Clouds in a Warmer Climate: Friend or Foe?
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Abstract
From our own personal experiences, we have felt the cooling of clouds shielding us from the sun on a hot summer day, and we have missed their warming during cold winter nights with clear skies. We have welcomed the rain during periods of drought, and have despairs from lost life and property when rain is too abundant. Understanding the behavior of clouds is critical for sustaining human life on the planet. Clouds help dictate the global mean temperature and the amount of water passing through the global hydrological cycle. From calculations based on observations over the last half-century, clouds reflect approximately 20% of the sun’s radiation back to space, and precipitate one meter of rainfall annually over the globe. Will these numbers increase or decrease as the earth warms? The answers are currently unknown, and are not easily found. This paper consists of a brief overview of the major issues relevant to clouds and climate change, followed by a presentation of new work performed by the author on the effects of a warmer climate upon the efficiency with which clouds precipitate.

Introduction
Past and Current Research, and Difficulties. The role of clouds in modulating the earth’s climate is complex. Clouds can shield the earth’s surface from incoming solar radiation, helping to cool the earth like the relief we feel beneath the shade of a tree. The clouds having the most impact are those that have smaller droplets, and are closer to the earth’s surface, and especially over the oceans. The emission of radiation by the earth, like that on a cold, clear night, is limited by the presence of higher-altitude clouds, warming the earth. The current best estimate is that the net effect of clouds on the radiation balance of the earth is a cooling effect- approximately 0.7 W m⁻². This figure is a median value of the estimates, and there is still a significant amount of uncertainty (Forster et al., 2007). In this sense, though, clouds can be thought of as “friend”, helping to offset the warming climate.

These two effects upon the radiation balance of the earth have dominated the literature related to clouds and climate change. The radiative roles of aerosol acting within clouds, the so-called “first indirect effect” that represents enhanced reflecting of solar radiation back to space via decreased droplet size within the clouds resulting from more aerosol, the “second indirect effect” that describes how additional aerosol can slow precipitation formation and thus increase cloud longevity and the amount of solar radiation reflected back to space, and the “semi-direct effect” of soot aerosol within cloud droplets warming the cloud and decreasing its lifetime and the amount of solar radiation reflected back to space, have all been under intense investigation (Forster et al., 2007). Quantification of these effects is paramount to understanding how much the earth will warm, globally and regionally (Stephens 2005). And yet, progress has been slow. The latest IPCC assessment states “The response of cloud cover to increasing greenhouse gases currently represents the largest uncertainty in model predictions of climate sensitivity…” (Trenberth et al., 2007) and furthermore, “In response to global warming, the cooling effect of clouds on climate might be enhanced or weakened…” (Randall et al., 2007).

Why is the influence of clouds so difficult to determine? The reasons are multifold. From a cloud microphysicist’s view, significant details of precipitation processes in clouds are still unknown. Current theory cannot explain how warm, shallow clouds form rain as quickly as they do, nor can it explain the large quantities of ice observed in deeper clouds. General principles of precipitation formation are understood, but fundamental knowledge essential for prediction of precipitation has remained elusive and thus confounds estimates not only of precipitation but also of cloud characteristics important for their influence on the radiation budget such as particle size, cloud areal coverage, and longevity. Although hypotheses abound regarding the details of precipitation processes, past and present capabilities in experimental, observational, and numerical methods fall short of providing enough information to test these hypotheses sufficiently. No method, experimental, observational or numerical, can address all the scales of the problem simultaneously: the aerosol that nucleate cloud droplets are on the order of tenths of micrometers, and the extent of clouds and their accompanying motions that must be considered can be as large as hundreds of kilometers (Fig. 1). Different methods can study a subset of the scales involved while neglecting effects outside of that range, but merging the results with those at other scales remains an ongoing challenge.

An Additional Area of Inquiry: Precipitation Efficiency. From calculations based on observations over the last half-century, clouds precipitate one meter of rainfall annually over the globe (e.g. Wallace and Hobbs, 2006). Different regions receive more or less than this amount, determined not only by large-scale and regional weather patterns, but also the local aerosol and thermodynamic characteristics of the environment. Recently, numerous studies have begun to investigate how the precipitation efficiency¹ of clouds (e.g. Douville et al., 2002;

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¹ The precipitation efficiency, defined in the simplest sense, is the ratio of the amount of water mass brought to the ground (i.e., precipitation) to the amount of water mass ingested by the storm (i.e., water vapor brought into the
Lau and Wu, 2003; Wang, 2005; Khain et al., 2005; Lin et al., 2006; Cohen and McCaul, 2007) with respect to aerosol and climate changes, but they have not yet converged upon a general result, if one exists. Trenberth et al. (2007) summarize the evidence of the changing character of precipitation and the limitations of such evidence, but note that some long-term trends in the last century are emerging: eastern North and South America, northern Europe and northern and central Asia are receiving significantly more precipitation, while the Sahel regions, southern Africa, the Mediterranean and southern Asia have seen a decrease in precipitation. In colder regions around the globe, some snowfall has been replaced by rainfall. And in many areas over the globe, heavy precipitation events have increased, even in regions where overall precipitation has been declining. Easterling et al. (2000) discuss the increasing trend in extreme precipitation events over the last century, and some of the financial and biological tolls associated with such events. It appears that with regard to precipitation as the climate changes, clouds can be both “friend” and “foe” to humankind, and there may not be one global answer.

Understanding how precipitation efficiency will be affected with respect to global warming could be accelerated by additional investigation of how precipitation processes may change, details that have not been widely studied. None of the studies discussed above have investigated these details, either because the observations were acquired over much larger scales, or the numerical modeling cannot represent these microphysical details. A preliminary study investigating one example of how the details in precipitation processes may change under the influence of global warming is now presented, to illustrate where further work is required.

Warm and Cold Rain Processes

In clouds having their entire depth at temperatures greater than 0 °C, rain may form from the so-called warm rain process, where cloud droplets nucleated upon special aerosol particles (called cloud condensation nuclei, or CCN) near the base of the cloud grow by condensation as they ascend within the cloud, and once achieving large enough sizes, grow by collection of smaller drops to produce drizzle or raindrops. As raindrops grow, they may collide and break up, or become unstable and break up without a collision, thereby increasing the number of large drops collecting smaller drops, and accelerating the formation of additional raindrops.

In clouds having their bases at temperatures greater than 0 °C, but tops at temperatures less than 0 °C, both warm rain and ice processes are active. In such clouds, warm rain processes act below the freezing level (the height at which the temperature is at 0 °C), but ice particles are also initiated above the freezing level that interact with the supercooled liquid cloud droplets in a variety of ways. As these frozen particles grow too large to be suspended in the cloud, they fall toward the earth’s surface and melt to form raindrops. The combination of warm rain and ice processes is responsible for the majority of rainfall over the earth.

Many factors can aid or hamper the production of rain, however. The amount of CCN that the cloud ingests, the thermodynamic environment in which the cloud grows, changes in the direction and speed of the wind over the depth of the cloud, the overall cloud lifetime, etc., all affect the amount of precipitation reaching the ground.

As discussed in the introduction, because of the broad range of scales involved in the problem, compromises must be made in studying factors influencing rain production. The role of the thermodynamic environment in controlling the efficiency of warm rain processes that may then impact ice processes is examined in the present study. This role is especially relevant as scientists work to understand how the weather on a warming Earth will change, how precipitation may change globally and regionally, and what feedbacks in the Earth’s hydrological cycle may act to enhance or counteract this warming.

Model Description and Setup

In this preliminary study, a compromise has been made to examine the effects of a warmer, moister atmosphere on the products of the warm rain process in deep convective clouds by using a very simplified treatment of the air motions within such clouds. The microphysical parcel model of Cooper et al. (1997) is an excellent candidate because it represents many microphysical details of warm rain processes faithfully (nucleation of cloud droplets according to the sizes and chemical composition of the nuclei, growth by condensation of water vapor, and growth by collection of other droplets). Raindrop breakup was not represented in the present framework. The model is initialized with a spectrum of CCN and an atmospheric profile of temperature, pressure and moisture. The model is one-dimensional, in that it represents a volume of air ascending in the center of a cloud, without mixing with any air outside of its boundaries, and ascends initially at a rate of 1 m s\(^{-1}\), and thereafter at a faster rate proportional to its buoyancy.

Four different runs of the model are initialized with different profiles of temperature, moisture and pressure based on regional climate model output (Diffenbaugh et al., 2005). Two of the runs use profiles based on long-term averages of high-buoyancy profiles over the months of March, April and May 1961-1989 for Oklahoma City, OK (denoted OKC) and St. Louis, MO (denoted STL), in the western central U.S. and Midwestern U.S., respectively, and thereafter at a faster rate proportional to its buoyancy.
respectively (J. Trapp, personal communication, 2007). The other two runs use predicted profiles from the regional climate model based upon the possible “SRES A2 scenario” averaged over high-buoyancy profiles from 2071-2099 for OKC and STL. These atmospheric profiles are only used in this study to demonstrate possible influences of a much warmer climate on precipitation processes; the intent of this study is not to predict rainfall changes at these sites specifically. The differences in the “past” and “future” profiles is substantial, as shown in Fig. 2, where the red profiles are shifted to the right on the plots, indicating greater temperatures and moister air. The future OKC temperature profile is approximately 4 °C warmer, and the future STL profile is 2 to 3 °C warmer, than their respective “past” profiles.

All of the microphysical model runs are initialized at the altitude where the base of the cloud would first form and run until the parcel reaches the altitude where the cloud temperature is -12 °C. The air rises in the model at a constant rate of 1 m s\(^{-1}\) until buoyant, at which time it accelerates upward at a faster rate determined by the buoyancy in the atmospheric profile. An aerosol spectrum representative of that which might be found over the central part of a continent is used for past and future runs for both locations.

**Results**

For both OKC and STL, the altitude of the cloud base was lower for the future (warmer) scenario, and as such the cloud base was warmer (Table 1) and had more initial moisture. As a result of the warmer cloud bases, fewer cloud droplets were nucleated in the future clouds (6-7%), consistent with the study of Johnson (1980) that looked at the thermodynamics of nucleated cloud droplets for different cloud base temperatures and pressures. Although this reduction in cloud droplet number is not substantial, it has long been established that lower droplet concentrations help to accelerate the warm rain process (e.g. Pruppacher and Klett, 2001).

More importantly, the vertical distance between the cloud base and the height of the freezing level (the height of the 0 °C isotherm) increases by 600-700 m from the “past” environment to the future environment for OKC and STL, respectively. In general, this allows more condensation and droplet collection to occur, before any cloud drops or raindrops can freeze. This difference in the height of the freezing level is also indicated by the liquid water content differences in the past and future scenarios (Table 1), where the liquid water content at the height of the freezing level increases by 0.5 g m\(^{-3}\) for OKC, and 0.7 g m\(^{-3}\) for STL. This implies that significantly greater amounts of liquid water are present to enhance ice processes in the future clouds than in the past. However, the time for growth by the warm rain process is also important, and it is here that a difference between the OKC and STL results appears. In the OKC cases, the time that the cloud droplets have to grow before reaching the freezing level is approximately 30 min, and is nearly two minutes longer in the future scenario than in the past, because the buoyancy, which controls the ascent rate of the cloudy air, is nearly the same at the lower levels in the past and future scenarios. This extra time, coupled with the greater thermodynamic difference between the base of the cloud and the freezing level, creates a more favorable setup for the warm rain process, and results in a larger cloud droplet mode radius (Table 1) and an increase in precipitation water content (PWC) by over 60% (Table 1, Fig. 3 –top) in the future scenario for OKC.

For STL, the droplets actually have less time to grow from the cloud base to the height of the freezing level in the future scenario. Although the depth from cloud base to the height of the freezing level is greater in the future environment, the buoyancy at lower levels is also greater than in the past, resulting in a faster updraft that carries the droplets more quickly to the freezing level. Thus, although the total liquid water content at the freezing level is greater for the future STL cloud, and even significantly greater than the future OKC case, little of it has been converted to precipitation, because of the shorter time for growth to this altitude (approximately 21 min, compared to the 30 min for the OKC case). The time limitation in the future STL case is indicated by the small increase in the mode of the cloud droplet radii between the past and future cases; there is only a slight increase in the future run due to the limited time for droplet growth. Nonetheless, more precipitation is still produced in the future cloud than in the past: the amount has doubled at the freezing level (0.2 to 0.4 g m\(^{-3}\)) between the past and future scenarios (Table 1, Fig. 3 bottom).

Another difference in the OKC and STL results is the number concentration of drizzle and raindrops. The number concentration of drizzle and raindrops actually decreased between the OKC past and future scenarios, but increased for the STL runs (Table 1). This result is not surprising, given the neglect of raindrop breakup in the model. As raindrops grow by collection of smaller drops, they can break up into 1-20 satellite drops, which can then continue to grow by collection on their own (Low and List, 1982). Because this process was not represented in the model, raindrops greater than 7 mm are created in all cases (Fig. 4), and yet raindrops observed in nature in deep convective clouds are usually limited to a maximum radius of 2.5 mm. Thus, if drop breakup were represented in the model, the number concentration of raindrops listed in Table 1 would be much greater, at least an order of magnitude, and perhaps several more. In the STL results, where less time was available for the warm rain process...

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to act, and so fewer raindrops were able to grow to breakup sizes, the neglect of drop breakup does not mask the expected trend that greater numbers of drizzle and raindrops occur in the future scenario, although these numbers are still underestimated.

Implications

Given these trends of more raindrops entering the colder part of the clouds, what implications would these trends have on the cold rain processes, and the efficiency with which future storms precipitate? Because of the limitations of the simple model used here, the results of past studies are drawn upon to speculate on these issues. Future work will be needed to investigate which, if any, of these possibilities are realized.

The laboratory results of Bigg (1953) and others have shown that larger raindrops tend to freeze more quickly. Given that the future clouds tended to introduce larger raindrops into the colder levels of the clouds where freezing would start to occur (Fig. 4), this suggests that they would freeze faster in the future clouds. This releases latent heat, strengthening the buoyancy and thus the ascent rate of the air within the cloud (Cotton, 1972). These frozen raindrops then continue to grow by collection of the smaller supercooled droplets.

A study by Johnson (1987) showed that these frozen raindrops are capable of collecting much more cloud water than unfrozen raindrops, by the time they fall to the ground as precipitation. This then implies that more water mass from the cloud could be brought to the earth’s surface as precipitation, increasing the overall precipitation efficiency of the storms in the future, all else being the same. In fact, these results are exactly those that some past cloud seeding studies have tried to produce in order to increase rainfall (Cotton, 1982).

Many other factors need to be considered, however, to understand if this influence on precipitation efficiency would be realized. Other factors controlling the precipitation efficiency that need to be assessed include (i) the amount of water vapor brought into the cloud during its lifetime, (ii) losses of water mass by entrainment or evaporation of the falling raindrops, (iii) the effects of wind shear, (iv) the influences of atmospheric aerosol, and (v) more microphysical processes, including drop breakup, ice processes, and melting of particles as they fall to the ground. A plethora of studies, including more sophisticated models that look at the dynamics of these storms, as well as microphysical processes involving ice, must be conducted. Observational support of the model approximations and results will be required by using storm and precipitation observations from different parts of the world having different atmospheric temperature and moisture profiles. And finally, the influence of changes in aerosol on these precipitation processes must also be considered.

Conclusion

Are clouds a friend or foe with respect to global warming? From the most recent, best estimates, clouds appear to be a “friend” in that they help to cool the earth and offset global warming, but it is yet too early to tell how their assistance may change as the earth’s climate changes. Until now, the focus of such studies has been upon radiative effects of clouds, but the preliminary study presented here is designed to emphasize another important branch of inquiry: the efficiency with which clouds produce precipitation as the climate changes. The results illustrate that a warmer climate allows warm rain processes to act within deeper portions of deep convective clouds, and that raindrops formed by such processes should increase in number and size. As these more abundant, larger raindrops enter the freezing portions of the cloud, past studies suggest that they can increase the amount of water mass brought to the ground as precipitation. If all other factors are equal, then a warming climate may lead to an increase in precipitation efficiency in future storms. This increase could be beneficial in providing more rainfall, but also detrimental by encouraging flooding. Determining if this scenario is realized, and if its impact upon human life is favorable or not, awaits further study of other influences on precipitation processes that have not yet been included in the present model framework.

References


Table 1: Microphysical Modeling Results

<table>
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<tr>
<th>OKC RUNS</th>
<th>PAST</th>
<th>FUT_A2</th>
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<tbody>
<tr>
<td>Total run time (s)</td>
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<td>2020</td>
</tr>
<tr>
<td>Min T (°C)</td>
<td>-12</td>
<td>-12</td>
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<tr>
<td>Cloud base T (°C)</td>
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<td>15.5</td>
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<tr>
<td>Max altitude (km)</td>
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<tr>
<td>Altitude of FL (km)</td>
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<tr>
<td>Max velocity (m s^-1)</td>
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<td>19</td>
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<tr>
<td>Time run to FL (s)</td>
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<td>1870</td>
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<tr>
<td>LWC at FL (g m^-3)</td>
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<tr>
<td>PWC at FL (g m^-3)</td>
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<td>3.5</td>
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<tr>
<td>Mode radius at FL (mm)</td>
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<td>19</td>
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<tr>
<td>Initial drop conc (cm^-3)</td>
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<td>444</td>
</tr>
<tr>
<td>Driz/rain conc at FL (L^-1)</td>
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<td>0.3</td>
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</table>

<table>
<thead>
<tr>
<th>STL RUNS</th>
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<td>Total run time (s)</td>
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<td>1400</td>
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<tr>
<td>Min T (°C)</td>
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<tr>
<td>Cloud base T (°C)</td>
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<tr>
<td>Max velocity (m s^-1)</td>
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<tr>
<td>Time run to FL (s)</td>
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<tr>
<td>LWC at FL (g m^-3)</td>
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<td>PWC at FL (g m^-3)</td>
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<tr>
<td>Modal radius (mm)</td>
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<td>17</td>
</tr>
<tr>
<td>Initial drop conc (cm^-3)</td>
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<tr>
<td>Driz/rain conc at FL (L^-1)</td>
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<td>1.3</td>
</tr>
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</table>

Note. Model results are reported for calculations at 0 °C, based on the 1961-1989 average profiles (PAST) and the 2071-2099 A2 simulated climate average profiles (FUT_A2). ‘FL’ denotes freezing level, ‘LWC’ denotes liquid water content, and ‘PWC’ denotes precipitation water content.
Figure 1. Examples of the range of scales involved in precipitation formation.

- Cloud scale (1 km - 1000 km)
- Cloud Drops/Ice Crystals: 1 μm to 1 mm
- Cloud condensation nuclei (Aerosol): < 0.1 μm to 100 μm
Figure 2. Temperature (solid lines) and moisture (dashed lines) for 1961-1989 average atmospheric profile (dark grey) and the 2071-2099 A2 simulated climate average profile (light grey) for Oklahoma City, OK, USA (top) and St. Louis, MO, USA (bottom).
Figure 3. Amount of precipitation formed in the model for OKC (top) and STL (bottom) for the entire runs, using the atmospheric profiles indicated. Dashed vertical line indicates amounts of precipitation crossing the 0 °C threshold, entering into the colder parts of the cloud.
Figure 4. Drop size distributions (number per unit volume, versus size) for the past and future OKC runs (top) and STL runs (bottom). Note largest drops are produced in the future runs, and that the sizes at the peaks in the distribution (mode radius, in Tables 1 and 2) are larger for the future runs.