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Interactive comment on "Transport and chemical transformations influenced by shallow cumulus over land" *by* J. Vilà-Guerau de Arellano et al.

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Response to the interactive comment on "Transport and chemical transformations influenced by shallow cumulus over land" (anonymous referee #1)

8813 line 9 What is meant by 'shallow cumulus clouds usually form in the same meteorological situations that favour the accumulation of pollutants in the ABL.

Poor air quality events are frequently associated with benign weather and weak synoptic forcing, which are conditions favorable to the formation of shallow cumulus over land. In the manuscript, we have clarified this sentence to the following: "Shallow cumulus clouds generally form in synoptically high pressure regions which are conducive to the formation and accumulation of both passive and photochemically generated pollutants in the boundary layer because of the low wind speeds, the intensification of capping inversions, and high insolation."

8813 line 21 Is the argument here simply that concentrations are higher above the boundary layer due to cumulus transport, and hence lower in the BL?

The sentence reports that previous studies have found that the sub-cloud layer has less pollutant when shallow cumuli are present than when they are not present. The previous studies attributed the lower pollutant concentrations below cloud to enhanced vertical transport due to the presence of cumulus clouds. The effects of the shallow cumulus on pollutant concentration are discussed further in the results of our paper. To clarify, we have modified the sentence to: "Ě leads to a reduction of the pollutants in the sub-cloud layer due to enhanced vertical transport by cumulus clouds."

8815 line 16. Presumably there is at least some diurnal cycle in the friction velocity (larger with strong turbulent mixing in the afternoon that it is in the early morning)?

The referee is right. The friction velocity follows a diurnal cycle with maximum values in the afternoon. However, the variation between the maximum value (0.54 m/s) and the minimum value (0.45 m/s) is not very strong. We are now more precise in our explanation: "The friction velocity follows a weak diurnal cycle with a maximum value of 0.54 m/s and a minimum value of 0.45 m/s."

8820 line 7. Presumably the results are not extremely close to those of Brown et al (fig5) as the present simulations used the slightly more unstable profile designed to give more rapid cloud top growth.

The cloud top height presented in Figure 5 of this manuscript is similar to that presented in Figure 10b of Brown et al. (2002). The Brown et al. paper also displays cloud base height and cloud fraction in their Figure 5. In our paper, we have modified the text to associate our Figure 5 with Figure 5 from Brown et al. and included the phrase that our results are somewhat different because of the weaker inversion used. We also ran

ACPD

5, S3526–S3530, 2005

Interactive Comment

cases under identical conditions to that of the standard Brown et al. case with quite good agreement but only present the case with enhanced cloudiness.

8820 line 21. As the surface buoyancy flux is fixed, and the subcloud layer buoyancy flux profiles are presumably linear, does this imply a different cloud base buoyancy flux in the two models?

Yes, despite the fact that both codes use the same sub-grid scale model and vertical advection scheme for the scalar, the NCAR model gives slightly higher flux values in the upper part of the sub-cloud layer compared with the WUR model. This is particularly the case in the early stages of the simulation (see figure 7 at 14.30 LT). We speculate this difference results from the fact that the NCAR code is pseudo-spectral in the horizontal and the WUR code is finite difference in all three directions which means that the NCAR code uses an explicit wave-cutoff filter to remove the top one-third wave numbers while the WUR code employs an implicit grid-scale filter.

8825 eq. (11) and following text. It was unclear to me what this quantity is really telling us (and specifically why it gives an indication of buoyancy driven transport). I also did not feel that enough details have been given of the cloudy simulation (how steady, what levels are cloudy, what the cloud cover is etc etc) to make the comparison with simulation particularly enlightening.

An important aspect of the paper is the quantification of the vertical transport of reactants associated to the presence of clouds. The divergence of the vertical turbulent flux is the most appropriate term in the conservation equation of reactive species to estimate the vertical transport. Since the flux at cloud top is almost zero (see figure 7), the most relevant contribution for the flux divergence is the flux at the cloud base. We now include the following statement to clarify this point. “The horizontally-averaged vertical flux divergence integrated from cloud base to cloud top quantifies the net transport of species from the sub-cloud layer to the cloud layer.”

We have provided more information on the LES simulation that produces larger cloud

ACPD
5, S3526–S3530, 2005

Interactive Comment

EGU

cover. Essentially the initial specific humidity vertical profile was increased to produce more cloud. This resulted in a cloud fraction $>$ 0.5 for the time period between 14 and 16 LT.

8826 line 12 Is the zi the depth of the subcloud layer (which I believe would be conventional) or the depth to the top of the Cu (called h, but also referred to as boundary layer depth elsewhere).

In the definition of the Damköhler number, zi is a boundary layer height whose definition depends on local clear or cloudy conditions. Following Sullivan et al (1998), under dry conditions zi is defined as the maximum of the gradient potential temperature and under cloudy boundary conditions by the maximum of the liquid water potential temperature. The latter definition is similar to the cloud top height defined as the highest level where the liquid water exists. We have modified the text to clarify the definition of zi used here to the following: "... and zi is found by the local gradient method (Sullivan et al., 1998), which determines the local inversion height based on the maximum of the liquid water potential temperature gradient."

The referee raises an interesting point in the discussion that it is relevant to atmospheric studies: what is the definition of the boundary layer depth in the presence of shallow cumulus clouds and is this definition representative of the whole ABL? Is the cloud layer considered to be within the PBL? Moeng et al. (JAS, 2005) recently evaluated three different methods to obtain zi for a stratocumulus-topped boundary layer; 1) the height of cloud top, 2) the local gradient method of Sullivan et al. (1998), and 3) the height at which turbulent mixing completely ceases. Moeng et al (2005) suggested that the air between cloud-top and the height of the maximum gradient in liquid water potentail temperature is still turbulent due to intermittent penetration of the cloud up to the height of the maximum liquid water potential temperature gradient and therefore the region below the maximum liquid water potential temperature gradient should be considered to be within the PBL. They also found that although there is still limited mixing that occurs above the maximum liquid water potential temperature gradient, this mixing is not induced by the cloud but instead is likely a result of enhanced velocity shear. How these different definitions of zi apply to the shallow cumulus boundary layer should be a topic of further study.

Interactive comment on Atmos. Chem. Phys. Discuss., 5, 8811, 2005.