Final Report

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(I) Project Overview

This document reports on the research that we have done over the course of our two-year project. The report also covers the research done on this project during a 1 year no-cost extension of the grant. Our work has had two main, inter-related thrusts: The first thrust was to characterize the response of stratocumulus cloud structure and dynamics to systematic changes in cloud infrared radiative cooling and solar heating using one-dimensional radiative transfer models. The second was to couple a three-dimensional (3-D) solar radiative transfer model to the Large Eddy Simulation (LES) model that we use to simulate stratocumulus. The purpose of the studies with 3-D radiative transfer was to examine the possible influences of 3-D photon transport on the structure, evolution, and radiative properties of stratocumulus. While 3-D radiative transport has been examined in static cloud environments, few studies have attempted to examine whether the 3-D nature of radiative absorption and emission influence the structure and evolution of stratocumulus. We undertook this dual approach because only a small number of LES simulations with the 3-D radiative transfer model are possible due to the high computational costs. Consequently, LES simulations with a 1-D radiative transfer solver were used in order to examine the portions of stratocumulus parameter space that may be most sensitive to perturbations in the radiative fields. The goal was then to explore these sensitive regions with LES using full 3-D radiative transfer. Our overall goal was to discover whether 3-D radiative processes alter cloud structure and evolution, and whether this may have any indirect implications for cloud radiative properties. In addition, we collaborated with Dr. Tamas Varni, providing model output fields for his attempt at parameterizing 3-D radiative effects for cloud models.

(II) Activities and Main Results

During the course of our studies, we discovered that clouds with low liquid water paths (LWPs) have some hither-to undiscovered responses to changes in drop concentrations through aerosol indirect effects. Our studies show that increases in drop concentrations through increases in aerosol cause an effective decrease in cloud top radiative cooling for nocturnal stratocumulus. This reduction in cooling then leads to a decrease in vertical motion strength, cloud liquid water path, cloud fraction, and a decrease in cloud emissivity as Figure 1 indicates. Increasing drop concentrations leading to reductions in cloud liquid water paths is in contrast to other studies that have been done of stratocumulus (Lee et al., 2009; Garett et al., 2009). Since the submission of our last

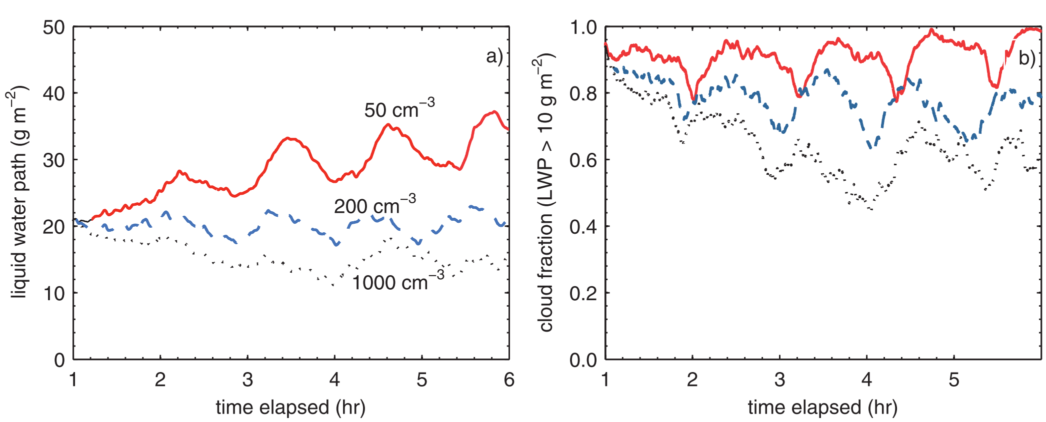

Figure 1: Impact of drop concentration on liquid water path (a) and cloud fraction (b) in low liquid water path clouds. The LES model was spun up for one hour at which time drop concentrations were perturbed.

report, we have discovered reasons for this response. When drop concentrations are increased in the model, entrainment produces stronger drop evaporation and cooling in the vicinity of cloud top. This result occurs because of the increased drop surface area leading to larger evaporation rates. The greater evaporative cooling produces initially stronger downdrafts that can drive even stronger entrainment further reducing the LWP; this process is known as an evaporative-entrainment effect (Wang et al., 2003; Hill et al., 2009) and it can cause decreases in cloud liquid water amounts over time. In clouds with low LWPs, the infrared cooling will also decrease rapidly with the LWP until a new quasi-steady state is reached, or the cloud dissipates. In our case, clouds with higher drop concentrations (200 to 1000 cm^{-3}) approach quasi-steady states whereas the LWP in the low drop concentration case (50 cm^{-3}) continues to climb. The reason our case produces an effect opposite to that of other studies appears to be related to the warmer, and drier, air overlying the boundary layer top. This suggests that the kind of aerosol response one might expect in low LWP clouds may depend on the strength of the thermal and moisture inversions. These results may have important climate implications for geographic locations like the Arctic where thin, low level clouds are frequently observed.

Stratocumuli that occur during the daytime are also susceptible to the radiative-entrainment-dynamic feedbacks described above for nocturnal stratus. During the first hour of diurnal simulations, prior to sunrise, the LWPs

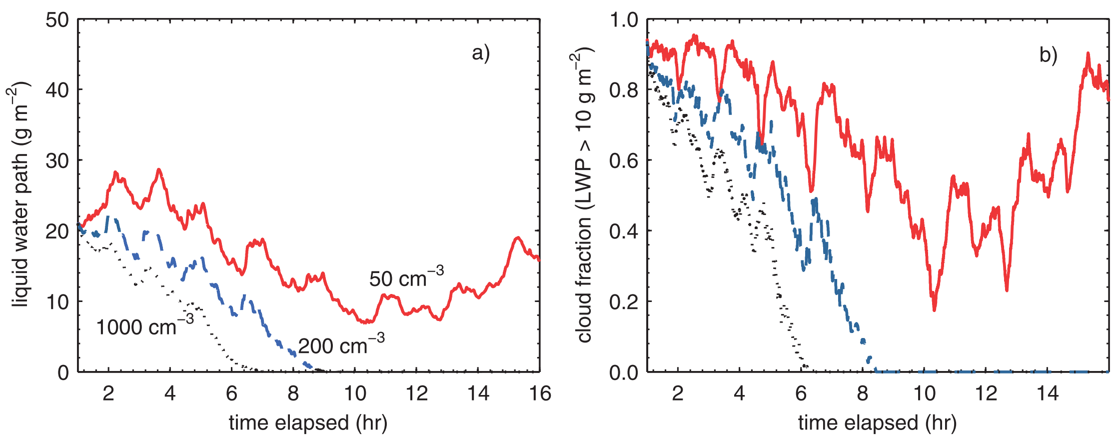

Figure 2: Evolution of the domain-averaged liquid water path (LWP) and cloud fraction for simulations with a diurnal cycle. Sunrise occurs at around hour 2 with maximum solar heating occurring at around hour 8. One-dimensional radiative transfer is used in these simulations.

decrease in the higher drop concentration simulations (Figure 2), and this is due to the entrainment-evaporative feedback described above. These lower LWP clouds are more susceptible to solar heating, which can warm and dry the cloud. Moreover, for the same LWP, clouds with higher drop concentrations can absorb greater amounts of solar energy leading to even greater warming and drying. Therefore increasing drop concentrations for low LWP clouds during the daytime leads to a positive feedback in a negative sense: Larger drop concentrations produce stronger solar heating within the layer which then dries the cloud and reduces circulation strengths. The lower water paths lead to even weaker cloud top radiative cooling that leads to thinner clouds over time and even leads to cloud dissipation for higher drop concentration cases (Figure 2). These results have been published in a paper that appeared this year in the Journal of the Atmospheric Sciences (Petters et al., 2012).

Our LES studies of thick, unbroken and thin, broken stratocumulus with a 1-D radiation model showed that the evolution of thinner clouds tend to be more susceptible to changes in the radiative cooling and heating. This is perhaps not surprising given that cloud top radiative cooling is relatively insensitive to cloud LWP until the LWP becomes less than about 50 g $m^{-2.}$. These clouds seemed to be the most likely candidates for a strong response to the 3-D nature of the solar radiative fields. Because of this, a small set of simulations was run for thinner, broken stratocumulus. In particular, we picked cases that showed a relatively strong sensitivity to changes in solar heating. Despite these “ideal scenarios” we found that including 3-D radiative computations had little effect on the structure, evolution, and radiative properties of the simulated stratocumulus. Our limited studies suggest that it is possible that 1-D radiative transfer may be sufficient for computing the radiative fields for evolving stratocumulus. We stress that our conclusion is based on only a few simulations. There very well could be cloud systems that do show a response to 3-D solar heating. One possibility is cirrus. Cirrus clouds are driven by weaker dynamics, and weaker radiative processes than stratocumulus. As a consequence, cirrus may be susceptible to the 3-D nature of the radiative fields in ways that stratocumulus are not.

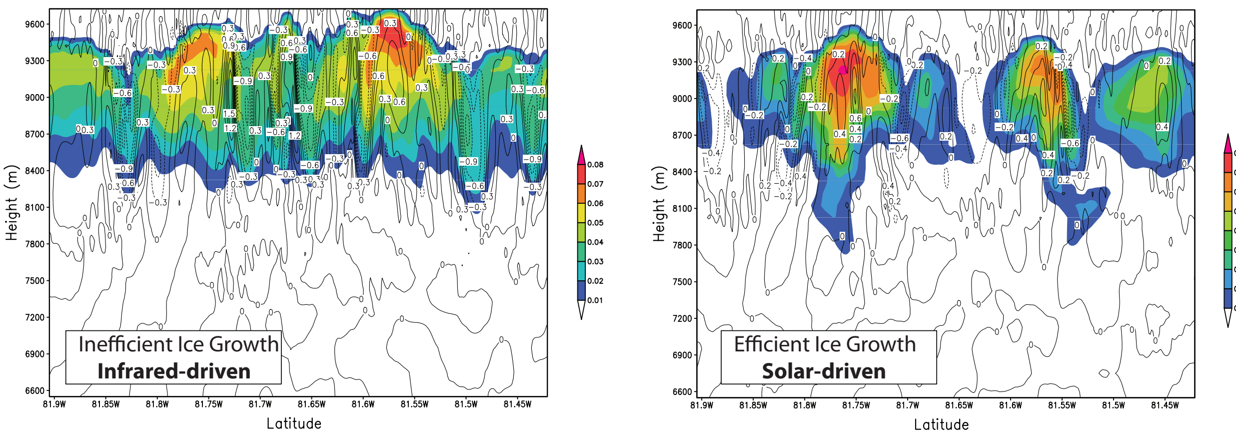

Figure 3: LES simulations of cirrus after 8 hours of simulation. Shades are ice water content (IWC, g m^{-3}) and contours are vertical motion (w, m s^{-1}). Inefficient ice growth produces layered cirrostratus that are dynamically driven by cloud top infrared cooling (left panel). Efficient growth produces broken cirrus uncinus that are dynamically driven by latent and solar heating of the uncinus heads (regions of high IWC, right panel).

The no-cost extension allowed us to finish the stratocumulus work, and publish it, and to begin work on modeling cirrus in an attempt to determine whether 3-D radiative effects may have an impact on cirrus evolution. Harrington et al. (2009) showed that the efficiency with which ice crystals grow in cirrus can determine whether cirrus become layered or broken, cirrus uncinus. During the last year of this grant, graduate student Chengzhu Zhang worked on modeling these scenarios. Each cloud type is driven somewhat differently in terms of the cloud dynamics. The layered cirrus are driven primarily by cloud top infrared cooling, whereas the uncinus are driven by a combination of latent and solar heating of the uncinus heads. When ice crystal growth is efficient, broken uncinus appear and are quite susceptible to the solar warming that occurs (Figure 3). Indeed, once solar heating dies as the sun sets, the uncinus dissipate in our cloud model simulations. Moreover, the transition from cirrostratus to uncinus appears to depend, in part, on the strength of the solar heating. Because the simulated uncinus are sensitive to solar radiative heating, it is certainly possible that the evolution of these clouds may depend on the three dimensional nature of the radiative field. This work formed the final part of Chengzhu′s dissertation, which she successfully defended in August of 2012. We plan to continue this work and attempt to model 3-D photon transport within the cloud model in order to examine whether the 3-D nature of absorption has an impact on the structure and evolution of cirriform clouds.

One journal article based on this work has been published (Petters et al., 2012) and we plan to publish a note on the lack of any sensitivity of 3-D radiative transfer on the structure and evolution of simulated stratocumulus. Jon Petters defended a Ph.D. based on this work and his dissertation is available on line. Chengzhu Zhang completed simulations of cirrus producing layered and broken cirrus. The last chapter of her dissertation is based on this work, and we hope to continue these studies in the future by including 3-D photon transport.

Publications and Dissertations Generated

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