Nature versus nurture in shallow convection

David M. Romps and Zhiming Kuang (Harvard University)

Nature or nurture?

Clouds are highly heterogeneous in their thermodynamic properties. For shallow, non-precipitating trade cumuli, this can be illustrated by scatterplotting air parcels from some height in the cloud layer – here, 1275 meters – on axes of total water, q_t, and liquid-water potential temperature, θ_l.

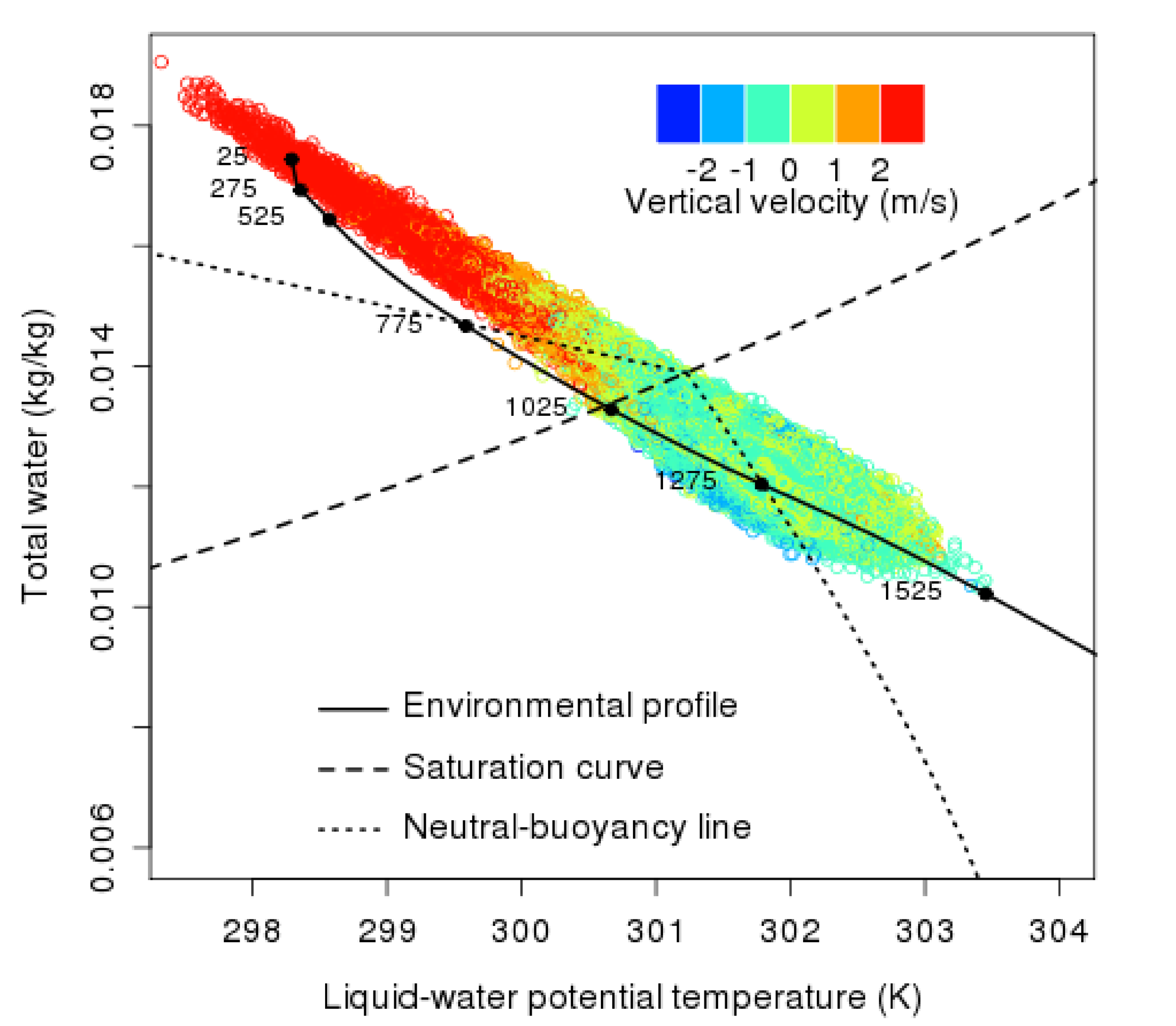


Figure 1: For air parcels at 1275 meters, a scatterplot of total water, q_t, versus liquid-water potential temperature, θ_l.

The points above the saturation curve are the cloudy air parcels. Note they form a long streak – a Paluch tail – that extends over a large range of q_t and θ_l. What is the source of this variability?

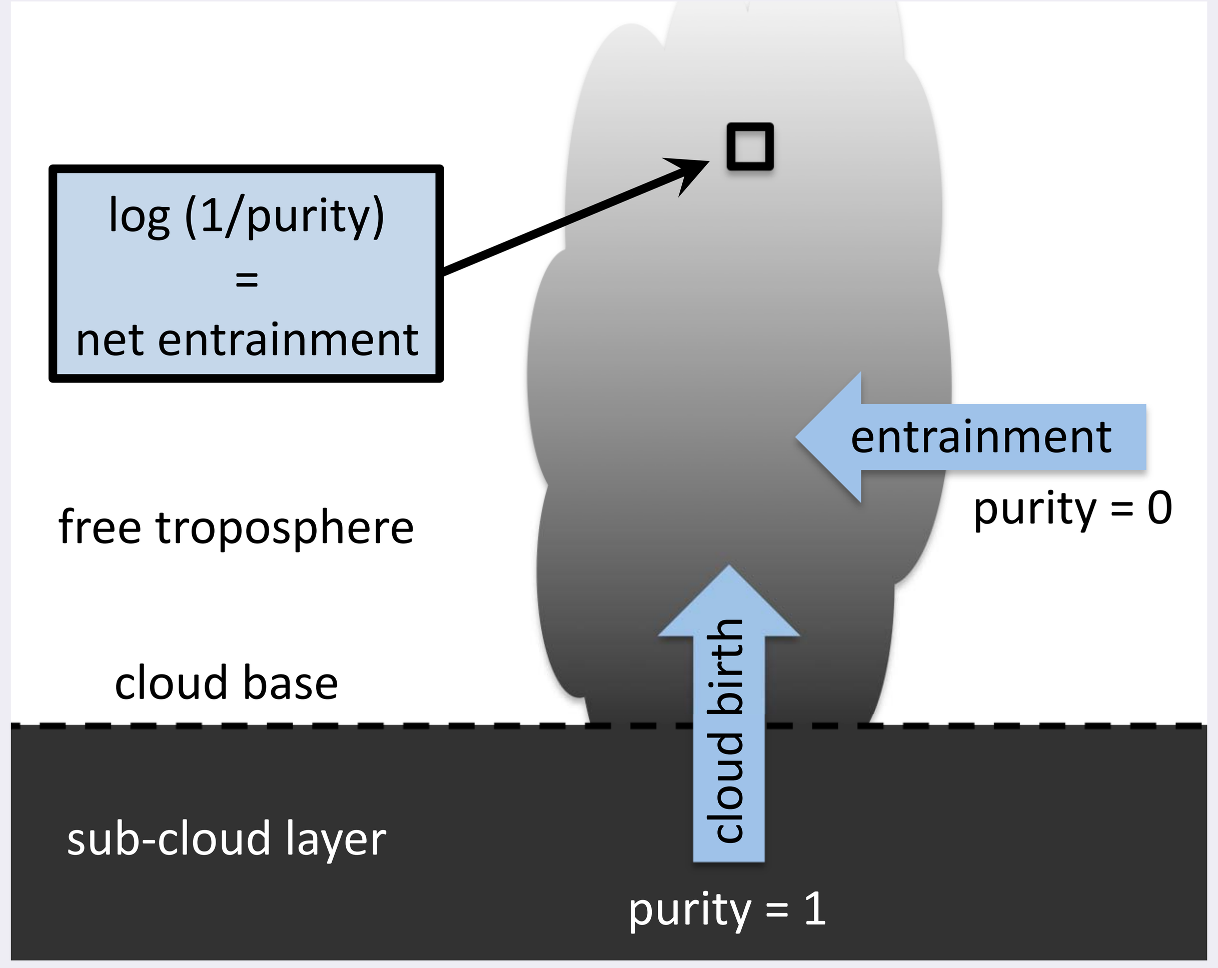
There are two possible sources of variability: variability among cloudy parcels as they are born at the cloud base (nature), or variability introduced by stochastic entrainment during a parcel's lifetime (nurture).

Model

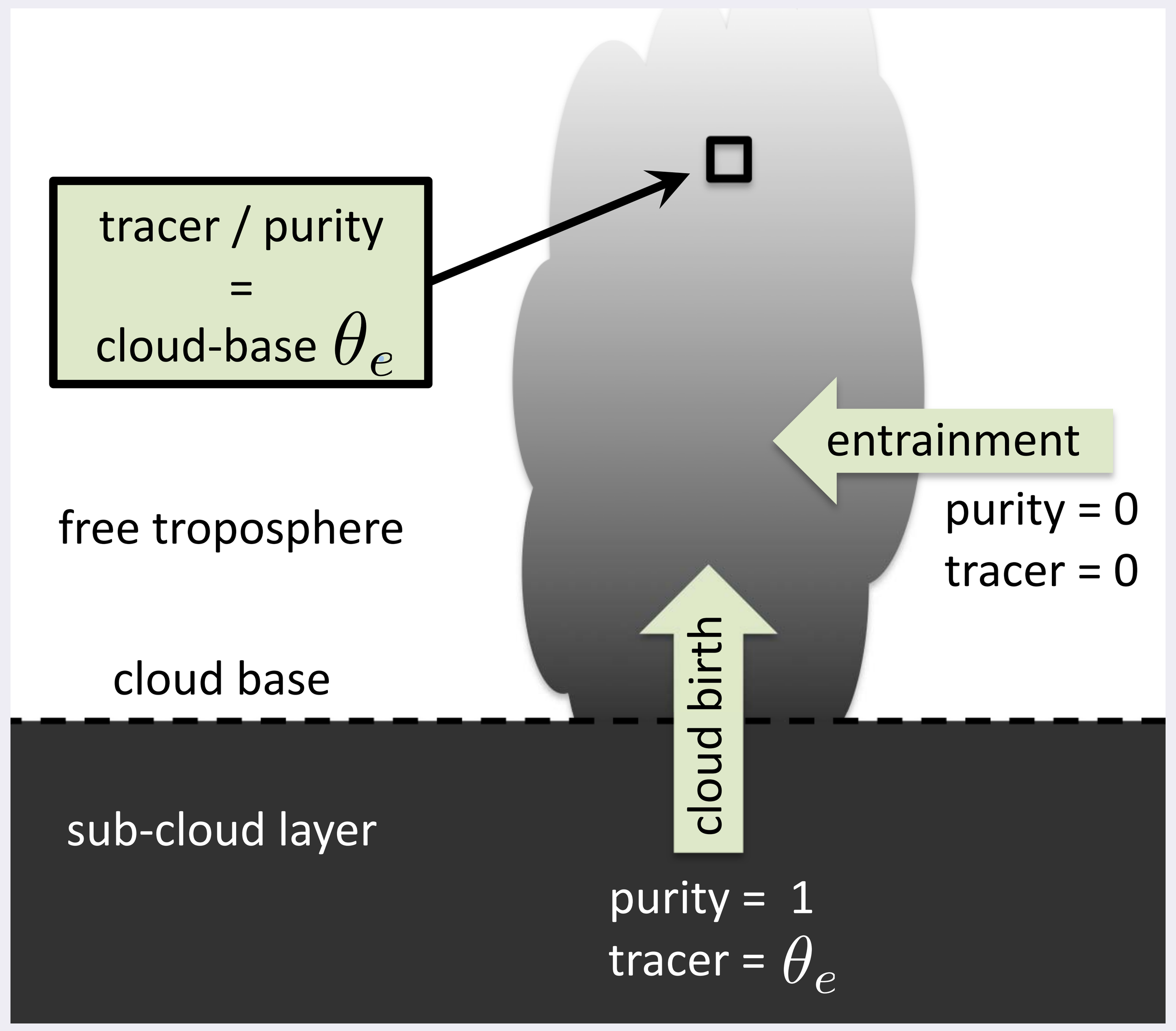
The results presented here are from a large-eddy simulation of non-precipitating trade cumuli under the conditions observed during BOMEX (Siebesma et al., 2003) and simulated using a 50-meter grid spacing with Das Atmosphärische Modell (DAM; Romps, 2008). For more details, see Romps and Kuang (2009b).

Tracers

We can keep track of the net fractional entrainment by using a "purity tracer." The purity tracer is set to 1 below the cloud base and 0 above. Clouds born at the cloud base have a purity mixing ratio of 1 kg/kg, but they entrain air with a mixing ratio of 0 kg/kg. For any cloudy parcel, the log of one over purity is equal to the net fractional entrainment.



With an additional "theta-e tracer" – set to θ_e below the cloud base and 0 above – we can encode the cloud-base value of θ_e in the cloudy parcels. Since entrainment dilutes the two tracers by the same fraction, their ratios are unchanged. Therefore, the ratio of the two tracers is equal to the parcel's cloud-base θ_e.



The answer is nurture

Armed with these tracers, we can now assess whether the cloud-base variability is the source of the variability at 1275 meters. For example, using a "w tracer" and a "theta-e tracer," we can calculate the correlation between a parcel's buoyancy at 1275 meters and the w and θ_e that the parcel had when it was born at the cloud base. We see from Figure 2 that there is no correlation.

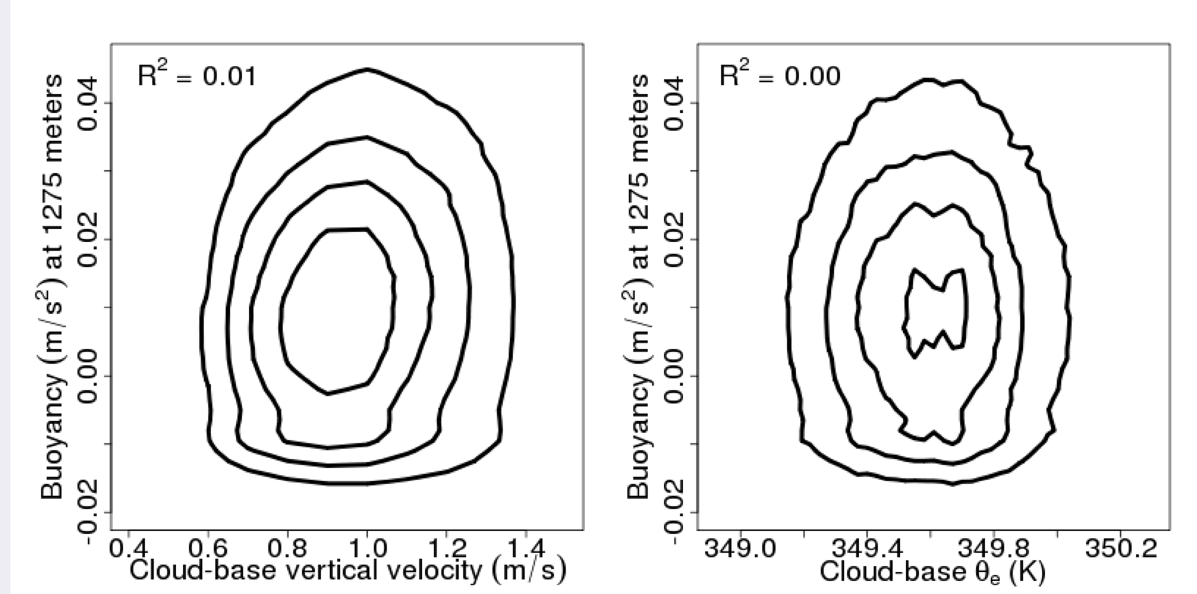


Figure 2: For cloudy parcels, a scatterplot of 1275-meter buoyancy versus cloud-base w (left) and cloud-base θ_e (right).

The only other possible source of the variability is from stochastic entrainment events. To check this, we can calculate the correlation between the buoyancy of parcels and their net entrainment. As shown in Figure 3, the variance in parcel purity explains 90% of the variance in buoyancy.

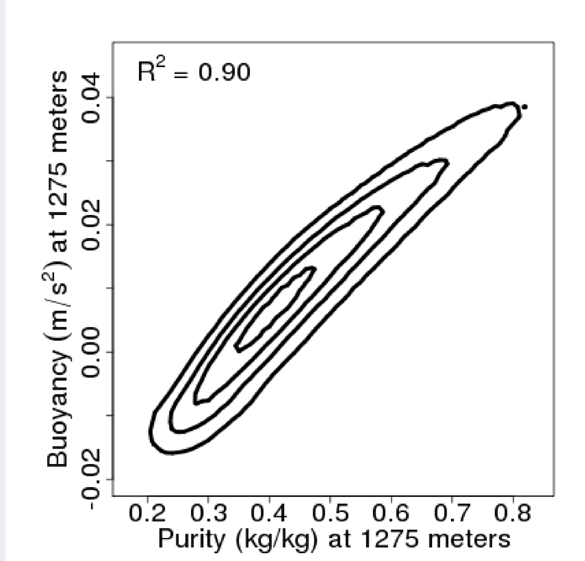


Figure 3: For cloudy parcels at 1275 meters, a scatterplot of buoyancy versus purity.

Stochastic parcel model

One way to illustrate the relative importance of cloud-base variability and entrainment variability is to use a parcel model. We use the parcel model described by Romps and Kuang (2009a), which consists of the ODE's that govern a spherical bubble's height, $z(t)$, vertical velocity, $w(t)$, volume, $V(t)$, etc.

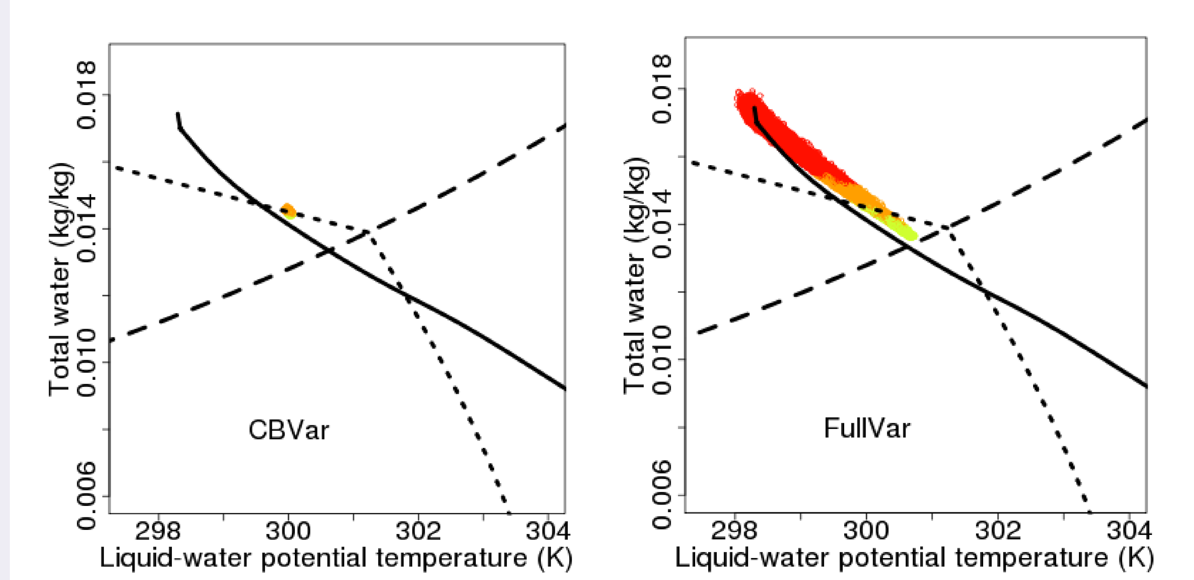


Figure 4: The 1275-meter Paluch diagram for the parcel model initialized with cloud-base variability and using constant entrainment (left) or stochastic entrainment (right).

In the left panel of Figure 4, we initialize the parcel model with four-million initial conditions as observed at the cloud base in the LES, but use a constant entrainment rate. This does not produce the Paluch tail seen in Figure 1.

On the right, we use the four-million different initial conditions and we subject the parcel to discrete entrainment events modeled as a Poisson process. This closely resembles the Paluch tail in Figure 1.

This success suggests that the stochastic parcel model could serve as a foundation for future convective parameterizations.

References

Romps, D. M., 2008: The dry-entropy budget of a moist atmosphere. *Journal of the Atmospheric Sciences*, **65 (12)**, 3779–3799.

Romps, D. M. and Z. Kuang, 2009a: Do undiluted convective plumes exist in the upper tropical troposphere? *Journal of the Atmospheric Sciences*, **in press**.

Romps, D. M. and Z. Kuang, 2009b: Nature versus nurture in shallow convection. *Journal of the Atmospheric Sciences*, **in press**.

Siebesma, A., et al., 2003: A large eddy simulation intercomparison study of shallow cumulus convection. *Journal of the Atmospheric Sciences*, **60 (10)**, 1201–1219.