RADAR ANALYSIS OF PRECIPITATION DEVELOPMENT IN FLORIDA CUMULUS CLOUDS

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1. INTRODUCTION

The initiation and rapid acceleration of the precipitation process through collision-coalescence in warm cumulus clouds requires a mechanism for droplet spectral broadening, specifically the growth of the large end tail of the droplet spectrum. One of the simplest hypotheses, developed more than a half century ago, is that giant and ultragiant aerosols, such as sea-salt particles in marine environments, form large droplets upon entering cloud base (Woodcock and Gifford 1949). Although giant and ultragiant aerosols have the potential to produce large raindrops in time frames consistent with the growth of warm cumulus clouds, it is uncertain whether the concentration of these particles is sufficient to produce significant amounts of rain at the ground.

One of the goals of the Small Cumulus Microphysics Study (SCMS), which was conducted in the summer of 1995 near Cape Canaveral Florida, was to study warm cumuli in their earliest stages, with the goal of understanding the factors that control the time to onset of precipitation. During SCMS, there were significant variations from day to day in the CCN concentrations, ranging from more maritime conditions (359 $\pm$ 142 cm^{-3}) to continental conditions (1411 $\pm$ 388 cm^{-3}) (Hudson and Yum 2001). These variations were associated with the prevailing wind direction, which in different time periods was either onshore or offshore of the east Florida coast. Hudson and Yum (2001) found that an apparent cloud droplet mean size threshold for the onset of drizzle was almost never exceeded in the continental clouds but was often exceeded in the maritime clouds, especially at higher altitudes. They concluded that in the SCMS clouds higher CCN concentrations suppressed drizzle formation. Hudson and Yum's study suggests that giant and ultragiant aerosols apparently had little effect on the formation of precipitation in these clouds.

The purpose of this paper is to investigate the radar reflectivity evolution of SCMS clouds with the goal of determining whether any significant differences are detectable in the time to onset of precipitation that can be associated with the clouds' continental or maritime characteristics. For this study we have examined the entire SCMS radar data set and identified those clouds in which a sufficient radar history of the cloud from its earliest detection through precipitation was clearly documented.

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2. THE SCMS FIELD PROJECT

During SCMS, small cumuli were studied using radar, three instrumented aircraft, atmospheric soundings, and time-lapse videos. Small cumuli typically first appeared in mid-morning and developed precipitation when their tops reached 3 to 4 km MSL. Precipitation typically developed within 20 to 30 min of the initial detection of the clouds with radar. During SCMS, radar data were collected on 44 consecutive days from 3 July through 19 August 1995. Aircraft operation began on 19 July and continued through 19 August.

The data used in this paper were acquired with the National Center for Atmospheric Research (NCAR) CP2 dual-wavelength radar. The radar, which was located on a barrier island, operated at 3 cm (X-band) and 10 cm (S-band) wavelengths, with the antennas collocated on the same pedestal and adjusted to the same pointing angle. During SCMS, radar studies of clouds were conducted almost exclusively using Range-Height Indicator (RHI) scans over a narrow range of azimuth (typically 15° to 30°). The RHI scans were typically spaced about 1° to 1.5° apart. Radar volumes were repeated approximately every 2.5 minutes. These volumes were interrupted for a 360° surveillance scan every 10 min. The time between RHI radar volumes when interrupted by a surveillance scan was $\sim$4 min. Range gates were every 100 m and the vertical beam spacing ranged from 0.3° to 0.7°. The beam width in both the azimuthal and elevation directions was approximately 1° for both S- and X-band.

3. DATA ANALYSIS METHODOLOGY

The critical parameters governing precipitation onset of warm developing cumuli are the updraft velocity, the liquid water content (LWC), the initial aerosol spectra, and the entrainment rate. Figure 1a shows an example of series of RHI scans through a cloud's maximum reflectivity which represents a typical temporal evolution of an SCMS cumulus cloud in X-band radar reflectivity. Figure 1b shows the corresponding time-height cross-section of the same cloud. This time-height approach was first used e.g. by Knight and Miller (1998) to study precipitation development in convective clouds. The

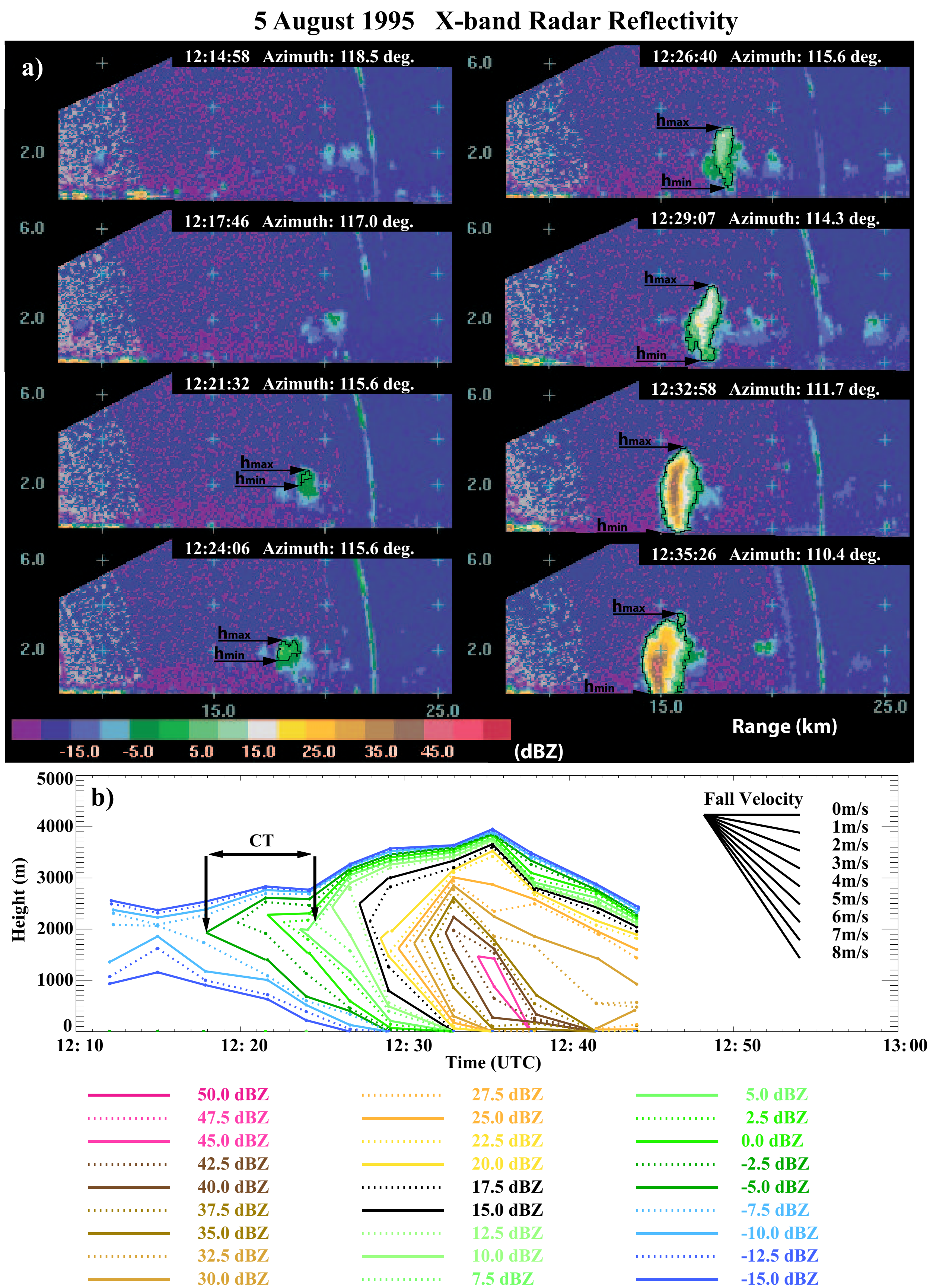

Figure 1: *a) Series of RHI scans representing the time evolution in X-band radar reflectivity of a cloud on 5 August 1995. Maximum and minimum heights of the 0 dBZ contour are indicated. b) Corresponding time-height cross-section.*

goal of our study is to use X-band radar reflectivity measurements similar to those illustrated in Fig. 1 to determine if a significant difference can be detected in the *characteristic time required for precipitation development* (CT) and the *characteristic maximum liquid water content* (CLWC) present at the time of precipitation onset in different populations of SCMS clouds. For this study, the CT was defined as the length of time between the first occurrences of two threshold reflectivity values -5.0 dBZ and 7.5 dBZ (e.g. 400.5 seconds in Fig. 1b). The CLWC was defined as the adiabatic LWC determined at the altitude of the first occurrence of the 7.5 dBZ reflectivity value. The adiabatic LWC is only a function of height above cloud base, and it was calculated using aircraft or sounding measurements of cloud base altitude, pressure and temperature (Laird *et al.*, 2000).

The updraft speed, which was not measured, is not necessary to characterize the evolution of precipitation using the technique described above. This is because the analysis implicitly include vertical velocity by considering the time between the occurrence of two Rayleigh reflectivities and the CLWC. Thus, the analysis can be viewed as considering a characteristic height and time, and thus a characteristic vertical velocity.

4. RESULTS

A total of 45 clouds that feature radar histories suitable for this analysis were found in the entire SCMS data set. Our first approach was to segregate the clouds based on their motion. Each analyzed cloud was tracked to determine whether the cloud moved in an offshore direction, an onshore direction, or parallel to the shoreline. The cloud tracking method was compared with the data from Hudson and Yum (2001). Hudson and Yum found that continental periods (CCN concentrations characteristic of continental clouds) were associated with boundary layer winds that were primarily westerly (offshore of the east coast of the Florida peninsula), while the maritime conditions (CCN concentrations characteristic of maritime clouds) were associated primarily with easterly (onshore) flow.

Twenty-three clouds were found during days with onshore winds, 15 clouds during days with offshore winds, and 7 clouds during days with shore-parallel winds. Figure 2a shows a scatter plot of CT versus CLWC. Each point represents the analysis of one growing cumulus cloud. Clouds that developed during days with onshore winds are depicted as black dots, clouds developed during days with offshore winds as gray dots and clouds developed during days with shore-parallel winds as white dots.

The second approach was to segregate the clouds based on the mean surface wind speed (surface to 300 m). Giant and ultragiant aerosol concentrations are a function of the low-level wind speed because of

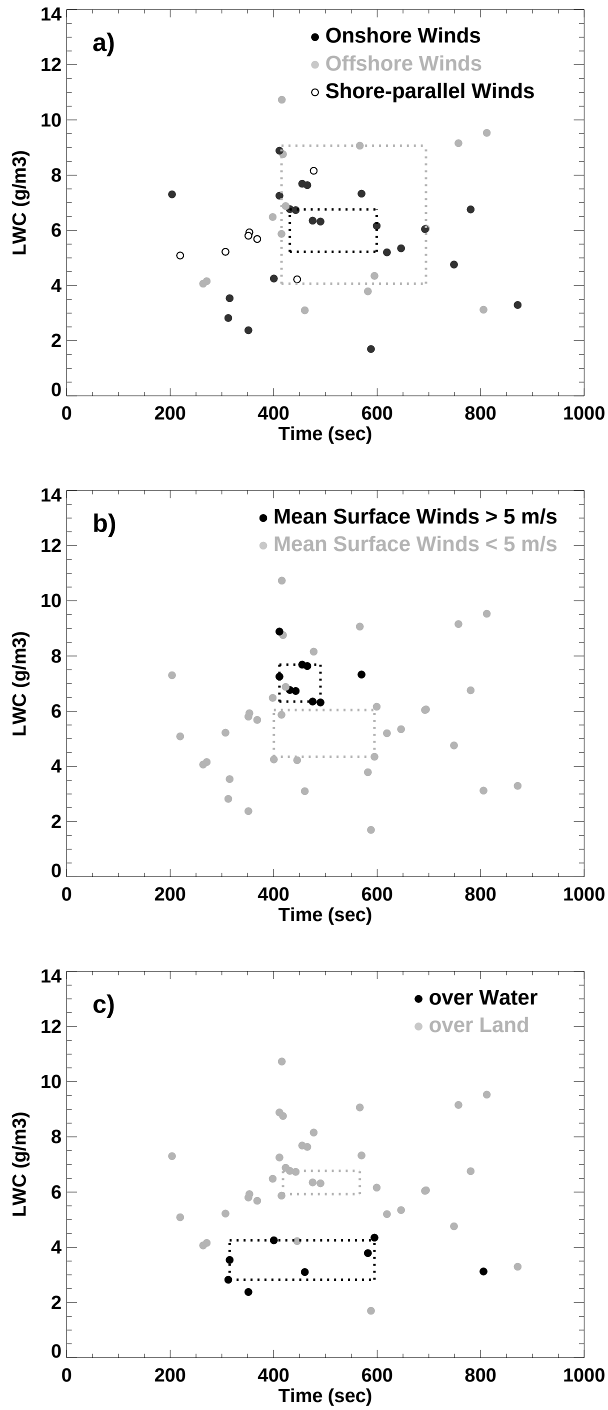

Figure 2: *Scatter plot of CT versus CLWC for 45 growing SCMS clouds. a) Clouds developed during days with onshore winds (black dots), offshore winds (gray dots) or shore-parallel winds (white dots). b) Clouds developed during days with mean surface winds* > 5 *m* s^{-1} *(black dots) or* < 5 *m* s^{-1} *(gray dots). c) Clouds developed over the ocean (black dots) or over land (gray dots).*

the action of wind in creating waves and sea spray. Figure 2b shows a scatter plot of CT versus CLWC for the growth of each cloud with surface winds < 5 m s^{-1} (gray dots) or surface winds > 5 m s^{-1} (black dots).

The third approach was to segregate the clouds based on the location where each cloud developed, either over the ocean or over the land. The swamps of the Florida peninsula represent a potential significant source of CCN (Sax and Hudson 1981). Since the rate at which precipitation develops within clouds depends on the CCN concentration, CT and CLWC required for precipitation development may differ in these two cloud populations. Figure 2c shows a scatter plot of CT versus CLWC for the growth of each cloud either over land (gray dots) or over the ocean (black dots).

The nonparametric 90% confidence limits in each dimension are depicted as dotted vertical and horizontal lines in Fig. 2. There is a 90% certainty that the true median CT is between the two vertical lines, and the true median CLWC is between the two horizontal lines.

5. DISCUSSION

Considering only the onshore and offshore moving clouds in Fig. 2a, the two cloud populations and their confidence intervals overlap completely. This indicates that there is little difference in X-band radar reflectivity evolution between these two cloud populations. Figure 2b shows the influence of the surface wind speed and thus the concentration of giant and ultragiant aerosols on the rate at which precipitation develops in SCMS clouds. The CT confidence intervals overlap completely. Thus there is little difference in the time required for precipitation development for these two populations of clouds. The CLWC confidence intervals on the other hand are set off. Clouds that developed during days with mean surface wind speeds > 5 m s^{-1} require slightly higher CLWC and thus greater depth compared to clouds that developed during days with mean surface wind speeds < 5 m s^{-1}. Finally, Fig. 2c suggests that the location, whether the clouds grew over land or over the ocean, has a significant influence on the CLWC. Clouds growing over the ocean seem to be rather shallow (low CLWCs) whereas clouds growing over land seem to require greater depth before precipitation forms (higher CLWCs).

Sax and Hudson (1981) showed that the Florida peninsula itself appeared to exert overwhelming influences in rapidly modifying the CCN characteristics. The authors analyzed CCN and other aerosol data obtained during east-west traverses over the southern Florida peninsula at the cloud base level. The traverses started from a point approx. 50 km offshore the east coast and terminated at a point approx. 50 km offshore the west coast. During all 13 cross-peninsula flights, conducted in the month of July, the highest concentrations of CCN were consistently measured along the east coastal region and appeared well correlated with high concentrations of Aitken particles. Sax and Hudson (1981) concluded that a boundary-layer aerosol distribution of oceanic origin undergoes a rapid modification as it crosses the south Florida peninsula with the result that the CCN activity spectra takes on continental and extreme continental characteristics. As a consequence not the characteristic of the air mass but rather the location of the cloud development should influences the precipitation formation in SCMS clouds. This becomes evident when studying Fig. 2a and c. The influence of the surface wind speed (Fig. 2b) and thus the concentration of giant and ultragiant aerosols is less significant in the context of these drastic differences in CCN concentrations over land versus over water. Since all nine clouds that grew on days with onshore winds and mean surface wind speeds > 5 m s^{-1}, developed over land, the CCN concentrations took on continental characteristics and thus the clouds required greater depth before precipitation formed.

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