AIRBORNE RADAR OBSERVATIONS OF NON-DRIZZLING MARINE STRATOCUMULUS

Gabor Vali

Department of Atmospheric Science, University of Wyoming.

1. INTRODUCTION

Since drizzle is nearly ubiquitous in marine stratocumulus, observations are sparse from situations where drizzle was absent. The case here described fits in that category and is interesting to examine because the Doppler radar data allows air motions to be diagnosed without serious contamination by the fallspeed of precipitation.

As part of the Dynamics and Chemistry of Marine Stratocumulus-II (DYCOMS-II) experiment in July 2001, nighttime observations were made in the vicinity of 31°N latitude and 122°W longitude. Main features of the study are given by Stevens et al, 2003. Observations were made with the NSF/NCAR C-130 aircraft carrying cloud physics probes, aerosol and trace gas (O_3, DMS) instrumentation, the SABL lidar and the Wyoming Cloud Radar (WCR). This paper focuses on information derived from the radar data on one flight,18 July, 2001 0619-1541UTC; flight RF05. The flights pattern consisted of circles of 60 km diameter at various altitudes while allowing the aircraft to drift with the ambient winds, hence approximately tracking a given cloud region.

2. GENERAL CHARACTERISTICS

During the 7-h study period, the sampled area moved a total distance of 200 km with the mean boundary layer flow. Cloud depth was near 250 m under a temperature inversion of about 8°C. The average depth of the boundary layer remained relatively constant near 820 m during the first 3.5 h of the flight, then increased to 960 m during the next 3.5 h, accompanied by an apparent thickening of the cloud layer. In addition to smaller-scale variations, the top of the boundary layer was tilted, by up to 150 m over the 60-km dimension of the observation area; the direction of the tilt changed on the scale of hours. The following discussion refers to observations made at about the mid-point of the total study period, i.e. prior to the onset of BL deepening. At that time, the BL was relatively uniform in depth, with <50 m variation, over the 60-km study area.

Corresponding author's address: Gabor Vali, Dept. Atmospheric Science, 1000 E. Ivinson Ave. Laramie, WY 82070, USA; E-Mail: vali@uwyo.edu.

The cloud layer was 95 to 98% unbroken. Cloud base[1] measurements from detectable amounts of LWC during soundings range between 590 and 705 m; inferred upper limits from adiabatic LWC assumption indicate lower values near 580 - 600 m. From uplooking SABL data (during the circle flown 1300 - 1350 UTC), the average cloud base altitude was 596 m. Liquid water content maxima were near 0.5 g m^{-3}; highest droplet concentrations were about 150 cm^{-3}. At about mid-level in the cloud, the in situ probes detected only a few dozen drizzle drops (>50 µm diameter) dispersed during nearly 1000 km of sampling; the maximum sizes detected were 200 µm early in the flight and 400 µm near the end. Halfway between cloud base and the ocean surface, no drizzle drops were detected. Based on this, and on evidence from the radar, it is justified to refer to this case as a non-precipitating stratocumulus layer, though more precise characterizations will be attached to that definition in the following.

Much detail about the observations for this case is available on the web page http://www-das.uwyo.edu/~vali/dycmos/dy_rept/rf05_part1.html, and in Part 2 which is accessible from there via a link. Only the main features of the findings are summarized here. In addition, some new material is presented.

3. REFLECTIVITY PATTERNS AND ECHO TOP VARIATIONS

Radar data from the full cloud depth was obtained during the 10:30-10:58 UTC circle flown at 998 m MSL above the cloud.

The dominant pattern in radar reflectivity is an upward gradient, from values near -30 dBZ at the base to values near -15 dBZ at the top of the cloud layer. This is consistent with the upward gradient in liquid water content, and with the assertion that the radar reflectivity is dominated by populations of cloud droplets, not drizzle drops. In many other cases drizzle is observed to produce strong vertical striations in reflectivity.

Since the strongest reflectivities are at cloud top, the echo top is well defined in the data; comparison

[1] All altitudes quoted are from radar altimeter data.

with lidar data shows that the lidar-detected mean cloud top is 11 m higher than the mean echo top over a 200-km sample (10:30-10:58 UTC). In the following, echo top and cloud top are used almost interchangeably. Both measurements show cloud top altitude to be strongly skewed (S_k = -1.1) with a long tail toward low values. The standard deviation of cloud top altitude is 35 m. Associated with the variations in cloud top altitude, there is a well-correlated variation in the maximum local reflectivity: for 1-km horizontal averages r=0.84, with roughly 10 dBZ higher values for each 50 m increase in the altitude of the echo top.

Interestingly, the reflectivity pattern is neither uniformly flat independently of variations in echo top (implying a uniform cloud base altitude), nor is it a simple parallel variation with the echo top altitude. Taking the -21 dBZ level as a mid-cloud value (at a mean altitude of 727 m, 101 m below the mean echo top) it is seen to vary parallel to the echo top on the large scale and out of phase on the scale of kilometers. On the 20-km scale, the two altitudes have r=0.8, while deviations from the 20-km means show no correlation at all (r=0.014). The implications of these results will be further elaborated later on, when discussing reflectivity gradients.

4. ECHO BASE

Most complete radar data from the lower portions of the cloud, and corresponding in situ measurements, were obtained from two circles flown in cloud during 11:08-11:30 and 11:33-12:03 UTC.

With the mean *cloud base altitude* (**CB**) just about 180 m below the flight level, the resulting greater radar sensitivity benefits examinations of reflectivity near cloud base. After careful (but nonetheless still subjective) noise thresholding, the mean *echo base altitude* (**EB**) was found to be 545 m with standard deviations of 42 m for 30-m horizontal averages, and 30 m for 0.6-km averages. The distribution of **EB** is negatively skewed (S_k = -0.5), i.e. toward lower values. The best data for **CB** is from SABL during a period two hours later than the **EB** data. It yields **CB** = 596 m, and, for 110-m horizontal averages, has a standard deviation of 36 m and no skewness. This value for **CB** (reasonably well supported by other determinations from earlier periods) is roughly 50 m higher than the mean **EB**. The difference, even if not precisely known, indicates that in fact there were radar-detectable hydrometeors present of the order of 50 m below the cloud base, and that these were, most likely, small drizzle drops of perhaps 50-100 μm diameter which are difficult to measure with the in situ probes. Also, these drizzle drops were evidently evaporating and only extending to about something like 50 to 100 m below cloud base.

When **EB** is stratified by the Doppler velocity measured near cloud base, a strong correlation is found for velocities <1 m s^{-1}: **EB** = 517 m for -2 m s^{-1} and **EB** = 557 m for +1 m s^{-1}. There is no change in the mean **EB** for vertical velocities >1 m s^{-1}. The coincidence of lower echo bases with downward velocities supports the idea that these echoes are due to larger drops which are evaporating slower in moistened downward plumes.

There is additional evidence for lower values of **EB** to be associated with drizzle in the strong negative correlation (r = -0.7) observed between **EB** and the 90-percentile reflectivity directly above the given **EB** location. The lowest echo bases correspond to reflectivities near -20 dBZ, while the highest ones correspond to -30 dBZ. This also implies the presence of negative vertical velocities at the echo base at locations where the reflectivity above is stronger, and vice versa, though the direct correlation between the reflectivity and the velocity at the base is weaker.

Reflectivity gradients in the lowest 75 m of the observed echoes have also been stratified by the vertical velocity measured in the same location. The gradients for velocities >1 m s^{-1} are near 14 dBZ per 100 m. For velocities in the range -1.75 ± 0.25 m s^{-1}, it is near 8 dBZ per 100 m. The values of these gradients can be best judged when compared to results from parcel model calculations (Snider and Petters - <http://www-das.uwyo/ccp/web/model.html>). With C=250 cm^{-3}, k=0.3, cloud base (defined as 50% final drop concentration) at 590 m and for updrafts in the range 1 to 4 m s^{-1}, the model indicated that by the time reflectivity values reach -34 dBZ (comparable to the observed values near **EB**) the rate of increase of reflectivity is between 12 and 18 dBZ per 100 m of lift. These values bracket the observed 14 dBZ per 100m for upward vertical velocities. The implication is that the reflectivity gradient, for updrafts, is dominated by the condensation of droplets, but with the absolute value of the reflectivity increased from -34 to about -29 dBZ (at 590 m altitude) by recirculating drizzle drops. Admittedly, this is not a fully developed description. To firm up these ideas, it will be necessary to collect simultaneous data, at a minimum, on **CB**, **EB** and vertical velocities.

5. VERTICAL VELOCITIES

In contrast with the horizontal stratification of reflectivity, vertical velocities[2] vary predominantly along the horizontal, and exhibit greatest variation near cloud base. Images accessible from the web page cited at the beginning of this paper demonstrate

[2] The measured Doppler velocities are affected by the fall velocities of droplets to a minor extent, comparable to the estimated 0.2 m s^{-1} accuracy of the measurements. Hence, for simplicity, Doppler velocities and air velocities are referred to here, interchangeably, as "vertical velocities".

this pattern quite clearly. For both positive and negative values near **EB**, the velocity diminishes toward zero at cloud top.

Frequency distributions of vertical velocity at given altitudes are symmetrical and quite broad. Using 10-m resolution data, the range of values at the 0.01 percentile level extend to ±3.5 m s^{-1}. At the echo base, the 1, 5, 10, 90, 95 and 99-percentile values are [-2.1, -1.4, -1.1, +1.1, +1.4, +2.2], and at cloud top these values are [-1.5, -0.80, -0.57, +0.42, +0.60, +1.3]. Mean values are very close to zero at all levels.

Perhaps the most important aspect of the vertical velocity observations is the patchiness of updraft and downdraft regions in the lower part of the cloud. Again, the best way to see this is from the images. The size distributions of regions of given velocity thresholds (variously defined) are all exponentially decreasing. Yet, contiguous regions of larger sizes can be seen to have the greatest significance in terms of upward penetration, correspondence with echo top altitude (both of these indicating longevity), and in terms of drizzle development. Thus, it is worth quoting that 100-m patches of vertical velocities exceeding 1 m s^{-1} (either positive or negative) are about 3 km apart and 200-m patches are on the average 30 km apart. For >0.5 m s^{-1}, 200-m patches are 3 km apart. These numbers relate to sampling along a line (a circle) so the dimensions quoted are random sections of patches of yet unknown shapes.

6. COMMENTS

Not surprisingly, even in this simplest of the stratucumulus cases from the DYCOMS experiment, rich structure has been revealed by the data so far examined. Perhaps the key deduction at this point is that updrafts are modest in horizontal extent (very few are large) but are relatively vigorous, and that they appear to penetrate cloud regions already containing low concentrations of small drizzle drops. From the point of view of drizzle growth, this implies that the residence time of droplets is lengthened by updrafts for some unknown fraction of the total cloud volume. This is not re-circulation in the sense that other cases suggest, but a simpler floatation of the cloud volume, more the way repeated parcels have been modeled for cumulus. The drizzle drops evaporate within about 100 m of cloud base, and so play a different role in sub-cloud forcing of circulations than in cases with more profuse drizzle.

The proposition for re-lifting of growing drizzle drops is neither really surprising, nor novel. It has also been made by Vali et al. (1998) on the basis of a positive correlation between velocities and reflectivity in the upper parts of coastal Sc, and similar ideas have been expressed by others. It is the specific form and documentation of the process that is the contribution made here. The plausibility of this model could be countered by recognizing that divergence at cloud top is associated with updrafts and that this flow might transport drizzle, or incipient drizzle, away from the updraft. Resolution of these two notions depends on the steadiness of the updrafts, i.e. on the likelihood of persistent circulations throughout the boundary layer. For the current case, images from dual-Doppler analysis presented at http://www-das.uwyo.edu/~vali/dycoms/dy_rept/rf05_sixplot.pdf show that divergence is on fact found in some cases, but most updrafts, even some of stronger ones, while they push the cloud top higher, do not have clear divergence associated with them This is most likely a consequence of diminishing updraft velocities with height. So, it may be appropriate to think of the updrafts as pulses (of only moderate energy) which do not have longer lifetimes than a single rise to cloud top.

There are, of course, weaknesses in the data from which the foregoing construct was drawn. Worst of all, aircraft data provide snapshots of the cloud, from which the time evolution on the scales kilometers and tens of minutes cannot be evaluated. Neither can three-dimensional features be well observed. A more specific weakness, whose importance is well demonstrated by the analyses here given, is the lack of simultaneous data on cloud base (lidar seems the best tool of observation), radar data from the full cloud depth and in situ data from at least one level in the cloud. Such data sets can be generated with currently available tools. Further quantitation of the data here presented (such as the spectral characteristics of fluxes at the base of the cloud) and comparisons with chemistry data are yet to be performed. The analysis of similar cases (RF01) can also be expected to be helpful in refining or modifying the picture here discussed. Clearly, this is just a progress report.

Finally, a reminder: referring to this case as non-drizzling (in the title and elsewhere) is only an approximation.

7. References

Stevens, B. et al., 2003: Dynamics and chemistry of marine stratocumulus -- DYCOMS II. *Bull. Amer. Meteor. Soc.*, **84**, 579-593.

Vali, G. et al., 1998: Finescale structure and microphysics of coastal stratus. *J. Atmos. Sci.*, **55**, 3540-3564.

Acknowledgements: Much credit is due to the NCAR/ATD/RAF staff for the conduct of the DYCOMS field experiment and to JOSS for data management. Thanks to Drs. Lenschow and Stevens for organizing the field project and for many fruitful ideas, to D. Leon for data processing and refinement, and for helpful discussions, to S. Haimov for preparing and operating the radar. Dr. Bruce Morley (NCAR) is thanked for providing SABL data. Funding for this work was provided by NSF grant ATM-0094956 and by ONR.