Observations of the width of cloud droplet spectra in stratocumulus

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This paper discusses in-situ aircraft observations of cloud microphysics in eight cases of marine stratocumulus investigated during the Second Aerosol Characterization Experiment (ACE2) in the eastern subtropical Atlantic. The emphasis is on the spectral width of cloud droplet spectra, an important parameter affecting radiative properties of clouds and the development of drizzle and rain. For a given flight (i.e., for given characteristics of the cloud condensation nuclei, CCN), local droplet concentration varies considerably. The standard deviation of the cloud droplet spectra, σ, is typically in the range of 1 to 2 μm. It does not vary systematically between maritime and polluted clouds, and shows a surprisingly small difference between near-adiabatic and diluted cloud samples. The relative dispersion, d, the ratio between σ and the mean radius r is between 0.1 and 0.4. In agreement with previous studies, larger values are typically associated with polluted clouds, mostly because such clouds have smaller droplets. For all flights, d either decreases with height or does not change significantly. Based on these observations, a simple parameterization of the relative dispersion d is proposed.


1. Introduction

[2] Representation of clouds is one of the biggest challenges facing contemporary large-scale models of weather and climate. This is because cloud-scale processes are typically subgrid-scale, both for the cloud dynamics and for the cloud microphysics. For the dynamics, one is primarily concerned with spatial scales larger than tens of meters because the smaller scales can be modeled by established subgrid-scale techniques used in large eddy simulation (LES) models. Cloud microphysics, on the other hand, involves microscopic properties such as phase (i.e., liquid versus solid), size, and concentration of cloud and precipitation particles; and it remains a challenge even for LES models. The latter is especially true when a LES model is coupled to the radiative transfer; see discussions by Chosson et al. [2004] and Grabowski [2006]. For models that cannot resolve cloud-scale circulations (e.g., atmospheric general circulation models; AGCMs), the situation is even more complicated because processes affected by cloud microphysics (such as precipitation development or impact on radiative fluxes) have to be included into subgrid-scale representations of clouds.

[3] Radiative processes within clouds depend on cloud microphysical properties, especially for the shortwave (solar) radiation. For ice-free clouds, the relevant parameter is the effective radius, the ratio between the third and the second moment of the cloud droplets size distribution [e.g., Stephens, 1978]. Given the bulk cloud properties (i.e., the local cloud water mixing ratio), the effective radius depends on the mean volume radius and on the spectral width of the cloud droplet spectrum [e.g., Pontikis and Hicks, 1992; Martin et al., 1994; Liu and Daum, 2000]. The mean volume radius is inversely proportional to the cubic root of the droplet number concentration. The spectral width was argued to increase with the droplet concentration [e.g., Liu and Daum, 2002] and to partially compensate the expected decrease of the droplet effective radius, so that the optical thickness increases less than predicted by the change of the droplet concentration alone. Moreover, spectral width does affect the development of drizzle and rain, and some bulk microphysics schemes require information about the spectral width to represent this process (e.g., the scheme of Seifert and Beheng [2001]).

[4] The key processes affecting microphysical properties of warm clouds include: i) the cloud-base nucleation of cloud droplets on cloud condensation nuclei (CCN); ii) the adiabatic growth of droplets above the cloud base; iii) changes of the cloud droplet spectrum due to entrainment and subsequent cloud dilution; iv) additional nucleation of cloud droplets above the cloud base due to either increasing updraft strength [e.g., Pinsky and Khain, 2002] or entrainment [Paluch and Knight, 1984; Brenguier and Grabowski, 1993; Su et al., 1998; Lasher-Trapp et al., 2005], and v) collision-coalescence. Some of these processes narrow the droplet spectra (i.e., adiabatic growth above the cloud base), whereas others tend to increase the spectral width (e.g., nucleation above the cloud base or collision-coalescence). Although most of these processes are relatively well understood (i.e., cloud droplet nucleation, adiabatic growth, collision-coalescence), the effects of entrainment and mixing on cloud droplet spectra still lack solid theoretical foundation; see discussions by Su et al. [1998], Andrejezuk et al. [2004, 2006], F. Burnet and J.-L. Brenguier (Observational study of the entrainment-mixing process in warm convective clouds, submitted to Journal of the Atmospheric Sciences, 2006), among many others. The interaction among all of these processes determines the shape of the spectrum at a given spatial location within a cloud.

[5] This paper discusses observations of cloud microphysical properties collected in marine stratocumulus (Sc) in the subtropical Atlantic with the emphasis on the width of cloud droplet spectra. The paper extends the analysis previously presented by Pawlowska and Brenguier [2000, 2003]. The next section discusses the data and data analysis.
procedures. Section 3 presents the results and their brief discussion in section 4 concludes the paper.

2. Data

[6] The data used in this study come from ACE2 (Second Aerosol Characterization Experiment [Brenguier et al., 2000]). Cloud microphysical properties are derived from measurements made by the Meteo-France Merlin IV aircraft using the Fast FSSP [Brenguier et al., 1998] for the droplet size distribution in radius range 1.3–18 μm. Eight flights, each characterized by different aerosol conditions, were analyzed [Pawlowska and Brenguier, 2000, 2003] ranging from clean maritime conditions (June 25 and 26), through partly polluted clouds (July 16, 17, and 19), to polluted clouds (July 8, 9, and 18). Table 1 of Pawlowska and Brenguier [2003] documents main characteristics of observed Sc clouds. Observed aerosol and CCN characteristics for most of the flights considered in this paper are discussed by Snider and Brenguier [2000]. On selected days the aircraft performed flights along a 60 km square flight track. Data presented below come from 10Hz data, i.e., averaged over about 10 m of the horizontal distance. Regions with drizzle were excluded from the analysis.

[7] Data collected during ascents and descents through the cloud layer are used in the present analysis. They allow for a good vertical representation of cloud droplet microphysical properties. Each cloud sample is characterized by its location with respect to the cloud base. Because various relationships between parameters of the cloud droplet spectrum and the cloud droplet concentration (N) are used in current AGCM cloud parameterizations [e.g., Liu and Daum, 2002; Rotstayan and Liu, 2003], we represent the parameters as a function of N at a given altitude above the cloud base (h). The dependence of these parameters on h is separately investigated. Cloud samples are grouped in bins of width of 10 m for h and 20 cm$^{-3}$ for N. The Fast-FSSP misses small droplets that are common near the cloud base and are often present near the cloud top due to entrainment. Therefore, altitudes close to the cloud base and cloud top are excluded from the analysis. To make a distinction between microphysical (condensation and collisional growth) and dynamical (entrainment and mixing) processes, we select samples in clouds with different values of the liquid water content with respect to the estimated adiabatic value at a given altitude.

3. Results

[8] Figure 1 summarizes results from the analysis of all eight flights. It shows the mean radius $\bar{r}$ (top row), standard deviation $\sigma$ of cloud droplet spectra (middle row), and the relative dispersion $d = \sigma/\bar{r}$ (bottom row) as a function of the droplet concentration N. The left column shows results for cloud samples close to adiabatic (adiabatic fraction, AF, the ratio between the observed cloud water and its adiabatic value, larger than the 0.9), the middle one - for 0.5 $< AF < 0.9$, and the right one - for 0.1 $< AF < 0.5$. The figure combines observations from the relatively narrow altitude range of 80 to 110 m above the cloud base for all flights (i.e., 3 altitude bins). Extending this range results in minor changes of the figure, whereas narrowing it makes the statistical significance of results questionable (especially in strongly diluted samples). Results for other altitudes are similar and are not shown.

[9] As anticipated, the mean radius $\bar{r}$ (top row) decreases as N increases in near-adiabatic cloud samples. This is true for the average values between the flights (i.e., for different CCN characteristics) as well as within the individual flights (i.e., for the same CCN; note that we implicitly assume here that horizontal variability of CCN can be neglected for each of the flights). The same applies to the diluted cloud samples, but the range of droplet sizes is smaller. The decrease of $\bar{r}$ with increasing N reflects a simple fact that, for a given liquid water content, the mean volume radius cubed is inversely proportional to droplet concentration. For a given flight, different droplet concentrations in near-adiabatic cloud samples can only result from variations of the strength of cloud-base updraft that affects the number of nucleated droplets. The range of radii observed in different flights decreases as mean N increases, both in near-adiabatic and diluted cloud samples.

[10] The standard deviation $\sigma$ (middle row in Figure 1) shows considerable variations among different flights as well as within each flight for the near-adiabatic cloud samples (left panel in the middle row), with $\sigma$ ranging from less than 1 to above 3 μm. Contrary to expectations based on classical differences between maritime and continental clouds, there is no clear trend among various flights (i.e., polluted and pristine clouds have similar $\sigma$). This is likely the result of the range of cloud base updraft strengths in a given flight, which affects not only the number of nucleated droplets, but the initial width of the spectrum as well. The differences in the initial spectrum of cloud droplets are likely responsible for the $\sigma$-N relationship for a given flight as well, with larger N corresponding to smaller $\sigma$. This relationship applies to near-adiabatic as well as diluted cloud samples. In the diluted cloud samples, the spread of the standard deviations and their mean values for each flight are smaller, which again might be considered counterintuitive. In general, a robust $\sigma$-N relationship exists neither in near-adiabatic nor in diluted cloud samples.

[11] The lower row in Figure 1 shows results for the relative dispersion d, which is consistent with the pattern shown for $\bar{r}$ and $\sigma$. Relative dispersion ranges from about 0.1 to about 0.5. For near-adiabatic cloud samples, flight-averaged d seems to increase with N, which is consistent with some previous observations [e.g., Martin et al., 1994] and theoretical predictions that consider diffusional growth only [Liu et al., 2006]. However, the opposite is true for points within each flight, which is also in agreement with theoretical predictions for diffusional growth with given aerosol characteristics and at different vertical velocities [Liu et al., 2006]. The main point is that the overall pattern seems to result from the strong dependence of $\bar{r}$ on N combined with the weak dependence of $\sigma$ on N.

[12] Results shown in Figure 1 imply that the variability of mean microphysical parameters among various flights is typically smaller than the horizontal variability within each flight. This is especially true for the standard deviation $\sigma$ and the relative dispersion d. However, only these mean parameters are used in cloud parameterizations [e.g., Liu and Daum, 2002; Rotstayan and Liu, 2003] and, to the
authors’ knowledge, none of such parameterizations explicitly includes the variability illustrated in Figure 1.

Since the data presented in Figure 1 are collected at a narrow altitude range, it is instructive to stratify the data for each flight as a function of height. Martin et al. [1994] showed that the relative dispersion $d$ was quite uniform across the depth of clouds they investigated. In the case of clouds considered here, however, the data fail to provide a consistent picture. This is illustrated in Figures 2 and 3, which show $N$, $\bar{r}$, $\sigma$, and $d$ (and standard deviations of their horizontal variability) as a function of height for two selected flights: marine case of June 26 and polluted case of July 18. It needs to be stressed that these flights were selected because they provide limits of the variability of $\sigma$ and $d$ observed in all flights.

Change of the standard deviation $\sigma$ with height (the third row) is different in the two cases selected. For the marine case (Figure 2), $\sigma$ decreases with height in the near-adiabatic cloud samples. However, this trend is reversed when highly diluted samples are considered (see the right panel in the third row). For the polluted case (Figure 3), $\sigma$ increases with height for both near-adiabatic and diluted cloud samples. In most flights, $\sigma$ varies little with height for the near-adiabatic cloud samples and increases with height for the diluted samples. Typical values of $\sigma$ are in the 1 to 2 $\mu$m range with no clear trend between maritime and polluted cases. Large standard deviation of horizontal variability of $\sigma$, typically around 1 $\mu$m, is also worth pointing out. As a result of the variability of $\sigma$ and $d$, the mean relative dispersion $d$ (bottom row in Figures 2 and 3) varies between 0.1 for marine clouds (especially in the upper half of the cloud) to 0.3 for the polluted clouds, with the standard deviation of horizontal variability around 0.1. These values are typical for other flights as well (not shown). In summary, it appears that the increase of droplet size with height is the only systematic impact on the relative

**Figure 1.** Results from eight flights plotted as a function of cloud droplet number concentration $N$. Top, middle, and bottom rows show the mean droplet radius $\bar{r}$, the standard deviation of cloud droplet spectrum $\sigma$, and the relative dispersion $\sigma/\bar{r}$, respectively. Left, middle, and right columns are for near-adiabatic ($AF > 0.9$), diluted ($0.5 < AF < 0.9$) and strongly diluted ($0.1 < AF < 0.5$) cloud samples, respectively. Maritime, partly polluted, and polluted cases are shown using blue, green, and red colors, respectively. Lines show results binned as explained in text, whereas the large symbols show the averages for the entire flight. Data for levels between 80 and 110 m above the cloud base.
4. Discussion and Conclusions

In this paper, the variability of cloud microphysical parameters in marine Sc was investigated in order to provide a guidance for cloud parameterizations and to compare the results with theoretical predictions [e.g., Liu et al., 2006] and previous observations [e.g., Martin et al., 1994]. The emphasis was on the spectral width of cloud droplet spectra, an important parameter affecting radiative properties of clouds [e.g., Liu and Daum, 2002] and development of drizzle and rain [e.g., Seifert and Beheng, 2001]. The results presented here paint a rather complex picture as far as the width of cloud droplet spectra in Sc is concerned. This comes from a combination of various factors. For given CCN characteristics (i.e., for a given flight), local droplet concentration varies considerably both within adiabatic and diluted samples, and reflects both the impact of spatially varying cloud base updraft (which affects the spectrum of cloud droplets just after nucleation) as well as the spectral changes due to entrainment and mixing. It appears that the main factor affecting the relative dispersion $d = \sigma/r$ is the mean size of cloud droplet radii $r$, which is larger in maritime clouds at the same height within a cloud (or, alternatively, at the same liquid water content). For all flights, $d$ either decreases with height or does not change significantly. This comes mostly from the increase of $r$ with height, with $\sigma$ varying differently (and unpredictably) with height in different flights.

As far as the parameterization of the spectral width is concerned, it seems that a reasonable approach is to assume a constant standard deviation $\sigma$ (say, in the range of 1 to 2 $\mu$m), and parameterize the relative dispersion $d$ using the constant $\sigma$ and the local mean radius $r$. For droplets growing by condensation, $\sigma$ decreases with height in adiabatic cloud samples. Growth of collision-coalescence counteracts this trend, especially when droplet sizes reach the 10–12 $\mu$m radius when the collision-coalescence becomes efficient. Another factor is the presence of cloud entrainment which also results in the increase of $\sigma$ due to the combination of partial evaporation of cloud droplets and activation of new
droplets, both tending to increase the spectral width. Note that such a simple parameterization reproduces the observed difference between relative dispersions in maritime and continental clouds (i.e., continental clouds having larger relative dispersion [e.g., Martin et al., 1994; Pawlowska and Brenguier, 2000]) because of smaller droplet sizes in continental clouds. This parameterization also simulates a decrease of the relative dispersion with height which was observed in some, but not all, of the flights presented here. More data is needed to develop more sophisticated observationally-based parameterizations of the relative dispersion.

[18] Finally, it has to be stressed that horizontal variability of the cloud droplet number concentration, size, and spectral dispersion in Sc are all significant on a given day, presumably due to the spatial variability of the cloud base updraft (which affects the cloud droplet nucleation) and spatial/temporal variability resulting from entrainment and mixing (which affects macroscopic, e.g., cloud water content, as well as microphysical cloud properties). Such variability needs to be accounted for in large-scale models of weather and climate.

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