Observed impacts of vertical velocity on cloud microphysics and implications for aerosol indirect effects

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Received 17 August 2012; revised 28 September 2012; accepted 5 October 2012; published 8 November 2012.

[1] The simultaneous measurements of vertical velocity and cloud droplet size distributions in cumuli collected during the RACORO field campaign over the Atmospheric Radiation Measurement Program's Southern Great Plains site near Lamont, Oklahoma, US, are analyzed to determine the effects of vertical velocity on droplet number concentration, relative dispersion (the ratio of standard deviation to mean radius), and their relationship. The results show that with increasing vertical velocity the droplet number concentration increases while the relative dispersion decreases. The data also exhibit a negative correlation between relative dispersion and droplet number concentration. These empirical relationships can be fitted well with power law functions. This observational study confirms the theoretical and numerical expectations of the effects of vertical velocity on cloud microphysics by analyzing the data of vertical velocity directly. The effects of vertical velocity on relative dispersion and its relationship with droplet number concentration are opposite to that associated with aerosol loading, posing a confounding challenge for separating aerosol indirect effects from dynamical effects. **Citation:** Lu, C., Y. Liu, S. Niu, and A. M. Vogelmann (2012), Observed impacts of vertical velocity on cloud microphysics and implications for aerosol indirect effects, *Geophys. Res. Lett.*, *39*, L21808, doi:10.1029/2012GL053599.

1. Introduction

[2] It is well known that an increase in aerosol concentration results in increases in cloud condensation nuclei (CCN) concentration and thus cloud droplet number concentration (N_c). Holding liquid water content (LWC) fixed, the increased N_c reduces effective radius, enhances cloud albedo [*Twomey*, 1974, 1977], and suppresses rain formation [*Albrecht*, 1989]. In addition to the CCN effect on increasing N_c (hereafter referred to as "the number effect"), *Liu and Daum* [2002] showed that an increase in aerosol concentration also leads to an increase in relative dispersion (ε, the ratio of standard deviation to mean radius) of cloud droplet size distributions. While the number effect's enhancement of cloud albedo exerts a cooling effect on the climate system, the "dispersion effect" reduces this cooling effect and thereby exerts a warming effect on climate [*Peng and Lohmann*, 2003; *Rotstayn and Liu*, 2003, 2009; *Liu et al.*, 2008].

[3] Although the aerosol indirect effect has been studied intensively, many aspects are still poorly understood and full of uncertainty (even controversy) [*Tas et al.*, 2012]. For example, the empirical dependence of N_c on aerosol loading varies from study to study and the resulting relationships lead to a wide range (from -1.85 to -0.22 W m^{-2}) in model estimates of the global mean radiative forcing [*Ramanathan et al.*, 2001; *Forster et al.*, 2007]. Even more uncertain is the dependence of ε on aerosol loading. Some studies found a positive correlation [*Martin et al.*, 1994; *McFarquhar and Heymsfield*, 2001; *Liu and Daum*, 2002; *Wood et al.*, 2002; *Rotstayn and Liu*, 2003, 2009; *Yum and Hudson*, 2005; *Liu et al.*, 2008] whereas others report a weak or negative correlation [*Martins and Silva Dias*, 2009; *Ma et al.*, 2010]. The contrasting relationships indicate that the dispersion effect could act to reduce or enhance the cooling by the well-known number effect.

[4] A reason for these different and even contrasting observational results is that changes in aerosol loading are often intertwined with changes in other factors such as cloud dynamical conditions, which makes the separation of aerosol indirect effects from non-aerosol effects extremely difficult [*Shao and Liu*, 2006; *Xue and Feingold*, 2006; *Kim et al.*, 2008]. One important dynamical factor is vertical velocity (w) in clouds, which affects both N_c [*Twomey*, 1959; *Ghan et al.*, 1993; *Reutter et al.*, 2009] and ε [*Liu et al.*, 2006]. *Liu et al.* [2006] showed theoretically that, while an increase in aerosol loading often leads to an increase in N_c and ε, an increase in w increases N_c but decreases ε. This theoretical result has been confirmed by simulations with adiabatic parcel models [*Liu et al.*, 2006; *Peng et al.*, 2007].

[5] However, such observational studies about the effects of w on N_c, ε and their relationship are rare, especially for w effects on ε and the ε-N_c relationship. *Pawlowska et al.* [2006] and *Zhao et al.* [2006] speculated the w effect on the relationship of ε vs. N_c with observational data, but they did not analyze the data of w. Thus further observational studies of the w effects are desired. To improve our understanding, this study investigates the w effects on ε, N_c, and the ε-N_c relationship together. This is done by examining the data of cumulus clouds collected during the Routine AAF (Atmospheric Radiation Measurement (ARM) Aerial Facility) Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO) field campaign, which operated over the ARM Southern Great Plains (SGP) site

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0094-8276/12/2012GL053599

near Lamont, Oklahoma from 22 January to 30 June 2009 [*Vogelmann et al.*, 2012].

2. RACORO and Data

[6] During RACORO, the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft made comprehensive measurements of cloud, aerosol, radiation, and atmospheric state parameters. The aircraft flew at multiple levels in clouds and cloud droplet size distributions were measured by Cloud and Aerosol Spectrometer (CAS). The CAS probe measures particle radii from 0.29 to 25 μm in 20 size bins at a 10 Hz sampling rate. Here, only the particles with a bin-average radius larger than 1 μm are considered to be cloud droplets for calculations of N_c, ε and LWC. The Cloud Imaging Probe (CIP) also measured drops in the range of 7.5–782 μm (radius) at 1 Hz. Vertical velocity measurements were obtained with a 5-hole gust probe on the nose of the Twin Otter. A wide range of w values was encountered during RACORO, providing a great opportunity to empirically quantify the effects of w on cloud microphysics. For further information about RACORO, see *Vogelmann et al.* [2012].

[7] During RACORO, a total of 260 h of data were collected during 59 research flights to study continental boundary-layer clouds and their environment. Among the 59 flights, clouds were sampled in 29 flights. This study focuses on the 568 non-drizzling cumuli collected during 6 cumulus flights (May 22, May 23, May 24, May 26, June 23 and June 26, 2009). Cloud droplet size distributions with $N_c > 10$ cm^{-3} and LWC > 0.001 g m^{-3} are considered to be cloud records; these criteria are used to eliminate those samples that may be composed of large aerosols instead of cloud droplets [*Deng et al.*, 2009; *Zhang et al.*, 2011]. Non-drizzling clouds must further satisfy the condition that the mean drizzle LWC (radius >25 μm from the CIP) in cloud over the observation period was smaller than 0.005 g m^{-3}. Only the observations from the long horizontal legs flown are examined to ensure the accuracy of vertical velocity measurement. For each leg, cloud droplet size distributions are considered to be within the same individual cumulus cloud when the distance between them is less than 50 m (the data were collected at ~5 m spatial resolution, based on the 10 Hz CAS sampling and an aircraft speed of ~50 m s^{-1}). Individual clouds are established based on this criterion; clouds with horizontal sizes smaller than 50 m are not included to avoid cumulus clouds that are too small for adequate sampling statistics. Only the results with $w > 0$ and LWC > 0.01 g m^{-3} are presented here to minimize the influence of entrainment-mixing processes. A total of 19,472 cloud droplet size distributions satisfy all of the above the criteria and are used for the analysis reported next.

3. Results and Discussions

[8] As mentioned before, a complete characterization of the aerosol indirect effect calls for examining N_c and ε as a pair. Figures 1 and 2, respectively, show N_c and ε as a function of w in the form of a joint probability density function (PDF) for each cumulus flight. The total numbers of samples in the six flights are 3,641, 4,586, 2,829, 3,525, 776 and 4,115, respectively. The reason for examining the relationships flight by flight is that aerosol concentration and composition and availability of water vapor could be assumed fixed in each flight; then we can focus on the effect of vertical velocity to the extent possible. Figures 1 and 2 show that larger w corresponds generally to a larger N_c but smaller ε, consistent with theoretical expectations [*Liu et al.*, 2006] and parcel model simulations [*Liu et al.*, 2006; *Peng et al.*, 2007].

[9] According to *Liu et al.* [2006], the w-dependence of N_c and ε can be quantified via power-law relationships such that,

$$N_c = Aw^b, \tag{1}$$

$$\varepsilon = Cw^d, \tag{2}$$

where the parameters A, b, C and d are related to CCN concentrations and meteorological conditions. The six RACORO cumulus clouds follow the power-law relationships; A, b, C and d for each cloud are shown in Figures 1 and 2. The regression coefficients are obtained using a weighted least squares method [*Chatterjee and Hadi*, 2006].

[10] Combining equations (1) and (2), the w variation (with all the other factors unchanged) results in a negative correlation between ε and N_c given by,

$$\varepsilon = CA^{-\frac{d}{b}}N_c^{\frac{d}{b}}. \tag{3}$$

To confirm this relationship, Figure 3 shows the joint PDF for ε vs. N_c in each cloud. Superimposed on the figure are the power-law fits obtained from the weighted least squares method (red line), and that computed from equation (3) using the regression coefficients from Figures 1 and 2 (black line). The inverse ε-N_c relationship is obvious, which is different from the pattern associated with increased aerosol loading and suggests that the variation in vertical velocity dominates the effects of aerosol loading in these cases.

[11] The observational result of the w effect on the ε-N_c relationship confirms the conclusions in theoretical and numerical work [*Liu et al.*, 2006; *Peng et al.*, 2007]. The effects of w have also been emphasized and speculated as a possibly major factor in previous observational analysis. For example, *Pawlowska et al.* [2006] analyzed stratocumulus clouds with aircraft observations and found that flight-averaged ε seemed to increase with increasing N_c, consistent with the dispersion effect, whereas ε decreased with N_c within each flight. They speculated that the negative correlation between ε and N_c is caused by the dominance of w effect. *Zhao et al.* [2006] also speculated that ε converged to a small range of values with increasing N_c when the effects of aerosol and w were comparable. Both *Pawlowska et al.* [2006] and *Zhao et al.* [2006] obtained their conclusions about w effects by speculation without analyzing observational data of w. With the analysis on the data of w directly in this study, the relationships of N_c-w, ε-w, ε-N_c and the fitting curves will be useful in cloud parameterizations in large scale models.

[12] Furthermore, Figure 4 shows joint PDF of ε vs. N_c with all the data in the six flights and the relationship between ε and N_c based on the flight-averaged data. Similar to Figure 3, superimposed on Figure 4 are the power-law fits

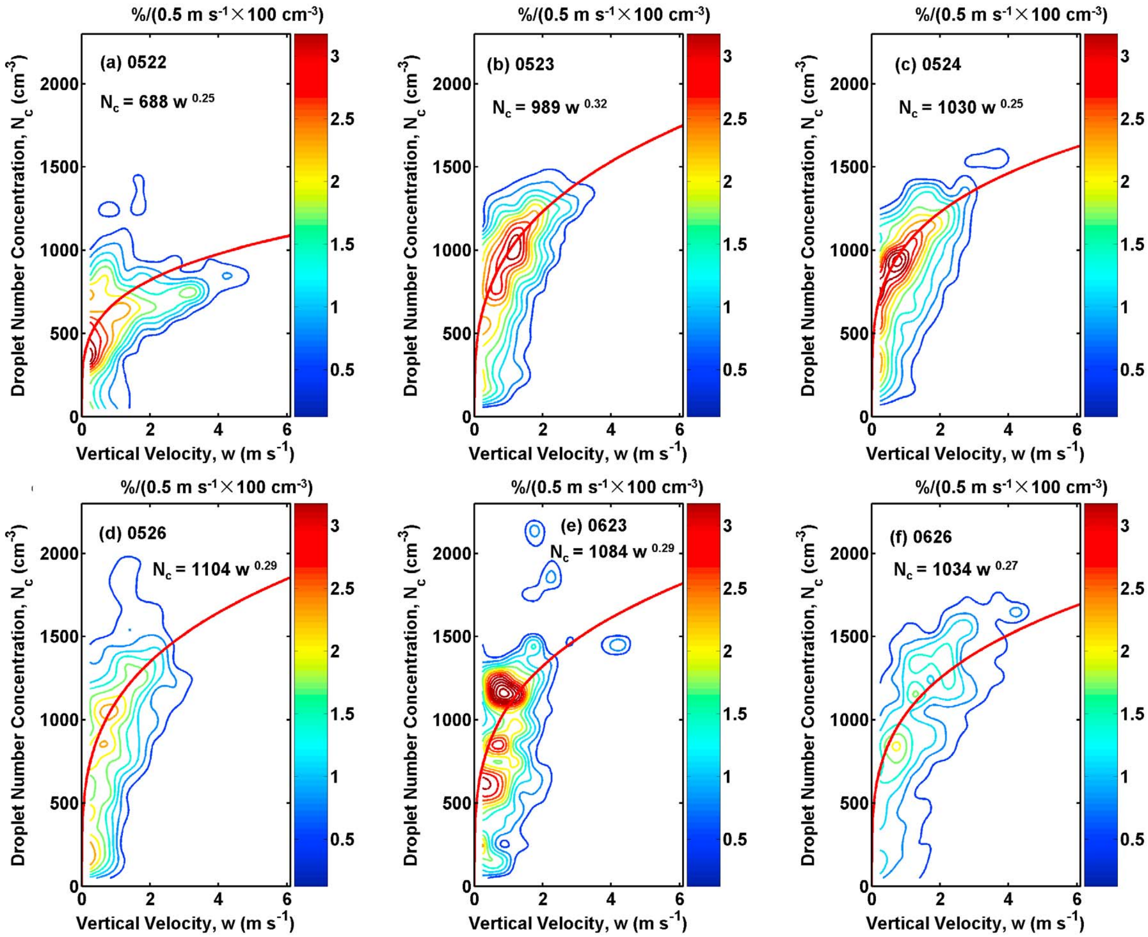

Figure 1. Joint probability density functions (PDF) of droplet number concentration (N_c) vs. vertical velocity (w) along horizontal aircraft legs for each cumulus flight (date given in legend). The bin widths of N_c and w are 100 cm^{-3} and 0.5 m s^{-1}, respectively. Contours represent the frequency of occurrence; the total numbers of samples in the six flights are 3,641, 4,586, 2,829, 3,525, 776 and 4,115, respectively. Only the mesh grids that have percentages ≥0.3% are shown. The red lines denote weighted least squares fits of the data. See text for the details.

obtained from the weighted least squares method (red line), and that computed from equation (3) using the regression coefficients from the relationships of ε vs. w and N_c vs. w with all the data in the six flights (black line). The joint PDF shows a negative relationship between ε and N_c, similar to the results in each flight shown in Figure 3; the flight-averaged ε and N_c are also negatively correlated, different from the results obtained by *Pawlowska et al.* [2006]. The negative relationship of flight-averaged ε vs. N_c indicates that the effect of vertical velocity dominates even on the scale of individual flights. The w-induced negative correlation in the ε-N_c relationship, as opposed to the aerosol-induced positive correlation in the ε-N_c relationship, is important to emphasize because the ε-N_c relationship has been widely used in the context of the dispersion effect since *Liu and Daum* [2002], although N_c was only used as a proxy of aerosol concentration. The contrasting effects of w and aerosols on ε and the ε-N_c relationship demand extra care and caution when investigating the aerosol dispersion effect. *Peng et al.* [2007] analyzed the effects of aerosol and vertical velocity with a parcel model and found that the positive correlation between ε and N_c due to the aerosol effect was weakened with increasing w; when w increased and approached 0.55 m s^{-1}, the positive correlation disappeared.

4. Summary

[13] Aircraft measurements of cloud droplet size distributions and vertical velocity from 568 non-precipitating cumuli collected in 6 flights during the RACORO field campaign over the SGP site are analyzed to empirically quantify the effects of vertical velocity on droplet number concentration, relative dispersion, and their relationship. The results show that with increasing vertical velocity the droplet concentration increases but relative dispersion decreases. The data also exhibit a negative correlation between relative dispersion and droplet concentration, which is different from the pattern associated with increased aerosol loading and suggests that the variation in vertical velocity dominates the effects of aerosol loading in these cases. Furthermore, quantitative analysis shows that the empirical relationships can be fitted well with power law functions, following the theoretical expectations in the work by *Liu*

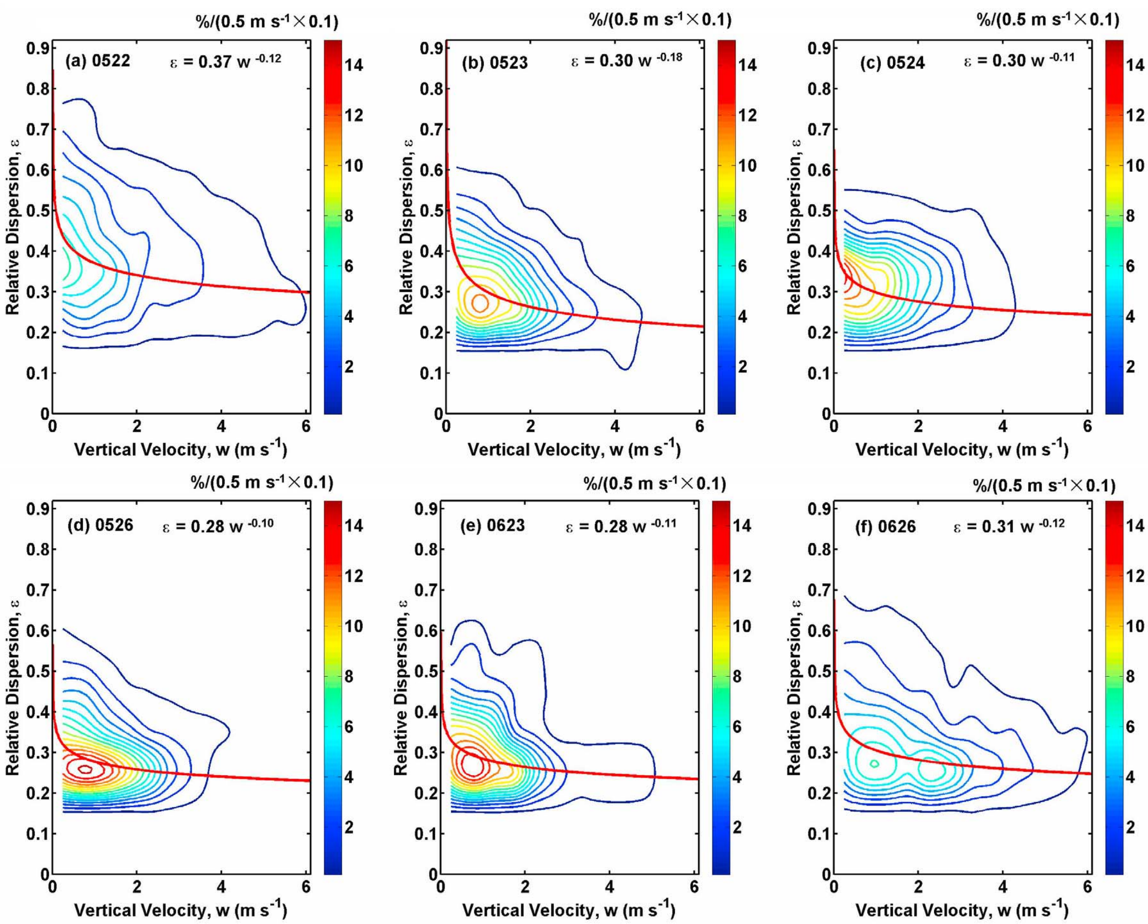

Figure 2. Joint probability density functions (PDF) of relative dispersion (ε) vs. vertical velocity (w) along horizontal aircraft legs for each cumulus flight (date given in legend). The bin widths of ε and w are 0.1 and 0.5 m s^{-1}, respectively. Contours represent the frequency of occurrence; the total numbers of samples in the six flights are 3,641, 4,586, 2,829, 3,525, 776 and 4,115, respectively. Only the mesh grids that have percentages $\geq$0.3% are shown. The red lines denote weighted least squares fits of the data. See text for the details.

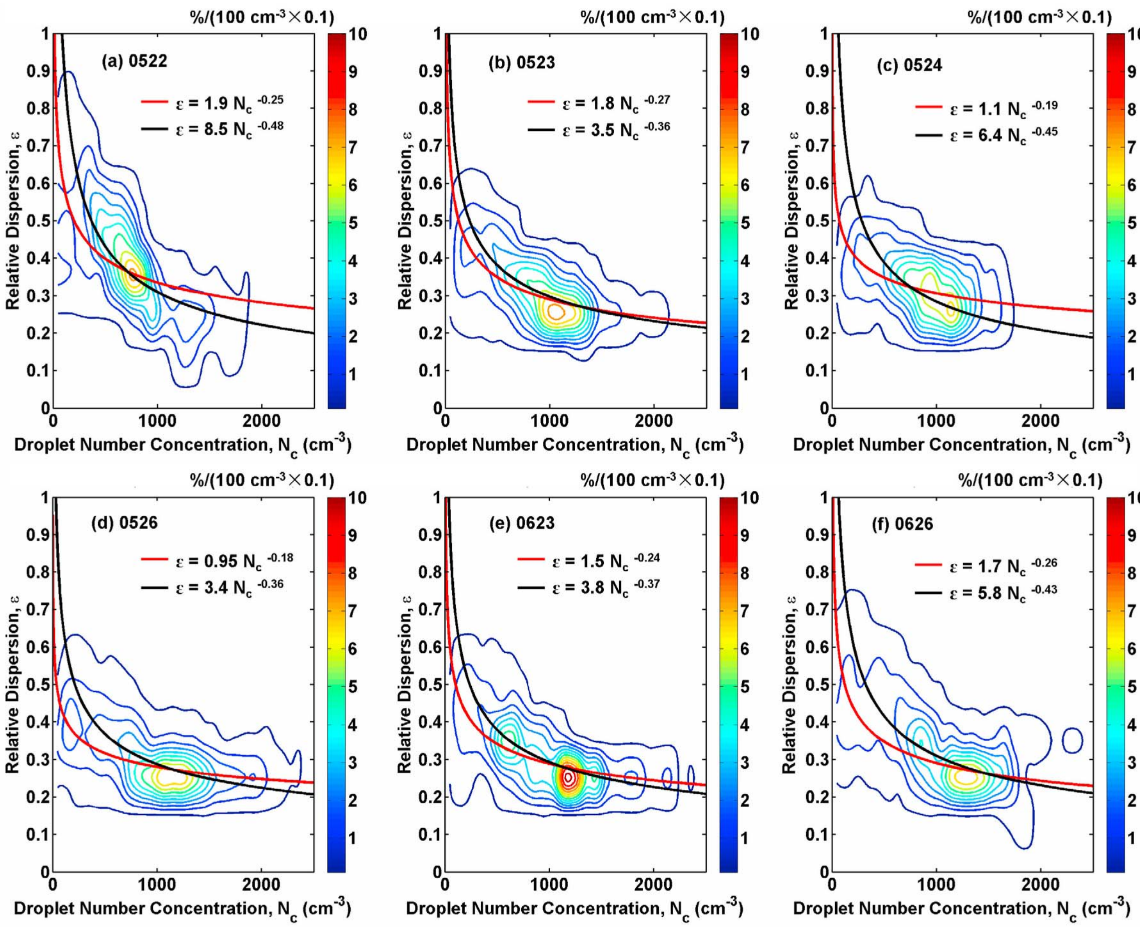

Figure 3. Joint probability density function of relative dispersion (ε) vs. cloud droplet number concentration (N_c) along horizontal aircraft legs for each cumulus flight (date given in legend). The bin widths of N_c and ε are 100 cm^{-3} and 0.1, respectively. The contours represent the frequency of occurrence; the total numbers of samples in the six flights are 3,641, 4,586, 2,829, 3,525, 776 and 4,115, respectively. Only the mesh grids that have percentages ≥0.3% are shown. The red lines are the weighted least squares fits of the data; the black lines are based on equation (3) and the regression coefficients obtained from Figures 1 and 2. See text for the details.

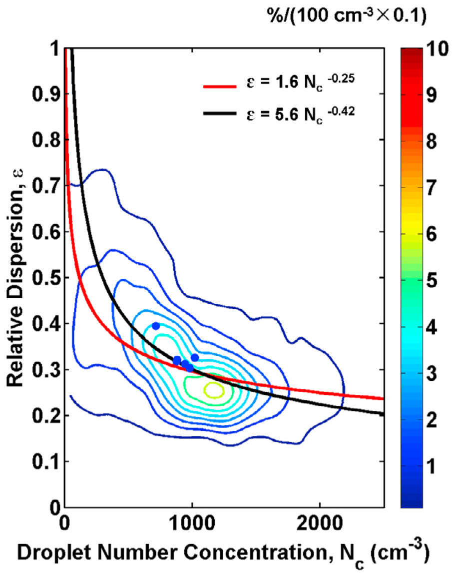

Figure 4. Joint probability density function of relative dispersion (ε) vs. cloud droplet number concentration (N_c) along horizontal aircraft legs for the six flights. The bin widths of N_c and ε are 100 cm^{-3} and 0.1, respectively. The contours represent the frequency of occurrence; the total number of samples in the six flights is 19,472. Only the mesh grids that have percentages ≥0.3% are shown. The red lines are the weighted least squares fits of the data; the black lines are based on equation (3) and the regression coefficients obtained from the relationships of ε vs. vertical velocity (w) and N_c vs. w with all the data in the six flights. See text for the details. The blue dots show the relationship between flight-averaged ε vs. N_c in the six flights.

et al. [2006]. Although the effect of vertical velocity has been pointed out in theoretical and numerical work [*Liu et al.*, 2006; *Peng et al.*, 2007], and has been speculated in previous observations [*Pawlowska et al.*, 2006; *Zhao et al.*, 2006], this study examines the effects of vertical velocity by analyzing the data of vertical velocity directly.

[14] It is important to emphasize that the change of relative dispersion and its relationship to droplet number concentration caused by variations in vertical velocity is in clear contrast with those caused by aerosol changes. On one hand, the opposite influences of aerosol and vertical velocity on the dispersion effect pose more of a challenge to analysis than for the number effect, since increases in aerosol and vertical velocity both enhance droplet number concentration. On the other hand, the opposite influences help distinguish the dominant factors in clouds.

[15] In addition to vertical velocity and aerosol, entrainment-mixing processes [*Liu et al.*, 2002; *Lu et al.*, 2011], chemical composition of CCN and gas pollutants such as HNO_3 [*Liu and Daum*, 2002; *Xue and Feingold*, 2004; *Peng et al.*, 2007] may also affect cloud droplet size distributions and thus the relationships between microphysical properties. Another complication may stem from the possible relationship between aerosol and vertical velocity. These additional factors may be responsible for the scatter shown in the figures in this paper and warrant further investigation.

[16] **Acknowledgments.** Lu, Liu and Vogelmann were supported by the U.S. Department of Energy's (DOE) Earth System Modeling (ESM) program via the FASTER project (www.bnl.gov/esm) and Atmospheric System Research (ASR) program (DE-AC02-98CH10886). Niu was supported by the Qing-Lan Project for Cloud-Fog-Precipitation-Aerosol Study in Jiangsu Province, China, and a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions. Data used in this article are from the U.S. Department of Energy ARM Aerial Facility's RACORO Campaign. We appreciate the helpful discussions about the CAS with Haf Jonsson, Greg McFarquhar and Hee-Jung Yang.

[17] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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