Influence of low-level wind speed on droplet spectra near cloud base in trade wind cumulus

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[1] Data collected during the Rain In Cumulus over the Ocean (RICO) campaign demonstrate a relationship between the low-level wind speed, droplet concentrations and the presence of large cloud droplets near cloud base in trade wind clouds in a clean marine background atmosphere. Weak winds were associated with fewer activated cloud droplets, larger mean droplet sizes, and more large cloud droplets, even though the concentration of giant/ultragiant sea-salt aerosol increased with increasing near-surface wind speed. The data suggest that in unpolluted trade wind cumuli: (1) the production of large cloud droplets near cloud base is controlled primarily by the intensity of the cloud base updraft rather than the concentration of giant/ultragiant sea-salt particles; (2) higher droplet concentrations are more likely under conditions of stronger low-level wind speeds, primarily because stronger low-level wind speeds are associated with more intense cloud base updrafts.


1. Introduction

[2] The droplet concentration near cloud base in marine cumuli is controlled by the concentration of cloud condensation nuclei (CCN) entering cloud base and the peak supersaturation occurring in updrafts, which is closely related to the updraft intensity just above cloud base [Twomey, 1959]. In unpolluted marine airmasses, CCN are primarily composed of submicron sea-salt particles and, to a lesser extent, ocean-generated organics and sulfates [e.g. Twomey, 1977; O’Dowd et al., 1999]. The concentration of sea-salt particles is controlled by wind-induced stress on the ocean surface [Lewis and Schwartz, 2004, and references therein]. Over the ocean, sub-micron (dry radius, \( r = 0.05–1.0 \) µm), giant (\( 1 < r \leq 10 \) µm) and ultragiant (\( r > 10 \) µm) sea-salt particle concentrations have been observed to increase with increasing near surface wind speeds (within the range of 2–30 m s\(^{-1}\)) [e.g. Woodcock, 1953; O’Dowd and Smith, 1993; Bigg et al., 1995; O’Dowd et al., 1999; Mason, 2001].

[3] The importance of giant/ultragiant cloud condensation nuclei (GCCN) to the onset of precipitation in warm (>0°C) clouds remains one of the more-studied questions in cloud microphysics [e.g. Woodcock and Gifford, 1949; Woodcock, 1953; Ochs and Semonin, 1979; Johnson, 1982, 1993; Szumowski et al., 1999; Laird et al., 2000; Lasher-Trapp et al., 2001; Knight et al., 2002]. Although giant and ultragiant sea-salt particles have been observed near cloud base in marine environments [e.g. Woodcock, 1953], and numerical studies suggest that these particles can grow to form precipitation in the lifetime of a typical cumulus cloud [Johnson, 1982; Szumowski et al., 1999; Lasher-Trapp et al., 2001], it remains unclear whether these particles primarily control the production of large cloud droplets near cloud base and the amount of drizzle produced by warm marine cumuli.

[4] Modeling studies have found that the concentration of submicron CCN strongly modulates the importance of GCCN in the initiation of precipitation in marine clouds [Ochs and Semonin, 1979; Johnson, 1982; Feingold et al., 1999; Rosenfeld et al., 2002]. In general, these studies predict that at the very low concentrations of CCN found over the open oceans, GCCN are no longer critical to the production of large cloud droplets, a key precursor to the initiation of precipitation. Although these modeling results have yet to be verified, studies using data have indirectly implied that GCCN do not strongly influence precipitation in clouds with low CCN concentrations [Woodcock et al., 1971; Hudson and Yum, 2001].

[5] In this paper, we use data from flights of the National Center for Atmospheric Research (NCAR) C-130 aircraft during the Rain In Cumulus over the Ocean (RICO) field campaign to investigate the influence of the low-level wind on droplet concentrations and the production of large cloud droplets near cloud base in warm, unpolluted, maritime trade wind cumuli. In doing so, we address the question of whether GCCN are important to the production of large cloud droplets in these clouds.

2. Data Sources

[6] The RICO campaign took place over the tropical Atlantic off the Caribbean island of Barbuda (17.20°N, 61.48°W) between 26 November 2004 and 24 January 2005. Clouds at this location were expected to have maritime characteristics since trade winds in this region blow from the east-northeast over the open Atlantic.

[7] The C-130 flew 19 missions during RICO. Most eight-hour flights began and ended with three 60-km diameter circles at altitudes of approximately 5 km, 300 m and 100 m above the ocean surface. The central four hours of each flight were used to sample trade wind cumuli. Data presented here were obtained using aircraft-mounted probes – a TSI 3760 CN counter (0.01–3 µm range), a PMS Passive Cavity Aerosol Specrometer Probe (PCASP/SPP-200, usable diameter range 0.14–2.75 µm), a PMS Forward Scattering Spectrometer Probe (FSSP/SPP-100, 3.1–46.5 µm), a PMS
optical array probe (OAP 260X, 35–625 μm), a PMS two-dimensional cloud OAP (2DC, 42–1592 μm with image reconstruction), and a Giant Nuclei Impactor (GNI) system. Information concerning the spectrometers and OAPs is given, for example, by Knollenberg [1970], Heymsfield and Parrish [1978], Dye and Baumgardner [1984], Cooper [1988], Strapp et al. [1992], and Jensen and Granek [2002]. The GNI, initially constructed at CSIRO (Australia) and further developed by NCAR, was used to impact giant aerosols on glass slides exposed outside the aircraft in the free airstream. The glass slides were subsequently humidified in a chamber to 91.5% relative humidity and sized using an automatic optical microscope system. The particles, based on electron microscopic analysis (Anderson, personal communication, 2006), were primarily sea-salt that deliquesced to form spherical droplets on the slide upon humidification. Using the Köhler equation, giant sea-salt particles with dry diameter greater than 4 micron were sized into bins of 1 micron width. One further measurement, vertical velocity, is used in this paper. The vertical air velocity was calculated using the C-130 five hole nose cone in conjunction with inertial and Global Positioning System measurements.

Three missions (RF01, RF02, RF16) were eliminated from this study either because of instrumentation problems or unsuitable flight patterns. On a fourth flight (RF19) only microphysical data from the PCASP and CN counter were used. Average clear air aerosol concentrations above the ocean surface were calculated from the 1 Hz CN counter, PCASP, and FSSP data collected during the 100-m circles. Sections of the 100-m circles where rainshafts were penetrated (regions with 2DC > 0.00 L−1/C0) or rain cooled air was encountered were eliminated from the data to insure that the spectra were characteristic of the ambient air over the ocean. In addition, sharp, narrow spikes associated with possible ship plumes were eliminated from the PCASP and CN data. For convenience, the accepted regions of the circles will be referred to as “clear regions”. Particle size spectra were developed from FSSP and GNI data collected in these same clear regions. The average relative humidity in clear regions for morning circles was 77.1 ± 4.4% and for the afternoon circles, 76.8 ± 4.5%.

Particle concentrations were compared to average wind speeds measured by the aircraft on the same circle segments. To insure that the 100-m winds were representative of winds near the ocean surface, they were compared with wind speed measurements from dropsondes launched from the aircraft during the 5-km altitude circles. No significant variations in wind speed were observed at altitudes of 10 m, 50 m and 100 m from dropsonde data collected during each of the flights included in these analyses.

Droplet concentrations reported herein were made between 600 m (nominal cloud base) and 900 m above the ocean surface. Average droplet concentrations and spectra for each flight were determined from 10 Hz FSSP data, and limited to areas with liquid water content (LWC) ≥ 0.25 g m−3, vertical wind speeds ≥ 0.5 m s−1, and no droplets with diameters ≥ 65 μm recorded by the 260X probe. The latter criterion was intended to reduce the chance that raindrop breakup on the FSSP probe arms would influence the droplet spectra. The three criteria together were chosen to focus on air that has recently passed through cloud base. Vertical velocities were averaged over the same flight segments as the FSSP data. Flight segments within cloud were required to have at least three consecutive data points at 10 Hz that met these criteria to be included in the flight-averaged spectra. Note that a cloud penetration may contain more than one segment.

Figure 1. (a) Haze particle concentrations measured with the FSSP, (b) dry particle concentrations measured with the PCASP, and (c) particle concentrations measured with the CN counter in clear air regions as a function of wind speed measured on each 100-m altitude circle. In each panel, the circles denote mean values and the bars denote standard deviations. The inset table in Figure 1a shows the mean 100 m wind speed for both morning (M) and afternoon (A) circles.

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Figure 2. (a) Haze particle size distributions measured with the FSSP in clear air regions of the 100-m altitude circles of selected flights spanning the range of wind speeds observed during RICO (see Figure 3a). (b) Same data as in Figure 2a, but shown as a cumulative size distribution where the ordinate is the total concentration of particles larger than diameter D. (c) Dry particle size distributions measured with the GNI in the same clear air regions as in Figure 2a. (d) Same data as in Figure 2c, but shown as a cumulative size distribution. The second column in the inset table in Figure 2c shows the number of slides exposed during the circle and included in the average for each GNI spectra. The third column shows the mean wind speed (m s⁻¹) measured in clear air regions of the 100 m circles.

meeting the criteria. The above criteria were met in clouds sampled on twelve of the fifteen flights.

3. Measurements

3.1. Sub-cloud Aerosol

Figure 1a shows particle concentrations measured by the FSSP in the diameter range of 3.1–46.5 µm in clear regions of each 100-m altitude circle as a function of average wind speed measured on the circle. The embedded tables give the average wind speed values. The particles measured by the FSSP are likely to be deliquesced sea-salt aerosol because of their size. The data in Figure 1a show a linear relationship (Pearson product moment correlation coefficient, R = 0.87), with higher concentrations of particles present at stronger wind speeds. In contrast, no relationship was observed between accumulation mode particle concentrations measured by the PCASP (R = 0.06, Figure 1b) and the CN counter (R = 0.17, Figure 1c) as a function of average wind speed on each circle. The CN and PCASP concentrations were over two orders of magnitude larger than the FSSP haze particle concentrations.

Figure 2a shows the FSSP particle size spectra averaged over both 100-m circles from each of five flights chosen to span the range of average wind speeds on Figure 1a. Figure 2b shows the same data as a cumulative distribution, where the ordinate is the total particle concentration larger than diameter D. Similar spectra determined from GNI slides collected on the 100-m circles during the same flights appear in Figures 2c and 2d. The FSSP particles were deliquesced (presumably sea salt) at ambient relative humidity whereas the GNI particles are reported as dry diameter. The particle concentrations show similar trends. Particles as large as 20–30 µm diameter were present in low concentrations at all observed wind speeds in the marine atmosphere, with particles as large as 40 µm appearing at higher wind speeds. From both sets of measurements, it is apparent that stronger wind speeds generate higher particle concentrations across the spectra, especially for particles larger than about 10-µm diameter.

The data in Figures 1a and 2 are consistent with airborne measurements of Woodcock [1953] and many studies of sea-salt concentrations close to the ocean surface (see reviews by Fitzgerald [1991], O’Dowd et al. [1997], and Lewis and Schwartz [2004, and references therein]) that show that the marine atmosphere is populated with giant and ultragiant sea-salt particles, and that the concentration and size spectra of these particles in the sub-cloud layer are related to the strength of the low level wind, which acts to produce wave breaking on wind-generated waves. The data in Figures 1b and 1c are consistent with measurements reported by O’Dowd and Smith [1993, Figure 7]. These authors show that although sea-salt particles in the diameter size range of 0.1–3.0 µm have a log-linear relationship with low-level wind speed, non sea-salt sulfate particles in the same size ranges are poorly related to wind speed. The particles comprising Figures 1b and 1c are composed of all types of marine aerosol and therefore do not show a relationship between their concentration and low-level wind speed.

3.2. Near Cloud-Base Droplet Characteristics

The peak droplet concentration is controlled by CCN entering cloud base and the peak supersaturation. Because sea-salt aerosol are typically the largest aerosol and the first activated at cloud base [Pruppacher and Klett, 1997, pp. 172–175], and their concentration is a function of low-level wind speed, we might expect that droplet concentrations and the production of large cloud droplets near cloud base in marine cumuli should be related to the low-level wind speed. However, it is possible that the cloud organization itself may be related to low-level wind speed. If this is true, the strengths of updrafts, and consequent maximum supersaturations near cloud base, might vary in a systematic way as the low-level wind speed changes. In this section, we explore these ideas for marine cumuli observed during RICO.

Figure 3a shows the average droplet concentration observed near cloud base for segments of each C-130 flight meeting the sampling criteria as a function of wind speed 100 m above the sea surface. The correlation coefficient associated with the linear regression (R = 0.71) suggests that the average droplet concentration near cloud base also depends, in some way, on low-level horizontal wind speed. The relationship between the average updraft velocity and the low-level wind speed is shown in Figure 3b for the same flight segments. The correlation coefficient was higher (R = 0.79), although the spread in vertical velocities observed on each flight is significant. Figure 3b shows that, on average,
the clouds observed during RICO had stronger vertical velocities near cloud base under conditions of stronger low-level winds. Figure 3c shows the relationship between droplet concentration and vertical velocity directly (R = 0.66). Although there is significant variability in these data, the data suggest a trend of increased droplet concentrations with stronger vertical velocities.

[16] Figure 4 shows the effect of low-level wind speed on average cloud base droplet spectra. Five out of the twelve flights (RF-07, RF-08, RF-09, RF-12, RF-14), spanning the range of wind speeds shown in Figure 3a, are plotted in Figure 4 to show the general trend in the droplet spectra. The flights not appearing on Figure 4 that also followed this trend were RF-03, RF-05, RF-10, RF-13 and RF-15. There were two exceptions to this general trend (RF-06 and RF-18), both shown on Figure 4. For a comparison of these spectra to be valid, the LWC derived from the spectra should be similar. The LWC values from each spectra, listed in Figure 4a, had a mean and standard deviation of (0.33 ± 0.04 g m⁻³) with extreme values of 0.29 and 0.43 g m⁻³, all within a narrow range.

[17] Figures 4a and 4b show the spectra in linear and logarithmic coordinates to emphasize the smaller and larger droplets, respectively. A narrow, tall spectrum with a mode near D = 14 μm was observed for flight RF-14, the highest wind case. For progressively lower wind cases, the mode continually shifts to larger diameters. The mode of the spectrum representing the lowest wind case, RF-07, was 24 μm. The concentration of the largest particles in the spectra can be determined from Figure 4b. The highest concentration of large droplets occurred in the case with the lowest wind speeds. Concentrations of large droplets in the other spectra decreased with increasing wind speed. The two exceptions to the general trend, both with weak low-level winds, had moderate droplet concentrations and few large droplets. Flight RF-06 had stronger vertical velocities, which may have contributed to the narrower spectra. The reason for the departure of RF-18 from the general trend is not obvious. These flights are also noted on Figure 3 (points with filled squares). Except for these two flights, at high (low) wind speeds, the concentration of largest droplets near cloud base was low (high), the exact opposite behavior expected if the giant and ultragiant sea-salt particles were solely governing the production of large cloud droplets.

[18] To understand the role of GCCN in the production of the largest droplets, it is instructive to compare the cumulative sub-cloud particle distribution (Figures 2b and 2d) with the cumulative droplet distribution near cloud base (Figure 4c). The concentration of sub-cloud particles in the size range of the FSSP matches the concentration of droplets with D > 42 μm for the lowest wind case and the concentration of droplets with D > 32 μm for the highest wind case. Although the concentration of large droplets is greater in the low wind speed cases, GCCN may still account for the production of large droplets.

Figure 3. (a) In-cloud droplet concentrations for each flight day averaged over regions meeting the sampling criteria specified in the text as a function of wind speeds averaged from the morning and afternoon 100 m altitude circles. (b) Average updraft velocities within regions meeting the sampling criteria for each flight day as a function of wind speeds averaged from the morning and afternoon 100 m altitude circles. (c) Average droplet concentrations within regions meeting the sampling criteria for each flight day as a function of updraft velocity. The inset table in Figure 3a shows the average of morning and afternoon 100-m altitude wind speeds (WS) (see tables in Figure 1a). In each panel, the open circles or filled squares denote mean values and the bars denote standard deviations. The points denoted with filled squares correspond to the exceptions to the trend in the droplet spectra in Figure 4.
largest droplets in the spectra. This is particularly true for high wind speed cases, where the concentration of sub-cloud GCCN is greatest.

4. Discussion

[19] The RICO data demonstrate a relationship between the low-level wind speed (over the range of $5 \sim 14 \text{ m s}^{-1}$), droplet concentrations and the production of large cloud droplets near cloud base. Weak low-level wind speeds were associated with fewer activated cloud droplets, a large mean droplet size, and many more large droplets just above cloud base (Figure 4), despite the fact that weak winds generated fewer GCCN. At strong low-level wind speeds, where GCCN concentrations were larger, the concentration of largest droplets just above cloud base was surprisingly low.

[20] A factor influencing droplet concentrations and the production of large cloud droplets in these clouds was the magnitude of the updraft velocity. Evidence presented suggests a relationship between the low level wind speed and updraft strength, with stronger updrafts associated with stronger low-level winds. The effect of more intense updrafts would be to increase the peak supersaturation, leading to activation of more cloud droplets and smaller cloud droplets near cloud base. The total concentration of smaller CCN, as inferred from the PCASP and CN measurements, did not show a clear dependence on wind speed (Figures 1b and 1c). This suggests that variability in the cloud base updraft was an important control on the growth of drops. The data suggest that stronger horizontal low-level wind speeds led to fewer large drops just above cloud base in the RICO trade cumuli because of the low-level wind’s association with updraft strength. This is despite the fact that stronger low-level wind speeds were associated with more and larger GCCN.

[21] Should these results be taken as an argument against the action of giant aerosol particles in precipitation formation? Not necessarily, since the very largest cloud droplets (which may indeed later become the first precipitation drops in both high and low wind speed regimes) are still likely to form on the giant and ultragiant aerosol particles. However, given that the highest concentration of large cloud droplets occurs in cases with weak low-level wind speeds, we may hypothesize that warm rain formation is more efficient in clean marine cumulus clouds occurring in weak wind environments, provided that other factors (e.g. entrainment, cloud depth) are similar. This hypothesis will need to be tested using additional analyses and modeling studies.

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