Response to comments for "Quantifying the Oscillatory Evolution of Simulated Boundary-Layer Cloud Fields Using Gaussian Process Regression"

Loren Oh*

June 25th, 2024

We appreciate the constructive feedback for the submitted manuscript.

Responses to Comments

1. Quite a few studies that have discussed oscillations in cloud systems are referred to. These range from shallow cumulus (BOMEX) to the deeper CGILS case discussed here to open cell stratocumulus. I don't think enough distinction is made between these cases. For example, an open-cell stratocumulus system is characterized by significant internal coupling through colliding outflows associated with surface precipitation such that clear oscillatory behaviour is expected. The 90 min periodicity in those systems is likely a time required for spatial rearrangement of the up- and down-drafts (or charging vs discharging areas). Shallow BOMEX clouds barely precipitate at the surface and are in a different class so that arguments about cloud-rain charge-discharge don't seem relevant, and certainly the fact that the signals are weak is to be expected. The CGILS S6 case precipitates more significantly and is quite different from BOMEX. Another study of precipitating Cu (10.1029/2019JD031073) shows that aerosols can change the charge-discharge time depending on the degree of clustering (e.g., Fig. 10). The paper would really benefit from a more nuanced discussion that discriminates between cloud types, cloud organization, precipitation amounts, and coupling in the cloud system. Note, I thinks this is important even for a GMD publication.

As the reviewer noted, this manuscript is primarily meant to be a technical paper, where the focus is in introducing the GP regrssion method with Bayesian inference, and in confirming

*Corresponding author: loh@eoas.ubc.ca

that the estimated oscillation corresponds well to earlier studies. Still, we agree that we can expand on the discussion of physical mechanisms driving the observed oscillatory behaviour within the LES modelled cloud field. The revised manuscript will include a new LES simulation of the CGILS S6 case with precipitation turned off, and it will allow us to directly analyze the role of precipitation in driving the oscillatory behaviour.

We should also mention that we have in fact not observed the 90-minute period in the shallow BOMEX case. As the reviewer suspected, shallow clouds for the BOMEX case barely precipitate, and the oscillatory behaviour cannot be driven by precipitation. This was an error on our end, and we apologize for the confusion. We have performed the analysis again for all the cases discussed in the manuscript, and the revised manuscript will include a discussion on the oscillatory behaviours of different cloud fields.

> 2. The imbalance between the more technical parts of the paper and the interesting discussion that starts on pg 16 could be corrected a bit. I felt that there were missed opportunities on the discussion to dig into the boundary layer physics. Examples: lines 412-414, lines 415-417, but I think there is much more that can be said in Sections 3.2, 3.3, and 3,4. The figures require some work since one has to mentally superimpose plots of b and M, or pick off peaks and troughs in different plots to see that they are out of phase. Also, because b is normalized, it should be made clearer that a smaller b is a more negative b, i.e. a larger fraction of small clouds. The plots contain important information but reference to them is too cryptic in my opinion.

We have come up with an additional figure that shows how the oscillations occur in different phases (see Figure 1 here), which will be added to the revised manuscript. Figure 1 makes it clear that the average vertical mass flux $\mathcal{M}$ varies inversely to the slope of the cloud size distribution. The reviewer is also correct that the time-series is normalized and the slope of the cloud size distribution has a negative sign. We will ensure that this is clear in the revised manuscript.

> 3. What about the possibility of a charge (production of instability) - discharge (consumption of instability) as a driver of oscillations. Is this how non-precipitating systems differ from precipitating systems?

I am somewhat confused about this comment. Did you mean convective organization instead of the charge-discharge cycle, which is discussed in detail? If so, the revised manuscript will include an extended discussion based on the results from the non-precipitating CGILS S6 case. We believe that given the oscillatory behaviour in cloud fraction, convective organiza-

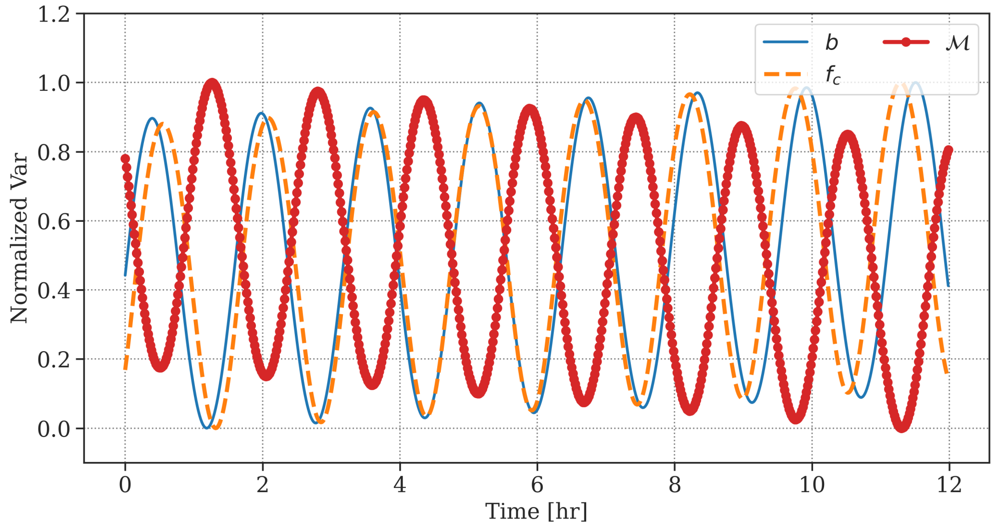

Figure 1: Mean posterior distributions from the GP regression for the slope b of the cloud size distribution (blue), cloud fraction f_c (orange) and average vertical mass flux $\mathcal{M}$.

tion will certainly play a role in the oscillatory behaviour of the cloud field.

> 4. Oscillations in M lead the oscillations in CF by 45-50 minutes. This made me wonder which size clouds contribute most to CF, which of course depends on b. I also wondered how detrainment at cloud top contributes to this (see Fig. 1). Could you strengthen this analysis and discussion?

Because we ignore the smallest clouds in the estimation of the slope of the cloud size distribution (see Figure 3 in the submitted manuscript), medium-sized clouds contribute the most to both cloud fraction and mass flux. Figure 1 also makes it easier to see this. Cloud-top detrainment is directly responsible for the formation of anvil-like structure near the top of the cloud layer, as the reviewer noted. As you can see in Figure 1, f_c is in phase with b, which indicates that cloud-top detrainment of large clouds corresponds to the peak in cloud fraction. Figure 1 will be added to the revised manuscript, and will allow us to expand the discussion on the physical mechanisms behind the oscillatory behaviour.

> 5. Dagan et al. (2018) change their domain size and show that oscillations get smoothed out for larger domain sizes - at least for BOMEX. Have you tested the sensitivity of the periodicity to domain size. One could imagine that small domains introduce higher frequency oscillations because of the periodic boundary conditions. If the oscillations become harder and harder to discern at large domain size, are they really important? The fact that they can be discerned by your GP regression is very nice but they may not have much physical significance

in a natural cloud system unless the system experiences strong internal coupling (e.g., open-cell Sc)

That is exactly the merit of this manuscript, we'd say; that is, although the oscillations become more difficult with increasing domain size, numerical methods can be used to identify the oscillatory behaviour and estimate the uncertainties involved using Bayesian inference. Feingold et al. (2017) also did this on a smaller domain, but had difficulties in identifying the period in the cloud size distribution. It becomes more and more difficult to identify the oscillatory behaviour due to the variability in the time-series as the domain size becomes larger. So the effect of the oscillatory behaviour is simply hidden in a large cloud field, and the variability in the properties of the cloud field can be better determined if we can account for the oscillatory evolution.

6. It would be nice to know how the normalized b values translate to actual b values that e.g., a satellite imager would see.

We have added a paragraph on the range of b based on the posterior distribution in Figure 9 of the submitted manuscript.

7. Line 132: could you help with physical meaning of 'bandwidth h'?

This has to do with translating a point measurement into a probability distribution (which we assume to be Gaussian). The bandwidth h is the width of this probability distribution, representing the uncertainty in the measurement. This concept comes up again in the GP regression method, and we will make its physical significance clearer in the revised manuscript.

8. Line 102, $q_l > 0$ is a very low threshold, unless your cloud edges are very sharp. Does $q_l > 0.01$ g/kg change the picture?

Definitely not for the cases being presented in the manuscript. We have tested different conditional criteria for cloud sampling in the past, but have not found any differences in statistical distributions.