Reply by the authors to Dr Declan Finney's comment on "Assessing and improving cloud-height based parameterisations of global lightning flash rate, and their impact on lightning-produced NO_x and tropospheric composition" (#acp-2020-885)

Comment:

Thank you to the authors for their work. I appreciate their bringing together these details regarding the cloud-top height scheme, and its importance in atmospheric chemistry models.

I have a comment relating to p3(L26-29) and p25(L29-31).

From the evaluation of Clark et al. (2017), I would say that there is not much between the PR92 scheme and the Yoshida et al. (2009) scheme based on cold-cloud depth (CCD). The CCD scheme does, however, show a much smaller increase in lightning activity in the climate change projections.

The CCD scheme incorporates the freezing level, and indirectly relates to the climate change effects on cloud structure and cloud ice. Therefore, I see it as an important lightning scheme that includes the popular cloud-top height variable but also doesn't ignore potential changes in cloud structure under climate change.

Have the authors considered the scheme? And I would like to suggest that this alternative approach to modifying the cloud-top height-based lightning scheme is at least presented and discussed in their paper.

Clark et al. (2017) GRL. https://doi.org/10.1002/2017GL073017

Yoshida et al. (2009) JGR-Atmos. https://doi.org/10.1029/2008JD010370

Response and changes in the manuscript: We thank Dr Declan Finney for his comment on our work and for raising the point about the cold cloud depth (CCD) approach of calculating lightning flash rate.

The quantity CCD is defined as the convective cloud-top height minus the freezing (i.e., 0°C) level. Based on satellite observations, Yoshida et al. (2009) derived an empirical relationship in which lightning flash rate is proportional to the fifth power of CCD.

Clark et al. (2017) show that the PR92 flash-rate parameterisation, which is solely based on cloud-top height, gives the best spatial correlation with satellite data ($r = 0.83$), followed by the CCD based parameterisation of Yoshida et al. (2009) ($r = 0.80$). So, yes, there is not much difference between the two schemes. In a way, that is understandable. The thunderstorm data analysis presented by Price and Rind (1993, Geophys. Res. Lett., https://doi.org/10.1029/93GL00226) suggests that freezing levels remains relatively constant compared to CCD values, meaning that it is largely the cloud-top height that provides the variation in the lightning flash rate in the CCD based approach. If that is generally true, then both the cloud-top height and the CCD based schemes would perform very similarly, which is what the comparison analysis of Clark et al. (2017) shows.

The study by Clark et al. (2017) also shows, as pointed out by Dr. Finney, that compared to the cloud-top height based schemes considered, the CCD-based scheme yields a much smaller increase in lightning flash density under future projected warming (with the RCP8.5 scenario). They attribute this behaviour to the fact that with warming global temperatures there is an increase in the freezing level in the deep tropics, so the relative increase in CCD is smaller than that in cloud-top height, and hence an increase in flash density projected by a cloud-top height based scheme under a warming climate would generally be greater than that from a CCD based scheme.

For our present study, we did not consider a CCD based scheme; all schemes are based on cloud-top height. Essentially, the CCD approach heuristically adds an additional parameter (i.e. the freezing level) to the cloud-top approach. It is based on the reasoning/assumption that the vertical ice charged region of a convective cloud is a better parameter for representing lightning than cloud-top height alone. It is perhaps the simplest extension of the cloud-top height approach and could potentially quantify lightning flash rate better. However, based on the 'present-day' observations and evaluation given by Price and Rind (1993) and Clark et al. (2017), the two schemes are very similar. Thus, the studies done so far do not definitively tell as to what extent the incorporation of the freezing level represents the influence of cloud structure and cloud ice on lightning flash rate. Clearly, more observations and comprehensive evaluation are necessary to test these schemes further, and to test any potential advantages of the CCD approach.

A full discussion in the paper on the CCD approach versus the PR92 cloud-top height approach would be unbalanced without also discussing other approaches mentioned in the paper, such as those based on convective precipitation and upward mass flux; convective available potential energy (CAPE); maximum vertical velocity and updraft volume; upward cloud ice flux; and combinations of these. Moreover, such a discussion, we think, is outside the scope of our paper which focuses on the cloud-top height based approach (as implied by the title of the paper). However, we have extended the relevant text in the 2nd last paragraph of Introduction (P3L28–P4L7 in the non-tracked version of the revised paper), as follows, to expand on the CCD approach a little:

"For example, Clark et al. (2017) tested flash-rate parameterisations based on cloud-top height, cold cloud depth (CCD), mass flux, convective precipitation rate, and cloud-top height with column-integrated cloud droplet number concentration, in a global model, and found that the PR92 parameterisations had the best correlation with the observations, closely followed by the CCD based parameterisation of Yoshida et al. (2009). The PR92 scheme had a higher value of the spatial standard deviation compared to observations due to a large land-ocean contrast in this parameterisation. The quantity CCD is defined as the convective cloud-top height minus the freezing level. The thunderstorm data analysis presented by Price and Rind (1993) indicates that freezing levels remains relatively constant compared to CCD values, meaning that it is largely the cloud-top height that provides the variation in the lightning flash rate in the CCD based scheme, which suggests that the cloud-top height and the CCD based schemes would perform very similarly."