A close look at the cumulus-valve mechanism and its potential implications for cloud-base cloudiness

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(1) Motivation and background

In many GCMs, the trade-cumulus cloud feedback is driven by changes in the cloud fraction at cloud base (C). Using LES and observations, we aim at better understanding the sensitivity of C to changes in convective mixing and the environment.

The cumulus-valve mechanism holds that the convective mass flux M acts like a valve, which maintains the sub-cloud layer top h close to the lifting condensation level LCL [1,2]. M may thus limit variations in humidity and cloudiness at h [2,3]. Defining $M=a_{co} \cdot w_{co}^*$, and assuming that the increase in M needed to relax h to the LCL is driven by a_{co}, the mechanism could also explain a larger C with increasing M—opposite to what many GCMs do [4,5].

*where a_{co} and w_{co} are the cloud-core area fraction and vertical velocity

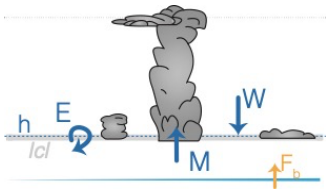
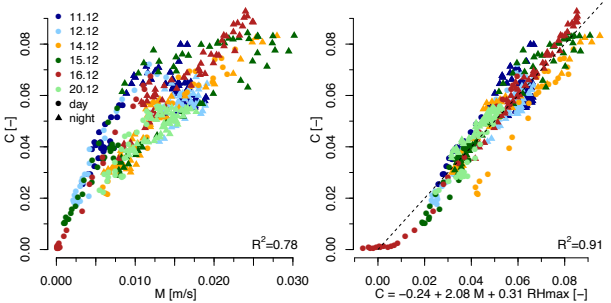


Illustration of mass budget and valve mechanism, with h, M, entrainment rate E, large-scale vertical velocity W, as well as the LCL and surface-buoyancy flux F_b

(2) Relationship of cloud-base mass flux and cloud fraction

Does C increase with M in realistic ICON-LEM simulations? Mostly yes! The maximum relative humidity at the mixed-layer top RH_{max} is an important additional control of C. During nighttime, increases in M often go along with decreases in RH_{max}, limiting C increases.

So what sets M and RH_{max}, and what controls their interaction?

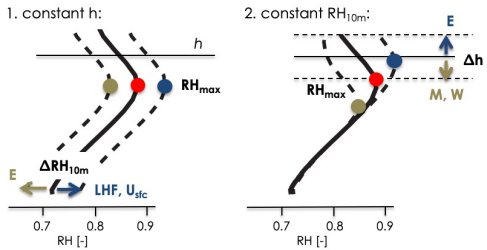


Relationships in ICON-LEM. 150m resolution, averaged over a 1°x2° box near Barbados for 6 days in Dec 2013

(3) M set by mass budget

Previous analyses of the mass budget indicate that an equilibrium estimate $M_{mb}=E+W$ captures well the magnitude and variability of $M=a_{co} \cdot w_{co}$ [6].

(4) What controls RH_{max}?

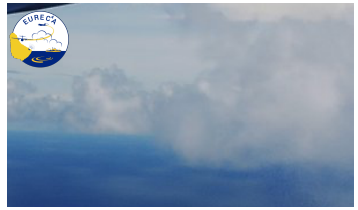


Schematic of the sub-cloud layer RH structure with its governing processes

Assuming near well-mixedness, RH_{max} can be changed by (1) the surface RH and (2) the layer depth h.

E has a ↓ (entraining dry and warm air) and an ↑ (deepening h) effect on RH_{max}. Interestingly, the latter tends to win both in a simple mixed-layer model and in the ICON-LEM simulations, resulting in a net positive effect of E on RH_{max}. Adjusting h in response to a change in M is thus crucial to capture the dynamics.

(5) Conclusions



View from the French ATR aircraft flying at cloud base

In summary:

- C closely linked to M, but also RH_{max}
- M set by E and W
- RH_{max} depends strongly on h

How C depends on the environment, and the role of M and h variations in this dependence can soon be tested with EUREC^{4}A observations.

References: [1] Betts 1976 | [2] Neggers et al. 2006 | [3] Nuijens et al. 2015 | [4] Sherwood et al. 2014| [5] Vial et al. 2016 | [6] Vogel, Bony, Stevens 2020