

Second Response to Reviewers: Dry and moist convective upper bounds for near-surface temperatures

Reviewer 2

The authors have done a good job responding to my earlier comments. I like the paper a lot and think it makes a nice contribution to the literature. I have listed two minor points below. Addressing them will further strengthen the paper, which I look forward to seeing published.

We are delighted to hear that the reviewer was mostly satisfied with the changes we brought. We learned a lot about land-atmosphere coupling studies in the process and thank you for that.

1. In my prior review, I asked that the authors better review and acknowledge work on “bottom up” approaches that already exist in the literature. The authors write in their response that: “... the vast majority of these studies look at the processes that grow the PBL, and not those that can arrest its growth.” This is true, to some extent, but there is still lots of work looking at processes that arrest the growth of the PBL – specifically, the process in which boundary layer growth is halted on hitting the lifting condensation level. The authors have included citations to Ek and Holtslag (2004), and to Gentine et al. (2013b) around line 285; but there are many, many other papers that examine this case, which should be cited, too (including, but not limited to, Juang et al. 2007a,b; Siqueira et al. 2009; Konings et al. 2010; Manoli et al. 2016; de Arellano et al. 2012; de Arellano 2007; Zhu and Albrecht, 2002; van Heerwaarden et al. 2009). Because there is already a large literature that looks at the case in which boundary layer growth is halted by reaching the LCL, the authors should note this and might instead want to emphasize possible other limits to PBL growth that may be of interest in future work.

We thank the reviewer for pointing us to these studies, **which we have cited in the revised version**. With this wealth of studies, it is now clear to the reader that the subject was covered in prior literature in great detail.

We discuss another pathway through which boundary layer growth could be halted, perhaps in a column too dry to support cloud formation. That framework is essentially that of Manabe and Strickler (1964, their fig. 4) in which dry convective heating is balanced in equilibrium by tropospheric radiative cooling – in that framework, boundary layer growth stops because the troposphere becomes warm enough that radiative cooling can balance the convergence of the upward flux of heat due to dry convection in the deep boundary layer. We believe that a further ingredient needed to allow for hot surface temperatures in such a framework is free-tropospheric subsidence warming. This is a very speculative and idealized situation (in which many processes, e.g. horizontal heat advection, are neglected), but we believe it may provide a relevant theoretical limit.

We have emphasized this limit set by a radiative–dry-convective–subsidence equilibrium a little more in the revised version, and have also cited the lifetime of weather systems supporting the growth of very deep PBLs in dry environments as a potential other limit. **These edits feature I. 276–285 of the revised manuscript.**

2. Along similar lines, the authors note one aspect of their work that is distinct from prior “bottom up” literature that uses bulk mixed layer models: “We believe that little focus has been placed on superadiabatic layer strength in the context of heatwaves. Many studies using a bulk model of the convective boundary layer do not include a superadiabatic layer...” This is incorrect – these zero-order bulk models represent the superadiabatic layer by a temperature discontinuity between the land surface and the atmosphere. While somewhat crude, a discontinuity in the temperature profile is certainly superadiabatic! I bring this up because I still think the superadiabatic layer is being a little unduly emphasized in the abstract and elsewhere. The superadiabatic layer exists because the coupled system dictates that there must be a sensible heat flux, which is proportional to the superadiabatic layer lapse rate (to a first approximation), and the magnitude of that flux is strongly dictated by land surface controls. I’d like to see it noted in the manuscript that zero-order bulk mixed layer models coupled to a land surface do, in fact, include a superadiabatic layer, so that the novice reader does not unduly dismiss the nice work that already exists in this field.

We apologize for this oversight. We note that the manuscript did not state that studies using bulk CBL models did not contain a superadiabatic layer (this statement was only in the response to reviewers), and instead emphasized on l.300 that “*Controls on surface sensible heat fluxes during heatwaves are relatively well understood thanks to land-atmosphere coupling studies (see Section 5.1.1), suggesting a promising way forward to constrain $\Delta\theta_{SA}$.*” Nevertheless, **we have modified the beginning of section 5.1.2 (l. 291–296) to clearly state that the superadiabatic layer is no new discovery and is always represented in land-atmosphere coupling studies, including in bulk CBL models. We have also clarified that section 5.1.2 presents review material rather than new results. Finally, we have slightly modified the abstract (l. 10–12) to put forward deep PBLs, rather than superadiabaticity, as the main control on the exceedance of the dry adiabatic bound.**

The focus we placed on the superadiabatic layer is largely influenced by our initial ignorance: before this study, we were not aware that this layer could be as large as several K, especially when measured from the 2-m level (as opposed to the skin temperature). However, we believe that many in the large-scale dynamics community may not be aware of this fact either, and we think that this paper is a good opportunity to bring the topic forward.

Reviewer References

Arellano, J.V.-G. de, 2007. Role of nocturnal turbulence and advection in the formation of shallow cumulus over land. <https://doi.org/10.1002/qj.138>

de Arellano, J.V.-G., van Heerwaarden, C.C., Lelieveld, J., 2012. Modelled suppression of boundary-layer clouds by plants in a CO₂-rich atmosphere. *Nature Geosci* 5, 701–704. <https://doi.org/10.1038/ngeo1554>

Juang, J.-Y., Porporato, A., Stoy, P.C., Siqueira, M.S., Oishi, A.C., Detto, M., Kim, H.-S., Katul, G.G., 2007a. Hydrologic and atmospheric controls on initiation of convective precipitation events. *Water Resources Research* 43. <https://doi.org/10.1029/2006WR004954>

Juang, J.-Y., Katul, G.G., Porporato, A., Stoy, P.C., Siqueira, M.S., Detto, M., Kim, H.-S., Oren, R., 2007b. Eco-hydrological controls on summertime convective rainfall triggers. *Global Change Biology* 13, 887–896. <https://doi.org/10.1111/j.1365-2486.2007.01315.x>

Konings, A.G., Katul, G.G., Porporato, A., 2010. The rainfall-no rainfall transition in a coupled land-convective atmosphere system. *Geophysical Research Letters* 37. <https://doi.org/10.1029/2010GL043967>

Manoli, G., Domec, J.-C., Novick, K., Oishi, A.C., Noormets, A., Marani, M., Katul, G., 2016. Soil-plant-atmosphere conditions regulating convective cloud formation above southeastern US pine plantations. *Global Change Biology* 22, 2238–2254. <https://doi.org/10.1111/gcb.13221>

Siqueira, M., Katul, G., Porporato, A., 2009. Soil Moisture Feedbacks on Convection Triggers: The Role of Soil-Plant Hydrodynamics. *Journal of Hydrometeorology* 10, 96–112. <https://doi.org/10.1175/2008JHM1027.1>

van Heerwaarden, C.C., Vilà-Guerau de Arellano, J., Moene, A.F., Holtslag, A.A.M., 2009. Interactions between dry-air entrainment, surface evaporation and convective boundary-layer development. *Quarterly Journal of the Royal Meteorological Society* 135, 1277–1291. <https://doi.org/10.1002/qj.431>

Zhu, P., Albrecht, B., 2002. A Theoretical and Observational Analysis on the Formation of Fair-Weather Cumuli. *Journal of the Atmospheric Sciences* 59, 1983–2005. [https://doi.org/10.1175/1520-0469\(2002\)059%253C1983:ATAOAO%253E2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059%253C1983:ATAOAO%253E2.0.CO;2)

[Author references](#)

[Manabe, S., and R. F. Strickler, 1964: Thermal Equilibrium of the Atmosphere with a Convective Adjustment. *J. Atmos. Sci.*, **21**, 361–385, \[https://doi.org/10.1175/1520-0469\\(1964\\)021<0361:TEOTAW>2.0.CO;2\]\(https://doi.org/10.1175/1520-0469\(1964\)021<0361:TEOTAW>2.0.CO;2\).](#)