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

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We sincerely appreciate the constructive feedback for the submitted manuscript. We have made extensive changes to the manuscript based on the reviews, and performed additional model runs to reflect the points raised by the reviewers. The following document summarizes those points, and the changes we've made.

The line numbers in the responses refer to those in the revised 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.

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> 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.

We must first apologize for the confusion concerning the BOMEX case. There were two errors in the draft caused by an unintentional mix-up. The original analysis included in the draft was actually done on a CGILS case on a small domain, not the BOMEX case. The BOMEX case we meant to analyze also had precipitation turned off, and upon performing the correct analysis, we found no oscillatory evolution in the cloud field as expected.

The CGILS S6 case used for this study is not meant to represent deeper convection, but strictly shallow convection with more precipitation. We have added more details about the CGILS case; the relevant paragraph at line 90 now reads: "The System for Atmospheric Modeling (SAM; Khairoutdinov and Randall, 2003) version 6.11.8 was used to simulate CGILS (CFMIP/GASS Inter-comparison of Large-Eddy and Single-Column Models) case (Blossey et al., 2013; Zhang et al., 2013). In this study, we use the large-scale forcing and thermodynamic tendencies of the *CGILS S6 regime*, representing marine sub-tropical shallow cumulus convection". The clouds in the CGILS S6 regime used in this study do not appear to be significantly different from the ones in BOMEX (see also Bretherton and Blossey, 2017; https://doi.org/10.1002/2017MS000981), except that the precipitation seems to be more vigorous.

We do, however, agree that the manuscript is rather light on the discussion of the literature. We have replaced the paragraph starting at line 36, which now reads: "Marine boundary-layer clouds have been observed to organize into cellular patterns (Malkus and Riehl, 1964; Nair et al., 1998; Seifert and Heus, 2013) as a response to the formation of cold pools, formed by evaporative cooling due to precipitation (Zuidema et al., 2012). The cold pools promote the formation of negatively buoyant downdrafts that inhibit further growth of thermals (Seifert and Heus, 2013; Seifert et al., 2015; Seigel, 2014). At the boundaries of these open cells, convective formation is promoted due to the moistening of downdrafts (Seifert and Heus, 2013) and mechanical lifting due to the convergence of cold pool outflows (Xue et al., 2008).

This dynamics between the formation of cold pools from precipitation and the subsequent formation of clouds manifests as temporal oscillations; the cloud field goes through a relatively weak convective phase, until multiple downdrafts from the cold pools collide into a convergence zone, where convective growth begins anew. For the mesoscale marine boundary- layer stratocumulus clouds, the spatial organization of precipitation is found to be important in promoting subsequent cloud formation and the evolution of open cell convection (Feingold et al., 2010; Koren and Feingold, 2013; Wang and Feingold, 2009; Yamaguchi and Feingold, 2015). High-resolution large-eddy simulations have confirmed the formation of cold pools as the main mechanism that drives organized marine stratocumulus convection, which corresponds well to long-term satellite measurements (Bretherton and Blossey, 2017; Seifert and Heus, 2013; Zuidema et al., 2012).

The temporal oscillation has also been observed in modelling studies of precipitating cumulus convection (Dagan et al., 2018; Feingold et al., 2017). For both shallow and deep clouds, the dominant mechanism that drives this oscillatory evolution is found to be the formation of cold pools due to evaporative cooling from precipitation in the sub-cloud layer (Seifert and Heus, 2013; Yano and Plant, 2012; Tompkins, 2001). This mechanism is referred to as the recharge-discharge cycle of thermodynamic instability by Dagan et al. (2018), motivated by Bladé and Hartmann (1993), where the evaporative cooling due to precipitation charges instability in the atmosphere, which is discharged by convection.

Precipitation facilitates both the spatial organization and temporal oscillation of the cloud field, and is governed by a number of factors including cloud microphysics and cloud layer depth. Aerosols, acting as cloud condensation nuclei (CCN), can influence the cloud microphysics by enhancing the cloud droplet number concentration but suppress droplet growth (Twomey, 1974), and large-eddy simulation (LES) studies have shown that when the aerosol concentration is increased, the cloud layer deepens, which then affects rain formation (Dagan et al., 2017; Seifert et al., 2015). Furthermore, modelling studies have shown that an increase in aerosol concentration influences both the amount and the timing of precipitation; in a polluted environment, the efficiency in precipitation formation is reduced, and as a result, rain formation is suppressed and delayed (Dagan et al., 2018; Seifert et al., 2015; Yamaguchi et al., 2019)".

Furthermore, to ensure that we have a clear picture of how precipitation influences the cloud size distribution, We performed two new model runs based on the CGILS case with the precipitation turned on and off. In all cases where precipitation was suppressed (for both BOMEX and CGILS), no oscillatory behaviour was observed. The corresponding paragraph has now been moved to line 528, which now reads: "To further examine the effect of precipitation in the recharge-discharge cycle, we performed a follow-up simulation of the CGILS case with precipitation manually turned off in the microphysics scheme. Likewise, we have tested the GP regression method to the mass flux time-series in weakly-precipitating shallow convection during BOMEX (Holland and Rasmusson, 1972) case. In both cases, the GP

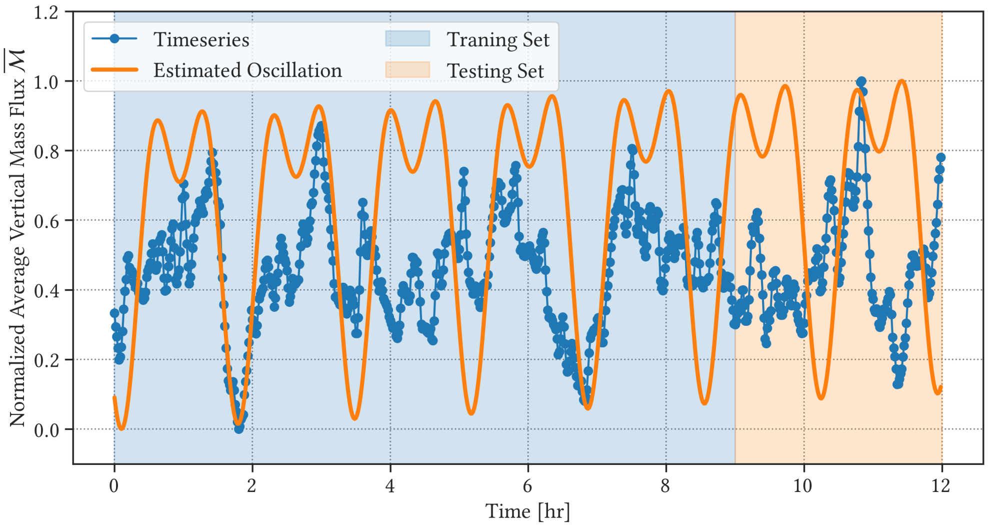

Figure 1: Mean posterior distributions from the GP regression for vertical mass flux $\overline{M}$ (orange) and the observed time-series of vertical mass flux (blue) from the CGILS case where precipitation has been suppressed.

regression method described in Section 2 failed to converge towards a single periodicity”. The result of the non-precipitating CGILS case run is shown in Figure 1 below.

As the new paragraph suggests, we have performed another simulation of the CGILS case with precipitation manually turned off. Figure 1 shows the time-series of vertical mass flux $\overline{M}$ and the mean posterior distribution from our GP regression model. As shown here, the GP regression model fails to pinpoint the oscillatory behaviour, as the resulting posterior distribution (orange line) seems to consist of more than one period. We have tested different priors, but when there is no precipitation, the GP regression model fails to model the observed data points with a single periodicity.

> 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.

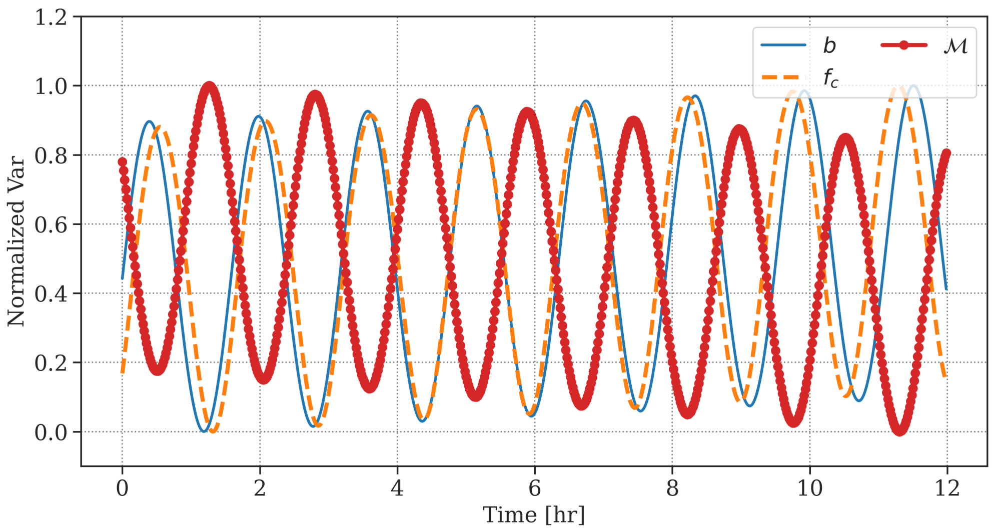

Figure 2: Mean posterior distributions from the GP regression for the slope $b$ of the cloud size distribution (blue), cloud fraction $f_c$ (orange) and average vertical mass flux $\overline{M}$.

We have come up with an additional figure that shows how the oscillations occur in different phases (see Figure 2), which will be added to the revised manuscript. Figure 2 makes it clear that the average vertical mass flux $\overline{M}$ varies inversely to the slope of the cloud size distribution. We have also added an additional paragraph, which reads (line 512): “Figure 15 shows the oscillatory evolutions of the mean posterior distributions for $\tilde{b}$, $f_c$ and $\overline{M}$, which gives more insight about how the marine boundary-layer cumulus clouds evolve over time in a high-resolution model. When there is a relative abundance of larger clouds, the normalized slope $\tilde{b}$ of the cloud size distribution and cloud fraction $f_c$ become larger, which corresponds to a less negative (less steep) slope $b$ of the cloud size distribution. Hence, the changes in cloud fraction $f_c$ is correlated to the number of large clouds; that is, the number of large clouds (mostly observed as anvil-like structures near the cloud layer top) determines how much of the model domain is covered by clouds”.

We agree that normalization makes it difficult to see what $b$ represents. We tried to relate the normalized $b$ values to the actual slope. For example, line 367 now reads: “The normalization, however, makes it more difficult to see that the time-series of the slope $b(t)$ of the cloud size distribution has a negative sign (see Figure 6). A small value in the normalized slope $\tilde{b}$ indicates a more negative slope, or a steeper slope where there is a relative abundance of smaller clouds. On the other hand, a large value in $\tilde{b}$ represents a less negative slope where there is a relative abundance of larger clouds”.

We have also added more discussions about the boundary layer physics, especially the factors that disrupt the oscillation. For example, we discuss the deviations in $b(t)$ at line 419 reads: “Based on Figure 9 at around $t = 4$ hours, the cloud field is expected to go towards a phase of relatively weak convection where there is a relative abundance of smaller clouds. Small normalized values correspond to more negative slopes of the cloud size distribution. However, upon inspecting the evolution of the cloud field during this time, large structures form at the top of the cloud layer (light grey regions in Figure 11) as a result of strong convective activity, which persist until $t = 5$ hours into the simulation. Once the large, thin layer of clouds at the top dissipates, the deviation the observed time-series of $b$ becomes much smaller. During this time, as shown in Figure 11, the cloud field is dominated by the growth of small clouds. However, a thin layer of clouds persist at the top of the cloud layer, which skews the slope $b$ of the cloud size distribution”.

> 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?

We believe this can be answered by our response to the first point. We re-ran the simulations to confirm that, as the reviewer noted, the time-series of vertical mass flux and cloud fraction in non-precipitating systems clearly differ from precipitating systems. We would like to apologize again for the confusion concerning the BOMEX case, which we have confirmed to behave like non-precipitating CGILS case with no apparent oscillatory behaviour.

> 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?

We have added a discussion on which clouds contribute most to cloud fraction. Line 512 reads: “Figure 15 shows the oscillatory evolutions of the mean posterior distributions for $\tilde{b}$, $f_c$ and $\overline{M}$, which gives more insight about how the marine boundary-layer cumulus clouds evolve over time in a high-resolution model. When there is a relative abundance of larger clouds, the normalized slope $\tilde{b}$ of the cloud size distribution and cloud fraction $f_c$ become larger, which corresponds to a less negative (less steep) slope $b$ of the cloud size distribution. Hence, the changes in cloud fraction $f_c$ is correlated to the number of large clouds; that is, the number of large clouds (mostly observed as anvil-like structures near the cloud layer top) determines how much of the model domain is covered by clouds”.

> 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 aim of this manuscript; 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. The variability due to the oscillatory behaviour still exists; we believe that the more we know about the internal dynamics of these large cloud fields, the better we can understand their behaviour.

We added a relevant discussion starting line 592: "We have also observed the spatial organization of shallow convective clouds that disrupts the oscillatory evolution (Figure 12), which can also be seen in studies modelling the boundary-layer cloud field over a smaller domain (Wang and Feingold, 2009). Reducing the size of the model domain may reduce the effect of spatial organization and make it easier to estimate the periodic behaviour of the cloud field using traditional methods. However, given that these factors can manifest even on a smaller domain, a robust method to estimate the periodicity of a noisy, non-stationary time-series is still useful, especially if no smallest, *optimal* domain size exists where the recharge-discharge cycle can be isolated".

> 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.

Thank you for pointing this out. We briefly compare this to Neggers et al. (2003) and Brown (1999) (line 159 in the updated manuscript), but we should have brought this up again when we calculate *b*. The corresponding discussion starts at line 192, which reads: "The cloud size distribution C(a) given in Figure 3b represents a normalized probability density function, which will differ from the histograms obtained from observations. Here, the slope is measured to be roughly $b = -0.65$. We have calculated b for non-normalized values of $C(a)$, and the time-series is found to vary roughly between $-1.4$ and $-1.7$, which corresponds to a range of $-0.7$ to $-0.85$ based on the methods by Neggers et al. (2003), and $-1.7$ to $-1.85$ by Benner and Curry (1998). The measured slopes are slightly smaller in magnitude but comparable to the slope of $b = -1.7$ found in a large-eddy simulation (Neggers et al., 2003) and the slope of $b = -1.98$ from remote sensing observations (Cahalan and Joseph, 1989; Benner and Curry, 1998)".

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

We have re-written the following paragraph in hopes of making it clearer. The paragraph starting at line 157 now reads: "Each cloud size sample is added to a distribution not as a single point of observation, but a probability distribution based on a Gaussian distribution. It can be considered as an uncertainty in the measurement; that is, each cloud sample is considered to be a Gaussian probability distribution whose width is defined by the bandwidth $h$".

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?

$q_l > 0.01$ g/kg is typically used for large-scale models, but not widely for large-eddy simulations. We have tested different conditional criteria for cloud sampling in the past, but have not found any differences in statistical distributions, likely thanks to the sheer number of cloud samples taken from the model run.