NOTES AND CORRESPONDENCE

On Estimating the Entrainment Level in Cumulus Clouds

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ABSTRACT

The existence of small-scale inhomogeneities in cumulus clouds leads to a reinterpretation of the experimental data on total water mixing ratio Q and wet equivalent potential temperature θ_q. This reinterpretation indicates that the height of the level of entrained air may be sometimes overestimated.

1. Introduction

Paluch (1979) has proposed a method of determining the origin of entrained air in a cloud based on two parameters that are conserved with adiabatic altitude changes and that mix in a nearly linear manner. These parameters are the total water mixing ratio Q and the wet equivalent potential temperature θ_q; the latter is a measure of the specific entropy. The method is applicable only to cloud regions without significant amount of ice or drops of precipitation size.

The graphical method proposed by Paluch is as follows: Let us plot the environmental sounding (ES) in θ_q–Q coordinates and mark on the diagram the cloud base (CB) conditions (θ_{q1}, Q_1). If points (θ_{qs}, Q_s) of the sampled cloud air and (θ_{q1}, Q_1) determine the straight line (so-called mixing line), one can suspect that the in-cloud air is a mixture of the CB air and environmental air from only one level. This level is determined by the intersection of the mixing line with the ES curve.

Paluch's method is well known and widely used by many researchers (e.g., Reuter and Yau 1987; LaMontagne and Telford 1983; Jensen et al. 1985; Gardiner and Rogers 1987; Pontikis et al. 1987). Although from a theoretical point of view the method is simple and easy to use, its practical application creates some doubts. In particular, we object to the way the total water mixing ratio Q and wet-equivalent potential temperature θ_q are determined from experimental data.

2. Interpretation of the experimental data

In most cases instrumented aircraft are not equipped to measure directly the total water mixing ratio Q. For the purpose of Paluch's analysis, Q is usually calculated from the measurements of liquid water content (LWC) obtained from an FSSP or the Johnson–Williams probe, with the assumption that the measured sample of the cloud air is saturated. Additionally, the measured temperature T and LWC are averaged over 1 s intervals. That means that spatial resolution of measurements is 45–200 m depending on the aircraft speed. Thus, for a sample of the in-cloud air the estimated values of T, Q and θ_q are

$$T = T_a, \tag{1}$$

$$Q = q_{\mathrm{sat}}(T_a) + V_a, \tag{2}$$

$$\theta_q = \theta_q(T_a, Q), \tag{3}$$

where T_a is the temperature measured by an aircraft, averaged over a 1 s period, V_a the liquid water mixing ratio averaged over the same time interval, and θ_q the calculated wet equivalent potential temperature of air having temperature T_a and total water mixing ratio Q. The averaging implies the assumption that the air, sampled during each 1 s interval, is uniformly mixed although different samples may be mixed in different proportions. There is evidence, however, that mixed volumes in clouds are not uniform. For example, Austin et al. (1985) found regions of distinct variability in dynamic and microphysical properties both at cloud top and midlevels. The transition between different regions can take place in a few meters. Also Paluch and Baumgardner (1989), basing their argument on fine scale measurements, state that large changes in droplet concentration in mixed cloud volumes take place over distances of meters. Thus the assumption about the uniformity of the mixture is often incorrect and leads to errors in determining the values of Q and θ_q.

In order to prove our statement we will make some simple calculations. Let us assume that the sample of cloud air is a coarse grained mixture containing a mass fraction F of air from the cloud base (with parameters

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θ_{q1} and Q_1) and a mass fraction $(1 - F)$ of unsaturated air entrained into the cloud from outside (θ_{q2}, Q_2). We assume also that the mass fraction H of the sample is uniformly mixed (θ_{qh}, Q_h), retaining for sake of simplicity the same fraction F of the cloud base air. Varying this restriction complicates the reasoning and only slightly affects our final conclusions. In this case the parameters of a sample are as follows:

$$Q' = (1 - H)[FQ_1 + (1 - F)Q_2] + HQ_h, \quad (4)$$

$$\theta'_q = (1 - H)[F\theta_{q1} + (1 - F)\theta_{q2}] + H\theta_{qh}. \quad (5)$$

In such a sample the measured average temperature (1) is

$$T = (1 - H)[FT_1 + (1 - F)T_2] + HT_h, \quad (6)$$

while the value obtained from measurements of LWC the total water content Q is, in fact, calculated from the following formula

$$Q = (1 - H)[FV_1 + (1 - F)V_2] + HV_h + q_{\rm sat}(T), \quad (7)$$

where V_1, V_2 is the liquid water mixing ratio of the air at the CB and from outside, respectively (adiabatic values), V_h the liquid water mixing ratio of the uniformly mixed part of the sample, and $q_{\rm sat}(T)$ the saturation vapor mixing ratio at temperature T. It can be seen that formula (7) overestimates the total water mixing ratio because of the assumption of saturation, while for $H < 1$ a mass fraction $(1 - F)(1 - H)$ of air (Q_2, θ_{q2}) is not saturated. On the other hand, the nonlinearity in the expression for θ_q as a function of T and Q implies that θ'_q is not equal θ_q (except the case $H = 1$). The physical reason for this is that the phase transition of water in the process of homogenization changes the average temperature T of the sample.

3. Case study

As an illustration of this effect let us consider Fig. 1. The environmental sounding, cloud base conditions and mixing line are adopted from Jensen et al. 1985 (the only paper at our disposal containing sufficient data for analysis). Additionally, some calculated points (θ_q, Q) for different F and H for mixing from CB and the 585 mb level are plotted. All of these points (except the uniform case $H = 1$) are displaced to the right and upwards to the CB-585 mb mixing line. The displacement reaches its maximum for an extremely nonuniform mixture ($H = 0$). Because of this displacement, the new apparent mixing line determined by the CB and nonuniformly mixed samples differs from the previous one by being turned counterclockwise around the CB point. Let us, for instance, consider the case of a slightly nonuniform mixture ($H = 0.8$). In this case the mixing line determined by the CB and computed values (θ_q, Q) for $F = 0.7, 0.8, 0.9$ suggests entrainment from a level lying higher than 585 mb. This means that

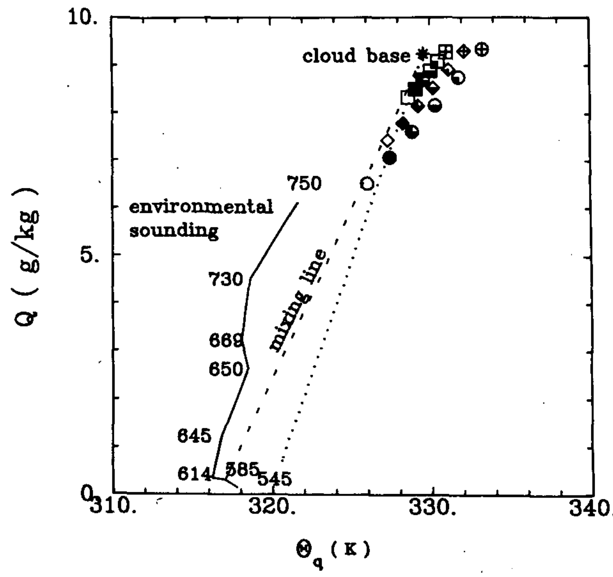

FIG. 1. Paluch diagram for 660 mb level. Environmental sounding (after Jensen et al. 1985) is labeled by its pressure levels in mb. The dashed line represents the mixing line between the cloud base and 585 mb level. Squares, diamonds and circles represent calculated (θ_q, Q) points for $F = 0.9$, 0.8 and 0.7 respectively and for different values of H in each group ($H = 1$ open marks, $H = 0.8$ filled marks, $H = 0.6$ three-quarters filled marks, $H = 0.4$ half-filled marks, $H = 0.2$ quarter filled marks, $H = 0$ marks with crosses inside). The points for $H = 0.8$ are marked by filled figures. They determine dotted line suggesting mixing from level higher than 585 mb.

ignoring even the slight nonuniformity of the cloud air may result in a considerable overestimation of the height of the entrainment level. On the other hand, such a slight nonuniformity may be sometimes difficult to detect even with 2 m resolution FSSP measurements; $F = 0.8$ and $H = 0.8$ means that over the 100-m long sampling distance only 4 m is droplet free. If this droplet-free region is not coherent it may be overlooked.

In Fig. 2 the experimental points taken from paper by Jensen et al. (1985) are supplemented with the computed points representing mixing of cloud base air and the air entrained from 650 and 669 mb levels in different proportions and with different nonuniformity. The computed points fall into the region of Jensen's experimental points and close to his CB-585 mb mixing line. So we suspect that some of Jensen's experimental points may represent nonuniform mixture of CB air with the environmental air lying close to the sampling level (660 mb) rather than uniform mixture of CB and 585 mb air.

Indirect arguments for our supposition about the errors in estimating Q and θ_q from experimental data may be found in Pontikis et al. (1987). In Fig. 3, reproduced from this paper, one can see that there are some sampled (θ_q, Q) points lying right and above CB point. Pontikis attributes this scatter of the experimental points to the natural variability of the atmosphere. Comparison of this figure with Fig. 1 suggests that ob-

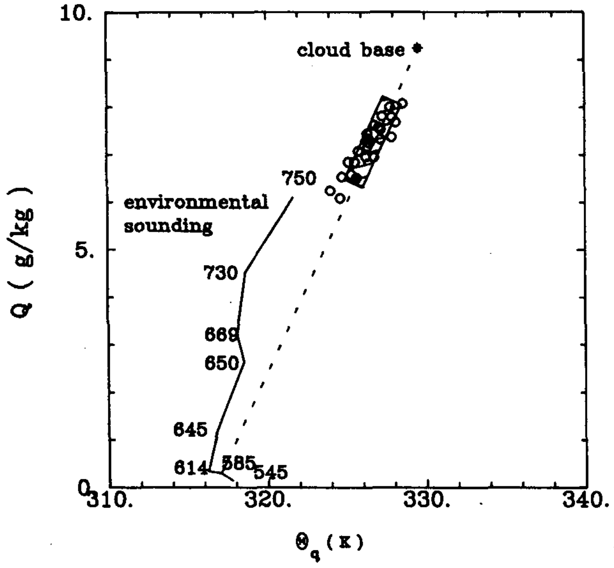

FIG. 2. The environmental sounding and mixing line are the same as the Fig. 1. Circles represent the calculated (θ_q, Q) points for mixing from 650 mb and 669 mb for different values F and H (F = 0.5, 0.6 and 0.7; for each F the values of H are equal to 0.4, 0.6, 0.8 or 1). The dashed figure covers the area of experimental values (θ_q, Q) obtained by Jensen et al. (1985).

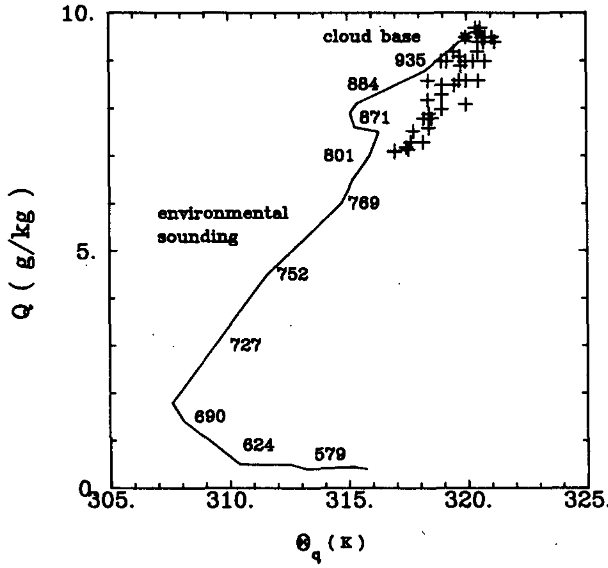

FIG. 3. Paluch diagram for 750 mb level after Pontikis et al. (1987). Note some (θ_q, Q) points left and above the cloud base point.

served scatter of Pontikis experimental points right to CB may partly be due to nonuniformity of the cloud structure.

4. Conclusions

The present argument leads to the conclusion that the Paluch analysis, in its typical form, may essentially overestimate the entrainment level. This results from small scale nonuniformities existing in mixed cloud volumes, which may cause overestimation of the total water mixing ratio Q and wet equivalent potential temperature θ_q and which may remain overlooked even with 50 Hz FSSP sampling. We think that it would be valuable to reinterpret the available experimental data, taking into account the possible consequences of the inhomogeneous mixing and verifying our theoretical speculations in this way. The new high resolution measurements of thermodynamic parameters of cumulus clouds, especially with direct determination of the total water mixing ratio Q (use of Coulman and Parker (1982) or similar instrumentation), should also be performed.

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