Response summary

We would like to thank both reviewers for their insightful comments and helpful recommendations to improve the manuscript. The manuscript has undergone significant changes, and figures in particular were changed to reduce file size and improve viewing. Several figures were removed from the manuscript.

Reviewer 1

General Comments

1) Role of sensible heat flux in maintaining the open cell state: The simulations conducted and time series provided in Fig. 13 do a nice job of showing how a reduction in sensible heat flux leads to a cooler, moister surface layer with a lower lifted condensation level (LCL) and increased rain rate, eventually leading to a sharp increase in number of rain areas, downscaling cell sizes and desynchronization of convection. However, time series also show that the sharp changes in organization only occur in the final six hours of simulation Shybrid. The LCL decreases substantially early on in the simulation, and yet the dramatic shift in organization doesn't appear to occur until thirty hours in. Nothing in the text, Fig. 13, or any of the other figures provides a means to understand the reason for this delay, ...



Fig. R1: Total heating (latent + long-wave) in downdrafts (left) and updrafts (right), after 24 h (thin curves) and 32 h (thick curves) in simulation S_{\circ} (blue) and S_{\circ} (red).

This very helpful comment prompted us to examine simulation S_{\otimes} in more detail to identify a fundamental difference between S_{\circ} and S_{\otimes} with a shorter lead time before the collapse in S_{\otimes} than the cooling and humidification of the surface layer. Such a difference was identified in the vertical distribution of thermal forcing in the boundary layer (Fig. R1). Figure R1 has been added as Figure 15 in the revised manuscript, together with the following text:

"With the onset of the runaway multiplication of rain locations (24-32 h of the simulation), a change in the vertical distribution of thermal forcing takes place in S_{\circ} (Fig. 15): Downdrafts in S_{\circ} lose forcing by

cloud top cooling (characteristic for stratiform cloud elements), and assume a more cumuliform thermal forcing, dominated by contributions from the lower and middle boundary layer. In contrast, the open-cell state in simulation S_{\circ} maintains forcing of downdrafts by cloud top cooling."

... and further, it is not clear that the base simulation Sopen would not undergo a similar transition if run for an additional 24 hours. The authors correctly point out that none of these simulations are in equilibrium (though simulation Sclosed may be approaching it); thus, at best, the simulations suggest the desynchronization and rapid growth in number of rain areas is prevented by the higher sensible flux for the 36 hour length of the simulations Sopen and Sopen".

The reviewer is correct. An eventual collapse of the open-cell state in simulation S_{\circ} (if run for a sufficiently long time) is a likely outcome, given its continuously decreasing surface heat fluxes. This is discussed in Section 4.4:

"Even though it was shown that the open-cell state in simulation S_{\circ} creates surface fluxes required for its perpetuation, this decrease with time raises the question whether, and in what conditions the opencell state can attain a steady state, and thereby maintain itself indefinitely, or whether, and in what conditions, and how quickly the continuous decrease in the surface fluxes causes its downfall."

However, such an eventual collapse in S_\circ should differ from the collapse in S_\diamond . This is because the sensible surface heat flux in S_\circ decreases much more slowly than in S_\diamond , while the latent heat flux in S_\circ decreases much more rapidly. Hence a dissipation of the cloud deck due to a drying of the boundary layer and a reduction of of cloud-top cooling appears a more likely eventual outcomes in S_\circ . This is supported by the emergence of broken and less well-formed open-cell walls in the course of the simulation S_\circ (Fig. 2 of the manuscript) and a more stable surface rain rate (Fig. 3c of the manuscript). In any case, the conclusions of the manuscript are unaffected; in particular, it remains true that the open-cell state creates conditions conducive to its maintenance, by enhancing the surface sensible heat flux. In order to avoid misunderstandings because "perpetuation" may also imply "infinite continuation", the above passage was modified as follows:

"Even though it was shown that the open-cell state in simulation S_{\circ} creates surface fluxes required for its maintenance, this decrease with time raises the question whether, and in what conditions the opencell state can attain a steady state, and thereby maintain itself indefinitely, or whether, and in what conditions, and how quickly the continuous decrease in the surface fluxes causes its downfall."

The word "perpetuation" was similarly replaced with "maintenance" in other places.

If the specific mechanism or criterion could be established for the onset of growth in the number of rain areas, this would significantly strengthen the results.

In order to better illustrate the processes accompanying the collapse of the open-cell state in simulation S_{\otimes} , the following passage was added to the manuscript:

"Lewellen at al. (1996) investigated the differences between (non-precipitating) stratocumulus clouds with different forcing by surface latent versus sensible heat flux. At a reduced Bowen ratio (corresponding to a reduced sensible heat flux or increased latent heat flux), they found that the boundary layer becomes more surface driven, and develops a greater horizontal heterogeneity in liquid water path, with significant local liquid water path enhancements. This is qualitatively consistent with the behavior seen in simulation S_{*} (Fig. 13): a steady decrease in the Bowen ratio increases the liquid water path, leads to enhanced collision-coalescence, and the formation of rain at more locations. This is accompanied by a change in heating profiles that become more cumuliform (Fig. 15) with the runaway multiplication of rain locations (Fig. 14)."

This qualitative analysis that draws from the insights of Lewellen et al. (1996) does not dissect in all

detail the mechanisms of the transition from the open-cell state to the collapsed state. In particular, it does not identify the key process or "root cause" that gives rise to the collapse of the open-cells state and the runaway increase in the number of precipitation locations, after the open-cell state has survived for a significant period of time with a more humid and cooler surface layer. The analysis and discussion in Lewellen et al. (1996) provides guidance but no definitive explanation.

The quest for a root cause for the collapse of the open-cell state in S_{\bullet} is not straightforward: The quantities that are traditionally employed in the analysis of the cloudy boundary layer provide few hints for the mechanism of the collapse. For example, Figure R2 shows the resolved-scale TKE in S_{\circ} and S_{\bullet} ; TKE is decreasing more rapidly in S_{\bullet} than in S_{\circ} . This means that there is less TKE available for driving the open-cell circulation, as the increasing precipitation cools and thereby slows down updrafts earlier in their life cycle in S_{\bullet} than in S_{\circ} . This is consistent with a transition toward a cumuliform circulation, with more individual updrafts of shorter duration. However, TKE is reduced gradually from an early stage in both simulations, and there is no indication of a change that would occur around the time (24-32 h) of the onset of the runaway multiplication of rain location in S_{\bullet} (as seen in the vertical profiles of thermal forcing in Fig. R1). We have investigated numerous quantities (time series and vertical profiles) that are common in the analysis of boundary layer processes for such a change around the onset of the runaway multiplication in S_{\bullet} , e.g. w², w³, liquid water, rain rate, and others, and all show only a gradual change, as seen in TKE (Fig. R2).

In the preparation of the manuscript we have attempted to expand the discussion beyond the traditional analysis. One hypotheses pursued postulated that in simulation S_{\otimes} , precipitation locations are not only more numerous, but are distributed on a less regular grid than in simulation S_{\circ} (owing to the stochastic nature of collision-coalescence, which would manifest itself more strongly in a system in which higher liquid water paths cover a greater area). This more irregular distribution (and the associated irregular distribution of cold downdrafts and cooling profiles therein, which drive the open-cell state) would desynchronize the open-cell state dynamics.

Different metrics were used to measure the irregularity of precipitation locations. Fig. R3 shows examples in which a Delaunay triangulation was constructed from precipitation locations and cold

pools. The Delaunay triangulation is then used to measure the deviation of the grid from a hexagonal grid (the ideal distribution of precipitation in the open-cell state). It could not be shown that precipitation in S_{\circ} is distributed more irregularly than in S_{\circ} . Other hypotheses were pursued but did not reveal the root cause of the collapse.

The identification of the key process or "root cause" of the open-cell state collapse will require a focused follow-up effort.

Fig. R3: Delaunay triangulation of rain locations (top) and cold pools (bottom) in simulation S_{\circ} (left panels) and S_{\circ} (right panels), after 28 h. Different metrics were applied to measure the irregularity of the Delaunay grid relative to a hexagonal grid. One metric is the mean distortion (mean of the longest/shortest edge ratio at each vertex), which is 1 for the hexagonal grid. In the above examples, the mean distortion is 3.29 for the rain locations and 2.57 cold pools in S_{\circ} (left panels) and 3.17 for the locations rain and 2.93 cold pools in S_{\circ} (right panels). The Delaunay triangulation appears to extend out of the domain because of the periodic boundary conditions.

Attention to the average properties and depth of the surface mixed layer might be useful here, and in general, some additional attention to the vertical structure of the boundary layer might help clarify what is going on. Analysis of the time evolution of histograms for column LCL or column rain rate might be helpful, as well.

We have analyzed PDFs of the LCL and vertical profiles of the rain rate. These show only gradually

growing differences between the simulations S_{\circ} and S_{\diamond} , as seen in TKE (Fig. R2). It is hence possible that owing to resilience of the open-cell dynamics (inertia of the moving air masses) against gradual changes in quantities such as LWP, rain rate, and below-cloud evaporative cooling, the breakdown in S_{\diamond} occurs when these gradual changes have accumulated to a tipping point, without an abrupt change in any of these quantities being required.

2) Synchronization of convection: While the magnitude of domain-wide oscillations certainly seems to damp more in the final six hours of Shybrid, it would be nice to have a way to gauge this process. Perhaps looking at anomalies of the various quantities by separating the domain into quadrants and showing that anomalies by quadrant decorrelate with each other would do this. Additionally, strong correlations between the anomaly time series in each quadrant of the base simulation Sopen would reinforce the idea that the processes really are synchronized domain-wide in persistent open cell convection.

S_∞ (bottom).

The anomalies of liquid water path in the four quadrants of S_\circ and S_\diamond are shown in Figure R4. The LWP anomalies of each quadrant are not particularly well-synchronized, but exhibit a periodicity of approximately 2 h. In simulation S_\diamond , the anomalies fade after 31 h, while they persist in simulation S_\circ . Despite the apparent lack of a synchronization between the quadrants, the domain-wide LWP anomaly has a relatively regular beat with a periodicity of 2 h throughout S_\circ (rev. manuscript Fig. 6), which fades in simulation S_\diamond (rev. manuscript Fig. 16). This combination of the not very well synchronized LWP anomalies of the quadrants into a regular beat on the entire domain is likely not coincidental.

However, a domain-wide synchronization of dynamics by which these domain-wide oscillations would emerge is not obvious from the LWP anomalies of the individual quadrants. The text of the revised manuscript has been therefore changed accordingly; e.g., we have replaced the sentence

"The persistence of the oscillations and of their delay pattern demonstrates the domain-wide synchronization of the open-cell dynamics over the duration of simulation S_{\circ} ."

with

"The oscillations in latent heat release, liquid water path, and surface rain reflect the presence of open-cell dynamics throughout the simulation S_0 ."

The manuscript text was changed accordingly in other places.

3) Figures: The majority of the figures, especially multi-panel plots of various quantities, domain-wide, attempt to do far too much. Redundant axis and contour labels result in quite a bit of waste white space. Vector field layers in multi-panel plots of this type are simply inappropriate, as printing the paper in color at normal size renders such fields illegible, and thin contours are not much better. While enlarging the document by 1600% on a laptop allows the figures to be reasonably appreciated, this brings even a reasonably high spec machine to its knees, making it very difficult to make use of the paper at all. These are perhaps reasonable in the SI, but not elsewhere. Specific comments on the figures are given below.

The figures underwent major revisions (described in detail in the following) to reduce file size and improve viewing, and the number of figures has been reduced.

Specific Comments

Introduction

How is closed-cellular mesoscale organization different from the organization of precipitating trade cumulus, where cloud arcs are the result of cold pooling? E.g. Seifert and Heus, 2013 (ACPD).

We are unsure how to satisfactorily answer this question - we would have expected a question to regarding the difference between the precipitating trade-wind cumuli investigated by Seifert and Heus (ACP, 2013) and the *open*-cell cloud field (rather than the *closed*-cell cloud field) in our simulations. Juxtaposing closed cells and precipitating trade wind cumuli appears difficult owing to the very different dynamics of these clouds – cold pools are absent in closed cells, while they are key in the precipitating trade wind cumuli (Seifert and Heus, ACP, 2013). We will therefore briefly juxtapose the *open*-cell cloud state and the trade-wind cumuli in the following. Seifert and Heus (2013) are cited in the revised manuscript.

Seifert and Heus (ACP, 2013) conducted (among other) a cluster analysis of the trade wind cumulus cloud fields in their simulation: Based on the nearest neighbor distances, they quantified whether the horizontal distribution of clouds is random, regular, or clustered. They found that the trade wind cumuli in their simulations were either randomly distributed or clustered, and found no evidence of regular cloud fields (clouds located on a grid).

In contrast, the open-cell state exhibits a regular grid pattern (at least in its idealized, theoretical manifestation): Locations with the densest clouds, precipitation, and downdrafts are located on the vertices of a hexagonal grid (Feingold et al., Nature, 2010). This regular pattern leads to synchronization of updrafts, cloud formation, and precipitation in the open-cell state, as cold pool outflows roll along the ocean surface to collide with corresponding counter-flows, to form the next

generation of open cells. Such regular and synchronized dynamics appears to be absent in trade-wind cumuli.

Simulations

For clarity, is the FT aerosol concentration initialized identically to that in the boundary layer?

Yes. A corresponding statement has been added in the revised manuscript.

Results and discussion

Simulation names: A more descriptive, somewhat less hieroglyphic naming approach would be easier to follow in the text, obviating the need to constantly refer back to Table 1.

The simulation symbols are intended to indicate of the nature of each simulation: filled circles (S_{\bullet}) represent closed cells; open circles (S_{\bullet}) open cells, and crossed circle (S_{\bullet}) the collapsing open-cell state. As an alternative, we have considered (but rejected) S_{CC} , S_{OC} , S_{COS} , with CC = closed cells, OC = open cells, COS "collapsing open-cells" - their clarity is somewhat debatable as well. We regret that the ACP manuscript style file does not provide the simulation symbols used for S_{\bullet} , S_{\circ} , S_{\bullet} in equal sizes, as our originally submitted manuscript.

Based on LWP trace in Fig. 3 for run Sclosed, it seems possible that the boundary layer has decoupled around hour 18. How does the degree to which the boundary layer is coupled project on surface flux correlations with cellular structure in the closed simulation?

The boundary layer is well-mixed throughout simulation S_{\bullet} (Fig. R5). However, it has deepened in the course of the simulation, resulting in entrainment of dry free-tropospheric air, the likely cause of the decline in LWP. However, we agree that a decoupling of the boundary layer would likely affect the correlation coefficients. We have therefore added a statement in the revised manuscript that explains the fact that the boundary layer is well-mixed in simulation S_{\bullet} .

P18863L3: What causes the opacity reduction in cell centers? Have the effective radii of cloud droplets there significantly changed?

The opacity reduction in the cell centers in the course of the simulation is mainly due to a reduction of LWP; the cloud effective radii change little (Fig R6).

P18865L15-20: Does the conclusion regarding detrainment include the effects of the imposed large scale divergence? From Fig. 5, it appears that while closed cell entrainment is approximately 5mm/s, the open cells, based on a 130m drop in zi from hours 20-36, are entraining at $w_e = dz_i/dt - w_{ls} = -0.0023 - (-3.75e-6*1000) = 0.0014$ m/s.

This is indeed a very helpful comment – as we have not taken into account the entrainment by large-scale subsidence. The sentence

"This means that free tropospheric air entrains into the boundary layer in the closed-cell state, while boundary layer air detrains into the free troposphere in the open-cell state."

was replaced with

"When large scale subsidence is accounted for, the boundary layer entrains free tropospheric air in both simulations, however, on average at a higher rate in S_{\bullet} and at a lower rate in S_{\circ} ."

P18874L13-29: An attempt at a simple aerosol budget would be nice here. What fraction of the aerosol activate?

To reduce output size, the number of variables written to file has been limited for the simulations used in this work (still, the overall output from the simulations exceeds 2 TB), and this information is not available in the current simulations.

What is the estimated loss rate due to collision coalescence?

Unfortunately we did not save the model output at sufficiently high temporal resolution to do so. Our prior work (Kazil et al. 2011) focused more closely on the aerosol budget.

P18876L7-25: The role of the balance between entrainment and large scale subsidence seems worth mentioning here, as well.

The passage in question was amended as follows (in bold-face):

"Prima facie, this question may appear unimportant, because in nature, the open-cell state will be subject to changing environmental conditions and a steady state may never materialize - e.g., the air mass in which the open-cell state is embedded may be advected along a gradient in sea surface temperature, which would change the surface sensible heat flux. **This, together with a changing balance between large scale subsidence and entrainment as geographic location changes would modify cloud properties and the dynamic state of the boundary layer.** However, it is the stability of the open-cell state or the absence thereof in given conditions which prevents or enables changes in the environmental conditions to extend or shorten the lifetime of the open-cell state."

P18877L3-14: It is a nice result that the small scale variability of fluxes seems to have limited impact on the statistics of the boundary layer evolution as a whole. However, since the domain-mean fluxes are determined by the net result of interactions between the fine scale dynamical fields and the surface, the circulation still must be resolved (which, based on results of UKMO modeling, seems to require roughly 1km resolution) or parameterized adequately (potentially quite difficult).

This is a very good point which we have not adequately addressed. The passage has been modified by removing all generalizations for large-scale and global models. The work of Seifert and Heus (2013), who arrived at similar findings with respect to the homogenization of surface heat fluxes in the case of trade wind cumuli, is cited.

Figures

Fig. 6: For clarity, recommend stacking panels vertically and stretching plots horizontally, increasing separation between individual peaks in the anomaly time series.

Done.

Fig. 7: This figure is very difficult to use and hard to read. As the full time series for each of the plotted variables have already appeared in Figs. 4e, f and 6b, recommend choosing a representative six hour period to allow easier examination over a shorter number of cycles; alternatively, compositing over the peaks in rain rate might give a clearer picture of the leads and lags the figure is trying to display.

Figure 7 was modified so that the time series and the delays between the peaks are easily viewable. These are key to illustrate the sequence of the physical processes discussed in the text.

Fig. 8: The vector fields, even in this best case usage against a mostly white background, are quite difficult to use at the given density for the panel size. Also, the main idea in the text discussing the figure on P18867 seems to be the divergence. As such, perhaps a better alternative would be to use a filled contour plot of divergence using a jet color map with white contours of rain rate for 1 mm day-1.

A second panel could use a contour of surface temperature of 289 K to show the asymmetry of cold pools due to the mean surface wind. If the original plotting choices are preferred, cropping down to a single domain quadrant would perhaps make the vector field usable.

Figure 8 was modified to be more easily viewable. As recommended by the reviewer, only a selected region of the model domain is shown, which ensures that wind field vectors are clearly visible. To accommodate the request to reduce the number of figures, Figure 8 b was removed, as it showed the actual (as opposed to the residual) wind field, which is not essential to convey the key points of the manuscript.

Fig. 9: The discussion of P18867L25-P18868L19 cannot be easily understood without extreme magnification of the figure. Perhaps focusing on a single quadrant of the domain would enlarge these features enough to appreciate the patterns; even so, the residual wind field is quite difficult to see; a separate shaded contour plot of surface divergence would be more helpful.

Figure 9 was modified to be more easily viewable. As recommended by the reviewer, only a select region of the model domain is shown, which ensures that wind field vectors are clearly visible.

Fig. 10: Much as in Figs. 8 and 9, there is simply too much going on here. Vector field in panels (a) and (b) is illegible at any reasonable printing size. The needless repetition of the contour color scale and horizontal/vertical axis labels uses extra white space that could be used to enlarge panels and improve readability. As above, perhaps choose a single quadrant to show.

Figure 10 was modified to be more easily viewable; redundant information was removed from the figure. As recommended by the reviewer, only a select region of the model domain is shown, which ensures that wind field vectors are clearly visible. Contours and color bar captions were retained as they give information that is cumbersome to convey in the figure caption.

Fig. 11: As in Fig. 10, recommend choosing a single quadrant.

Figure 11 was modified to be more easily viewable; redundant information was removed from the figure, as were the panels b, d, and f. The entire domain is shown, as it is a key finding of this manuscript that the horizontal structure of the open-cell state creates a corresponding horizontal structure in surface properties.

Fig. 14: Vector fields are illegible. Recommend same strategy as in Fig. 8.

Figure 14 was removed as it only provided an illustration of the spatial distribution of what is shown in Figure 14 of the revised manuscript.

Fig. 17: Panels (a) and (c) are essentially useless: simply relying on text to describe the case as non-precipitating and overcast should be sufficient.

Done.

Technical Comments

Text

P18859L24: perhaps "...parameterized using the Community Atmospheric Model scheme..." rather than "...described with..."

Done.

P18866L23: prefer "jumps" over "hikes" to describe elevated surface water vapor

Done.

Figures

All multi-panel figures: move panel letters to upper left from bottom left corners.

Done.

Fig. 3: Delete redundant right hand y-axes, they take up unnecessary space and are distracting. Consider only including x-axes labels for bottom row.

Done.

Fig. 4: Perhaps find a way to visually indicate which panels correspond to which simulation, e.g. the simulation name with a left brace or bracket grouping the top row for Sclosed and the second and third rows with Sopen

Done.

Fig. 5: Delete redundant right hand axis

Done.

Fig. 7: depending on final presentation, delete redundant color bars.

Done (We assume this comment refers to Figure 8 rather than to Figure 7).

Figs. 9, 10: Legend for contour intervals wastes space, recommend simply listing contours and colors in caption. Since fields are at synchronous times in all panels, list time/date once at top of figures and delete from all other field titles to save space

Redundant information was removed from the figures, and the figures were modified to be more easily viewable. As recommended by the reviewer, only a selected region of the model domain is shown, which ensures that wind field vectors are clearly visible. Contours and color bar captions were retained as they give information that is cumbersome to convey in the figure caption.

Fig. 13: Delete redundant right hand y-axes. Consider only including x-axes labels for bottom row.

Done.

Fig. 14: Regardless of final form, delete contour legends and simply list in caption.

Figure 14 was removed as it only provided an illustration of the spatial distribution of what is shown in Figure 15 (Figure 14 of the revised manuscript).

Figs. 15, 17, 18: Delete redundant right hand y-axis.

Done.