Can aerosol decrease cloud lifetime?

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[1] Cloud responses to changes in aerosol remain a dominant uncertainty in the radiative forcing of climate. Two main constructs related to aerosol effects on clouds have been postulated: (i) the "albedo effect" whereby anthropogenic aerosol results in increased droplet concentrations that generate increases in cloud albedo, all else (particularly cloud water) being equal; (ii) the "lifetime effect" whereby anthropogenic aerosol suppresses precipitation and results in clouds with more liquid water, higher fractional cloudiness, and longer lifetimes. Based on new observations presented here, and supported by previous fine-scale modeling studies, we suggest that the balance of evidence shows that non-precipitating cumulus clouds can experience an evaporation-entrainment feedback, and respond to aerosol perturbations in a manner inconsistent with the traditional "lifetime effect." Because most cumulus clouds evaporate without producing significant precipitation, this is particularly relevant to estimates of aerosol indirect effects on climate. **Citation:** Small, J. D., P. Y. Chuang, G. Feingold, and H. Jiang (2009), Can aerosol decrease cloud lifetime?, *Geophys. Res. Lett.*, *36*, L16806, doi:10.1029/2009GL038888.

1. Introduction

[2] Small, non- or weakly-precipitating cumulus clouds have been shown to be important to climate. They are globally prevalent over ocean (∼15%) and land (∼25%) [*Norris*, 1998], are more numerous than large clouds, and also contribute significantly to cloud fraction and reflectance. One recent study found that 15% to 50% of the reflectance from cumulus derives from clouds with areas below 1 km^2 [*Koren et al.*, 2008]. Improving our understanding of small cumulus also is crucial to global climate models, as climate sensitivity (i.e., the global-mean temperature response to a given radiative forcing) in such models is strongly dependent on their representation of shallow convective clouds [*Bony and Dufresne*, 2005; *Medeiros et al.*, 2008]. Understanding impacts on climate sensitivity that derive from the interaction between aerosol and clouds is therefore of great importance.

[3] It has long been suggested that aerosol suppresses precipitation in warm (ice-free) boundary layer clouds [*Warner*, 1968; *Albrecht*, 1989]. Specifically, an increase in drop concentration N_d results in less drop coalescence, less precipitation, and therefore increased liquid water path LWP, cloud fraction f_c, higher albedo and possibly increased cloud lifetime [*Albrecht*, 1989]. These responses are collectively referred to as the "lifetime effect." In recent years this hypothesis has come under scrutiny as high resolution models [*Wang et al.*, 2003; *Ackerman et al.*, 2004; *Xue and Feingold*, 2006; *Jiang and Feingold*, 2006] have revealed responses that are incongruent with this simple construct, and as observational evidence from satellite remote sensing has yielded results that both support [*Kaufman et al.*, 2005] and refute [*Matsui et al.*, 2006] this hypothesis. Here, we use *in situ* observations of small, non-precipitating cumulus clouds to examine their response to aerosol perturbations and shed light on the "lifetime effect."

[4] High resolution models have shown that the components of the "lifetime effect" do not necessarily act in unison [*Jiang et al.*, 2006; *Xue and Feingold*, 2006; *Jiang and Feingold*, 2006; *Xue et al.*, 2008]: (i) LWP may increase or decrease with increasing aerosol depending on meteorological conditions; (ii) f_c may increase or decrease with increasing aerosol depending on meteorological conditions; (iii) the response of mean cloud lifetime (defined as the mean time from birth to demise of individual clouds) to aerosol perturbations is uncertain. Based on these studies, it has been proposed [*Xue et al.*, 2008] that there exist two distinct regimes: a precipitating regime where aerosol perturbations suppress precipitation, and increase LWP and f_c (consistent with *Albrecht* [1989] and *Ackerman et al.* [2004]), and a non-precipitating regime where aerosol perturbations result in enhanced entrainment of subsaturated ambient air, primarily as a result of enhanced evaporation rate of smaller droplets, leading to lower f_c. This study addresses the latter regime. It differs from the "semi-direct effect" which relies on absorbing aerosol to reduce cloudiness. Absorbing aerosol effects are not considered, but could potentially act in unison with the evaporation effects discussed here.

[5] An actively growing cumulus cloud consists of a positively buoyant updraft core surrounded by a shell of negatively buoyant air driven by entrainment and evaporative cooling [*Blyth et al.*, 1988; *Rodts et al.*, 2003; *Heus and Jonker*, 2008], as illustrated in Figure 1. The idea raised by *Jiang et al.* [2006], and to be explored here, is that aerosol perturbations result in smaller droplets that have shorter evaporation time scales. The enhanced evaporation rate intensifies the local cooling, generates stronger negative buoyancy around the periphery of the cloud, and therefore produces a cloud with a stronger horizontal buoyancy gradient B'_x ($= g/\theta_{v0} \cdot d\theta'_v/dx$, where θ'_v is the perturbation virtual potential temperature, θ_{v0} is the environmental potential temperature and g is gravitational acceleration). In turn, this stronger B'_x results in stronger vorticity, more efficient entrainment mixing with the sub-saturated cloud-free environment, and thus more evaporation, thereby closing the positive feedback loop (Figure 1). Clouds with reduced LWP (averaged over their lifetime) and lower f_c

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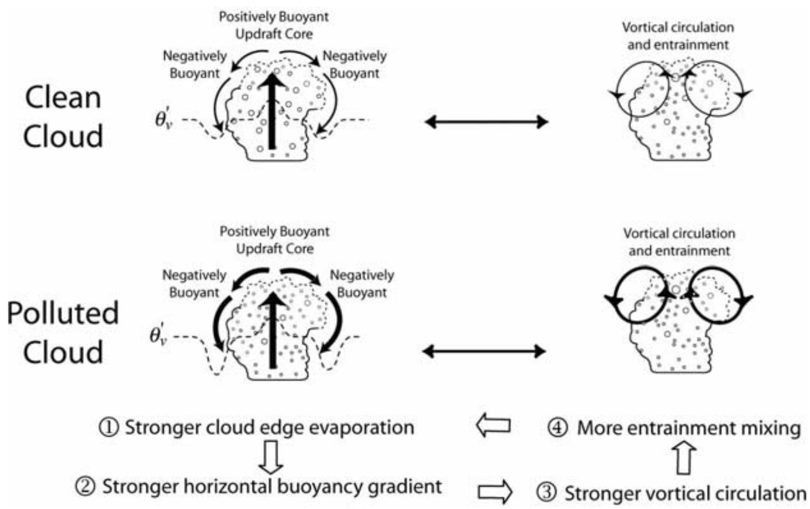

Figure 1. Schematic of the evaporation-entrainment feedback mechanism. (top) Clean and (bottom) polluted clouds are represented. The basic circulation features of small cumulus clouds are shown, indicating positively buoyant updrafts in the core of clouds and a shell of negatively buoyant air at cloud edges. θ_v', a measure of buoyancy, is represented by the dashed curves. At the edges of polluted clouds, evaporation is more rapid than in clean clouds, resulting in larger negative θ_v' and hence stronger horizontal buoyancy gradients. This in turn results in stronger vortical circulation in polluted clouds which leads to higher entrainment rates, thereby increasing evaporation and thus completing the feedback mechanism. We note that other positive and negative feedbacks within the cloud may dampen or amplify the feedback depicted here.

may be expected as a result of this feedback, depending on the thermodynamic environment in which the clouds evolve [*Jiang et al.*, 2006].

[6] In order for B_x' to change in response to a change in aerosol requires that the imprint of entrainment mixing and resulting cloud drop evaporation be sensitive to the cloud drop size distribution. Studies have shown that this process depends on the ratio of τ_{evap} to τ_{mix}, respectively the time scale for single cloud drop evaporation and the time scale for entrainment mixing [e.g., *Jeffery and Reisner*, 2006]. If these time scales are of similar magnitude, then there exists the potential for an aerosol effect on evaporation and, consequently, entrainment mixing. Some observational studies support the notion that $\tau_{evap} \cong \tau_{mix}$ [*Burnet and Brenguier*, 2007; *Jensen et al.*, 1985; *Hill and Choularton*, 1985; *Paluch*, 1986], and others that $\tau_{evap} \ll \tau_{mix}$ [*Jensen and Baker*, 1989; *Paluch and Baumgardner*, 1989]. It has also been shown that both regimes may exist during the cloud lifecycle [*Siebert et al.*, 2006]. This remains an open question and an area of active debate. See the online auxiliary material for further discussion of this issue.[1]

[7] If the nature of entrainment mixing in small, non-precipitating cumuli does indeed depend on drop size, then based on the schematic in Figure 1, observations should reveal stronger B_x' and reduced liquid water content in polluted clouds. Data sampled in warm convective clouds are now used to explore the relationship between aerosol concentrations, B_x' and cloud microphysical parameters.

2. Experiment and Results

[8] In late summer 2006, the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter completed 22 research flights exploring aerosol-cloud interactions in the vicinity of Houston, Texas (between 28.5–31°N and 93–97°W) as part of the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS). To test the feedback shown in Figure 1, we analyze data from non-precipitating clouds on six days: three particularly clean days (Aug. 22, 26, and Sept. 11) and three highly polluted days (Sept. 7, 8, and 15) based on a passive cavity aerosol spectrometer probe (PCASP). Clean days have leg-mean accumulation mode aerosol concentrations (N_{acc}, representing particles with a diameter between 0.1 and 2.6 μm) < 600 cm^{-3}, and the polluted days have N_{acc} > 1100 cm^{-3}. Measurements from two condensation particle counters, measuring aerosol number concentration (N_a > 3 nm and N_a > 10 nm dry, respectively) are also used for confirmation of aerosol regimes. See the online auxiliary material for more details regarding the measurements and analyses.

[9] Central to the hypothesis outlined in Figure 1 is that polluted clouds exhibit stronger B_x' than cleaner clouds. Figure 2 shows mean in-cloud vertical profiles of positive and negative buoyancy perturbations (θ_v') separately for clean and polluted days. The profiles have been normalized so that cloud base = 0 and cloud top = 1 (see online auxiliary material for details). Note that in all figures, solid symbols (open symbols) represent differences between clean and polluted days that are (are not) statistically significant at the 95% level. Figure 2 shows that we observe polluted clouds to be, at most altitudes, more negatively buoyant and, overall, to have stronger horizontal θ_v' gradients ($|\theta_{v,positive}'| + |\theta_{v,negative}'|$) than clean clouds, especially at cloud top. Because cloud widths for clean and polluted days show no statistically-significant differences (data not shown), this translates to stronger B_x'. These observational results qualitatively match very well model results [cf. *Jiang et al.*, 2006, Figure 3] and represent the first observational support for a link between aerosol and entrainment. Statis-

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038888.

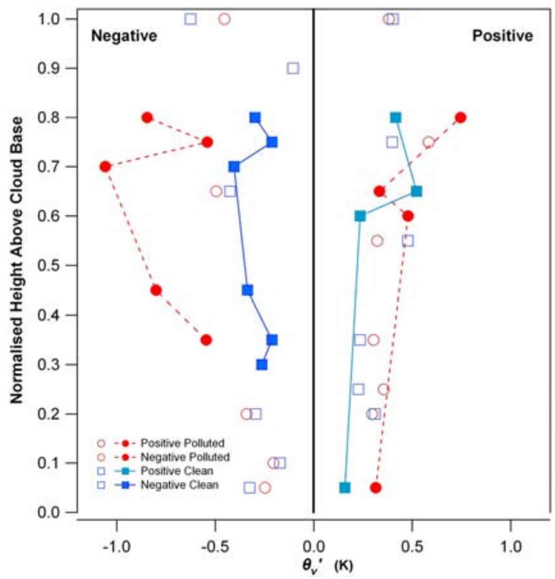

Figure 2. Virtual potential temperature perturbation (θ_v') as a function of normalized cloud height for clean (blue solid lines with square markers) and polluted (red dashed lines with circle markers) days. The difference between these two curves represents the horizontal buoyancy gradient. Buoyancy gradient is proportional to $d\theta_v'/dx$; cloud widths were not found to be statistically different, therefore differences in B_x' are driven by differences in θ_v'. Filled (empty) markers are used at normalized heights where the mean θ_v' values on clean and polluted days are (are not) statistically different. For clean and polluted negative θ_v', eight altitude bins exhibit statistically significant differences, while for positive θ_v', four levels pass this statistical test. The bias towards negative θ_v' values can be explained by the fact that there are more negatively buoyant samples; positively buoyant updrafts are typically narrow and focused while negatively buoyant downdrafts are typically more widespread and comprise a larger volume of cloud [e.g., *Xue et al.*, 2008], thus making it more likely to sample negatively buoyant parcels.

tically significant differences in B_x' cluster at mid-cloud and near cloud top where entrainment is known to be more prevalent [*Warner*, 1955; *Lu et al.*, 2008].

[10] If Figure 2 is valid, then we would expect decreases in LWC and drop size to accompany increased entrainment. Figure 3 shows vertical profiles of LWC normalized by the adiabatic value. The differences in the mid-cloud and cloud top regions are generally consistent with the expected response, including their tendency to decrease with increasing height in cloud. The differences in the vertical profiles of the median drop-diameter D_{50} are large and statistically significant at 12 levels from near cloud base to cloud top, which is consistent with our classification of clean and polluted days. The response of N_d is not very clear. Close to cloud base (normalized height less than 0.3), mean N_d tends to be either close to the same or larger in polluted clouds, weakly supporting our "clean" and "polluted" classifications. Moreover, updraft-mean N_d near cloud base is distinctly higher on the polluted days [*Lu et al.*, 2008]. At higher levels, no clear trend is seen, which we attribute to the fact that in polluted clouds the expected higher N_d is counteracted by increased evaporation. The balance between activation and evaporation/entrainment leads to a complex response of N_d to aerosol.

[11] Could the stronger B_x' on polluted days be attributable to differences in the environmental RH? Analysis of horizontal legs between clouds shows (see Table S2 in the online auxiliary material) that the polluted clouds grow in an environment that is similar in RH to that of the clean clouds. The cloud top environment even tends to be moister in the case of the polluted clouds. This could be at least partially due to moistening associated with more efficient evaporation, which then acts to slow evaporation. Regardless, we find no evidence for the enhanced B_x' being linked to drier environmental air on polluted days.

[12] Could the stronger B_x' on polluted days be attributable to differences in dynamical forcing? We find that subcloud vertical velocities w are not statistically different between clean and polluted days (not shown), implying that the observed clean and polluted clouds experience similar dynamical forcings. Profiles of mean in-cloud w (Figure 3d) also show that clean and polluted days do not exhibit statistically significant in-cloud differences in w at almost all levels. Model results [*Xue and Feingold*, 2006] show a very weak increase in cloud turbulence with increasing aerosol – a signal that is unlikely to be detectable in the observations, considering the short sample durations and the natural dynamical variability of cumulus clouds.

[13] The observational evidence therefore supports the hypothesis that the B_x' differences derive from aerosol differences rather than differences in environmental RH or dynamical forcing, in agreement with our previous small-scale modeling studies. This model/observational consistency is unlikely to be chance given that the results are derived independently, using different tools, with different biases, assumptions and uncertainties. The liquid water decrease (Figure 3b) is also broadly consistent with our models, but with some discrepancies: the models suggest that this decrease is expressed as a reduction in cloud size and fraction, whereas the observations presented here imply that the decrease is associated with diluted clouds and no change in cloud size.

3. Summary and Discussion

[14] Results presented here suggest that when small, non-precipitating cumulus experience aerosol perturbations, they respond in a manner consistent with enhanced evaporation around the shell of the small cumulus cloud and a stronger horizontal buoyancy gradient. This has been shown to result in stronger vorticity around the core of the cloud and stronger entrainment [*Jiang et al.*, 2006], constituting an "evaporation-entrainment feedback". This response is inconsistent with the simplistic "lifetime effect" construct since it results in decreases in cloud fraction and liquid water in response to aerosol perturbations that would offset the "albedo effect" [*Zuidema et al.*, 2008].

[15] By not accounting for the proposed evaporation-entrainment feedback, global climate models are likely to bias estimates of aerosol radiative forcing towards larger negative values. One might be tempted to conclude that non-precipitating cumulus will exhibit lower cloud water,

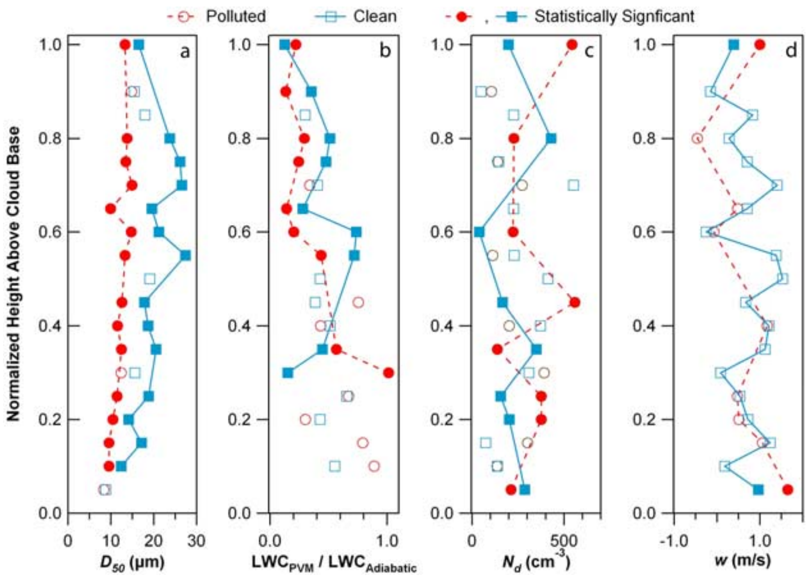

Figure 3. In-cloud vertical profiles of (a) median diameter D_{50} of the cloud drop size distribution, (b) ratio of observed PVM [*Gerber et al.*, 1994] LWC to adiabatic LWC, (c) cloud drop number concentration N_d, and (d) vertical velocity *w*. The adiabatic LWC is calculated from the (absolute) height in cloud, as well as cloud base temperature and pressure. Normalized height of zero and one represent cloud base and top, respectively.

cloud fractions, and lifetimes in response to anthropogenic aerosol perturbations. However, evidence from modeling suggests that factors such as the environmental relative humidity [*Ackerman et al.*, 2004; *Jiang et al.*, 2006], temperature, and vertical shear are likely to be important controlling factors. Simply assuming that the "lifetime effect" has the opposite sense in these small clouds is therefore unwise.

[16] It is well-established that most clouds evaporate without precipitating [*Pidwirny and Kundell*, 2008], and that the hydrological cycle will respond to greenhouse warming by increasing the frequency of heavy rainfall and drought events, with a concomitant decrease in the frequency of light precipitation [*Meehl et al.*, 2007; *Allan and Soden*, 2008]. It is therefore of interest to speculate on the role of aerosol in such a modified hydrological cycle. The evaporation-entrainment feedback is not expected to affect significantly the heavy precipitation regime, whereas clouds in the potentially more prevalent non-precipitating regime may be strongly susceptible to this feedback, which would result in reduced cloudiness. This feedback may also shift marginally-precipitating clouds to the non-precipitating regime, further intensifying the extremes of rainfall and drought.

[17] Dynamical feedbacks associated with anthropogenic aerosol perturbations on clouds may generate important and unexpected responses on a range of temporal and spatial scales [*Wood*, 2007] that must be explored before the full implications of aerosol-cloud interactions can be understood. Thus, the challenge of incorporating these effects in climate models is daunting. Further systematic study of small clouds and their response to aerosol at appropriate temporal and spatial scales is fundamental to progress in understanding climate change.

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References

Ackerman, A. S., K. P. Kirkpatrick, D. E. Stevens, and O. B. Toon (2004), The impact of humidity above stratiform clouds on indirect aerosol climate forcing, *Nature*, *432*, 1014–1017, doi:10.1038/nature03174.

Albrecht, B. (1989), Aerosols, cloud microphysics, and fractional cloudiness, *Science*, *245*, 1227–1230, doi:10.1126/science.245.4923.1227.

Allan, R. P., and B. J. Soden (2008), Atmospheric warming and the amplification of precipitation extremes, *Science*, *321*, 1481–1484, doi:10.1126/science.1160787.

Blyth, A., W. A. Cooper, and J. B. Jensen (1988), A study of the source of entrained air in Montana cumuli, *J. Atmos. Sci.*, *45*, 3944–3964, doi:10.1175/1520-0469(1988)045<3944:ASOTSO>2.0.CO;2.

Bony, S., and J. L. Dufresne (2005), Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, *Geophys. Res. Lett.*, *32*, L20806, doi:10.1029/2005GL023851.

Burnet, F., and J.-L. Brenguier (2007), Observational study of the entrainment-mixing process in warm convective clouds, *J. Atmos. Sci.*, *64*, 1995–2011, doi:10.1175/JAS3928.1.

Gerber, H., B. G. Arends, and A. S. Ackerman (1994), New microphysics sensor for aircraft use, *Atmos. Res.*, *31*, 235–252, doi:10.1016/0169-8095(94)90001-9.

Heus, T., and H. J. J. Jonker (2008), Subsiding shells around shallow cumulus clouds, *J. Atmos. Sci.*, *65*, 1003–1018, doi:10.1175/2007JAS2322.1.

Hill, T. A., and T. W. Choularton (1985), An airborne study of the microphysical structure of cumulus clouds, *Q. J. R. Meteorol. Soc.*, *111*, 517–544, doi:10.1256/smsqj.46812.

Jeffery, C., and J. Reisner (2006), A study of cloud mixing and evolution using PDF methods. Part I: cloud front propagation and evaporation, *J. Atmos. Sci.*, *63*, 2848–2864, doi:10.1175/JAS3760.1.

Jensen, J. B., and M. B. Baker (1989), A simple model of droplet spectral evolution during turbulent mixing, *J. Atmos. Sci.*, *46*, 2812–2829, doi:10.1175/1520-0469(1989)046<2812:ASMODS>2.0.CO;2.

Jensen, J. B., P. H. Austin, M. B. Baker, and A. M. Blyth (1985), Turbulent mixing, spectral evolution and dynamics in a warm cumulus cloud, *J. Atmos. Sci.*, *42*, 173–192, doi:10.1175/1520-0469(1985)042<0173:TMSEAD>2.0.CO;2.

Jiang, H., and G. Feingold (2006), Effect of aerosol on warm convective clouds: Aerosol-cloud-surface flux feedbacks in a new coupled large eddy model, *J. Geophys. Res.*, *111*, D01202, doi:10.1029/2005JD006138.

Jiang, H., H. Xue, A. Teller, G. Feingold, and Z. Levin (2006), Aerosol effects on the lifetime of shallow cumulus, *Geophys. Res. Lett.*, *33*, L14806, doi:10.1029/2006GL026024.

Kaufman, Y. J., et al. (2005), The effect of smoke, dust and pollution aerosol on shallow cloud development over the atlantic ocean, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 11,207–11,212, doi:10.1073/pnas.0505191102.

Koren, I., et al. (2008), How small is a small cloud?, *Atmos. Chem. Phys.*, *8*, 3855–3864.

Lu, H. L., et al. (2008), Aerosol-cloud relationships in continental shallow cumulus, *J. Geophys. Res.*, *113*, D15201, doi:10.1029/2007JD009354.

Matsui, T., et al. (2006), Satellite-based assessment of marine low cloud variability associated with aerosol, atmospheric stability, and the diurnal cycle, *J. Geophys. Res.*, *111*, D17204, doi:10.1029/2005JD006097.

Medeiros, B., et al. (2008), Aquaplanets, climate sensitivity, and low cloud, *J. Clim.*, *21*, 4974–4991, doi:10.1175/2008JCLI1995.1.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U. K.

Norris, J. R. (1998), Low cloud type over the ocean from surface observations. Part II: Geographical and seasonal variations, *J. Clim.*, *11*, 383–403, doi:10.1175/1520-0442(1998)011<0383:LCTOTO>2.0.CO;2.

Paluch, I. R. (1986), Mixing and the cloud droplet size spectrum: Generalizations from the CCOPE data, *J. Atmos. Sci.*, *43*, 1984–1993, doi:10.1175/1520-0469(1986)043<1984:MATCDS>2.0.CO;2.

Paluch, I. R., and D. G. Baumgardner (1989), Entrainment and fine-scale mixing in a continental convective cloud, *J. Atmos. Sci.*, *46*, 261–277, doi:10.1175/1520-0469(1989)046<0261:EAFSMI>2.0.CO;2.

Pidwirny, P., and J. Kundell (2008), *Precipitation and Fog, Encyclopedia of Earth*, Environ. Inf. Coalition, Natl. Counc. for Sci. and the Environ., Washington, D. C.

Rodts, S. M., P. G. Duynkerke, and H. J. J. Jonker (2003), Size distribution and dynamical properties of shallow cumulus clouds from aircraft observations and satellite data, *J. Atmos. Sci.*, *60*, 1895–1912, doi:10.1175/1520-0469(2003)060<1895:SDADPO>2.0.CO;2.

Siebert, H., et al. (2006), Probing finescale dynamics and microphysics of clouds with helicopter-borne measurements, *Bull. Am. Meteorol. Soc.*, *87*, 1727–1738, doi:10.1175/BAMS-87-12-1727.

Wang, S., Q. Wang, and G. Feingold (2003), Turbulence, condensation, and liquid water transport in numerically simulated nonprecipitating stratocumulus clouds, *J. Atmos. Sci.*, *60*, 262–278, doi:10.1175/1520-0469(2003)060<0262:TCALWT>2.0.CO;2.

Warner, J. (1955), The water content of cumuliform cloud, *Tellus*, *7*, 449–457.

Warner, J. (1968), A reduction in rainfall associated with smoke from sugarcane fires—And inadvertent weather modification?, *J. Appl. Meteorol.*, *7*, 247–251, doi:10.1175/1520-0450(1968)007<0247:ARIRAW>2.0.CO;2.

Wood, R. (2007), Cancellation of aerosol indirect effects in marine stratocumulus through cloud thinning, *J. Atmos. Sci.*, *64*, 2657–2669, doi:10.1175/JAS3942.1.

Xue, H., and G. Feingold (2006), Large-eddy simulations of trade wind cumuli: Investigation of aerosol indirect effects, *J. Atmos. Sci.*, *63*, 1605–1622, doi:10.1175/JAS3706.1.

Xue, H., G. Feingold, and B. Stevens (2008), Aerosol effects on cloud, precipitation, and the organization of shallow cumulus convection, *J. Atmos. Sci.*, *65*, 392–406, doi:10.1175/2007JAS2428.1.

Zuidema, P., H. Xue, and G. Feingold (2008), Shortwave radiative impacts from aerosol effects on marine shallow cumuli, *J. Atmos. Sci.*, *65*, 1979–1990, doi:10.1175/2007JAS2447.1.

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