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Identifying drizzle within marine stratus with W-band radar reflectivity

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Abstract

Airborne cloud radar and cloud microphysical data, collected in summertime stratus clouds off the Oregon coast, are analyzed to obtain an empirical threshold radar reflectivity above which drizzle can be expected in warm marine stratus. Such clouds, which are prevalent over the eastern subtropical oceans, have a profound impact on global climate.

This study finds that the threshold reflectivity for drizzle is a strong function of height within the cloud layer. Both radar reflectivities and calculated reflectivities (based on measured droplet spectra) indicate that the threshold is most crisply defined in the lower half of the stratus cloud deck. The use of the threshold reflectivity profile to flag drizzle is illustrated by examining the dependency of radar reflectivity on cloud water content. Such dependency is non-existent in marine stratus in general, but a clear relationship emerges when drizzle cases are excluded.

Keywords: Marine stratus; Drizzle; Cloud radar; Radar reflectivity

1. Introduction

Clouds are known to have a profound impact on global climate, yet many questions remain regarding feedback mechanisms linking clouds to climate. Much of the uncertainty about the magnitude of global warming hinges on the cloud-climate feedback question. In this context a cloud-probing satellite, called CloudSat, is being prepared for launch in 2004 (Stephens et al., 2002). CloudSat will be the first satellite to carry a 95-GHz Cloud

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Profiling Radar (CPR). Vertical profiles of cloud properties obtained by the CPR on the global scale, combined with passive microwave data from sister satellites, will fill a critical gap in our understanding of cloud-climate feedbacks.

The key strength of a 95-GHz (3 mm) radar is its cloud profiling capability, but radar reflectivity is not a measure of drop size distribution, and therefore it is not a direct measure of cloud radiative properties such as effective radius or liquid water content (LWC). We use an airborne 95 GHz radar, the Wyoming Cloud Radar (WCR). Essential in the interpretation of radar reflectivity profiles is the ability to place these profiles in the context of cloud characteristics as measured by probes on board the aircraft. The focus of this paper is on marine stratus clouds, which are ubiquitous over the eastern subtropical ocean basins. Their albedo contrasts against that of the underlying ocean, therefore they may have an important impact on global climate (e.g. Arking, 1991). The CPR vertical resolution (500 m) sometimes exceeds the depth of marine stratus, therefore thick marine stratus will be smeared out, and thin marine stratus may remain undetected (Baedi et al., 2002).

The interpretation of radar reflectivity is ambiguous because both the droplet number concentration and size contribute to the signal. For a 3-mm radar, cloud droplets and even most drizzle drops behave as Rayleigh scatterers. Such scattering is proportional to the sixth moment of particle size distribution. Therefore radar reflectivity is largely affected by the size of the largest droplets in a resolution volume. Marine stratus often produces drizzle, especially at night (Stevens et al., 2003), therefore drizzle may dominate the reflectivity of marine stratus. Drizzle is defined in this study as having a diameter of at least 50 μm, consistent with definitions elsewhere (Frisch et al., 1995; Hudson and Yum, 1997; Miles et al., 2000). Fox and Illingworth (1997a) argued that drizzle can increase the radar return by 10–20 dBZ above the echo due to cloud droplets in extensive marine stratocumulus deeper than 200 m. Typical concentrations of cloud droplets in marine stratus produce a reflectivity of about −18 dBZ, and typical drizzle amounts increase this value to about −5 dBZ, assuming Rayleigh scattering (Frisch et al., 1995).

Due to its low number concentration, drizzle has a negligible effect on cloud LWC and on cloud effective radius. Therefore, radar reflectivity cannot be used to characterize the LWC nor the radiative properties of cloud if drizzle is present. Much work has been done on the interpretation of cloud physical parameters from radar reflectivity measurements in the past few years (Sauvageot and Omar, 1987; Clothiaux et al., 1995; Frisch et al., 1995; Sassen and Liao, 1996; Fox and Illingworth, 1997b; Löhnert et al., 2001). Both theoretical and empirical relationships between radar reflectivity and other cloud parameters, such as LWC, can be found in literature, but these relationships fail if drizzle is present. Therefore the ability to flag drizzle presence in marine stratus is useful.

Given its sensitivity to large droplets, the radar reflectivity itself can be used to identify drizzly regions. Sauvageot and Omar (1987) and Löhnert et al. (2001) used −15 dBZ as the lower reflectivity limit to exclude drizzle-sized particles in their study on the relationship between LWC and radar reflectivity. Reflectivity values for warm-season land-based stratus are often contaminated by insects, adding uncertainty to this method.

Another radar parameter that can discriminate between cloud and drizzle echoes is the Doppler spectrum, for a vertically pointing radar beam (Babb and Albrecht, 1995; Fox and Illingworth, 1997b). In theory, the Doppler spectrum can be used to estimate the drop size distribution (Gossard et al., 1997; Babb et al., 1999). Drizzling stratus clouds produce a bimodal Doppler spectrum at 95 GHz, because drizzle falls at about 0.8 m/s (Frisch et al., 1995) to 1.0 m/s (Babb and Albrecht, 1995) relative to cloud droplets. Therefore the presence of a drizzle mode to the left of the cloud mode in the Doppler spectrum can be used to exclude drizzle cases. However Doppler spectra from an airborne radar are much affected by aircraft motion. Therefore they cannot be used to distinguish falling drizzle from steady cloud droplets.

A third method uses the reflectivity *profiles* measured by an up-looking ground-based cloud radar to distinguish clouds with drizzle-size drops (Fox and Illingworth, 1997a). Drizzle-free cloud profiles tend to have radar reflectivity increasing with altitude within cloud, due to the adiabatic increase in LWC. For drizzle cases the highest reflectivity is encountered lower in the marine stratus, because drizzle grows as it falls by collision/coalescence.

The primary objective of this paper is to assess the radar reflectivity value above which drizzle is likely to occur in marine stratus. As an extension of the Sauvageot and Omar (1987) study, we aim to demonstrate that the threshold reflectivity for drizzle is sensitive to altitude within the marine stratus. We then use this thresholding method to demonstrate that a strong relationship can be found between LWC and reflectivity in marine stratus, but only when the drizzle patches are excluded.

But first the data sources are described and the analysis methods are discussed.

2. Data sources and analysis

Data from Coastal Stratus 99 (CS99) are used. This project used the Wyoming King Air (WKA) aircraft and the Wyoming Cloud Radar (WCR) to study persistent stratus clouds off the Oregon coast in August 1999. Data from three flights are studied in detail, on 9, 16 and 17 August. Drizzle fell heavily on 17 August, and was present in patches on the two other flights. Visible satellite imagery reveals significant mesoscale variations of cloud albedo on these three days near the flight track, especially on 16 August (Fig. 1).

2.1. In situ probes

The WKA carried five cloud probes (Table 1). A continuous drop size distribution (DSD) can be composed with the in-situ measurements of the FSSP, 1DC and 2DC probes. The FSSP provides the distribution of droplets from 1.5 to 46.5 μm. Measurements of 1DC at droplet range from 50 to 100 μm compose the second segment of the spectrum. The spectrum of droplets larger than 100 μm is given by 2DC measurements. There is some overlap in the instrument measurement ranges (Table 1), but the probes are most reliable near the center of this range, and the overlapping tails may not agree well. Therefore two transitions occur in the measured drop spectrum, one at 50 μm (between FSSP and 1DC measurements) and the other at 100 μm (between 1DC and 2DC measurements). The first transition, 50 μm, is chosen to be the drizzle lower threshold diameter in this study. This probe-based discrimination of cloud droplets from

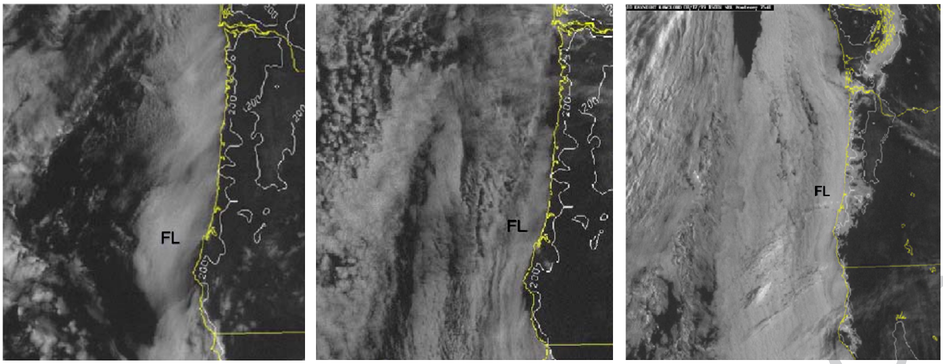

Fig. 1. Visible satellite images with approximate WKA flight locations (denoted as FL) for the three flights used in this study. The light lines represent the coast and the 200-m height contour.

drizzle at a diameter of 50 μm has a physical basis also, as it distinguishes between condensation and coalescence as dominant droplet growth mechanisms (Frisch et al., 1995).

Measurements of FSSP give the cloud DSD. Drops measured with the 1DC and 2DC are considered to be drizzle. When neither the 1DC nor the 2DC probes detect droplets during a given sample period, then the marine stratus traversed during that sample period is considered to be drizzle-free. Because 1DC measurements were less reliable than 2DC measurements in CS99 (the 1DC probe undersampled droplets), only the 2DC measurements are used to determine drizzle presence. Because the FSSP sampling rate is 10 × higher than the 2DC (Table 1), and because the number of drizzle drops is orders of magnitude less than the number of cloud drops, the cloud DSD can be described more accurately than the drizzle DSD.

Table 1
Parameters of the cloud probes aboard the WKA during CS99

Probe	Variable	Measurement range	Resolution	Temporal resolution (Hz)	Volume sampling rate ($cm^3\ s^{-1}$)
FSSP	drop size	1.5 to 46.5 μm	3 μm	10	50
1DC	drop size	25 to 175 μm	12.5 μm	10	10^3
2DC	drop size	50 to 800 μm	25 μm	1	5×10^3
PVM	LWC	0.002 to 10 g m^{-3}	15 μg m^{-3}	25	–
JW	LWC	0.0 to 3 g m^{-3}	15 μg m^{-3}	25	–
WCR	reflectivity	− 30 to + 40 dBZ	–	30	4×10^9

FSSP = forward scattering spectrometer probe; 1DC (2DC) = Particle Measuring Systems 200 × one (two)-dimensional optical array; PVM = Gerber particle volume monitor probe; JW = Johnson Williams hot-wire probe. The volume sampling rate is the volume of air sampled per unit time, assuming an aircraft speed of 100 m/s. For comparison, the Wyoming Cloud Radar (WCR) is added to the list. Its minimum detectable signal is − 30 dBZ at a range of 1 km, and at least 6 dBZ lower at 90 m. The WCR volume sampling rate applies to a range of 90 m and a pulse width of 250 ns.

2.2. Radar reflectivity

The 95-GHz (3 mm) WCR antenna can be directed in up or side directions with a reflector plate on the aircraft's fuselage. In order to relate in situ measurements to radar reflectivity, only the side-beam reflectivity is used, because in marine stratus vertical gradients are much larger than the horizontal ones. The nearest gate containing reliable reflectivity information is at 90 m (9 August) or 75 m (16 and 17 August) to the side of the aircraft. (The first gate, at 60 m from the aircraft, proved to be often contaminated by transmitter noise.) The nearest good gate has a volume of 36 m^3 at 90 m [assuming a 250-ns pulse length and a 0.7° circular beam width]. The nearest gate radar volume, cumulated over 1 s (100 m) along the aircraft track, is six orders of magnitude larger than the 2DC probe volume, and eight orders of magnitude larger than the FSSP volume (Table 1). This implies that WCR reflectivity measurements are much more robust, and can be made at higher frequency, than cloud probe estimates.

In short, the comparison of radar to in situ probe data faces two experimental constraints: (a) the radar and probe data are not spatially coincident; and (b) the radar samples much larger volumes of air than do the in situ probes. The first constraint will be assessed by means of a spatial correlation analysis (Section 2.3). The implication of the second one will be examined by comparing measured against computed reflectivity, assuming Rayleigh scattering (Section 3).

2.3. Spatial correlation analysis

An optically relatively uniform horizontal structure is often observed in marine stratus, yet mapped fine-scale radar reflectivity appears surprisingly patchy (Vali et al., 1998). Therefore, before we proceed with the analysis of the relation between in situ drizzle and adjacent radar reflectivity, some 75–90 m to the side of the aircraft, we must first evaluate how representative the laterally displaced WCR data are for in situ measurements, which are used to define drizzle and drizzle-free cases. The WCR reflectivity will hereafter refer to the nearest radar gate only.

To evaluate how much uncertainty is introduced by this lateral displacement, we analyze the horizontal structure of marine stratus along the flight track. Through the application of Taylor's hypothesis, the autocorrelation coefficient Cor(L), calculated with a time series of a variable along any level flight leg, can be used to examine the scales of horizontal variability of that variable:

$$\mathrm{Cor}(L) = \mathrm{Cor}(-L) = \frac{\sum_{k=0}^{N-L-1}(x_k - \bar{x})(x_{k+L} - \bar{x})}{\sum_{k=0}^{N-1}(x_k - \bar{x})^2} \tag{1}$$

where N is the sample size, L is the time lag, and $\bar{x}$ is the mean of the sample population $x=(x_0, x_1, \ldots, x_{N-1})$. The time lag can be converted to a spatial separation, since the aircraft speed is much higher than the rate of change within cloudy parcels. To examine the horizontal coherence of echo structures, only level flight legs are analyzed. The variable we use is the nearest-gate WCR reflectivity. We can of course use all WCR gates and examine spatial coherence along the radar range, sideways from the aircraft, but the echo would have to be corrected for attenuation first, which adds further uncertainty.

The autocorrelation coefficient of reflectivity decreases with the increasing distance (Fig. 2). An autocorrelation value of 0.50 can be considered to define the maximum size of coherent features. The bad news is that Fig. 2 suggests that both drizzle patches and echo-void areas are rather small in marine stratus, about 70 m to a few 100 m in diameter. The good news is that nearly all autocorrelation coefficients are larger than 0.50 at the distance between the aircraft and the radar nearest gate for each flight. The spatial correlations between in-situ measurements and WCR nearest gate echoes therefore are expected to be reasonable, but not excellent. The 75–90 m displacement will certainly introduce some uncertainty.

To reduce this uncertainty, we will only include those *drizzle events* that last at least 2 s (200 m), as measured by the 2DC probe. Thus we can focus on the larger drizzle patches, where the sideways WCR reflectivity is more likely to sample the same drizzle patch. Similarly, *drizzle-free events* are those series of at least 2 s, with non-zero FSSP data and zero 1DC and 2DC data. Another way to reduce the uncertainty due to non-coincidence is to compare the drizzle threshold reflectivity profile, based on WCR measurements, to that obtained from reflectivity values calculated from the in-situ observed DSD (Section 3).

2.4. Statistical methods

Two kinds of statistical methods will be used to assess the existence of a threshold reflectivity discriminating between drizzle cases and drizzle-free cases. A first method is based on an analysis of variance. In Table 2, the *2DC yes* includes all cases when the 2DC probe detects drizzle drops in the cloud. The *reflectivity yes* applies when the reflectivity exceeds an assumed threshold reflectivity. This reflectivity can either be that at the WCR nearest range gate or the reflectivity calculated from the DSD measured by airborne probes. The values in Table 2 are the number of situations satisfying both *2DC yes/no* and *reflectivity yes/no*, for example n_{00} counts the number of reflectivity measurements larger than the assumed threshold in the *2DC yes* group. A series of threshold reflectivity values between -35 and -10 dBZ then is assumed. The optimal drizzle threshold reflectivity is the one corresponding to the maximum *hit rate*. The hit rate is defined as:

$$H = \frac{n_{00} + n_{11}}{n} \tag{2}$$

A second method involves the division of reflectivity values into two groups, corresponding to in situ drizzle-free cases and drizzle cases. Since the reflectivity due to cloud droplets is generally less than that due to both cloud droplets and drizzle drops, the two groups of reflectivities are expected to form distinct probability density functions (PDFs). The reflectivity corresponding to the *cross point of the two PDFs* is then chosen to be the drizzle threshold reflectivity. Again this method can be applied both to adjacent WCR-measured reflectivities, and to reflectivities calculated from in situ DSDs.

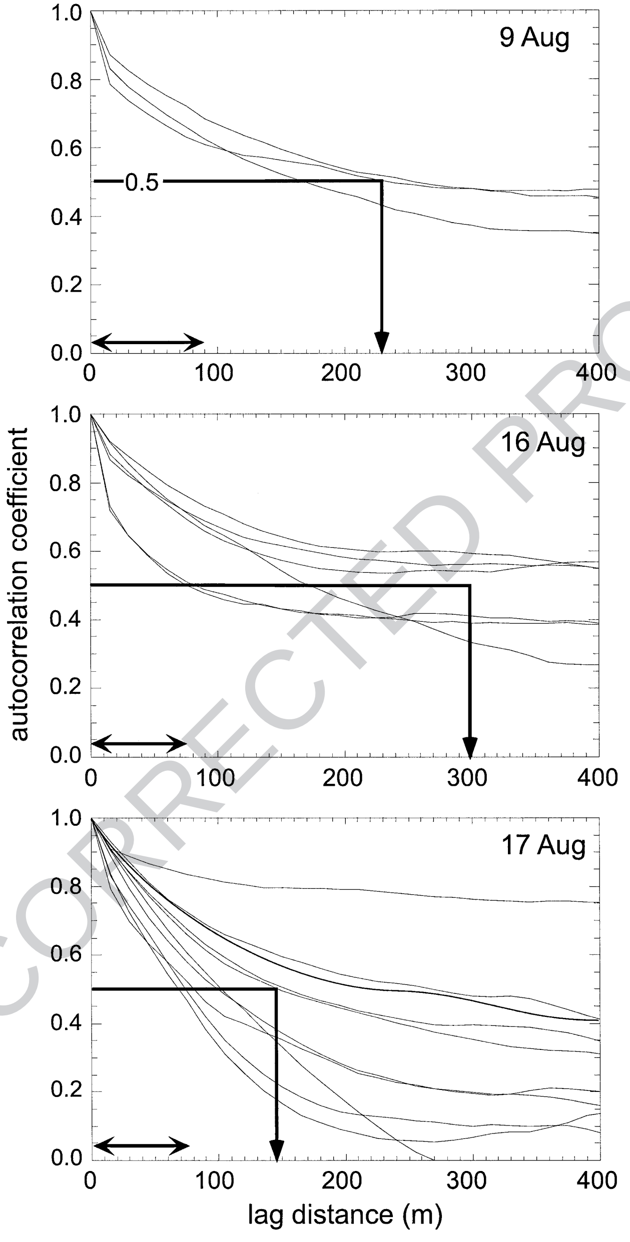

Fig. 2. Autocorrelation coefficients calculated for WCR nearest gate reflectivities for the three flights. The coefficient is shown for several straight flight tracks in each plot. The vertical arrow is the median lag distance at which the autocorrelation coefficient drops below 0.5. The horizontal double-arrow line indicates the distance between in-situ measurements and the radar nearest gate for each flight.

Table 2
Contingency table of drizzle based on 2DC measurements and on reflectivity

Drizzle presence	2DC yes	2DC no	total
Reflectivity yes	n_{00}	n_{01}	$n_{0\bullet}$
Reflectivity no	n_{10}	n_{11}	$n_{1\bullet}$
Total	$n_{\bullet 0}$	$n_{\bullet 1}$	n

2.5. Drizzle probability

The first question is whether drizzle really is more likely when the radar reflectivity is higher. Drizzle patches were more frequent on the 17 August flight, for instance, but was the reflectivity higher in these patches? Fig. 3 shows the probability of in situ drizzle (P_Z) for given values of sideways reflectivity Z, calculated as:

$$P_Z = \frac{N_{dZ}}{N_Z} \tag{3}$$

where N_Z is number of samples with a nearest-gate radar reflectivity value Z, and N_{dZ} is the number of these samples with in situ drizzle. In situ drizzle probabilities can be seen to sharply increase in the reflectivity range of − 20 to − 10 dBZ. This implies little uncertainty about the existence and validity of a drizzle reflectivity threshold in marine stratus. This also suggests a possible threshold, based on points of $P = 0.5$, between − 16 and − 12 dBZ for the whole cloud layer. This is consistent with the − 15 dBZ drizzle threshold proposed by Sauvageot and Omar (1987).

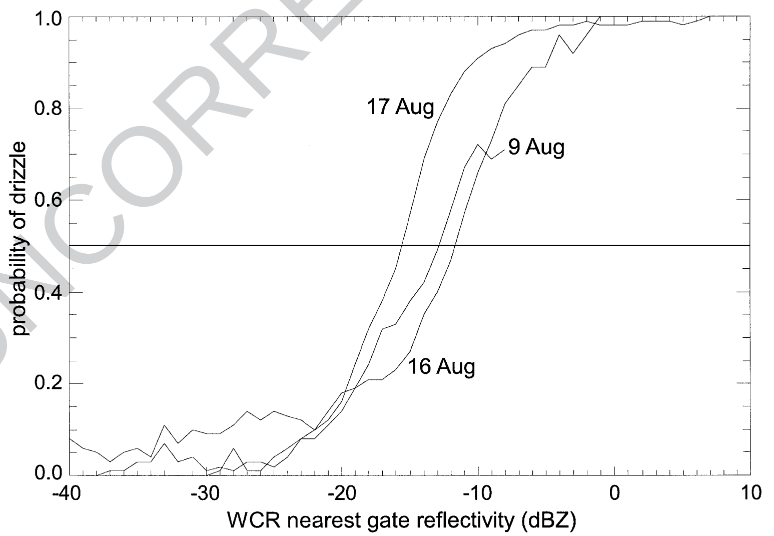

Fig. 3. The probability of drizzle, as measured by the 2DC probe, as a function of adjacent WCR reflectivity. Data from all flight levels in marine stratus are used.

2.6. Cloud height normalization

On each of the three CS99 flights, radar reflectivity has a distinct dependence on height in marine stratus. Therefore, it is assumed that the threshold radar reflectivity for drizzle also varies with altitude in cloud. Yet marine stratus cloud depths vary significantly from day to day, and regionally. Therefore, to facilitate comparisons, a normalized altitude in cloud will be used in this study. Assume that the normalized cloud top is 1.0 and the cloud base is 0.0. Then the normalized altitude in cloud ϕ can be calculated as:

$$\Phi = \frac{h - h_{\mathrm{b}}}{h_{\mathrm{t}} - h_{\mathrm{b}}} \tag{4}$$

where h is the cloud altitude, h_{b} is the altitude of the cloud base, and h_{t} is the altitude of the cloud top. Data will be binned in nine normalized cloud layers between $\phi = 0.05$ and $\phi = 0.95$, each with a depth of 0.1.

When the WCR points sideways, the radar beam may not be exactly horizontal. A small correction of the altitude of the radar nearest gate is calculated as:

$$\Delta h = d \times \sin\theta \tag{5}$$

where d is the distance between aircraft and radar nearest gate, and θ is the angle of the radar beam from the horizontal plane. An implication of this correction is that merged in situ probe and lateral WCR reflectivity data may end up in a different normalized cloud layer. This occurs in less than 0.1% of the merged data.

This normalization requires a knowledge of cloud top and base. In situ LWC estimates are used to determine the altitudes of cloud top and cloud base. The WKA did several ascents and descents through the cloud layer on all flights. The LWC of marine stratus increases with altitude from the cloud base (Fig. 4), as expected from moist adiabatic processes without precipitation. The LWC estimates based on the integration of FSSP bin measurements generally are smaller than those of the PVM and JW hot-wire probes. The latter two agree well.

The altitude from which point LWC begins to increase from near zero values is considered to be cloud base. Since the stratus layer is capped by a much drier, warmer airmass, the cloud top is unambiguously defined as the altitude where the LWC drops off suddenly. Here the LWC can vary from zero (higher than cloud top) to the largest value of the vertical profile (just below the cloud top) within less than 100 m.

The LWC profiles (Fig. 4) reveal two types of heterogeneities. A large LWC range at a given altitude suggests non-uniformities of cloud *horizontal* structure. Such variations in marine stratus (or rather, stratocumulus) are related to boundary-layer and cloud-scale dynamics (Stevens et al., 2003). These variations probably occur at all flight levels, but are only sampled at select flight levels in Fig. 4. Especially on 16 and 17 August the lower LWC range at a given height is as low as zero. This suggests that the stratus deck was broken on these flights. Secondly, the cloud *vertical* structure varies: several cloud bases may exist, from which the LWC increases adiabatically, especially on 17 August (Fig. 4). Marine stratus cloud top variations occur as well, both on the small and the regional scales, the latter on account of the proximity to coastal topography (Nuss et al.,

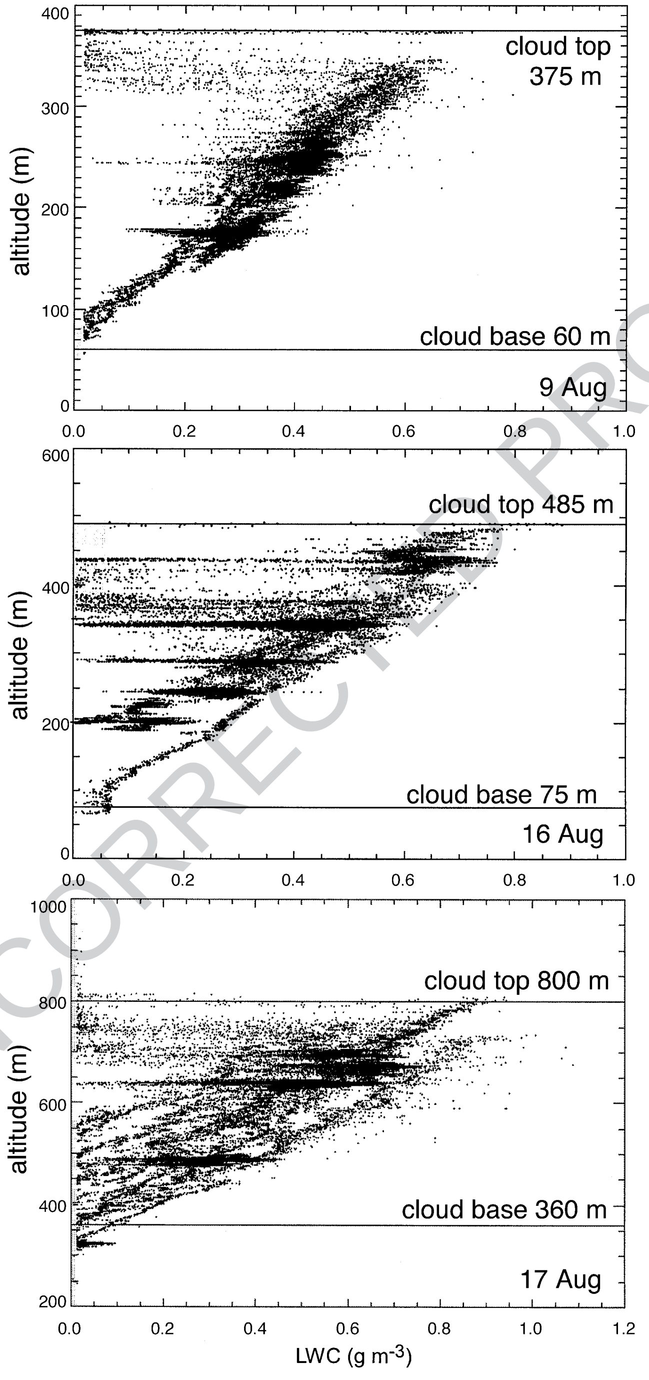
cloud top
375 m
cloud base 60 m
9 Aug
altitude (m)
cloud top 485 m
cloud base 75 m
16 Aug
altitude (m)
cloud top 800 m
cloud base 360 m
17 Aug
altitude (m)
LWC (g m-3)

Table 3
Altitudes of the top and base of marine stratus on three flight days

	9 August	16 August	17 August
Altitude of cloud top (m)	375	485	800
Altitude of cloud base (m)	60	75	360
Depth of cloud layer (m)	320	380	440

These are used to determine the normalized altitude in cloud.

2000). No systematic variations of cloud top height, e.g. as a function of distance offshore, were found on any of the three flights. The choice of a single cloud base and top for an entire flight (Table 3) is somewhat subjective, but it enables the generalizations proposed further in this study.

3. Threshold reflectivity profile

To assess the association between in-situ measurements and WCR radar reflectivity, two drizzle threshold estimation data sources are compared: one is based on the equivalent reflectivity calculated with in-situ measurements; the other uses WCR reflectivity.

3.1. Threshold reflectivity for drizzle based on in-situ measurements

The radar reflectivity can be calculated directly based on the observed composite DSDs, using the FSSP, 1DC and 2DC probes. The power returned at 95 GHz (3 mm wavelength) can be due to two kinds of scatter modes, Rayleigh scatter and Mie scatter. When the droplet diameter is no larger than about 1/10 of the radar wavelength, the particles will behave as Rayleigh scatterers. Larger particles behave as Mie scatterers. Virtually all droplets in marine stratus are smaller than 300 μm in diameter. Therefore, only the Rayleigh scatter mode is used to calculate equivalent radar reflectivity factor Z ($mm^6\ m^{-3}$) from observed DSDs, as follows:

$$Z = \int_0^{\infty} n(D) D^6 \mathrm{d}D \tag{6}$$

where D is the particle diameter (mm), and $n(D)$ is number density of droplets with diameter D ($mm^{-1}\ m^{-3}$). Since the magnitude of Z spans several orders of magnitude, a logarithmic scale is used as $\mathrm{d}BZ = 10 \log_{10} Z$. The term radar reflectivity factor is generally abbreviated to reflectivity in this text. While the logarithmic scale is used in the figures and text, all calculations assume the units of $mm^6\ m^{-3}$.

The two statistical methods, the hit rate method and the PDF cross-over method (Section 2.4), are applied to reflectivity values derived from the in situ probes to find

Fig. 4. Profiles of LWC for three flights, based on the entire flight record. PVM measurements are used on 9 and 17 August, and JW hot-wire measurements on 16 August. These profiles are used to determine the mean cloud top and cloud base, as shown.

a drizzle threshold reflectivity. The two methods yield similar results, with differences of 1dBZ at most. This coincidence confirms the validity of defining a reflectivity threshold for drizzle. This threshold increases monotonically with altitude, from about − 32 dBZ near cloud base to about − 19 dBZ near cloud top, for all three flights (Fig. 5). The agreement between the three flights is quite good, notwithstanding different synoptic conditions and drizzle frequencies. It is best in the lower half of the stratus deck.

The separation between drizzle and drizzle-free events is height-dependent as well. A distinct gap exists between the reflectivity PDF of drizzle-free events and that of drizzly events at lower levels, especially for 16 and 17 August flights. Therefore it is straightforward to select a drizzle reflectivity threshold in the lower half of the cloud. But at the upper part of the marine stratus, the PDFs are less separated and the threshold slopes become smaller (Fig. 6). Data from all three flights (not shown) confirm that the reflectivity PDFs for drizzle and drizzle-free cases merge near the cloud top, and that the drizzle threshold reflectivity is most crisply defined, and least variable from day to day, in the lower half of the marine stratus.

In all three cases the merging of the reflectivity PDFs for drizzle and drizzle-free cases towards the cloud top is due to an increase of the average reflectivity in drizzle-free stratus, towards the top, more than to a decrease in drizzly stratus. In other words, as the adiabatic

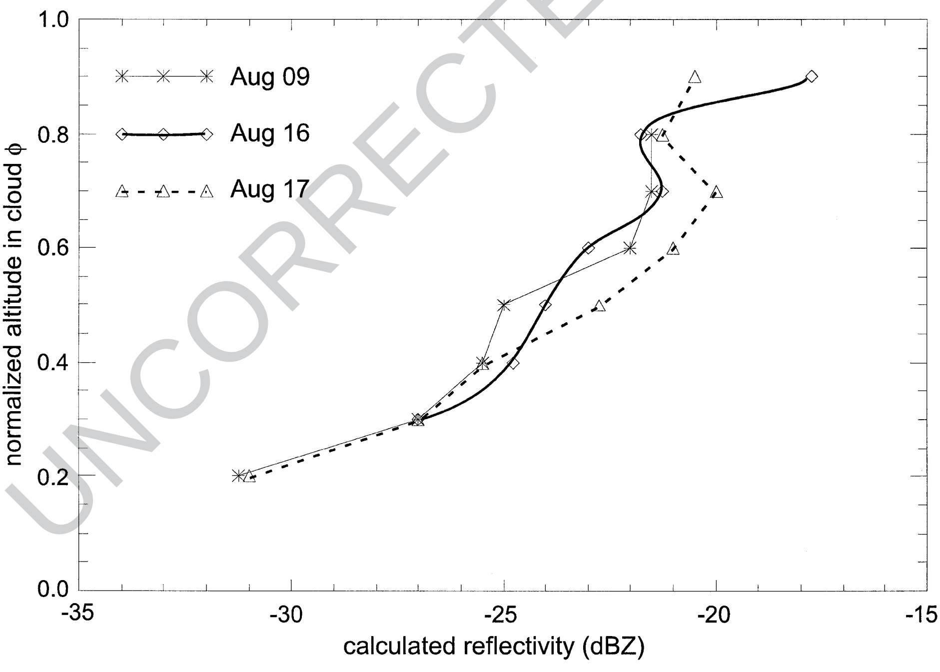

Fig. 5. Reflectivity threshold for drizzle in marine stratus, based on in-situ calculated reflectivity, as a function of normalized height in cloud. The threshold is the average between the hit rate and the PDF cross-over methods, which differ by less than 1 dBZ.

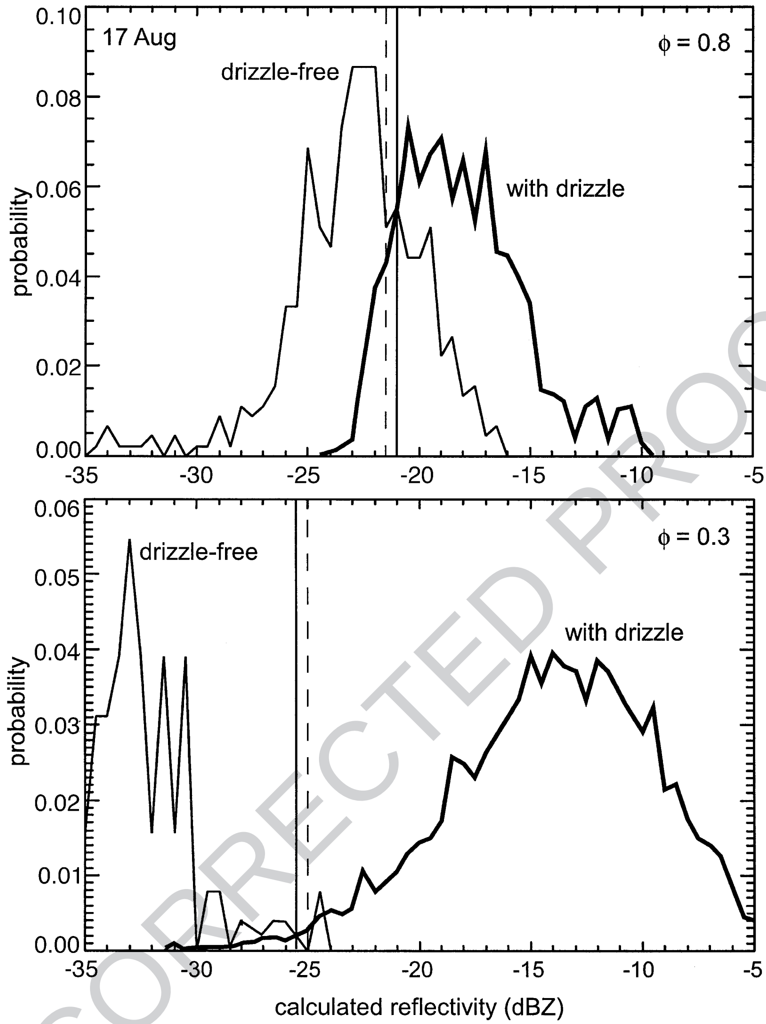

Fig. 6. Application of the crossover and hit rate methods for reflectivity values calculated from FSSP, 1DC and 2DC data. Shown are reflectivity PDFs for drizzle-free (thin curve) and drizzly (bold curve) events at two altitudes for the 17 August flight. The two PDFs cross at a reflectivity value shown by the solid vertical line. The dashed vertical line is the threshold reflectivity determined by the hit rate method.

LWC and droplet numbers increase towards the stratus top, so does the reflectivity, approaching values typical of drizzly stratus. Drizzle drops are present throughout the cloud depth and sometimes even below cloud base (Fox and Illingworth, 1997a; Stevens et al., 2003), because drizzle drops fall and may grow towards cloud base. Near the $\phi = 0.8$ height, 44% of the computed reflectivity is due to cloud droplets on 17 August flight, which experienced more drizzle, while near the $\phi = 0.3$ height, 95% of it due to drizzle. On 9 August, which experienced little drizzle, these numbers are 57% and 87%, respectively.

This explanation clarifies why the drizzle threshold reflectivity becomes more difficult to define towards the cloud top.

3.2. Threshold reflectivity based on WCR measurements

As mentioned above, only events with more than two successive seconds of non-zero 2DC measurements are included for drizzle cases, when comparing in situ to WCR data. Similarly, if there are at least two successive seconds with both zero 1DC and zero 2DC measurements, but non-zero FSSP measurements, a cloudy region with a diameter larger than 200 m is considered to be drizzle-free. For WCR nearest gate measurements, a reflectivity smaller than -36 dBZ is considered to be noise. All noise values in the merged in situ/WCR time series are excluded as well.

The two series of WCR reflectivities, 'with drizzle' and 'drizzle-free', are studied at different cloud altitudes to find a threshold WCR reflectivity to discriminate drizzle-free from drizzly marine stratus. The same two statistical methods (Section 2.4) are applied to WCR nearest gate measurements. The drizzle-free and drizzly PDFs of WCR reflectivity each have a distinct and well-separated peak, for all three flights. Again, as was observed using calculated reflectivity values, a larger separation between the two distribution peaks is present at the lower part of the cloud. The drizzle threshold reflectivity based on the hit rate is again within 1 dBZ of that based on the cross-over point between the two PDFs. This threshold increases monotonically with cloud altitude on all flights (Fig. 7),

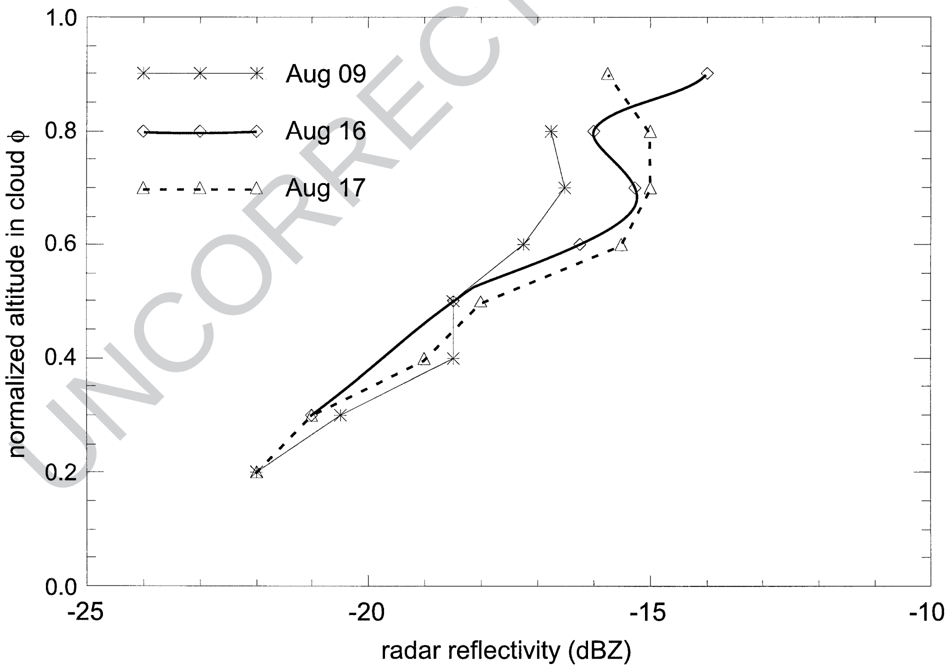

Fig. 7. As Fig. 5, but applied to WCR measurements.

as was the case for the calculated reflectivity (Fig. 5). Fig. 7 lends support to the existence of an unambiguous reflectivity threshold for drizzle, especially in the lower half of marine stratus.

The two PDFs for the drizzle-free and drizzly series are not as separate at the upper part of cloud. This is particularly true for the Aug. 16th flight (Fig. 8). This implies that drizzle presence is indiscernible from upper-cloud reflectivities on this day, perhaps because the patches were smaller. It is possible also that many drizzle droplets with diameter between 50 and 100 μm remained unsampled by the 1DC probe on 16 August. Such cases, probably with high WCR reflectivity values, are included in the drizzle-free data series. The undersampling of these droplets, due to the poor performance of the

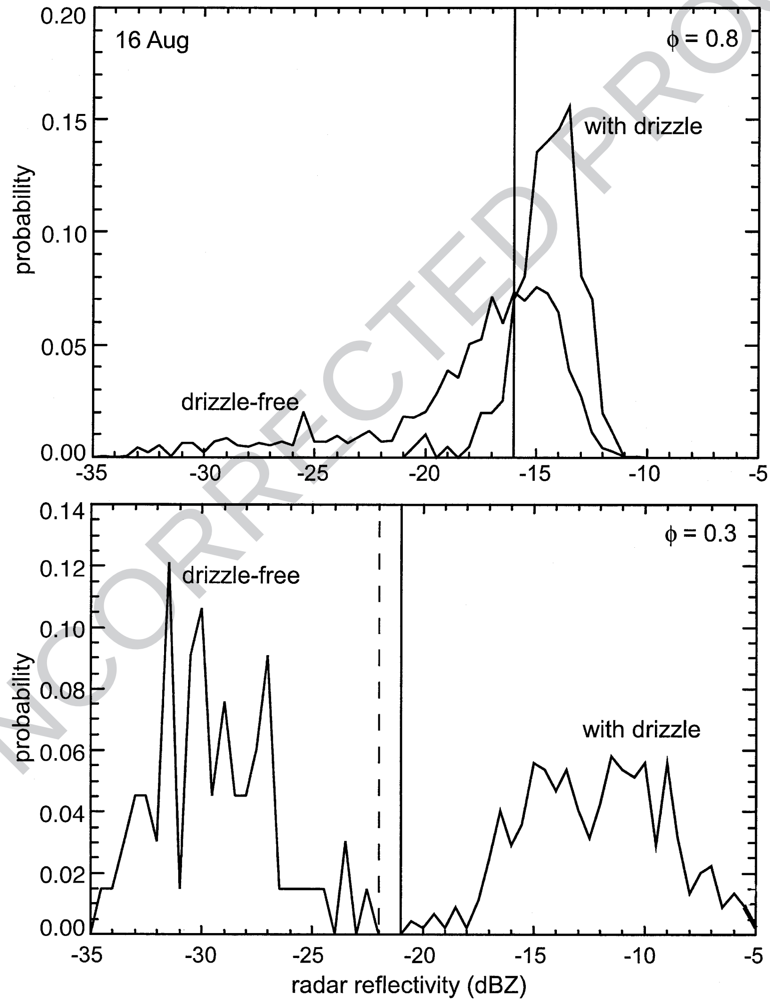

Fig. 8. As Fig. 6, but for WCR reflectivities for the 16 August flight.

1DC probe, introduces errors into the drizzle threshold reflectivity estimation. But even on 16 August, the two PDFs are separated clearly at lower levels, except for the $\phi = 0.4$ height, where a threshold value cannot be determined because the drizzle-free PDF has a wider distribution than the drizzle PDF. Although the 1DC data quality was more questionable on 16 August, and the patches were relatively small on some flight legs, a positive trend of drizzle threshold with cloud altitude reveals (Fig. 7), as on the two other flights.

In summary, similar threshold profiles are obtained using WCR reflectivity, for all three flights (Fig. 7). The drizzle threshold reflectivity slope with cloud altitude is similar to that based on calculated reflectivity (Fig. 5). The threshold is again most crisp in the lower half of the marine stratus, where the day-to-day variability is smallest. This proves that observed *cloud radar reflectivities alone can reliably flag drizzle presence, and that a clear, height-dependent reflectivity threshold exists for drizzle in marine stratus*.

3.3. Relation between calculated reflectivity and WCR reflectivity

One difference emerges when comparing the threshold reflectivity based on in-situ calculated reflectivities (Fig. 5) to that based on WCR measurements (Fig. 7). The two profiles show a similar variation with cloud altitude, but the calculated values are about 6 dBZ lower (Fig. 9). The question is then: which reflectivity values are

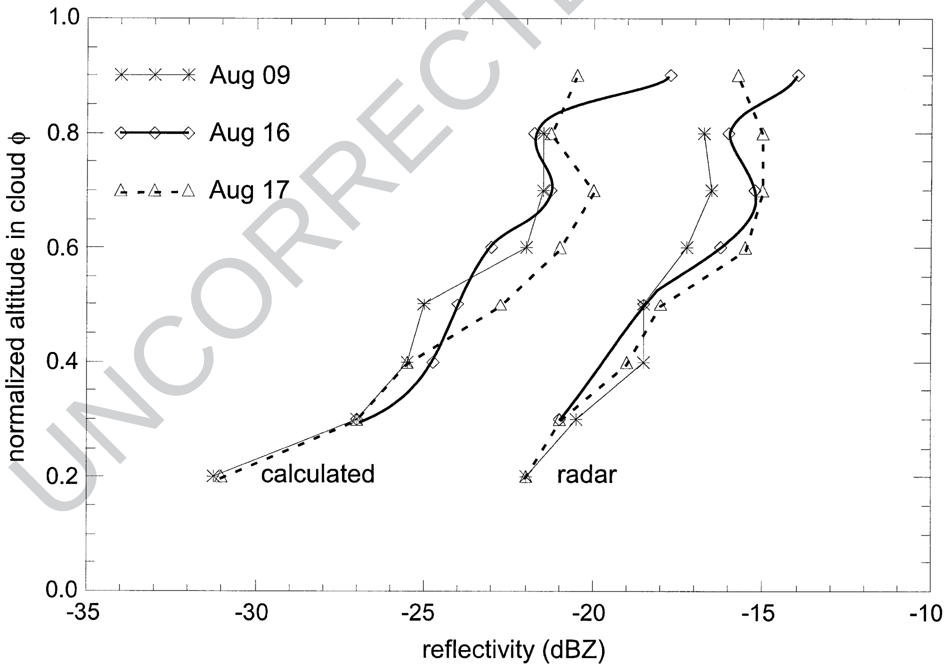

Fig. 9. Threshold reflectivity profiles based on in-situ calculated reflectivities (left) and the profiles based on WCR measurements (right).

biased, the WCR values or the calculated values? The WCR was carefully calibrated by means of a corner reflector, and the calibration difference before and after the CS99 field phase was within 1 dBZ (Haimov, personal communciation). The spatial offset between radar and in situ probes (Section 2.2) introduces more scatter, but there is no reason to expect that it induces a systematic bias. We believe that the reflectivity calculated from in situ probes (Section 3.1) is about 6 dBZ too low, because of the small sampling size (Table 1), especially for the 1DC and 2DC probes. The largest droplets in the distribution have a profound impact on the reflectivity (Eq. (6)). The average number concentrations of drizzle drops ranged from 0.2 to 1.8 per liter, on 9 and 17 August, respectively. This means that on 9 August the odds that a drizzle drop is recorded by the 2DC probe within one second of flight is only about 50% (Table 1). In fact a continuous log-normally distributed droplet spectrum, whose coefficients are based on FSSP and 2DC measurements cumulated over some time, reproduces the average WCR reflectivity within about 2 dBZ on all three flights (Wang, 2002). Even small droplets may be undercounted: the one-second LWC estimated from the integration of FSSP, 1DC and 2DC data is systematically lower than that from two independent LWC probes listed in Table 1, by 21% on average.

Therefore we propose to increase the calculated reflectivities by some value that is related to the difference between the WCR profile and the in-situ profile. To estimate the magnitude of this adjustment, we compare profiles of reflectivities computed from the in situ probes (Z_i) and corresponding WCR reflectivities (Z_w). For this purpose *all* WCR nearest-gate data are used, irrespective of drizzle presence. Again the data are categorized by normalized height and flight day. In-situ calculated reflectivities are obviously smaller than WCR echoes for 9 August (Fig. 10), and for the two other flights. The match between Z_w and Z_i is reasonable, at least the median values have a similar vertical variation. The median deficit of Z_i dwindles slightly from cloud base to cloud top for the three flights (Table 4). However the relationship between the Z_i deficit and cloud height is not linear, and it differs between the three flights. Multiple factors, such as spatial variance of cloud droplet spectrum and shortcomings of in-situ instruments, can affect the deficit. Therefore, and because the number of samples in each cloud layer varies by more than an order of magnitude, we cannot, with any confidence, propose a relationship between the Z_i deficit and cloud height. The mean reflectivity deficit for all levels is 6.4 dBZ for 9 August, 7.2 dBZ for 16 August and 5.8 dBZ for 17 August. We propose to simply *augment the in-situ calculated reflectivity profile by a constant value*, i.e. *6.5 dBZ*, the average deficit relative to radar measurements.

3.4. Threshold reflectivity applied to WCR measurements

Two independent reflectivity profiles flagging drizzle in marine stratus have been obtained, one based on Z_i and one on Z_w. The two threshold profiles have a similar slope, but a bias is detected in the in-situ reflectivity values, a bias which poorly correlates with cloud height. We increased the threshold profile by the mean difference between Z_w and Z_i. Therefore the *adjusted* calculated threshold profile is centered on the WCR threshold

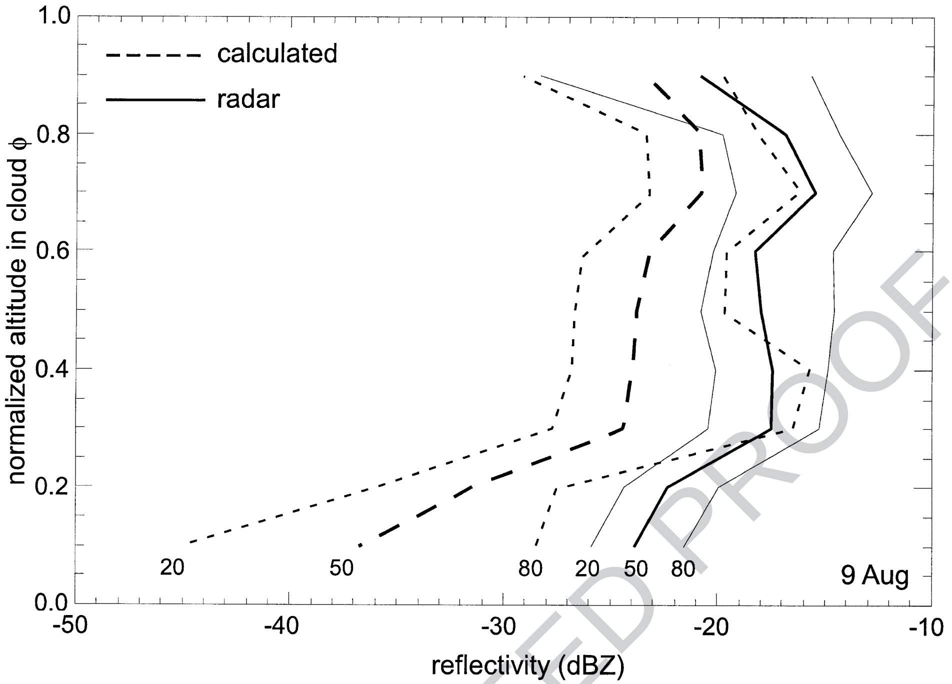

Fig. 10. Profiles of in-situ calculated reflectivity (dashed) and WCR reflectivity (solid) for the 9 August flight. From left to right, three lines of each kind represent reflectivity values of the 20, 50, and 80 percentiles of the reflectivity distribution at each level.

profile, and the difference between the two profiles is quite small. An example, for 17 August flight, is shown in Fig. 11.

The WCR is faulted by the non-coincidence of 2DC measurements, which are used to decide drizzle presence. The threshold profile based on in-situ measurements is not 100%

Table 4
The difference in median values (dBZ) of WCR reflectivity and calculated reflectivity, as a function of normalized height in cloud

ϕ	9 August	16 August	17 August	Average
0.9	2.42	5.58	4.82	4.5
0.8	3.99	5.82	5.96	5.3
0.7	5.31	5.98	5.15	5.5
0.6	4.90	6.99	5.00	5.7
0.5	5.80	6.73	4.85	5.9
0.4	6.57	7.03	6.76	6.8
0.3	6.91	7.88	7.51	7.5
0.2	9.07	12.78	8.07	10.5
0.1	12.92	6.39	4.43	9.5
Mean	6.3	7.2	5.4	

The mean for all levels is weighted by the number of samples in each layer; the average for the three days, at any level, is not weighted.

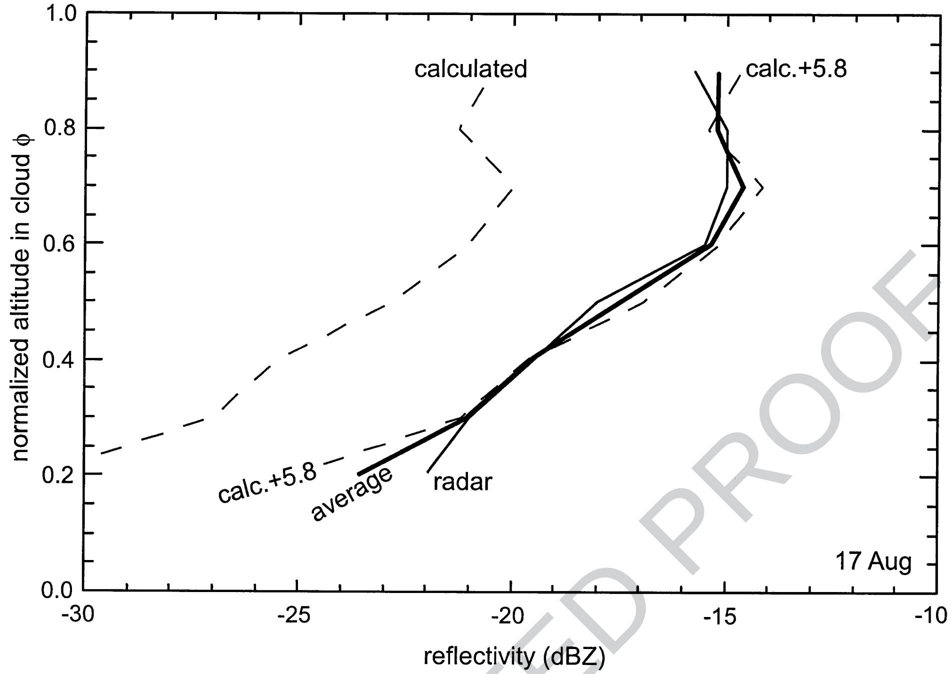

Fig. 11. Profiles of threshold reflectivity for drizzle for the 17 August flight. The left dashed line is the threshold profile based on in-situ measurements. The thin solid line is threshold profile based on WCR observations. The right dashed line represents a new profile, which is the in-situ calculated threshold plus 5.8 dBZ, which is the median difference between radar and calculated reflectivities. The thick solid line represents the average of the latter two lines.

exact either, because of sampling limitations. Therefore, we propose, as best-guess threshold profile for drizzle, the average of the three WCR threshold profiles (Fig. 7) and the three 'adjusted' calculated profiles. These profiles are shown in Fig. 12. The small variation between the three flights adds confidence to the result. There is one outlier, at a normalized altitude of 0.9 on 16 August (Fig. 12), but it is based on a relatively small sample size.

The small variation from day to day, evident in Fig. 12, justifies the definition of a single best-fit curve. A least-squares method is used to regress the threshold curve versus normalized altitude in cloud (Fig. 13). A weight of 0.5 is applied to the anomalous threshold at 0.9 altitude on 16 August, while a weight of 1.0 applies to all other values. A regression curve is thus obtained for the improved threshold reflectivities of all 3 days:

$$Z_{\mathrm{t}}\ (\mathrm{mm}^6\ \mathrm{m}^{-3}) = 0.046\phi^{1.413} \tag{7}$$

where Z_{t} is the reflectivity factor, with the units of ($\mathrm{mm}^6\ \mathrm{m}^{-3}$), and ϕ is the normalized altitude in cloud. This equation is considered to be the key result of this study. It represents the threshold reflectivity discriminating between drizzle cases and drizzle-free cases versus altitude in cloud. It can be applied to side-looking or profiling

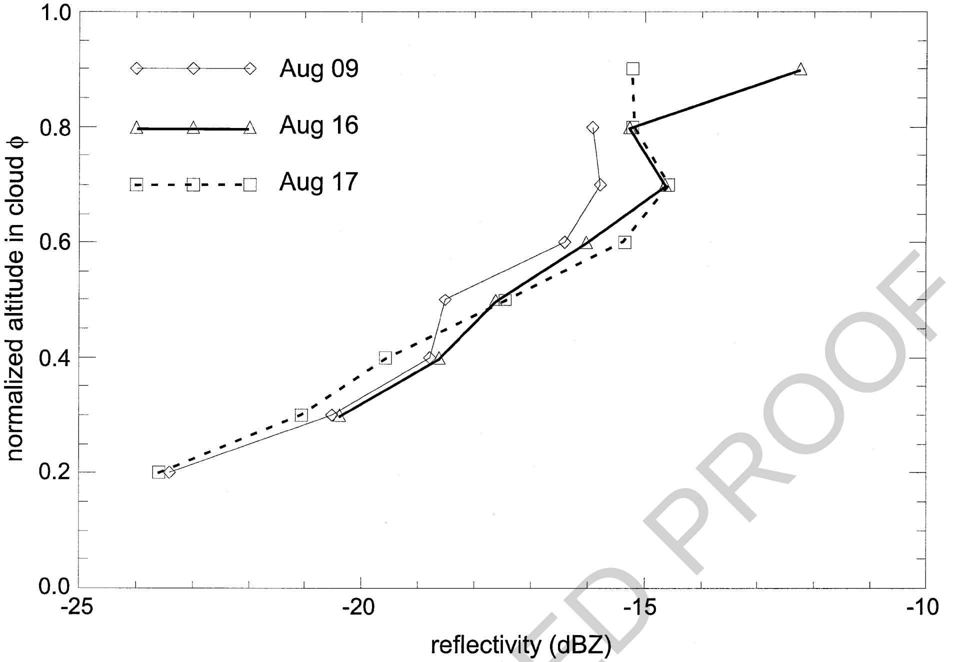

Fig. 12. Best-guess threshold reflectivity profile for drizzle in marine stratus, for three flights in CS99.

cloud radar measurements at any range, after attenuation correction, to flag the presence of drizzle in warm marine stratus.

4. An application: using radar reflectivity to determine cloud water content in drizzle-free marine stratus

4.1. Previous work

As an example of the use of the threshold reflectivity profile for drizzle, the relationship between LWC and WCR reflectivity is studied for drizzle-free marine stratus. The radar-based description of microphysical characteristics of stratocumulus and stratus cloud has been a topic of research for many years. Both empirical and theoretical relationships between Z and LWC have been retrieved. As early as 1954, Atlas suggested a theoretical relationship between X-band radar reflectivity and LWC, based on DSD measurements in precipitating clouds (Table 5).

No clear relationship exists between LWC and radar reflectivity in CS99 (Fig. 14). This conclusion has been reached by other studies of marine stratocumulus (Fig. 2 in Sauvageot and Omar, 1987; Fig. 6 in Fox and Illingworth, 1997a). Any value of LWC is possible over a large range of radar reflectivity values. Even below -15 dBZ a large range of LWC values is observed.

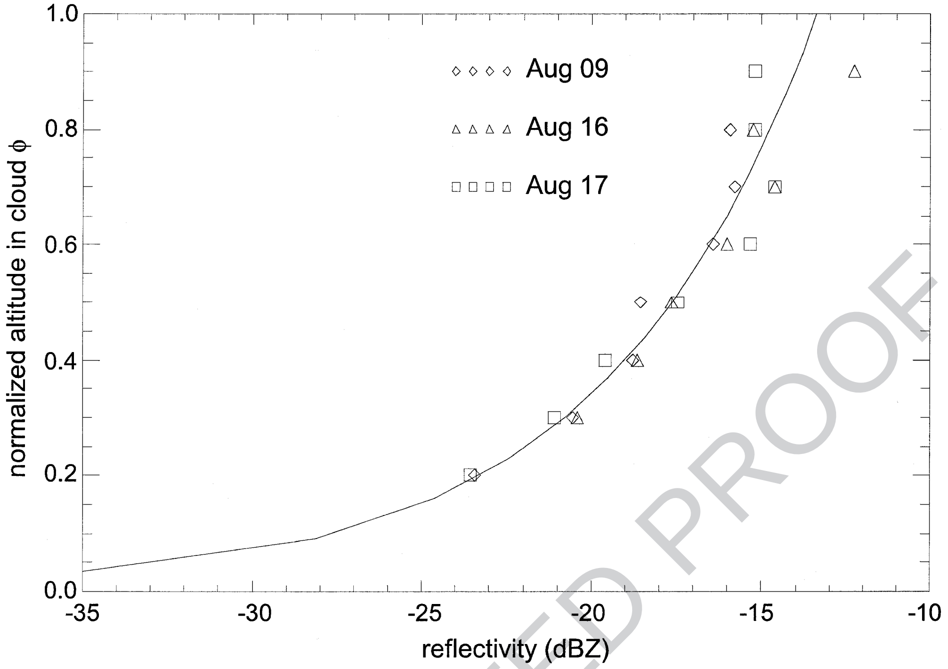

Fig. 13. Regression threshold reflectivity profile for drizzle in marine stratus.

Millimeter-wavelength radars for cloud research were developed in the 1980s, and Sauvageot and Omar (1987) proposed a relationship between cloud radar reflectivity factor and LWC based on instrumented aircraft measurements for non- or very weakly precipitating warm coastal cumulus and stratocumulus clouds. Their relationship (Table 5) is valid only for radar reflectivity values less than − 15 dBZ. The authors assumed that when the radar reflectivity is larger than this value, the cloud includes drizzle-size drops.

Table 5
Regression parameters for the equation $Z\ (\mathrm{mm}^{-6}\ \mathrm{m}^{3}) = a\mathrm{LWC}^{b} + c$, where LWC has units of g m^{-3}

	a	b	c
Source			
Atlas (1954)	0.048	2.0	0
Sauvageot and Omar (1987)	0.030	1.31	0
Fox and Illingworth (1997b)	0.031	1.56	0
CS99 flights			
9 August	0.040	1.33	0.0001
16 August	0.040	1.49	0.0020
17 August	0.055	1.20	− 0.0007
Mean of three flights	0.044	1.34	0.0005

Expressions from the literature are compared against the three CS99 flights.

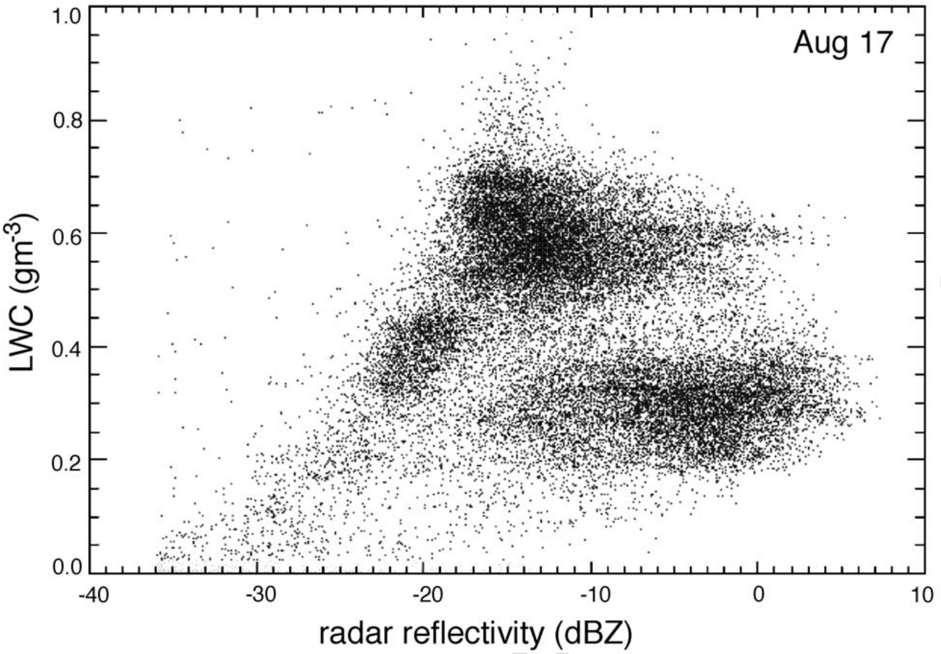

Fig. 14. LWC versus WCR nearest gate reflectivity for all flight legs on 17 August. The LWC is measured with the PVM probe.

Using the results of a one-dimensional adiabatic cloud model, Sassen and Liao (1996) found that the total droplet number concentration (N_d) affects the relationship between the W-band radar reflectivity and LWC in stratus cloud:

$$Z\ (\mathrm{mm}^6\ \mathrm{m}^{-3}) = \frac{3.6}{N_\mathrm{d}}\mathrm{LWC}^{1.8} \tag{8}$$

where LWC has units of g m^{-3} and N_d is the total cloud droplet number in cm^{-3}. This equation agrees well with Sauvageot and Omar (1987), assuming a typical number concentration $\mathrm{N_d} = 100\ \mathrm{cm}^{-3}$. Based on in-situ aircraft measurements of warm stratocumulus over the North Atlantic, Fox and Illingworth (1997b) separated drizzle-free and drizzle cases by analyzing the Doppler velocity spectrum. Then they developed a relationship between 3 mm radar reflectivity and LWC for drizzle-free cases. The slope parameter b in their equation (Table 5) falls between that of Atlas (1954) and that of Sauvageot and Omar (1987).

The above three relationships between LWC and radar reflectivity are only valid for clouds without drizzle-size drops. In these studies, it was either assumed that no precipitation-size particles were present, or their presence was eliminated based on circumstantial radar evidence. In this study, a rigorously tested, height-dependent reflectivity value is used to isolate drizzle presence in marine stratus (Eq. (7)). We now analyze the relationship between the W-band radar reflectivity and LWC in drizzle-free marine stratus.

4.2. Estimation of the liquid water content of drizzle-free stratus

A clear relation results between LWC and radar reflectivity (Fig. 15) when the drizzle cases are excluded from the sample in Fig. 14, based on the threshold reflectivity method (Eq. (7)). Considerable scatter still exists, and some points are located far from the regression curve, especially those with low LWC value. This can be explained by the distance between aircraft and WCR nearest gate, and by probing uncertainties, especially the inadequate performance of the 1DC probe and the slow sampling rate of the 2DC probe (1 s or 100 m). Therefore we introduce two boundary curves to exclude the points far away from the dense band (Fig. 15). These curves are exponential equations, $Z = a\mathrm{LWC}^b$, consistent with the literature (Table 5). Here a and b are chosen arbitrarily for each day to include the bulk of the points, but not the outliers.

An equation between radar reflectivity factor and LWC is regressed with the least-squares method:

$$Z\ (\mathrm{mm}^{-6}\ \mathrm{m}^3) = a\mathrm{LWC}^b + c \tag{9}$$

where Z is the radar reflectivity factor; LWC has units of g m^{-3}; and a, b, and c are regression parameters. The values of a, b, and c are determined based on data points delimited by outer bounds, as shown in Fig. 15, for the three flights in CS99 data. The

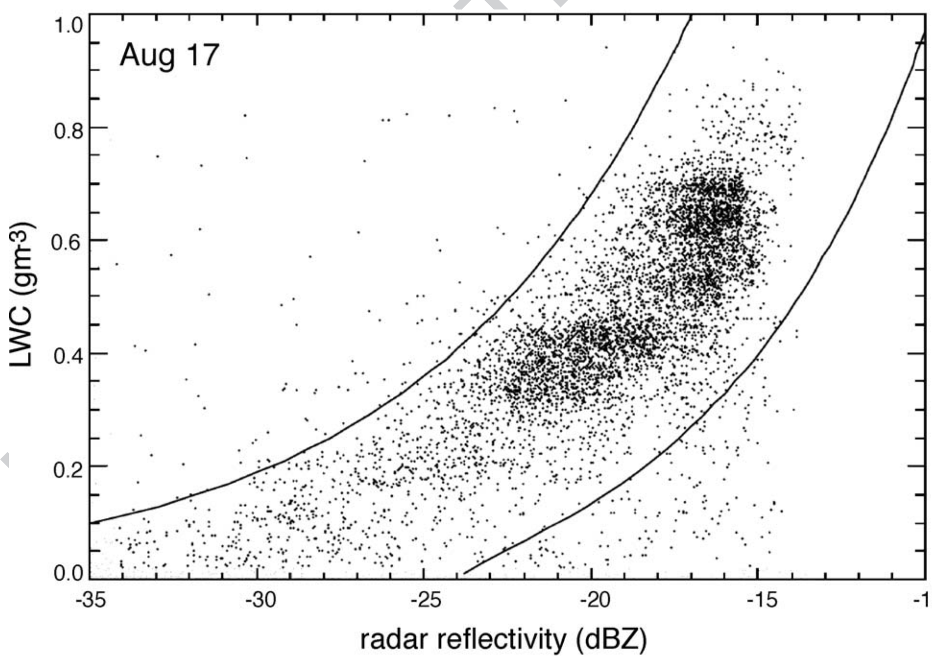

Fig. 15. LWC versus WCR reflectivity for drizzle-free cases for the 17 August flight. Solid curves represent the boundaries, which exclude points far away from dense band in further analyses.

values a and b vary little from flight to flight, notwithstanding varying synoptic conditions and drizzle regimes (Table 5). It is meaningful, therefore, to average the parameters and to propose the following equation to estimate LWC in drizzle-free marine stratus:

$$Z\ (\mathrm{mm}^{-6}\ \mathrm{m}^{3}) = 0.44\mathrm{LWC}^{1.34} + 0.00046 \tag{10}$$

The intercept a (0.044) is distinctly higher than the 0.030 value proposed by Sauvageot and Omar (1987) and by Fox and Illingworth (1997b), but the slope b is comparable. The parameter c only affects the shape of regression curve at low LWC values (Fig. 16). Only when the LWC is smaller than 0.2 g m^{-3} is there a clear difference between the two curves in Fig. 16. In that case the regression curve with $c = 0$ yields a slight underestimation. But because the radar reflectivity is near its sensitivity threshold at low LWC values (-30 dBZ at a range of 1 km), because of the relatively small value of c in Eq. (10), and because of the variability of c from flight to flight (Table 5), we choose to omit it. And we propose the expression

$$Z\ (\mathrm{mm}^{-6}\ \mathrm{m}^{3}) = 0.44\mathrm{LWC}^{1.34} \tag{11}$$

for the relationship between LWC and radar reflectivity for warm marine stratus.

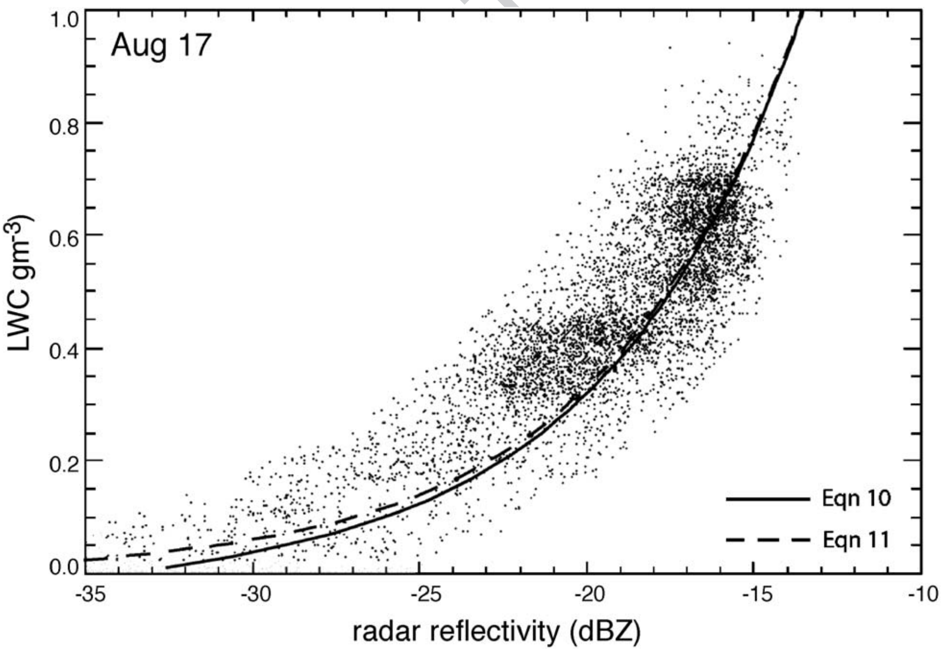

Fig. 16. As Fig. 15, but with the best-fit relationship between LWC and radar reflectivity for the three flights (Eq. (10)), and a simpler version (Eq. (11)).

5. Discussion

The identification of a threshold reflectivity above which drizzle can be expected assumes independent measurements of radar reflectivity and drizzle presence at the same location. In this study we define drizzle presence by means of airborne 1DC and 2DC probes. This definition has the advantage to be direct, but has the drawback that the 1DC and 2DC sample sizes are rather small, at least six orders of magnitude smaller than the adjacent radar volume, requiring an along-track sample distance that may exceed the size of a drizzle patch in marine stratus.

A second challenge is that radar measurements apply at some distance from the aircraft. In other words the radar may be measuring a different region than the aircraft, and marine stratus is known to be quite patchy in reflectivity structure (Vali et al., 1998). However (a) spatial autocorrelation analysis suggests that the patches generally exceed 75–90 m; (b) only those drizzle (drizzle free) cases are considered where probes measure drizzle (no drizzle) for at least 2 s (200 m along-track); and (c) the relation between drizzle presence and reflectivity is almost identical for radar-observed reflectivities and for reflectivities calculated from in-situ measured droplet spectra and further adjusted. These three arguments argue in favor of the robustness of the proposed threshold reflectivity flagging drizzle presence. We find that this threshold is a function of height in cloud. This height is normalized because marine stratus thickness and height vary substantially.

Two data sources are used to determine the threshold reflectivity profile for drizzle, reflectivity measured with WCR, and reflectivity calculated with in-situ DSD measurements, assuming Rayleigh scattering. The former of course is preferred since it represents a large sampling volume, but its drawback is that it may not represent the same air where the drizzle presence is detected (at the aircraft), but rather some 75–90 m to the side. Because of the assumptions involved, a bulk statistical method is required, and two different statistical methods agree very well on the definition the threshold reflectivity profile. The two profiles, one based on probe data (Z_i) and the other on WCR data (Z_w), display similar vertical variation. However the Z_i values are systematically 6–7 dBZ below the Z_w values on all three flights. A matching of probe data to continuous DSD functions suggests that the main reason for this discrepancy is that the cloud probes undersample the true DSD, mainly in the larger droplet range. This discrepancy is only weakly height-dependent, but the height-dependence pattern varies from flight to flight in marine stratus. Perhaps the discrepancy can be used to improve probe-based DSD estimations. In any event, we adjusted the probe-calculated reflectivity upward by 6.5 dBZ.

This work can be extended. In particular, the reflectivity threshold (Eq. (7)) can be used to examine the relationship between radar reflectivity and other cloud physical parameters, such as liquid water path (LWP), for drizzle-free marine stratus. And one can apply the drizzle threshold value to profile and map drizzle in marine stratus using vertical or horizontal radar reflectivity data. Drizzle maps may bring insights into the dynamics of the marine boundary layer and associated cloud microphysical processes, and they may validate cloud-resolving large-eddy simulations.

6. Conclusions

Airborne cloud radar and cloud microphysical data, collected on three summer days off the Oregon coast, are analyzed to obtain an empirical threshold radar reflectivity above which drizzle can be expected in warm marine stratus. Our key findings are:

- Increasing radar reflectivity always corresponds to increasing drizzle probability.
- The threshold reflectivity Z_t, above which drizzle can be expected in marine stratus, is a strong function of height within the cloud layer, as follows: Z_t (mm^6 m^{-3}) = $0.046\phi^{1.413}$, where ϕ is the normalized height in cloud. Both radar reflectivities and calculated reflectivities (based on measured droplet spectra) indicate that the threshold is most crisply defined in the lower half of the stratus cloud deck.
- Liquid water content (LWC) and radar reflectivity generally are unrelated in marine stratus. The use of the threshold reflectivity profile to exclude drizzle is illustrated by examining the relationship between radar reflectivity and LWC in drizzle-free marine stratus. That relationship turns out to be strong, and similar to those found in the literature.

Recent observations suggest that drizzle is surprisingly common in marine stratus, especially at night (Stevens et al., 2003). The results of this study can be used in the global assessment of drizzle properties in marine stratus, once spaceborne cloud radar data become available.

Acknowledgements

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