NOTES AND CORRESPONDENCE

Humidity Halos Surrounding Small Cumulus Clouds in a Tropical Environment

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ABSTRACT

A large dataset of aircraft cloud traverses from the Small Cumulus Microphysics Study (SCMS) was used to add to the existing knowledge of humidity halo characteristics for small cumulus clouds in a tropical environment. The findings from this investigation show a larger frequency of observed humidity halos than earlier studies. Regardless of the radial direction with respect to shear, humidity halos were observed with a frequency of 77%–90%. The difference in frequency of halo occurrences between upshear and downshear regions was much smaller than previously reported observations. These findings likely resulted from the absence of a strong vertical wind shear environment.

SCMS cumuli had a mean cloud diameter (i.e., in-cloud traverse distance) of 1.1 km and mean halo lengths of about 0.6, 0.7, and 0.8 cloud radii for upshear, cross-shear, and downshear regions, respectively. Humidity halos of less than one cloud radius were observed during about 70% of SCMS aircraft traverses. Approximately 98% of humidity halos had radial lengths of less than four cloud radii. Although considerable differences were not observed between upshear and downshear halo lengths for clouds of similar age, large increases in the frequency and length of halos occurred with an increase in cloud age.

1. Introduction

The environment in which cumulus clouds grow is continuously modified by transport of energy, moisture, and aerosol from below cloud base to the detrainment regions of clouds. Significant enhancements to humidity, above that in the undisturbed, ambient environment, have been observed in the near-cloud regions of cumulus clouds (e.g., Malkus 1949; Ackerman 1958; Radke and Hobbs 1991; Perry and Hobbs 1996; Lu et al. 2003). These regions of enhanced humidity surrounding clouds are often referred to as humidity halos. Information regarding humidity halos is applicable to investigations of cloud edge mixing, cloud radiative properties, cumulus exchange with the large-scale ambient environment, and cloud impact on subsequent particle and cumulus formation. An increased understanding of the characteristics of humidity halos may also help address points of contradictory research findings and important questions in cloud and precipitation physics that remain unanswered. As an example, what role might regions of enhanced humidity have in providing preferred locations for subsequent cloud growth and development? Telford and Wagner (1980) presented some observational evidence that suggested that high humidity regions represent preferred areas for new cloud development. Alternatively, a numerical cloud modeling study by Carpenter et al. (1998) showed there to be no evidence for favored new cloud growth as thermals ascended through the remnants of preceding clouds.

Although previous studies have established the existence of an enhanced region of humidity in the vicinity of cumulus clouds, a large sample of clouds has not been used to thoroughly characterize the radial distribution of humidity halos surrounding small cumulus in a tropical environment. Recently, Lu et al. (2003) (hereafter referred to as LU03) used aircraft measurements of cumulus clouds near Oahu, Hawaii, with a specific focus on 14 aircraft traverses of a single long-lived cumulus, to compare with results from numerical cloud model simulations. Using 203 aircraft traverses of 31 isolated cumulus clouds over the northeast Pacific

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Ocean near the Washington and Oregon coastlines, Perry and Hobbs (1996; hereafter referred to as PH96) found humidity halos broaden with cloud age and their frequency and average size directly related to the radial direction relative to the vertical wind shear.

Based on findings from previous studies (e.g., Malkus 1949; Ackerman 1958) and their observations, PH96 proposed a conceptual model describing the structure of the humidity halo surrounding small to medium cumulus clouds. Their model initially has air detrained from the cloud uniformly in all directions at levels where the in-cloud buoyancy decreases with height. If vertical wind shear is a feature of the environment, cloud growth occurs on the upshear side, and decay occurs on the downshear side. This pattern of growth results in an enlargement of the halo on the downshear side of the cloud and limits the length of the halo on the upshear side. The halo in the cross-shear directions would be equidistant and have radial lengths less than the downshear direction.

The goal of this investigation was to add to the existing knowledge and observations of humidity halos and to develop a better understanding of humidity halos by quantifying their characteristics and spatial distribution. This note uses a large dataset of aircraft cloud traverses from the Small Cumulus Microphysics Study to describe humidity halos of small cumulus clouds in a tropical environment.

2. Small cumulus humidity halos

a. Measurements and methods

The Small Cumulus Microphysics Study (SCMS) was conducted in July–August of 1995 along the east-central coast of Florida (i.e., in the vicinity of Cape Canaveral). The objective of the SCMS was to investigate the initial development and early evolution of warm cumulus clouds, specifically addressing 1) the onset of precipitation, 2) the evolution of droplet and raindrop size distributions, and 3) the processes of entrainment and mixing. This investigation used aircraft measurements from 12 flights of the National Center for Atmospheric Research (NCAR) C-130 during the SCMS and a total of 411 cumulus cloud traverses to examine the characteristics of humidity halos. Typically one to three aircraft traverses were made through each cloud sampled. The NCAR C-130 attempted to traverse through the center of clouds; therefore cloud diameter is generally equivalent to in-cloud traverse length for this investigation.

The small cumulus sampled on different days during the SCMS developed in relatively similar ambient thermodynamic environments that were systematically documented using aircraft and rawinsonde measurements. Aircraft measurements collected during take-off and landing on each flight provided vertical profiles of humidity, stability, and vertical wind shear in the undisturbed ambient environment. These profiles, collected in cloud-free areas typically located within 5–20 km of the aircraft cloud study region, were used as a point of comparison with aircraft humidity measurements near cloud edge regions to determine the presence and extent of humidity halos.

The humidity approaches the value of the undisturbed environment as the distance from the cloud increases within the cloud-free detrainment region surrounding a cloud. For purposes of this investigation, the cloud edge is defined using total particle concentration measurements from the forward scattering spectrometer probe (FSSP). These data had a collection rate of 10 Hz, approximately equivalent to an aircraft flight distance of 11 m. The cloud boundary was defined as the location where the cloud droplet number concentration decreased to, and remained below, 10 cm^{-3}. This threshold value was chosen to avoid clear-air background aerosol and particle concentrations that existed during SCMS (e.g., Laird et al. 2000, 2001) and have been previously observed in maritime environments (e.g., Meszaros and Vissy 1974; Hoppel et al. 1989). Absolute humidity measurements were examined to determine the extent of the humidity halo and were collected using the fast-response Lyman-alpha hygrometer with a sample rate of 25 Hz (~4.5 m distance) and response time of 2 ms. Humidity measurements collected at 25 Hz were interpolated to 10 Hz to determine the humidity halo existence and lengths away from cloud boundaries.

Similar to PH96 and LU03, the horizontal extent of the halo was represented by the *e*-folding distance prior to and following each cloud traverse. The *e*-folding distance was determined through a comparison of the average in-cloud absolute humidity with the absolute humidity of the undisturbed environment at the height of each aircraft cloud traverse. The *e*-folding distance was defined as the distance from the cloud boundary where the measured absolute humidity decreased to, and remained below, the *e*-folding absolute humidity (ρ_{ve}); ρ_{ve} is defined by

$$\rho_{ve}(z) = \overline{\rho}_{vc}(z) - \{[\overline{\rho}_{vc}(z) - \overline{\rho}_{venv}(z)] \times (1 - e^{-1})\}, \quad (1)$$

where $\overline{\rho}_{vc}$ and $\overline{\rho}_{venv}$ are the average absolute humidities of the cloud and the ambient environment at the height of the aircraft traverse (z), respectively. Figure 1 presents data from a cloud traverse showing an extension of the cloud humidity halo in the downshear direction

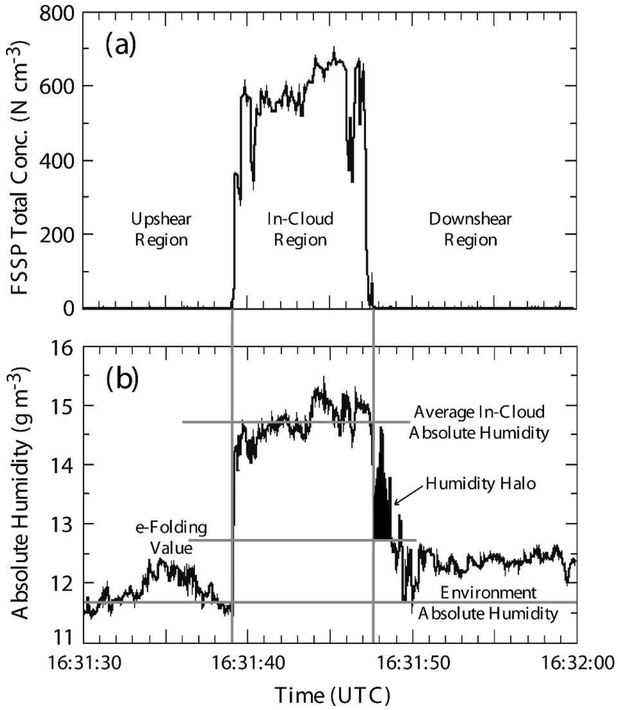

FIG. 1. NCAR C-130 measurements of (a) forward-scattering spectrometer probe (FSSP) total particle concentrations and (b) Lyman-alpha hygrometer absolute humidity from a traverse through a SCMS cumulus on 19 Jul 1995. (b) An example of a humidity halo in the downshear region. Average in-cloud, ambient environment, and *e*-folding values of absolute humidity are shown as horizontal gray lines. Vertical gray lines denote cloud boundaries.

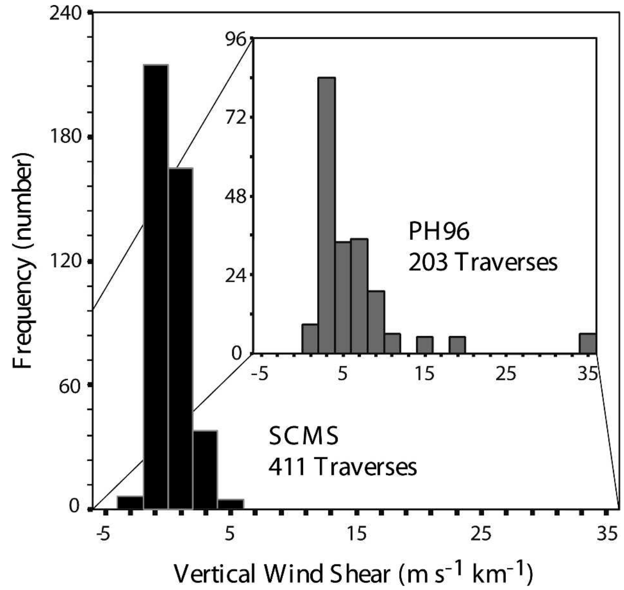

FIG. 2. Frequency distributions of vertical wind shear (m s^{-1} km^{-1}) for SCMS (black) and PH96 (gray: inset) aircraft traverses. Negative shear values imply that wind speed decreased with height.

with no evidence of a halo in the upshear direction. A "No Halo" region is defined as the coincident location of the *e*-folding distance, as determined by absolute humidity measurements, with the location of cloud boundary, as determined by FSSP measurements. Measurements from cloud traverses where the aircraft did not reach the maximum extent of the humidity halo (i.e., *e*-folding distance) prior to a subsequent cloud traverse were not included in the analyses.

b. Clouds, shear environment, and humidity halos

The winds within the ambient environment at levels ±200 m relative to each cloud traverse height were used to determine the vertical wind shear. Values of shear were generally less than ±2 m s^{-1} km^{-1}, with an average absolute vertical wind shear of 1.0 m s^{-1} km^{-1}. The mean diameter of the clouds included in the current study was 1.1 km. The conceptual model developed by PH96 and their results describing humidity halos were derived from measurements in a stronger vertical wind shear environment compared to those sampled during the SCMS (Fig. 2) and for clouds with a larger mean diameter (Fig. 3). The average vertical wind shear and cloud diameter for isolated cumulus traversed by PH96 were 6.1 m s^{-1} km^{-1} and 2.3 km, respectively. Figures 2 and 3 show noticeable differences in the vertical wind shear and cloud diameter distributions for the 411 cloud traverses of the current study and the 31 clouds sampled by PH96.

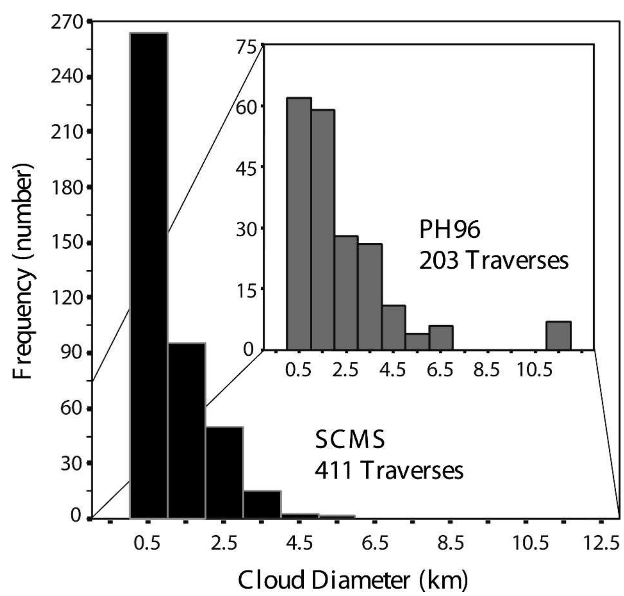

FIG. 3. Frequency distributions of cloud diameter (km) for SCMS (black) and PH96 (gray: inset) aircraft traverses.

Figure 4 shows that approximately 70% of halos observed during SCMS had lengths of less than one cloud radius and about 98% of observed humidity halos had a radial length less than four cloud radii. Similarly, PH96 found humidity halos were generally less than four cloud radii; however, halos in a few instances had a larger radial length. For larger trade wind cumulus clouds with an average diameter of about 3.6 km, LU03 found all halos were less than two cloud radii in horizontal extent. The average humidity halo lengths, relative to the cloud radius, reported by PH96 were 0.3, 0.7, and 1.3 for upshear, cross-shear, and downshear regions, respectively. The mean halo lengths, relative to cloud radius, for SCMS clouds were found to be 0.6, 0.7, and 0.8 for upshear, cross-shear, and downshear regions, respectively. These translate into halo lengths of approximately 660, 770, and 880 m for a mean SCMS cloud of 1.1-km diameter.

The SCMS measurements show a larger frequency of observed humidity halos than earlier studies. On average, approximately 86% of cloud boundary traverses had a humidity halo. PH96 found halos were present with frequencies of 74%, 40%, and 36% on the downshear, cross-shear, and upshear regions of clouds. LU03 identified the occurrence of a humidity halo approximately 44% and 55% of the time for upshear and downshear regions, respectively. Figure 4 shows that, regardless of the radial direction, humidity halos were observed with a frequency between 77% and 90%. Similar to previous studies, halos were most frequently observed in the downshear region (87%) and the frequency did not vary significantly in the cross-shear (86%) or upshear (83%) regions. The difference in frequency of halo occurrences between upshear and downshear regions was much smaller than previously reported observations. The observed high frequency and small differences in the frequency of halos in all radial directions was likely caused by the absence of a strong vertical wind shear environment during the SCMS.

Cloud age was shown by PH96 to have a significant effect on the radial lengths of the humidity halo. The appearance of penetrated SCMS clouds was examined using forward-looking flight videos to estimate the age of each cloud. Cloud age was determined using similar criteria employed by PH96. The visual clarity of cloud top and edges were used to distinguish younger clouds with well-defined, sharp boundaries from older clouds with ragged, nebulous boundaries. Not all clouds could be adequately classified using the forward-looking flight videos. The cloud age was estimated for 341 of the 411 SCMS cloud traverses and each was placed in one of two cloud age categories (young, old). The young

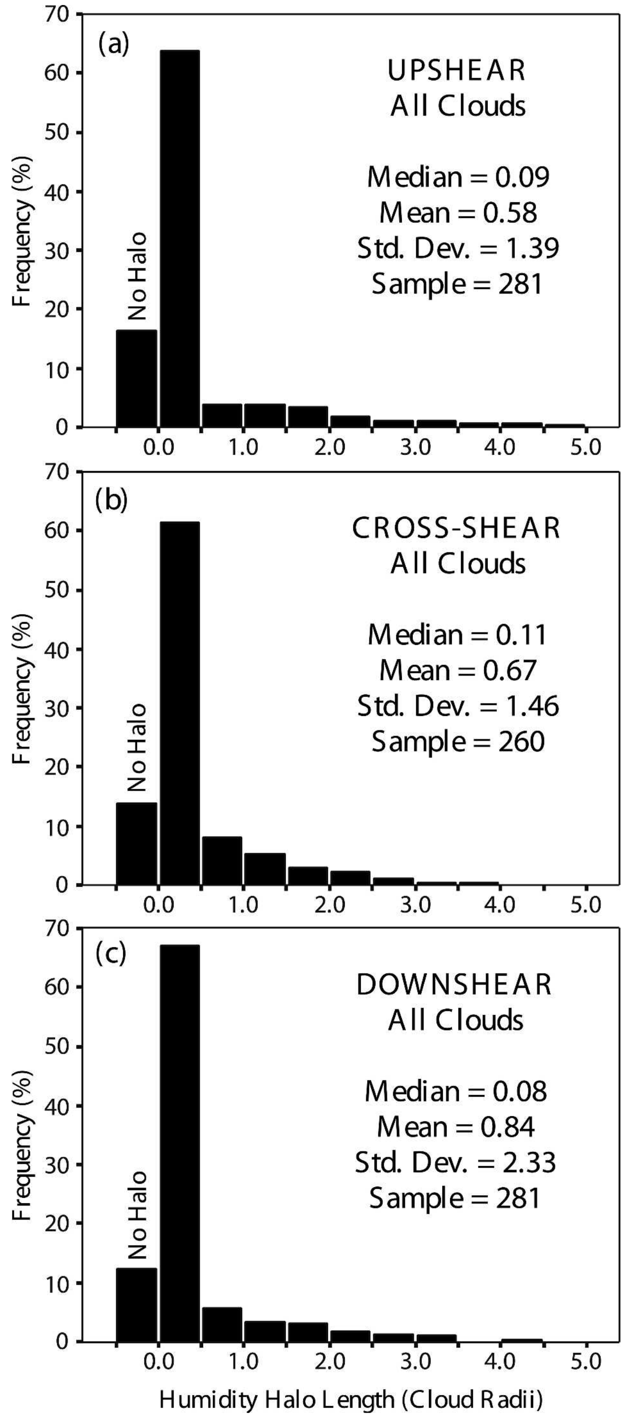

FIG. 4. Frequency distributions of humidity halo radial length for upshear, cross-shear, and downshear regions of all SCMS clouds. Observed humidity halo length is normalized by cloud radius for each aircraft traverse. Humidity halo median length, mean length, standard deviation, and aircraft traverse sample size are shown.

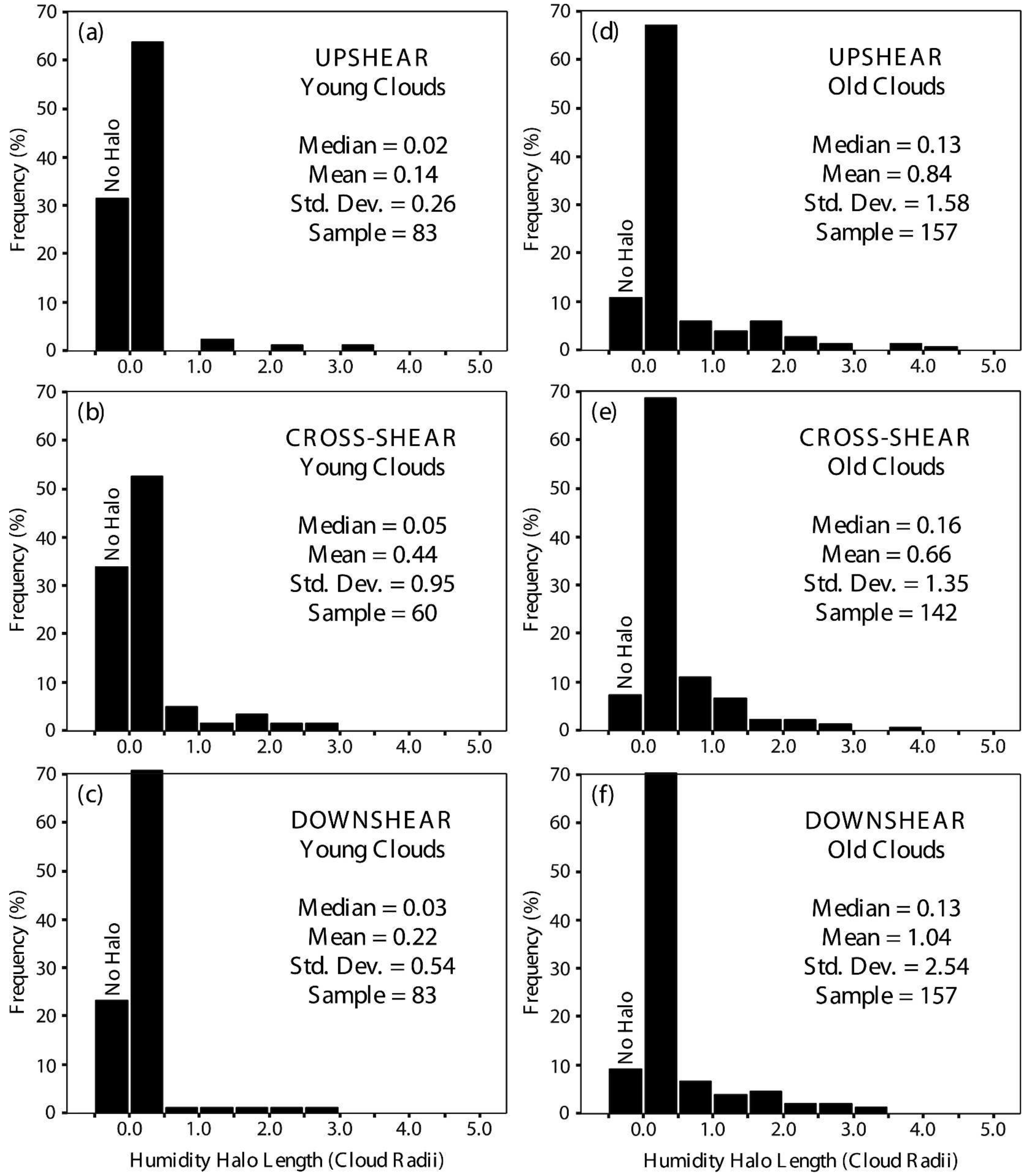

FIG. 5. Same as Fig. 4, but with (a)–(c) young and (d)–(f) old SCMS clouds.

cloud category represented cloud lifetimes up to and including the mature stage.

Figure 5 shows cloud age had a considerable effect on the existence of humidity halos, their average length, and the degree of their variability in length. Humidity halos were more prevalent for older clouds with an approximate frequency of occurrence of 90%. Alternatively, younger clouds had humidity halos with a frequency of 57%–85%. Although an increase of halo length was not always observed from upshear to downshear regions for clouds of similar age, a considerable increase in the average and variability of the halo length for each region occurred with an increase in cloud age. The smallest differences were in the cross-shear regions where old clouds had an average halo length 1.5 times larger than young clouds. The upshear and downshear regions showed an increase in average halo length of nearly one cloud radius from young to old clouds.

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