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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Coupled vs. decoupled boundary layers in VOCALS-REx" *by* C. R. Jones et al.

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We thank both referees for their thoughtful and helpful comments. The manuscript has been edited to reflect these contributions. In addition to the revisions made to the submitted manuscript, we will now address the points raised by the referees in this response.

Response to Anonymous Referee #1

1. Moisture was chosen initially for its simplicity and because it provides a clear measure of decoupling. There were a number of profiles that were clearly decoupled based on the mixing ratio, but for which the jump in θ_ℓ was insignificant.

This goes both ways, however, and it should be noted that classifying decoupling based solely on either the θ_ℓ or q_T profile introduces some uncertainty into the classification scheme.

At the risk of being too restrictive for the well-mixed classification, we have redefined our profile-based decoupling metric to require both $\Delta q_T < 0.5$ g kg^{-1} and $\Delta\theta_\ell < 0.5$ K. This has the advantage of ensuring that a well-mixed profile is well-mixed in both temperature and moisture. This change does not significantly alter the results of this study.

Averaged profiles for varying degrees of decoupling based on Δq_T have also been added to the revised manuscript, as requested.

2. Including the second term in Eq. (4) can yield a better approximation in Eq. (5). Eq. (4) can be rewritten as:

$$\Delta q \approx -\left(\frac{dq^*}{dz}\right)_{\mathsf{da}} (z_b - z_{\mathsf{LCL}}) - \left(\frac{\partial q^*}{\partial T}\right)_{\mathsf{LCL}} (\theta_\ell(z_b) - \theta_\ell(z_{\mathsf{LCL}})),$$

which, upon using $\theta_\ell(z_{\mathsf{LCL}}) \approx \theta_\ell(z_{\mathsf{SC}})$ and rearranging yields

$$\Delta z_b \approx \frac{1}{-(dq^*/dz)_{\mathsf{da}}} \left(\Delta q + \left(\frac{\partial q^*}{\partial T}\right)_{\mathsf{LCL}} \Delta\theta_\ell\right). \tag{1}$$

At a characteristic boundary-layer pressure of 950 hPa, temperature of 285 K, and $\Delta\theta_\ell/\Delta q = 1$ K/(g/kg) as argued by our new profile well-mixed criteria, Eq. (1) suggests that $\Delta q = 0.5$g kg^{-1} corresponds to $\Delta z_b \approx 166$ m. This is higher than the threshold of 125 m that we had previously used. The manuscript will be updated with this improved estimate. Specifically, bearing in mind the accuracy of the approximations made and the measurement uncertainty, we now identify a subcloud leg as well-mixed if $\Delta z_b < 150$ m and decoupled otherwise. It should

be noted that this new threshold has no noticeable impact on the results or conclusions of this study. Only three additional subcloud legs were re-classified as well-mixed.

Also, in response to the comment about no local buoyancy source below cloud base, the text on page 8440, lines 20-26 will be amended to read:

> The thicker cloud layer generates more entrainment to drive downward subcloud buoyancy fluxes that will decouple the boundary layer. The reason the thicker cloud generates more entrainment is that entrainment is driven by in-cloud turbulence, whose primary source is buoyancy flux integrated over the depth of the turbulent layer. The turbulent buoyancy fluxes are large within the cloud layer because the moist updrafts have more liquid water, whose condensation released more latent heat, than in the downdrafts. Below the cloud base, latent heating does not add to the buoyancy flux, which can therefore be small or even negative (with strong enough entrainment of warm above-inversion air). Thus, the turbulence is driven by the in-cloud contribution to vertically integrated buoyancy flux, which increases in proportion to cloud depth.

3. The argument given in Bretherton and Wyant (1997) has the following physical basis: More latent heat flux = stronger in-cloud buoyancy flux = more turbulence and more entrainment for a given cloud base, cloud top and inversion strength. We think this is adequately discussed in the Introduction on page 8434.

   The reviewer is correct that the increased entrainment will also cause the PBL to slowly deepen, which can feed back on the buoyancy flux profile and further favor decoupling. However, the decoupling criterion is diagnostic; it applies to the instantaneous vertical structure of the PBL before it undergoes this slow evolution.

4. The left-most panel in Fig. 11 only contains contributions from profiles with adjacent subcloud legs. This is required since the κ measurement is based on the

   profiles while the cloud fraction measurement comes from the subcloud legs. The middle panel is based entirely on profile measurements, so this restriction need not be imposed. Hence it contains more points. This has been clarified further in the text.

   As per the recommendations of both referees, Fig. 11 has been modified to identify well-mixed, decoupled, and POC profiles using the same scheme as in Fig. 8. It now shows much more clearly the relationship between κ, cloud fraction, and decoupling. Furthermore, the right panel has been removed as it contains information already available in the other two panels.

5. The identified relationship between Δz_M and decoupling is important and appealing because it is concise, robust, and qualitatively consistent with prior theoretical arguments. It suggests that at least within the VOCALS region, boundary layer deepening is the principal control on decoupling even though other mechanisms may contribute. It also supports the use of bulk mixing-line models of boundary-layer structure such as Park et al. (2004, J. Atmos. Sci.) which divide the boundary layer into a well mixed layer extending up to cloud base and a cloud layer in which the gradients of q_t and θ_ℓ depend on the cloud layer thickness Δz_M (although they assume a power-law relationship between the gradients and Δz_M rather than using no gradient up to a Δz_M threshold, which is what our study would suggest is appropriate).

Response to Anonymous Referee #2

1. We have added the following definition of θ_ℓ to the manuscript:

   > ...liquid potential temperature θ_ℓ, approximated as
   >
   > $$\theta_\ell \approx \theta - \frac{L}{c_p} q_\ell,$$

. . . .

2. We have clarified this:

   > The subscript "da" indicates a dry-adiabatic and hydrostatic displacement from the LCL.

   Since we assume the subcloud layer is well-mixed below the LCL, the subscript "da" can also indicate dry adiabatic and hydrostatic displacement from z_{SC}. In response to the comments of both referees regarding this argument, we have expanded the discussion and revised the argument to include $\Delta\theta_\ell$.

3. Equation (22) from Bretherton and Wyant (1997), on which our analysis is based, does not make assumptions about the amplitude of boundary layer radiative flux divergence ΔF_R. However, it does make a steady-state assumption that is inaccurate for the VOCALS cases, both due to the diurnal cycle of ΔF_R and due to horizontal advection, etc. These effects, in addition to the effect of precipitation already mentioned in the text, are important caveats preventing quantitative comparison of the Bretherton and Wyant (1997) model with the VOCALS observations, as is now mentioned in the revision.

4. Indeed, κ is highly dependent upon the identified inversion base and top, so presenting a range of values is more appropriate. The figure has been updated with nominal error bars for each κ, determined by taking the maximum and minimum values of κ that would have been calculated if the inversion base and top were allowed to vary through a range of ± 20 m.

5. Well-mixed and decoupled profiles are now both represented in Fig. 11 using the same color scheme as in Fig. 8. It appears that the set of profiles associated with low cloud fraction is predominantly decoupled, supporting the conjecture made in Lock (2009). However, there are a significant number of decoupled profiles

   with nearly 100% cloud cover for κ up to 0.5, so this measurement does not conclusively verify this claim.

Interactive comment on Atmos. Chem. Phys. Discuss., 11, 8431, 2011.