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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Initiation of coalescence in a cumulus cloud: a beneficial influence of entrainment and mixing" *by* W. A. Cooper et al.

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Response to Reviewers of Manuscript acp-2011-33

Response to Anonymous Referee #1:

This review is hard to respond to because it is basically a judgement that the material is not sufficiently new to be published in this form. That is a judgement that we acknowledge but do not share. Our response will therefore be to outline what we think is new, as is highlighted in the paper, and to suggest that this is indeed a worthwhile addition to the body of work on warm rain. The reviewer does not dispute the facts or conclusions of the paper, only its significance, so we will confine our response to that

topic also.

This work is an outgrowth of our 2005 paper, called LCB05 in the manuscript, which dealt with broadening of droplet size distributions. Here we extend those results to the initiation of warm rain. LCB05 established one aspect of the modeling effort needed for the present study, the ability to calculate droplet size distributions that are realistic, sometimes include larger sizes than produced by adiabatic ascent, and otherwise have characteristics similar to observed size distributions. This is a preliminary requirement if the development of droplet size distributions are to be used in a realistic calculation of the initiation of warm rain, and we argue that this is new and was certainly not part of the studies from the 1980s that the reviewer cites. Yes, it has long been known that entrainment is responsible for the broadening of droplet size distributions, and there have been many previous calculations supporting this. The advance, we suggest, is that those concepts are here presented in a detailed 3D model with realistic dynamics, thermodynamics, and entrainment, and in a modeling framework that includes a means of performing high-resolution microphysical calculations of the development of the droplet size distribution. We therefore argue that these results take those general concepts from earlier work and apply them in a rigorous test, to determine if it is possible to account for rain formation in the time available in a small cumulus cloud.

It is this quantitative test that is new in this work. The title, introduction, and conclusions highlight these aspects of the work, although we did think it useful to consider the effects of giant nuclei and other contributions that the reviewer cites. The summaries we offer do not emphasize, as the reviewer does, that the "ostensibly new feature here is that in order to form raindrops the few large droplets so produced must find themselves in regions of sufficiently high liquid water content that further collisions become probable." Instead, the new feature is that warm rain forms in a reasonable time through the modelled precesses, and that realistic calculations of the effects of entrainment show that the associated broadening of the droplet size distributions is an important contributing factor. Demonstration of this result is a long-standing goal in cloud-physics studies, and we argue that we are close but not quite fast enough to be realistic because the development of rain remains a little slower than in the observed cloud on which the study was based. The study still indicates that something is missing in these calculations, most likely the incorporation of realistic effects of turbulence on the collection kernel, or maybe even our knowledge of collision efficiencies.

The reviewer is right that we did not show detailed observational data, except for summary statements regarding the rate of radar-echo formation and the nature of the observed cloud. Detailed comparisons to droplet size distributions in a similar setting, based on observations from the same field experiment, were presented in LCB05, and we did not think it necessary to repeat those comparisons. Detailed comparison to the observed case would be a proper subject for a paper on its own, but the reviewer already complains that the paper is too long and we thought inclusion of additional observational comparisons here would add too much to the length and would detract from the main point, which is highlighted in the "central premise" of the paper.

The reviewer also argues, "No significant improvement in predictive skill comes from these studies because a few random events make the difference and these are basically unpredictable." Although our goal is to study fundamental processes rather than, at this point, to develop predictive skill, we argue that we have demonstrated an ability to develop warm rain through rigorous prediction based on a best representation of current knowledge. That is clearly an advance in predictive skill, in our opinion. Despite that, the development of rain is somewhat slower than expected, suggesting that there are still missing factors. That result is also significant and new, and worth follow-up calculations that will benefit from having this paper published.

Far from being at a dead end, as the reviewer suggests, we see this study as the foundation for several follow-up studies, including incorporation of still-missing effects (most importantly, the effect of turbulence on the collision kernel), further study of the roles of giant nuclei, detailed comparison to observations, and specific sensitivities to CCN and other variable aspects of the environment in which warm-rain forms. This study is

also preliminary to performing these calculations at higher resolution and in a fashion that integrates microphysics and dynamics without the need for the hybrid scheme that is the main weakness of the present approach. The hybrid scheme, while still necessary to achieve the desired resolution in this study, is unsatisfactory, and computing capabilities are reaching the point where it should not continue to be necessary. Nevertheless, the hybrid scheme used here clearly indicates the potential for proceeding via these pathways to a better capability for calculating the development of warm rain in a predictive sense.

Response to Anonymous Reviewer #2:

The first bullet in the review by Reviewer #2 is similar to the main point made by Reviewer #1, so please consider the preceding response as a response to Reviewer #2 also. We think there are clear explanations of the significance of the work in the manuscript, but it appears that we have erred on the side of not wanting to trumpet the significance of the work too much, expecting that this would be obvious. The key point here is that this work has arrived at these conclusions by more rigorous calculations than ever attempted before, in a manner that is dynamically and thermodynamically consistent, and have indeed found such calculations predict that warm rain can form in times that are roughly realistic. Past studies have had to compromise in the representation of either the dynamics or microphysics, leaving the scientific community to wonder if the results are applicable in real clouds. The modeling approach presented here makes no compromise in the microphysical calculations, and thus tests the hypotheses in the most rigorous way yet performed. Furthermore, it carries the calculations not only to the embryonic stages of droplet growth, but also includes collision and coalescence, to produce raindrops and to demonstrate that the broadening effects of entrainment and mixing are indeed important for warm rain formation, which other studies have failed to do. It is the totality of the process that is key in this paper. Previous studies, including our own in 2005, did not continue the calculations through to collision and coalescence. That step is significant because sedimentation has caused difficulties in many past numerical modeling approaches. We have found a way to address the issue in this work. It should not be forgotten that it is not possible in this age to run a 3D cloud model with a resolution of 25 m and detailed microphysics. This hybrid approach leading to the formation of raindrops by collision and coalescence is a major advance. Our title, introduction, and conclusions all highlight these aspects of the advance we think this paper reports.

The reviewer is correct that the “central premise” statement has been made before in various forms, but it has not been defended with detailed and realistic calculations such as those presented here. No other study has considered the 3D dynamics of the cloud and a realistic representation of entrainment to the degree it is done in this study. We did not have to conjecture that some larger embryos would be transported into regions of high liquid water content (something people have debated for years); we in fact have showed that it can happen in a dynamically and thermodynamically consistent manner. We argue that there is no other similar test of the statement we characterize as our central premise that is performed to anywhere near this degree of rigor.

Regarding Figure 1: We have found in presentations and discussions of this work that these figures are very helpful to those not used to thinking of turbulent diffusion in clouds and the associated effects on droplet trajectories. The reviewer correctly recognizes that this point was made in previous work, but we still think that the figure is helpful to those less familiar with the effects of turbulent mixing on droplets.

We agree that the results that the reviewer lists at the bottom of p. 1 of the review are not new, although the representation of these effects in detail and in quantitative terms is necessary to the extension to warm-rain. We show those results to illustrate that we have a realistic representation arising from the coupling between dynamics and microphysics and therefore can use the results in our extension to a quantitative calculation of the development of warm rain. This paper follows the entire process from the beginning to the end, resulting in precipitation, which no past study that incorporates all

these effects has done.

We should respond to one part of this list, though, the comment, “(Note that turbulence was not included in these calculations, but the authors indicate in the last section that it will be considered in the future).” In-cloud turbulence most certainly is included in these calculations, and it is central to the results. The 3D dynamical cloud model has a prognostic equation for subgrid-scale turbulent kinetic energy, and these values feed into the random velocity perturbations integrated into the drop trajectories. The turbulent effects that are not yet addressed in the present study are those that influence the droplet collection efficiencies. The latter study is in progress and will be the topic of a future paper.

p. 2 para. 2, re Section 6: The collision and coalescence calculations in the parcel model, leading to the embryos that are injected into the clouds, are based on stochastic coalescence. Only the embryos dealt with in Section 6 are treated via continuous coalescence because they are large enough that all growth occurs via collection of small cloud droplets and so stochastic effects are negligible. A weakness of the modeling approach we use is that these embryos move apart as they grow so we don’t have other large drops of different size in the same air parcels where they might collide with these.

p. 2 para 3, re Section 7: We are not testing to see if coalescence is important; of course it is. What we are trying to learn, by separating out these different effects, is where the effects of entrainment and mixing are most important versus other mechanisms for warm rain formation. The giant nuclei do have a strong effect, and a thorough study on their effects within the context of an entraining cumulus is being pursued, but is beyond the scope of this paper. The central premise is indeed very important to explaining the breadth of the droplet size distribution, as giant nuclei will not broaden the DSD toward smaller sizes. Indeed, it is the formation of drizzle via collisions among droplets in the main peak of the droplet size distribution that is highly dependent on the central premise. It complements the growth of precipitation on giant nuclei, which is also an important source of the first rain. The giant nuclei can have a larger role to play in precipitation formation under particular conditions, such as when the droplet concentration is higher and the rate of production of raindrops is otherwise reduced. We don't understand why the reviewer concludes that "it appears that perhaps the central premise of this study is not as important as suggested," because we think we made a fair assessment of its importance while we considered all these effects. In regard to giant nuclei, we noted on p.1 of the manuscript that "the reduction in rainfall when giant nuclei are excluded (1.9mm hr^{-1} to 0.7mm hr^{-1}, or 1.2 mm hr^{-1}) is similar to the rainrate when only single trajectories are considered (1.1 mm hr^{-1}). This supports the argument that the additional rainfall produced by coalescence in the modal peak of the droplet size distribution arises (in this particular cloud) because of broadening of that main peak via the mechanism that is the central premise ...". This shows that the single-trajectory calculations produce rain mostly because they still contain the giant nuclei, and the additional rain is therefore almost exclusively from the "central premise" effect.

Regarding the reviewer's concluding paragraph: We strongly argue against significantly shortening the paper, as explained in the previous responses. The details required to understand the steps have not been published, and explanation of the entire model approach is required. Furthermore, there are many improvements from previous work, all important to the quantitative conclusion. The model runs require significant effort and computer time, and continuing the studies such as presented in this paper to other clouds is not a practical extension to this paper.The suggestion of comparing with observations in more detail seems useful to us also, but we do not think it is appropriate for this paper because the paper is focussed on the modelling and we believe it has the right length for the results obtained. We do plan follow-up studies such as those suggested, and publication in the form of the present manuscript will be the right reference for those follow-up studies also.

Summary

We hope this response will convince the editor that there is important new material in this paper and that the results indeed represent a significant advance in efforts to understand the formation of warm rain. We urge that the paper be published without substantial shortening because the study is only understandable as a coherent approach in which all important processes are represented accurately.