Response to the comments of reviewer 3

Our responses are marked in italic and color.

We thank reviewer 3 for his helpful comments which helped us to improve the manuscript.

Summary:
The stated goal of this paper is to illustrate the effect of 3D thermal radiative transfer on simulated clouds. This is done by simulating a single plume cloud and a field of oceanic cumulus clouds using suite of thermal radiation configurations, ranging from no radiation to 3D thermal radiation. While this is an interesting study it is not clear what new information is brought forth. There are papers in the literature which discuss the effect of turning radiation on and off and the effect of using average instead of local radiation. New results should be the effect of interactive 3D thermal radiative transfer on the simulation but the author has missed, or at least not referenced, a key paper which has presented this sort of experiment. In addition, the results from single simulations are not particularly convincing of a clearly different response when using 3D, versus ICA, thermal radiative transfer.

With these comments in mind, I suggest that the authors perform a major revision of the paper taking into account the comments below and previous results in the literature.
General comments:

Single cloud results: I would say that the results when using 1D and 3D thermal RT are almost indistinguishable and it would be challenging to read much into these results. For example, if you performed the simulations with 1D thermal RT again, or several times, but with a small random perturbation, I suspect the results would be about as different as that between the 1D and 3D. The main thing I can take from these simulations is that interactive "local" radiation has an influence versus no radiation but the complexity of the radiation parametrization doesn't seem to be too important, at least for the variables included in the analysis.

The differences between 1D and 3D thermal radiation in this application are indeed not large. The main result is a stronger downward motion at the clouds side. However, to our knowledge, no direct comparison between the 1D and 3D thermal radiation effects on the development of a single shallow cloud exist. The study of Guan et al., 1997 only compares a no-radiation to a 3D radiation simulation. With this analysis, we tried to bridge the existing gap.
The effects of 3D thermal radiation may very likely depend on the amount of cloud side cooling, which again depends on the cloud side area. Our simulations produce clouds that are much broader than high. Therefore only small cloud side areas exist, which might also limit the 3D effects. The performance of the NCA might be another reason why these differences are small. We included an additional subsection in the revised manuscript where we address the performance of the NCA.

Cloud field results: I have the same comments here as for the single cloud experiment. For most of the variables the differences between results for 1D and 3D "local" thermal radiation are very similar. Is there an expectation that ensembles of simulations would show the differences to be statistically significant?

We added more discussion on the 100m resolution simulation, where 3D effects are stronger. As also commented, this is a rather surprising result, but we found that the NCA neglects some of the cloud side cooling early in the simulation in the 50m resolution simulation which might reduce the 3D effect significantly. We agree that running an ensemble would be useful to interpret results, but the simulations are quite expensive. By adding the 100m solution (which we repeated three times for the same setup) we actually increased the difference between 1D and 3D results, explaining that the 3D approximation misses part of the cloud side cooling at 50m resolution.

Specific comments:

Title: It does not accurately reflect of the contents of the paper. The 3D thermal radiation is a relatively small part of the paper and the paper focuses on a very particular types of cloud. I.e, I don't think the results could be generalized to all clouds.

We changed the title to: 'Effects of 3D Thermal Radiation on the Development of a Shallow Cumulus Cloud Field'

References: The highly relevant paper by Mechem is missing:
Mechem, D. B.; Kogan, Y. L.; Ovtchinnikov, M.; Davis, A. B.; Evans, K. F. & Ellingson, R. G. Multidimensional Longwave Forcing of Boundary Layer Cloud Systems Journal of the Atmospheric Sciences, 2008, 65, 3963-3977.
There are some papers that have discussed interactive cloud resolving simulations considering aspects of 3D solar radiative transfer:

Koracin, D.; Isakov, V. & Mendez-Nunez, L. A cloud-resolving model with the radiation scheme based on the Monte Carlo method Atmospheric Research, 1998, 47-48, 437-459
Frame, J. & Markowski, P. Numerical Simulations of Radiative Cooling beneath the Anvils of Supercell Thunderstorms Monthly Weather Review, 2010, 138, 3024-3047

And there are papers that discuss the effect of using domain mean radiative fluxes (here I give just two examples, I am sure there are others),
Petch, J. C. and Gray, M. E. B. (2001), Sensitivity studies using a cloud-resolving model simulation of the tropical west Pacific. Q.J.R. Meteorol. Soc., 127: 2287–2306. doi:10.1002/qj.49712757705
Cole, J. N. S.; Barker, H. W.; Randall, D. A.; Khairoutdinov, M. F. & Clothiaux, E. E. Global consequences of interactions between clouds and radiation at scales unresolved by global climate models Geophysical Research Letters, 2005, 32, L06703

We added the missing papers and even more to the introduction and the discussion of the results.

Introduction, long paragraph stating at line 3, page 2: This paragraph is challenging to read and needs to rewritten since in its current state it comes across as an "information dump". From it reader needs to pull together information needed for the remainder of the paper. Breaking the paragraph into at least two would help as would putting the information into an order that fits with rest of the paper. I.e., general effect of thermal radiation on cloud development, previous results 1D versus 3D thermal radiation and a justification for examining local versus non-local radiation (1D versus slab averages) with discussion of previous results.

We restructured the introduction according to the suggestion and added the suggested literature.

Page 2 line 14: The discussion of the Guan study is a bit unclear since that study compared 3D thermal radiation against the case of no radiation, not versus 1D radiative transfer,

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The Guan study is discussed in more detail in the rewritten introduction.

Page 3, paragraph at line 5: Did you add modify the equations used for the cloud
microphysics to explicitly model enhanced emission by drops? My understanding of the papers by Harrington is that a term for the radiative heating and cooling of the drop is considered. If you did not add drop cooling to the microphysics the interpretation of this paragraph is tricky.

We did not modify the microphysics parametrization. We added in advance of this paragraph in the introduction the following sentence:
'The microphysical aspect mentioned before will not be addressed in this study, however, for the matter of completenes, we will briefly point out what was found in the past:'

Page 4, line 23: Is the shape of the cloud that sensitive to the structure of the perturbation?

Not necessarily, however, by chance the random numbers could be distributed in a way that produces a very different cloud. To avoid that we used the same random numbers to make sure that we really apply the radiative transfer to the same initial cloud.

Page 5, line 27: Why not show the clouds simulated using the 3D thermal RT? Would it not be the most realistic? Also showing the cloud field at the 20 minute point does not make sense given the discussion in the text. The text it is pointed out that it is cloud field in the period 40-80 minutes that are to be the focus of the analysis. Why not show the cloud at that point?

As this figure was only meant to give the reader an idea about the shape of the cloud, we chose an early time step where the clouds are still pretty similar. But we changed the figure according to the suggestion.

Page 6, line 13: The meaning of this statement 'from about 30 min onward the cloud stays rather constant at a certain height' is not clear. What exactly stays constant (liquid water path?)?

What we meant is that the cloud stays in one height and does not rise further up as it has until this time step. We changed the sentence as follows: '... 30 min onward the cloud stays rather constant at a certain height and does not rise any further ...'

Page 6, line 15: This sentence,
"All simulations show that the liquid water path (top row of Fig. 3) is reduced by thermal radiation in this "second stage" (from about 20 min to 40 min)."
is not clear. The same reduction is seen in all simulations without any radiation. Do you mean to say that thermal radiation causes liquid water path to be less than the case with no radiation? This difference is pretty small.

We deleted 'thermal radiation' in the sentence

Page 7, lines 1-27: This analysis seems to end abruptly or I'm missing something. There is an idea of "subsiding shells" to explain the subsidence around the edge of the cloud. As mentioned in the text, Heus and Jonker, 2005 attribute the presence of the shell to "negative buoyancy, resulting from evaporative cooling following lateral mixing of environmental air with cloudy air.". The results with thermal radiation have downdraft shells that are stronger than that in the no-radiation case.
Is it not possible to use the output from the model to further analyze and show why the shell is enhanced in the presence of thermal radiation? Is it the radiation directly producing more negative buoyancy, Figure 1 suggests large radiative cooling, or does it induce an environment that enhances the evaporative cooling? It must be possible to quantify statements like "This might be due to the thermal cooling at cloud tops, and in case of 3D Thermal NCA radiation at cloud sides." and "The stronger horizontal buoyancy gradient (difference between positive and negative buoyancy in Fig 6) generates enhanced turbulence and therefore stronger evaporation.".

Figure 6 shows the profiles of positive and negative buoyancy. This figure is useful in two ways. First, it shows that both thermal radiation simulations have larger values of negative buoyancy, which, as pointed out by Heus and Jonker, leads to the development of the subsiding shell. It is therefore the direct cooling of the thermal radiation which initiates the subsiding shell at first.
Second, this figure shows the horizontal buoyancy gradient which can be used to indicate evaporation at the cloud side. As the horizontal buoyancy gradient is stronger in case of the thermal radiation simulations, more evaporation is occurring, reducing the diameter of the cloud as seen in Figure 5. At the same time, there is of course more evaporative cooling produces. With our current simulations, it is not possible to differentiate at this point, if thermal radiation or evaporative cooling is driving the subsiding shell any further. But thermal radiation certainly initiates the development.
We modified this passage and hope that it is more precise now.

Section 3.2: What is special about the "restart time" at 3 hours? Was the model run differently up to this point?

We chose the restart time at 3h, as it is the time after spin up and where the

first clouds occur. For all simulations, the model run is therefore the same until this point. The initial simulation was driven by 1D solar and thermal radiation. From 3 hours on, we apply the different radiation setups. We modified our description in the model setup (section 2.1) as follows:
'All simulations are restarted and analyzed after a 3~h initialization run. Until 3~h, the initial simulation is driven by 1D solar and thermal radiation. From the restart time on, we switch on one of the five thermal radiation application or switch radiation off, thus skipping the spin-up. At 3~h, the first clouds form in the initial run.'
We show the figures from this time on, to see the development from the same initial state of all simulations.

Page 8, line 15: Are the liquid water path and other variables shown for this case averaged over the entire domain or sampled only over clouds?

Domain variables, if not otherwise stated are sampled in the entire domain. We added this information to the text.

Page 8, line 17: How robust are these results?

The differences do indeed not seem to be large. We would love to repeat he simulations various times and look at the statistical significance, however this was due to computational cost and storage space not possible. We repeated the simulation on 100m resolution and find (in 3 simulations there) the same behavior. It is clear however that 3 simulations are still not enough to provide statistical evidence. From other variables it is however clear that there is a definite difference between averaged and local radiation. For the liquid water path this might simply be smaller, as the cloud cover is higher in the averaged radiation simulations, but more liquid water is found in individual clouds (see e.g. max. liquid water content) in the local radiation simulations. This might lead to the small differences in this case. We added to this sentence:
'This differences are small however and might be a result of the larger cloud fraction but less maximum liquid water of the averaged radiation simulations versus the reduced cloud cover and higher maximum liquid water content in the local thermal radiation simulations.'

Page 8, line 19: Is it an expected result that "All quantities increase over time.". If you continued running the simulation would it go into a quasi-equilibrium state?

It is in some way expected as we add more and more cooling to the system by the thermal radiation, but do not allow for rain. Therefore more and more water should condense, cloud cover should increase and at some point (if we would drive the simulations longer), we would get a cloud cover of 100%.

Page 8, line 20: Remove this sentence as it is obvious,
"The different development of the No-Radiation simulation and the radiation simulations is related to the missing cooling of the thermal radiation in the No-Radiation simulation."

The sentence is removed.

Page 8, line 23: Why does the lack of thermal radiative cooling lead to a higher cloud base? It is not clear to me.

Simply by a shift of the condensation level. The temperature profile is shifted by 1-2 degree to higher values in the no-radiation simulation. Therefore condensation will take place further up in the atmosphere where it is cooler.
We modified the sentence as follows:
'The higher cloud base is also a result of the missing cooling which leads to a warmer temperature profile in the No-Radiation simulation'

Page 8, line 25: I don’t think you want to use the term "bias" here, perhaps the word "change" instead?

We changed the word to 'change'.

Page 8, line 26; Perhaps a clear term than "interactive" would be "local" since the
"averaged" radiation is also interactive since it still reacts to changes in the clouds.

We changed 'interactive' to 'local'.

Page 8, line 29: What is so interesting about the liquid water path and maximum liquid water content?

It is interesting that the liquid water path and maximum liquid water is lower, while the cloud cover is higher in the averaged radiation simulations. We changed the sentence to: 'Liquid water path and maximum liquid water content develop in the opposite direction: both are lower for the averaged radiation simulations until 20 hours'

Page 9, line 4: The rate of increase in cloud fraction for the "interactive" radiation after hour 22 is nearly as large as for the averaged radiation. How does this fit into the organization hypothesis?

This sentence is removed in the revised manuscript. Earlier in the text it is revered to development of the cloud field after 20 hours in the following way:
‘It shall be mentioned here (although not shown) that from about 24 hours on, large clouds form in the averaged radiation simulations and the const cooling simulation, in which the clouds oscillate: disappearing and then reappearing. No systematic difference between 1D and 3D radiation is found in these cases. The local radiation simulations still show cells, however, clouds become larger, especially in the 3D Thermal NCA simulation.’

Page 9, line 13: Initial profiles in first column not first row.

We changed the text accordingly.

Page 9, line 26: How significant is the approximately 5% greater liquid water content in the 3D NCA simulation at hour 10?

As pointed out before, it was not possible to re-run the simulation various times. The differences are indeed not large at this point in time but a tendency of what is happening in the following can already be seen. The liquid water path at 20h shows already a difference of 10%.

Page 9, line 33: Figure 11 first column, not Figure 11 (second column)?

We refer indeed to Figure 11, second column. The sentence before relates to the increased buoyancy production at 10hrs, which is shown in the second column.

Page 10, line 1: The 3D NCA simulations produce slightly more TKE through buoyancy in the upper cloud with stronger upward and downward vertical winds. Again, is this significant? As discussed further down in this section the more significant result is that horizontal averaging causes more significant differences.

We fully agree that there is more difference between the averaged and the local radiation simulations then between 1D and 3D thermal radiation simulations. However, we find stronger 3D effects in the 100m resolution simulation and explain this in the revised paper. Essentially, in the 50m resolution simulation the NCA misses some of the cloud side cooling, wherefore the 3D effects are only very small.

Page 10, line 24: From the results shown I would suggest that it is not conclusive that "3D Thermal NCA" increases the results shown. The differences relative to 1D ICA are quite modest and it is not clear if they are by chance or systematic.

We changed the sentence to:
'3D Thermal NCA radiation, in comparison to 1D thermal radiation shows a slightly stronger increase of these shown effects by an additional cloud side cooling and overall stronger cooling in the modeling domain.'

In general, we tried to point out throughout the text of the revised manuscript that 3D effects seen in these statistical variables show usually slightly higher values, but only slightly.

Page 11, line 2: spacial -> spatial

We changed the text accordingly.

Page 12, line 14: Can you quantify that "we find larger structures earlier in the 3D Thermal NCA radiation simulation"? Staring at the plots for 1D ICA and 3D NCA in Figure 14, it is not clear how one objectively comes to this conclusion. The color contouring gives some bias toward clouds with larger liquid water path, not necessarily larger cloud structures.

We added an additional figure of the cloud field which hows the spatial distribution of the clouds.
The above conclusion comes from a combination of the autocorrelation, looking into the data and the hovemoeller diagrams. We have rewritten this paragraph and hope it is more clear now.

Section 3.2.3: Were 3 simulations performed for each radiation configuration? If so, did the "small differences" lead to a stronger or weaker case for differences between the 1D and 3D interactive simulations? The results of the simulations, especially 3D NCA, seems rather sensitive to horizontal resolution (Figs. 17 and 18). Any speculation as to why? Should we expect different results if we reduced the horizontal resolution to 25 m?

We added the additional two runs in two figures in the revised draft to show the differences in the simulations. The new and additional chapter about the performance of the NCA shows why we see a stronger 3D effect in the 100m resolution simulation. Increasing the resolution to 25m is with the NCA not appropriate at present. It would require further development of the parametrization. Following our conclusions here, we would get 3D effects at 25m resolution with an improved parameterization.

Page 14, line 25: It is not a strong or clear result in this paper that the 3D interactive radiation is significantly stronger than the 1D ICA radiative transfer. Therefore, this statement is not well supported.

The conclusion is rewritten.

Table 1: Horizontal resolution does not match with text, 100 m in table and 50 m in text. If it is the latter then number of gridboxes is incorrect since domain size is quoted in text to 6.4 km by 6.4 km.

The tables are moved to the main part of the text as suggested by reviewer 2 and are consistent with the text now.

Figure 5: It is very difficult to read this figure. For example, the dashed lines are almost impossible to see on the printed document. For this figure titles indicating which are symmetric cloud and which are non-symmetric clouds is warranted.

We modified the figures accordingly.

Figures 10 and 11: The solid versus dash in the legend is very difficult to make out.

We modified the figures accordingly.