Aircraft measurements of high average charges on cloud drops in layer clouds

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[1] The first reliable aircraft measurements of characteristic cloud drop charges were obtained by utilizing a counterflow virtual impactor to substantially increase charge sensitivity and eliminate spurious contact charging that contaminated previous aircraft measurements. We find average drop charges more than an order of magnitude larger than expected from mountain surface measurements in similar clouds. Our evaluation of the data indicates that the high average charges on cloud drops originate in charge layers at the cloud boundaries and are carried into the cloud layer by vertical motions. These initial aircraft results demonstrate that cloud drop charges in layer clouds may be high enough to influence microphysical processes that promote precipitation. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0394 Atmospheric Composition and Structure: Instruments and techniques. **Citation:** Beard, K. V., H. T. Ochs III, and C. H. Twohy (2004), Aircraft measurements of high average charges on cloud drops in layer clouds, *Geophys. Res. Lett.*, *31*, L14111, doi:10.1029/2004GL020465.

1. Introduction

[2] The charge on cloud and precipitation drops can affect coalescence between colliding drops [*Ochs and Czys*, 1987; *Beard and Ochs*, 1995; *Pruppacher and Klett*, 1997] and the capture of aerosol particles and ice forming nuclei [*Grover and Beard*, 1975; *Beard*, 1992; *Tinsley et al.*, 2000] resulting from evaporated cloud drops [*Rosinski and Morgan*, 1991; *Rosinski*, 1995]. Previous measurements of cloud drop charges indicate only a few electronic charges per drop with averages near zero [*Webb and Gunn*, 1955; *Phillips and Kinzer*, 1958], but these data were obtained at the surface in mountain top clouds where the electrical environment differs from clouds with bases well above ground. In all other measurements, average cloud drop charges could not be accurately determined because of limited instrument sensitivity [*Twomey*, 1956; *Imyanitov et al.*,1972; *Takahashi*, 1972, 1975] and probable contact charging during aircraft sampling [*Gunn*, 1952; *Moore et al.*, 1961]. Here we report the first reliable aircraft measurements of average cloud drop charge.

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2. Measurements

[3] We obtained measurements of average cloud drop charges aboard a Lockheed Electra operated by the National Center for Atmospheric Research (NCAR) in layer clouds over Lake Michigan. Instrumentation included wing-mounted laser probes for measuring cloud drop and ice particle sizes and concentrations. Cloud drops were sampled with the NCAR Counterflow Virtual Impactor (CVI) with the CVI probe (Figure 1) and its coaxial flow-straightening shroud oriented into the air stream 0.6 m from the side of the aircraft fuselage. Cloud drops entering the CVI probe were slowed by a counterflow that prevents drops less than about 5 μm radius, as well as aerosol and outside air, from entering the carrier flow into the aircraft [*Ogren et al.*, 1985].

[4] During our flights in wintertime layer clouds over Lake Michigan, we measured average charges of drops with size ranging from the CVI threshold radius, specified as the size where 50% of drops are rejected, to the largest drop sizes encountered of 13 μm radius. An important feature of the CVI probe is the annular outflow at the CVI tip adjacent to wall (Figure 1). In contrast to previous aircraft sampling methods [*Gunn*, 1952; *Moore et al.*, 1961], grazing cloud drops with spurious contact charges were prevented from contaminating our measurements by this outflow at the CVI tip. While large drops could have enough inertia to contact the tip and breakup, with fragments possibly entering the sample stream, this should not occur unless drops are larger than 35–40 μm radius [*Twohy et al.*, 2003], much larger than those sampled here.

[5] The electrical current carried by the residue particles from evaporated cloud drops was measured using an absolute filter electrometer (TSI Model 3068) having a sensitivity of 1 femtoamp (1fA = 10^{-15} C s^{-1}). The current was recorded using a custom analog to digital interface and software on a laptop computer. The average charge on cloud drops was calculated for each second of data from q = I/(FN), where I is the electrometer current (fC s^{-1}), F is the electrometer flow rate (cm^3 s^{-1}), and N is the residue particle concentration (cm^{-3}) measured by a condensation nucleus counter (TSI Model 3760). For a series of multiple current peaks, the drop charges were obtained using several-second averages over the electrometer and CN peaks: $\langle q\rangle = \langle I\rangle/(f\langle N\rangle)$. Cloud drop radii and concentrations were obtained from drop spectra measured by a wing-mounted laser probe (PMS Model FSSP-100).

[6] Cloud drops carrying an average charge of a single electron could be measured reliably because of a typical 25-fold increase in concentration induced by drop deceleration in the CVI inlet. For a typical cloud drop concentration of 100 cm^{-3} and a CVI residue particle concentration of 2500 cm^{-3}, an average charge of one electron produces a

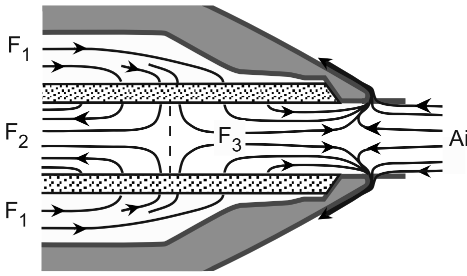

Figure 1. Cross section of the conical CVI probe tip showing the direction of internal and external flows [*Laucks and Twohy*, 1998; *Ogren et al.*, 1985]. Heated nitrogen under pressure (F1) flows radially through a porous tube where it splits into a sample flow (F2) and a counterflow out the tip (F3). Cloud drops larger than 4–5 μm radius (50% cut size) have sufficient inertia to penetrate the virtual stagnation plane (vertical dashed line) and those smaller than 25 μm radius are completely evaporated in the CVI probe. Only the drop residue particles with their charge are carried from the CVI probe to the instruments inside the aircraft.

current of 7 fA – seven times the electrometer sensitivity. The CVI substantially increase the sensitivity of our charge measurements while eliminating spurious contact charging that contaminated previous measurements.

3. Results

[7] The drop charge measurements shown in Figure 2 were obtained on January 20, 1998 during an ascent through a 600-meter stratocumulus (Sc) layer over the lake near Shelby, Michigan beneath a thin cirrus layer evident from a satellite image. The electrometer current was negative throughout the Sc layer with a maximum of −975 fA. The initial peak of $\langle q \rangle = -56$ e (elementary charges), occurred about 100 m above cloud base within a local updraft maximum of about 1 m s^{-1}. The mean cloud drop radius of $\langle r \rangle \sim 3.5$ μm was below the CVI threshold radius of 5.0 μm (50% cut size) so most of the cloud drops were rejected by the CVI. Another 200 m higher in the Sc layer, in a somewhat stronger updraft region, the average cloud drop charge reached its maximum value of −83 e, where over 80% of the cloud drops were large enough to enter the CVI. Above this level 90 to 95% of the drops entered the CVI. Since the charge on smaller drops is generally smaller, the peaks labeled −83, −77 and −54 e closely represent the average cloud drop charges in the cloud. Ice particles of 100–270 μm diameter at concentrations of 0.4–1.3 L^{-1} were measured by diode array probes during just six isolated one-second periods. There was no indication that these small ice particles affected the charge measurements.

[8] Cloud drop charges were also measured in a 250 m thick altostratus (As) layer on January 18, 1998 between 1034 and 1036 UTC (Figure 3). Electra descended under clear skies from above the As layer and leveled off at 3.0 km near Manistee, Michigan before entering the top of the layer that rose in the direction of flight. The increasing elevation of the layer was evident from the onboard IR lidar prior to entry. The Electra elevation varied by less than ±10 m in the cloud layer in response to vertical air motions between −1.8 and +1.2 m s^{-1}.

[9] Downdrafts predominated near the top of this nocturnal layer cloud where the cloud drops apparently formed in radiatively cooled parcels. The temperature before entering the cloud elements was −16°C. Typical minimums of −18°C were measured in the cloud elements. Small ice crystals were detected during just four isolated one-second periods and there was no indication that the ice particles affected the measurements of drop charge.

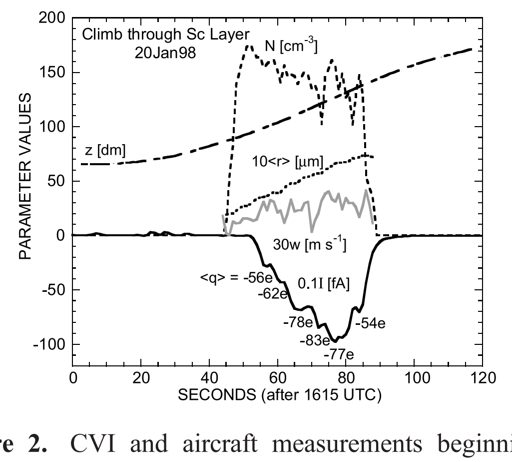

Figure 2. CVI and aircraft measurements beginning at 1615 UTC for a climb through a 0.6 km thick stratocumulus layer at an average airspeed of 114 ms^{-1}. Data are plotted for the cloud drop concentration (N), mean radius ($\langle r \rangle$) from the forward scattering spectrometer probe, CVI electrometer current (I), and the updraft velocity, where w(m s^{-1}) is obtained from the ordinate value divided by 30. The average cloud drop charge ($\langle q \rangle$) is given for the significant current peaks. The temperature range was −12°C to −19°C from layer base to top.

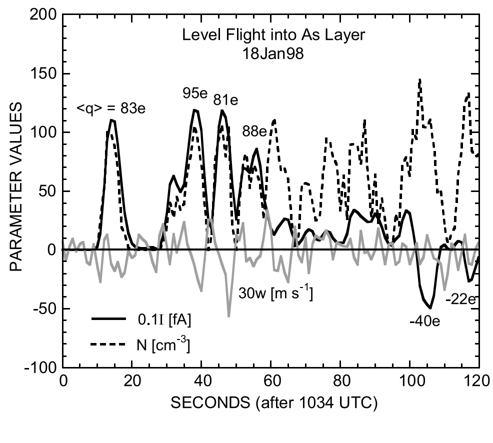

Figure 3. CVI and aircraft measurements during level flight at an average airspeed of 120 ms^{-1} at 3 km elevation into the top of a 0.25 km thick altostratus layer beginning at 1034 UTC. Shown are the cloud drop concentration (N), the CVI electrometer current (I), and the updraft velocity (w). The average cloud drop charge ($\langle q \rangle$) is given for the significant current peaks. The temperature varied between −16°C and −18°C. CVI data were unavailable after 1036 UTC.

[10] A series of four strong positive current peaks was observed in the first minute of cloud penetrations at the top of the As layer. Our corresponding measurement of average drop charges of 83, 95, 88 and 90 e were associated with downdrafts. With further penetration into the rising cloud layer, the downdrafts and positive currents weakened, giving way to negative current peaks with average drop charges of −40 and −22 e. These charge were associated with average cloud drop radii of about 6 μm.

[11] The average cloud drop radius of 6 to 8 μm from the FSSP spectra was significantly larger than the CVI threshold size of 4.1 μm (50% cut size). For the six peaks labeled with average charge, 98% of the cloud drops were large enough to enter the CVI. Therefore, our measurement of average cloud drop charge correspond to the actual average charges in the cloud.

[12] Our observed average cloud drop charges in the altostratus layer are similar in magnitude to our measurements in the stratocumulus cloud layer (Figure 2) and more than a factor of ten larger than previous measurements of average drop charges obtained in similar clouds from mountain observations at the ground [*Webb and Gunn*, 1955; *Phillips and Kinzer*, 1958].

4. Discussion

[13] Cloud drops at the boundaries of a layer cloud acquire a net charge from vertical ion currents driven by the fair weather electric field outside the cloud. In this conceptual model of layer cloud electrification [*Pruppacher and Klett*, 1997; *MacGorman and Rust*, 1998], the opposing ion currents inside the cloud layer are much weaker because ion concentrations are greatly reduced by diffusion to cloud drops. The vertical ion currents become more balanced as the electric field inside the cloud layer intensifies in response to the charges at the layer cloud boundaries. These boundary charges are perturbed when updrafts or downdrafts carry charged drops into the cloud layer.

[14] The time constant for a cloud drop to become charged at the boundary of a cloud layer is of the same order as the time constant for depletion of ions by diffusion to cloud drops. It is inversely proportional to drop radius and concentration [*Chiu and Klett*, 1976] and is about 30 seconds for drops of 6 μm radius at a concentration of 100 cm^{-3}. Cloud drops acquire most of their equilibrium charge in 30 seconds, or 30 meters for cloud parcels moving at an average vertical speed of 1 m s^{-1}. Because the vertical ion drift velocities in the weak electric fields inside these cloud layers are significantly less than 0.1 m s^{-1}, cloud parcels in updrafts at cloud base will generally outrun the external source of negative ions at cloud base. Cloud drops in downdrafts originating near cloud top will become separated from the source of positive ions at cloud top.

[15] Inside the cloud layer, the ion concentrations become more neutral as ion pairs, produced by cosmic rays, recombine or are captured by cloud drops. When ion concentrations of each polarity are nearly balanced inside the cloud layer, the discharging time constant for cloud drops is inversely proportional to the ion concentration and is about 3000 seconds for an ion concentration of 100 cm^{-3} in the cloud layer [*Gunn*, 1954]. Therefore, the charge on cloud drops acquired at the cloud boundary cannot decay to an equilibrium charge in the more neutral ion environment inside the cloud layer because the relaxation time is too long – possibly longer than the lifetime of a typical cloud parcel based on the estimated mean vertical velocity and cloud depth [e.g., see *Braham and Kristovich*, 1996].

[16] Our measurements of cloud drop charges in layer clouds are consistent with charging at cloud boundaries. The polarity of the cloud drop charge in Figure 2 is the same as expected from an excess flow of negative ions into cloud base. The upward velocities of 1.0 to 1.3 m s^{-1} carry the charged drops into the cloud layer. Similarly, the polarity of charges on drops in the top of the nocturnal layer cloud in Figure 3 is consistent with an excess flow of positive ions into cloud top, and the downward velocities of 1.0 to 1.7 m s^{-1} that carry the charged drops into the cloud layer. The negative drop charges found deeper in the 250 m thick altostratus layer probably resulted from upward transport of negatively charged cloud drops at cloud base.

[17] The significance of charge on cloud drops is its ability to accelerate precipitation formation. Drop charge is known to promote bridging between colliding drops [*Ochs and Czys*, 1987; *Beard and Ochs*, 1995] that results in coalescence and accelerates the warm rain process. Charge also contributes to the formation of very large cloud condensation nuclei that can trigger precipitation [*Beard and Ochs*, 1993]. When a large cloud drop falls through an entrained filament of dry air, the capture of residue particles carrying a charge 10–100 e will be enhanced by one or two orders of magnitude [*Tinsley et al.*, 2000, 2001]. This charge-enhanced scavenging of CCN through cycles of cloud formation and dissipation will produce broader CCN spectra that more readily trigger precipitation [*Ochs and Semonin*, 1979]. Moreover, the residue particles from evaporated drops may act as evaporation ice nuclei [*Beard*, 1992] because the ice nucleating ability of particles can be greatly enhanced by a condensation-evaporation cycle [*Rosinski and Morgan*, 1991; *Rosinski*, 1995]. Since ice initiation is often a precursor to precipitation, the charge on cloud drops may play a significant role in triggering precipitation by promoting contact between charged evaporation ice nuclei and cloud drops.

[18] Although our aircraft measurements have demonstrated that cloud drops within cloud layers have much higher charges than previously measured, the cloud drop sizes in the wintertime layer clouds were generally below the threshold necessary for initiation of significant ice particle concentrations [*Hobbs and Rangno*, 1985]. We plan to extend our charge measurements to stratiform and cumuliform clouds where ice and precipitation more readily form. Further measurements are also needed in other cloud types and seasons to further evaluate whether most of the charge on cloud drops acquired near cloud boundaries is carried into the cloud by vertical motion without substantial losses. In future aircraft studies we plan to use additional instruments to measure aerosol charge and ion concentration so that we can investigate the spatial distribution of the total charge density in non-precipitating clouds.

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