of particle size concentration had unique values for shortwave and longwave reflectivity and absorptivity. Total reflected upward shortwave fluxes and total emitted downward longwave fluxes were calculated for each iteration (each scaling). A change in total upward shortwave flux and a change total downward longwave flux, relative to the value for the original particle size distribution, was calculated for each iteration. Then, the difference between these changes at each iteration was taken as a net warming or net cooling and plotted in the figures below (Figures 2, 5, and 6). For example, if there was a larger increase in total shortwave reflectance than increase in total longwave absorption, there was a net cooling.

3. RESULTS

We present results for our initial sensitivity study, run with the following model conditions: assumed average cirrus cloud thickness of 4000m, zenith angle of 0°, and OLR and F_{short} as approximated for 45° N or S latitude as in Section 2. Figure 1 shows upward reflected SW radiation and downward absorbed (and emitted) LW radiation as a function of cloud thinning or seeding (i.e. scaled particle concentration). Reflectivity in the SW spectrum increases with cloud particle density up to a threshold, but then decreases. LW absorptivity under these conditions reaches 100% at around three times the measured cloud density used in our sensitivity study.

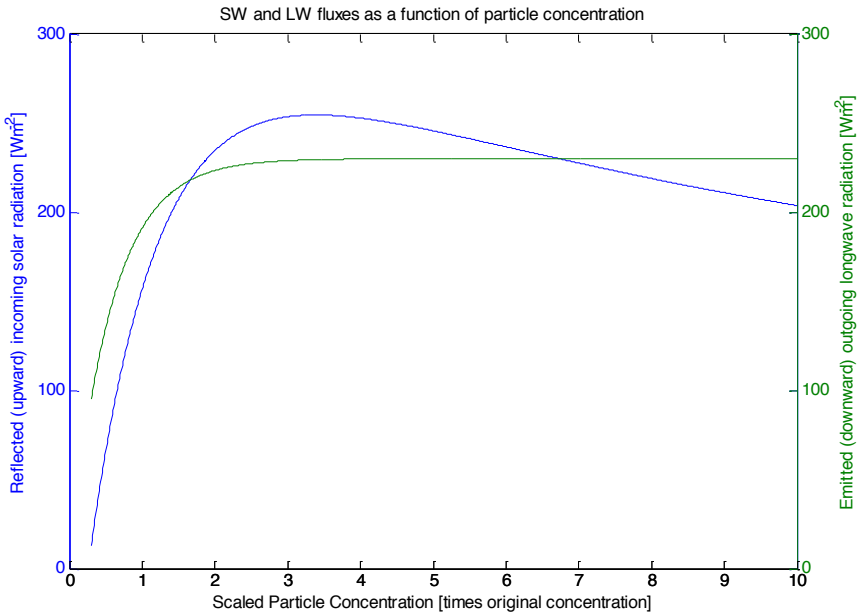

Figure 1: SW reflected and LW emitted fluxes for degrees of thinning/thickening

To determine the ideal degree (scaling) of thickening or thinning the cloud via addition or removal of particles, we performed two separate analyses: one for thinning and one for thickening. When we considered only the thinning, we found that for these assumed conditions (zenith angle of 0° and cloud thickness of 4000m) no amount of thinning would lead to a net cooling effect. That is, there is no scalar below one that, when multiplied by the initial particle distribution, would lead to a larger decrease in LW absorption than SW reflection. Figures 2 and 3 show the radiative effects of thinning.

Figure 2: Reduction in SW reflection associated with reduction in LW absorption for thinning

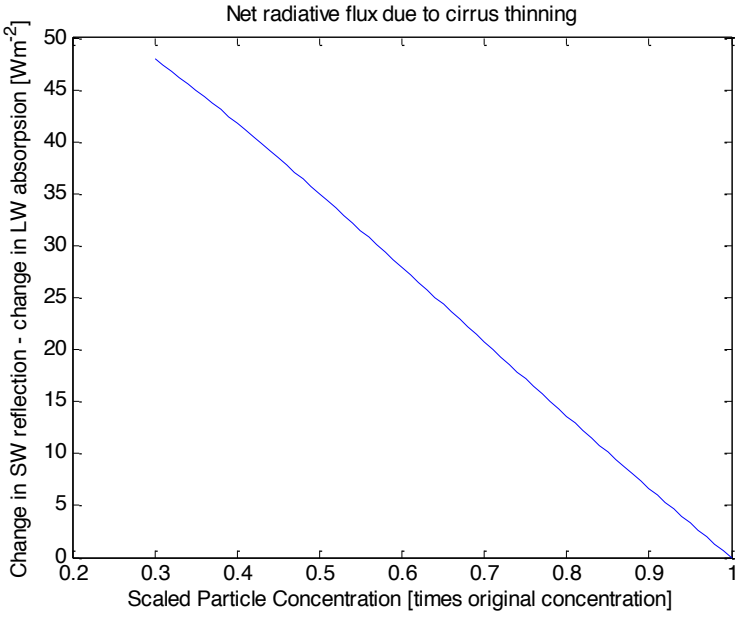

Figure 3: Net radiative flux for cirrus thinning. All values are positive and indicate net warming.

For the second analysis, we considered only cirrus thickening. By increasing the number of particles in the cloud, the net change in total reflected incoming SW exceeded the net change in total emitted LW. That is, for all thicker clouds (1-10 times the original size concentration), there was a net cooling effect. Figures 4 and 5 illustrate this finding. However, by extending the range of maximum particle density scaling, there appears to be a threshold at which increased LW emission is larger than increased SW reflection before reflection dominates once again, as shown in Figure 6.

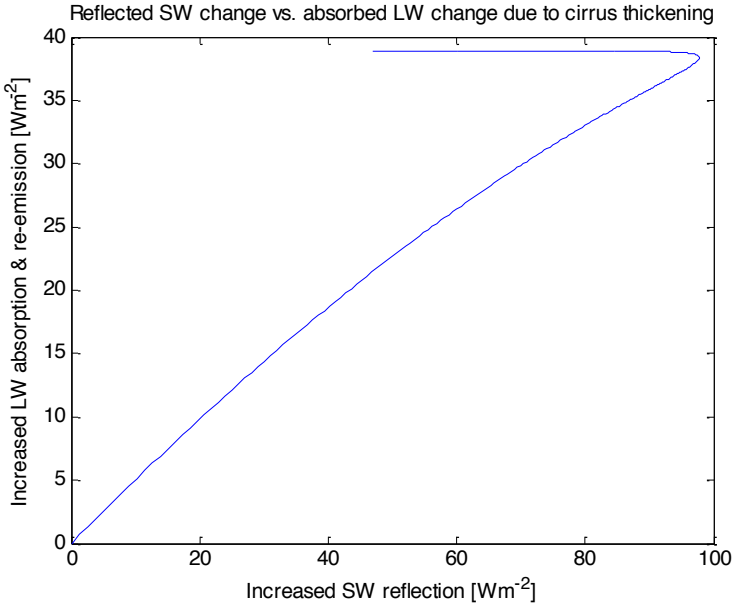

Figure 4: Relationship between increased SW reflection and LW emission for thickening.

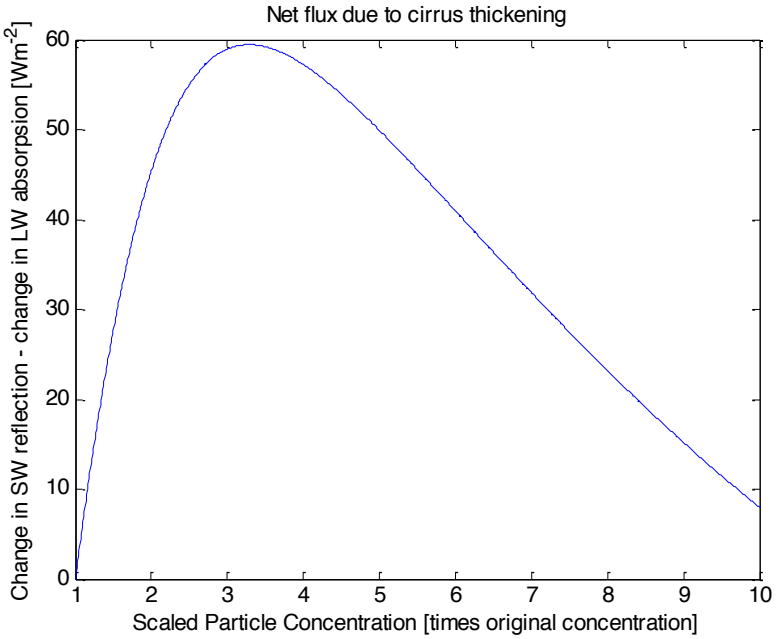

Figure 5: Net radiative flux for cirrus thickening. All values are positive and indicate net warming. Maximum cooling is achieved at 3.29 times the original particle density.

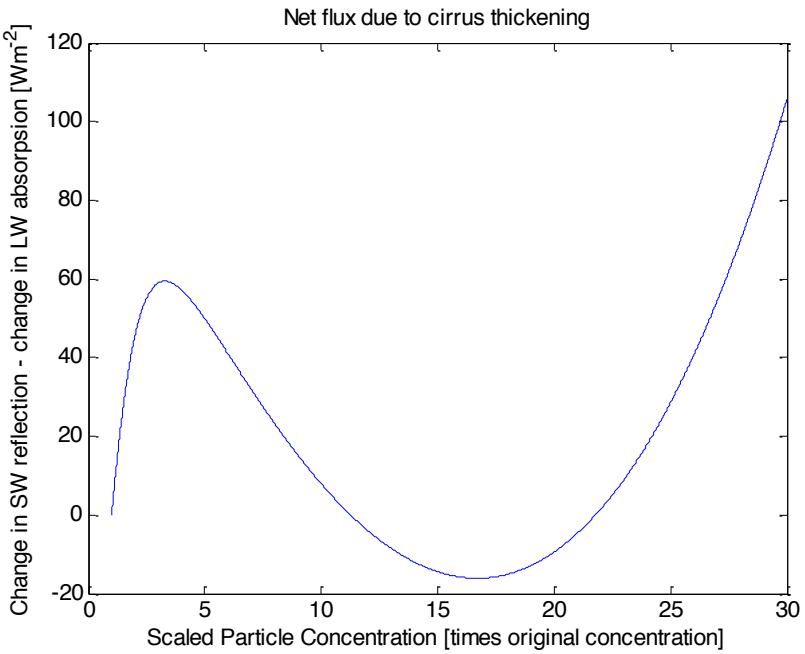

Figure 6: Net radiative flux for cirrus thickening after extending the particle density scaling range. Emission changes dominate reflection changes (net warming) from scalars of ~10 to 23.

4. CONCLUSIONS

In this study, we separately consider thinning and thickening of the cirrus cloud described by [*Orikasa et al.*, 2013] by decreasing the particle density to 0.3 times the original value to increasing the number of particle density tenfold. We considered net changes in total upward incoming SW reflection and downward outgoing LW absorption and emission. We consider a tenfold increase in the cloud particle density to be an upper bound on geoengineering possibilities, thus making a 30-fold increase as in Figure 6 unlikely.

Under our initial assumptions about the zenith angle and average cloud thickness, we found that a 3.29 times increase in the particle density of this particular cirrus cloud would maximize cooling. However, the zenith angle and cloud thickness play important roles in the radiative properties of clouds. Modifying them in this sensitivity study showed substantial changes in our maximal cooling outcomes.

Further analysis might include sensitivity of net radiative fluxes to altering the cloud depth, zenith angle, and assumed SW and LW fluxes coming into the cloud.

5. REFERENCES

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