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VERTICAL MOTIONS OF DROPS OF DIFFERENT SIZES IN MARINE STRATUS

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1. Introduction

The mechanism for drizzle formation in warm marine stratus is an important current topic. A key element to understanding the process is the characterization of the spatial and temporal history of drizzle drops. Simple upward moving parcel descriptions are clearly invalid in stratus. While the desired histories are unobtainable, some clues can be derived from the associations of drizzle drops, and of other droplets, of different sizes with air motions. This is the topic addressed in this paper, restricting the analyses at this stage to vertical air motions.

2. Basic features

Vertical motions of cloud (d < 50 μm) and drizzle drops within the cloud are not easily observed. These motions are a combination of turbulence and of regions of updrafts and downdrafts.

Several previous studies have shown positive correlations between upward air velocity (positive *w*) and FSSP measured droplet concentration (N_{FSSP}) in marine stratus or stratocumulus clouds (Curry, 1986; Hudson and Svensson, 1995; Hudson and Li, 1995, Vali et al., 1998, hereafter V98). These correlations apply to *N* and *w*-values averaged over roughly 100-m scales. In contrast, the liquid water content (LWC) contributed by cloud droplets (d < 50 μm) was generally found to be independent of *w*. In concert with these facts, the volume mean diameter of cloud droplets show negative correlations with *w*.

Because the concentrations of drizzle drops (d > 50 μm) are much lower than those of cloud droplets, sampling problems make it difficult to examine correlations with air velocities from in situ data. V98, using an airborne cloud radar showed that higher reflectivities (*Z*), i.e. regions of greater drizzle drop concentrations, coincided with smaller downward Doppler velocities (*V*) in the upper halves of cloud decks. In contrast, the expected coincidences of regions of higher reflectivities and larger downward Doppler velocities were found in the lower half of the cloud decks. These observations were made in unbroken stratus situations.

For the cases presented in V98 the in situ data from a PMS 1-DC probe (N_{oned}) showed positive correlations with the vertical air velocity. Possible explanations for the *Z*-*V* and N_{oned} - *w* correlations in the upper parts of clouds were seen as either reduced drizzle concentrations in downward moving air originating from entrainment, or increased drizzle concentrations in upward moving air.

3. New analyses.

In order to further refine the analyses, we have now moved from the simple cloud droplet vs. drizzle droplet stratification to an examination of spectral characteristics up to the resolution available from the FSSP and 1-DC probes. We have done this with both the data previously described in V98 and with additional observations made in 1999. Such analyses can only be performed with data of reasonable homogeneity over large sample regions, typically about 50 km in horizontal extent.

Further analyses were also directed toward shedding light on the nature of the correlations between vertical air velocity and drop concentrations. We have tried to identify the local events that lead to the correlations.

The 1999 field studies (Coastal Stratus 1999, or CS99) were again conducted in unbroken marine stratus off the coast of Oregon and utilized the Wyoming King Air and the Wyoming Cloud Radar (95 GHz airborne radar).

4. General cloud characteristics

Data from two days will be discussed in some detail in this paper. On 15 September 1995 a solid cloud cover, without visible breaks, was observed 30-80 km off the Oregon Coast. This day was analyzed in detail in V98. It is recommended that the reader consult this paper for more details about the observations made on this day. Cloud base was at about 380 m and cloud top was at 700 m. The lapse rate from the surface up to cloud top was –5.0 °C/km. The temperature inversion at cloud top was 7 °C over a 100-m height interval. The average LWC near

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cloud top was about 0.55 g m^{-3}, about 90% of the adiabatic value.

The second day, 17 August 1999 also had a solid cloud cover for most of the region studied. The area studied, again, lies 30-80 km off the Oregon Coast. Cloud base was about 400 m and cloud top ranged from about 730 m to 800 m. The lapse rate from near the surface to 500 m was about –9 °C/km and the lapse rate from this height to the inversion at cloud top was about –4 °C/km. The temperature above cloud top increased 7 °C over a distance of 200 m. The temperature at cloud base was 12 °C. The average LWC value for the cloud was 0.6. An adiabatic value of LWC would be near 0.7.

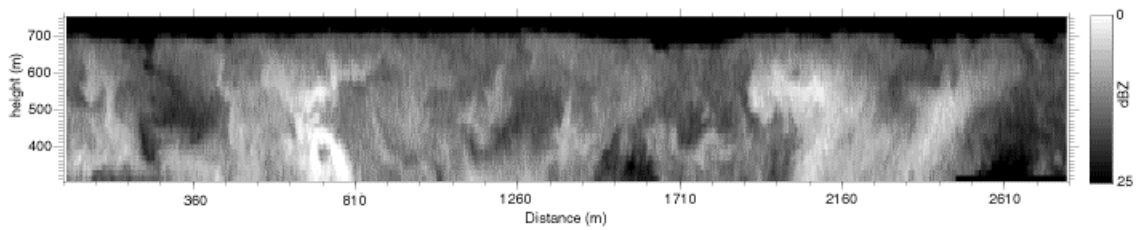

Fig. 1. *Vertical cross-section of the cloud deck for 17 August 1999 as observed by the Wyoming Cloud Radar on board the King Air. The distance traversed in the cross-section is nearly 2.8 km. The y-axis represents height in meters above sea level. Reflectivity ranges from 0 to –25 dBZ.*

5. Radar observations

A representative vertical cross-section of the reflectivity field is shown in Fig.1 for 17 August 1999. Maximum reflectivities were about –2 dBZ. The reflectivity field is similar to the reflectivity field for 15 September 1995 in V98. A cellular structure in the echoes can be seen; the high reflectivity cells extend downward from near echo tops. There is a thin layer of relatively uniform structure at the upper echo boundary. Echo top is less uniform in height than was the 15 Sept. 1995 case.

The correlation between reflectivity and Doppler velocity for 17 August 1999 shows the same reverse S shape as was described in V98. This has been also seen in several of the days analyzed so far in the CS99 data. At lower altitudes, higher reflectivity values correspond to downward Doppler velocities as would be expected when drizzle is present. However, the correlation reverses in the upper third of the cloud.

6. Vertical velocity correlations

Correlations between *w* and in-situ measurements of LWC, N_{FSSP}, N_{oned}, and mean drop size were examined for different level flight segments in the cloud deck. For all the days analyzed in V98 correlations between *w* and LWC were relatively weak at all heights in the cloud. Most were below 0.1 and the highest correlation of 0.3 was observed only once. The CS99 data yielded different results. For 17 Aug 1999, and for other days from CS99, correlation values are generally above 0.2 at various levels in the cloud deck, both low and high. There are several values above 0.3, and two highest values are 0.41, and 0.46. Correlations between *w* and N_{FSSP} are also strong. Correlation values for 15 Sept. 1995 were 0.39 in the upper part of the cloud deck and 0.44 in lower part of the cloud deck. For 17 Aug. 1999 correlations are between 0.26 and 0.46 for flight levels ranging from just above cloud base to about two thirds of the cloud depth. Correlations between *w* and N_{FSSP} are strong for all days studied during CS99.

A more detailed analysis of the nature of the correlations in the 1999 data was performed by comparing deviations in LWC and in *w from* their surrounding mean values over scales varying from 20-100 m. In general both coincidences of increases in LWC and increases in *w*, and coincidences of decreases in LWC and decreases in *w* were found. However, the number of the latter events far outweighed the former. This finding indicates a dominant role of downward moving air with reduced LWC, possibly as a result of entrainment of drier air from cloud top.

It should also be noted that on one occasion during CS99 (21 Aug 1999) we found a fairly strong negative correlation between LWC and *w* (values between –0.25 and -0.34). This day does not support the claims made above and so the idea of diluted regions of downward moving air does not seem to be a general one. Examination of the specific 'events' showed that on this occasion lower LWC accompanied positive pulses in w, while negative pulses in w had higher LWC. More analysis is needed to determine why this day is different.

Both 15 Sept. 1995 and 17 Aug. 1999 showed strong negative correlations between *w* and mean drop diameter. Other days studied in both 1995 and 1999 consistently show this correlation at all levels within the cloud deck. Values generally showed magnitudes greater than –0.15, going as high as –0.53. There seems to be no trend between weak correlations and height within the cloud deck. The strong negative correlations between mean drop size and *w* are also supportive of new drops being created in updrafts. The correlation between *w* and N_{onedc} (drops with d > 50 μm) is weak for 17 Aug. 1999: a maximum value of 0.26 occurs at lower levels in the cloud. This contrasts with the value of 0.45 for 15 Sept. 1995 in the upper portion of the cloud deck..

7. Vertical velocity correlations with different drop size ranges.

In order to further dissect the correlations described in the preceding, the relationships between *w* and the concentrations of drops in individual size bins of the 1-DC and the FSSP probes were investigated. A representative result is shown for a data segment (27 km in extent) from 15 Sept. 1995 in Fig. 2. These data are for 480 m altitude, about 1/3rd of the way up in the cloud layer.

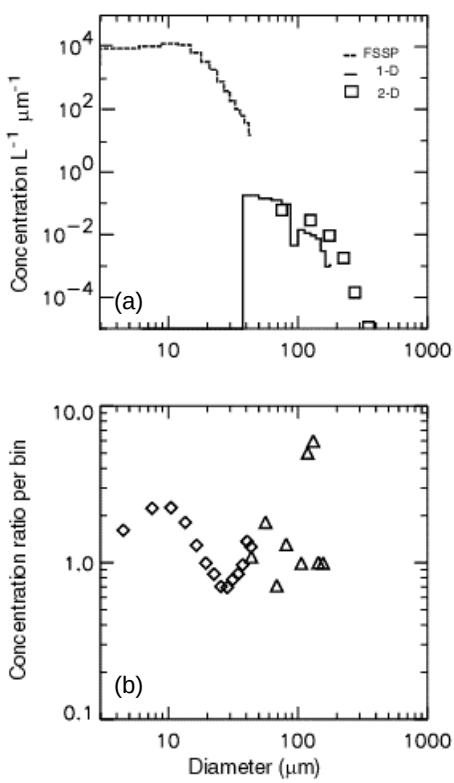

Fig. 2. *(a) Cloud drop distribution from FSSP, 1-D and 2-D data on 15 September 1995. (b) Plot showing the ratio, for each bin of the FSSP and 1-D probe, of drop concentrations in the 80th percentile of vertical velocities to drop concentration in the lower 20th percentile of vertical velocities.*

In order to maintain sufficient sample sizes in spite of the stratification by droplet size, the comparison is restricted to the uppermost and lowest 20% of the vertical air velocity. For the data shown in Fig. 2, the mean value of *w* for the uppermost 20 % of vertical velocities is +0.38 m s^{-1} . The mean N_{FSSP} value corresponding to these velocities is 196 cm^{-3}, the mean FSSP-calculated LWC is 0.24 g m^{-3}, and the total calculated reflectivity is –20 dBZ. For the lowest 20 percent of vertical velocities, the mean *w* is –0.48 m s^{-1}, N_{FSSP} = 115 cm^{-3}, FSSP calculated LWC is 0.2 g m^{-3}, and the total calculated reflectivity is –21.5 dBZ.

The ratios of concentrations in the uppermost to the lowest 20 percent of vertical velocities for the different drop sizes is shown in the lower panel of Fig. 2. Values significantly different from unity are evident. A first peak occurs at a diameter of about 10 μm with a ratio of drop concentrations of about 2.5, i.e. there were 2.5 times more droplets of these sizes in areas of the largest upward velocities than they were in areas of largest downward velocities. The second significant region of departures from unity is at a diameter little larger than 20 μm. The ratio at this dip is about 0.6 indicating that there are nearly twice as many drops of this size in downward moving air than in upward moving air. The third size region of interest is that of the drizzle drops (from the 1-DC data) where ratios are generally above unity and have values of about 6 near 120 μm diameter.

The pattern shown in Fig. 2(b) has been observed for about 22 level flight segments from 8 days at various heights within the cloud decks. There seems to be no dependence of the shape of this curve on height within the cloud deck. For almost all the days studied from 1995 and 1999 data, ratios at the first peak ranged from 2-3, for diameters of 9-11 μm. The dip in the curve has also been observed consistently, and found to be similar in amplitude and location, for all days analyzed, at all levels within the cloud deck. For the drizzle sizes, the range of ratios found on other days was from 2 to 7, at diameters from 50-100 μm. In the largest size bins of the 1-DC probe, ratios almost always drop to values of unity or slightly lower.

8. Conclusions

Data from the 1995 and 1999 observations support the findings of previous studies, as well as provide new information about the evolution of the droplet spectrum in unbroken marine stratus.

The positive correlation between cloud droplet concentrations and vertical velocity seems to be a quite general feature of marine stratus and stratocumulus. Our analyses show that this correlation is dominated by droplets of about 10 μm diameter and does not extend over the entire range of cloud droplet sizes. Indeed a negative correlation is the rule for droplets around 20 μm diameter. The pattern reverses again for drizzle drops, which are found in higher concentrations in upward moving air than in downward moving air. This latter finding is also supported by the correlation of radar reflectivity and Doppler velocity. There is a yet unresolved disagreement between the radar data and the in situ data, in that the correlation in the radar is as just described only in the upper 1/3 of the cloud layers while the in situ data show the same pattern at all heights within the cloud. The negative correlation for drops around 20 μm diameter is a puzzling result, which is yet to be explained.

The correlation between vertical air velocity and LWC appears to be variable from case to case. No correlation was reported by V98. Most of the 1999 data so far examined show reasonably strong positive correlations. One case in 1999 exhibited a strong negative correlation.

Examinations of the individual events (coincident local peaks in vertical velocity and in N_{FSSP} or LWC), which lead to the statistical correlations, reveal that in the 1999 data the strongest signals are from downward moving air and reduced N_{FSSP} or LWC. Negative buoyancy due to entrainment of dry air and evaporation may be one of the reasons for this observation, but other possibilities exist and we have not yet pursued the question far enough to know which explanation is the most credible.

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