TURBULENT ENTRAINMENT AND MIXING IN CLOUDS

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Turbulent entrainment hypothesis, i.e. hypothesis that the mean inflow velocity into the turbulent fluid across the border separating turbulent fluid from non-turbulent environment is proportional to a certain characteristic velocity of the flow was introduced by G. I. Taylor in war times and published in 1956 by Morton, Taylor and Turner [1]. It was quickly adopted to various geophysical flows [2], in particularly applied to explain mixing between cumulus/stratocumulus clouds and their environments.

Entrainment into the vertically developing cumulus cloud was considered as entrainment from the environment into turbulent vortex ring, starting plume or even jet. Entrainment from above into the horizontally extending stratocumulus clouds, occupying the topmost part of convective atmospheric boundary layer and capped by a temperature inversion, was deliberated as mixing into the turbulent layer across a density interface.

By analogy to entrainment a "detrainment" concept was introduced in order to characterize moistened cloud volumes, resulting from mixing of saturated cloudy air with the unsaturated environment, left in the environment outside the cloud border. It was widely adopted and is used until now in the most popular parameterizations of convective processes in global models of atmospheric flows [3].

An implicit, rarely expressed assumption behind the adoption of entrainment hypothesis to cloud processes was that the cloud-clear air interface, separating saturated cloud volumes containing small droplets or ice crystals from the unsaturated environment, coincide with the interface separating turbulent cloud interior from non-turbulent environment. There is, however, a wide experimental evidence that in prevailing number of cases this assumption is wrong.

To a large extent dynamics of multiscale cloud flows is governed by buoyancy variations resulting from phase changes of water. Latent heat release due to condensation in an organized updraft feeds growth of convective clouds, while evaporative cooling at the cloud edges in the course of mixing with the unsaturated environment produces negative buoyancy. In effect, cumulus cloud is protected from direct interaction with dry non-turbulent environment by a moist, subsiding turbulent shell. Elements (volumes, parcels) of this shell, evolving in the course of mixing process may reach level of zero buoyancy and stay there. This, in fact is the mechanism of detrainment, specific for convective clouds and rarely mentioned in a different context.

Also description of entrainment into stratocumulus in terms of generic mixing across a density interface with turbulent fluid below and non turbulent above, fails to explain the observed cloud top structure. Measurements show, that inversion layer is turbulent. Despite the high static stability it is dynamically destabilized by the shear related either to a large scale atmospheric flow or to circulations in the upper parts of convective cells. This turbulence controls mixing across the turbulent inversion, while effects of mixing depend on thermodynamic properties of the cloud and the environment. In a case of dry warm air above the inversion and sufficient liquid water content of the cloud, mixing produces parcels which are negatively buoyant and sink down into the boundary layer. This effect, named cloud top entrainment instability [4, 5], removes mixed air from the cloud top region and enhances convective circulations in the boundary layer. In a case of moist air above the inversion and/or insufficient water content of the cloud, evaporative cooling is weak and negatively buoyant parcels cannot be formed. This effects in a buildup of a moistened layer at the cloud top.

The above examples show that a straightforward adoption of the entrainment concept to explain mixing of clouds with their environments is not enough. A more sophisticated approach, addressing details of mixing process, properly specifying interface across which entrainment occurs, accounting for dynamic effects of phase changes, is necessary to describe cloud-environment interactions. A selection of experimental and numerical results, illustrating recent progress in understanding these processes will be presented in the course of the talk.

References

[1] B. R. Morton, G. I. Taylor, J.S. Turner, *proc. R. Soc. Lond. A* **234**: 1–23, 1956.
[2] J. S. Turner *J. Fluid. Mech.* **173**: 431–471, 1986.
[3] W. C. de Rooy, P. Bechtold, K. Frohlich, C. Hohenegger, H. Jonker, D. Mironov, A. P. Siebesma, J. Teixeira, J-I. Yano, Entrainment and detrainment in cumulus convection: an overview. *Q. J. R. Meteorol. Soc.*, DOI:10.1002/qj.1959, 2013.
[4] J. W. DeardorïňĂ, Cloud top entrainment instability, *J. Atmos. Sci* **37** 131–147, 1980.
[5] D. A. Randall, Conditional instability of the ïňĄrst kind Upside-Down,*J. Atmos. Sci* **37** 125–130, 1980.