Response to Reviewer 2

We thank the reviewer for the constructive comments to the manuscript. We especially appreciate the reviewer pointing out the clustering of cold pools as a matter of interest. We have therefore included a discussion about clustering in Section 3.1 and in the discussion section.

ACPD-13-11023-2013: Aircraft observations of cold pools under marine stratocumulus by Terai and Wood

This manuscript investigates the properties of cold pools found under marine stratocumulus on small and large scales from an extensive set of aircraft and satellite-based observations. The manuscript is very well written and provides a useful overview of cold pool properties that were known before but probably not documented as extensively as done here. I recommend minor revisions that mostly concern a more concise write-up of the composite results and a further exploitation of the observations to study an interesting aspect that the authors touch upon, that is, the clustering of multiple cold pools, as well as how the clustering affects the composite properties of the cold pools on smaller scales in the second part of the paper.

General comments

1. One of the first interesting results that the authors point out is the clustering of cold pools i.e., one often finds smaller cold pools within larger cold pools. This immediately triggered questions such as whether the localized cold pools inside larger cold pools show enhanced drizzle rates, a different cloud depth, etcetera. Such questions could be addressed with this dataset, but do not come out in detail using the composite analysis that the authors perform, because the anomalies of the smaller cold pools will be much smaller than that of the larger cold pools. In Figure 11 and 12a the authors do plot anomalies calculated using the edge of each cold pool, but for the other variables no anomalies are taken. For something such as the precipitation rate, any difference across a small cold pool edge will therefore be overshadowed because it is embedded in a larger cold pool that already has a different precipitation environment. Would it be helpful to instead scale or normalize precipitation and cloud tops/LWP's by its value at the cold pool edge?

We agree with the reviewer that from the composite figures alone one cannot determine whether any differences exist between cold pools that are embedded within larger cold pools and cold pools that are larger or stand alone. Since it would be interesting to see whether embedded cold pool edges are different from those that are not embedded, we looked at the temperature differences across the cold pool edges that were found embedded within larger cold pools. Of the total 90 identified edges, 43 of them were found embedded in a larger cold pool feature. In the plot below, the composite of temperature change across embedded cold pools is plotted in red, compared to the temperature composite based on all edges. No discernible differences between the two can be found.

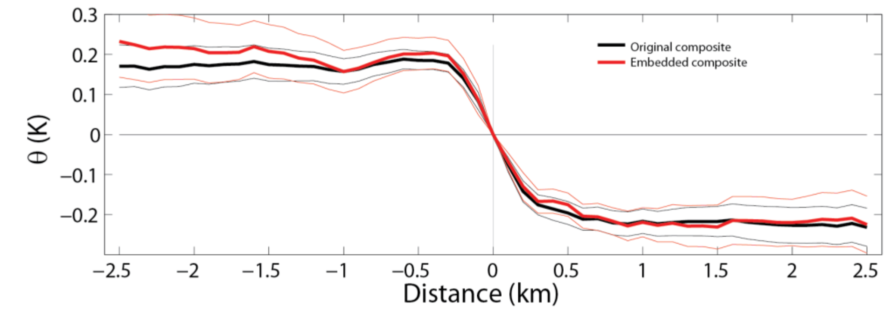


Figure: Theta composites from embedded cold pools

We also examined the changes in precipitation rate across the embedded cold pool edges to address the reviewer's concern that precipitation changes may be overshadowed by edges of larger cold pools. As in the plot above, the precipitation composites from the embedded edges are plotted in red, while those from all edges are plotted in black. We can see that the whole precipitation rate is shifted to higher precipitation rates, which implies that embedded cold pools are found in environments with higher precipitation rates. However, we also see that the change across the embedded edge (the slope) is not drastically different compared to the change across all edges. Since the y-axis is in log-scale, this suggests that the fractional increase in precipitation across the cold pool edge is not different whether we are looking at cold pools that are embedded in other cold pools or not. Furthermore, because we plot the 25th, 50th, and 75th percent values, we do not expect the larger precipitation rates to overshadow the changes seen across the edge in the first place.

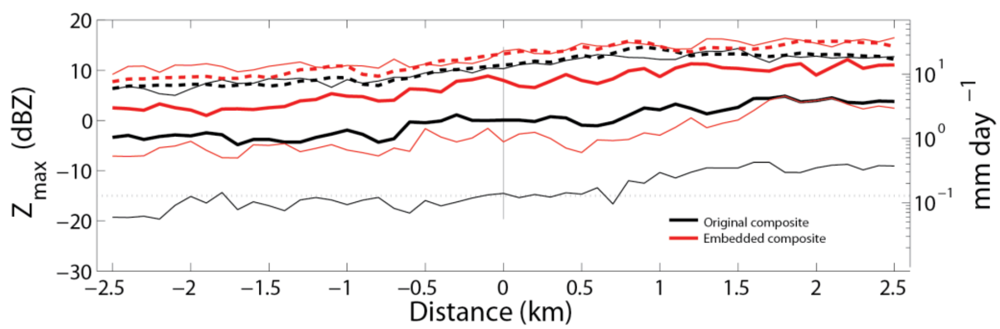


Figure: Precipitation composites from embedded cold pools

To summarize what we have found in looking at embedded cold pools, we have inserted the following at the end of Sect. 3.1:
Indeed the clustering of cold pools is so common that of the 80 identified cold pools, 42 of them were found embedded within a larger cold pool. Although comparisons of the edges do not reveal systematic thermodynamic differences in the airmass of the embedded cold pools, the precipitation rate over the edge of embedded cold pools tend to be higher.

2. In section 4 of the paper, and especially from section 4.3 onwards, the writing gets rather descriptive and long, and the manuscript would benefit from a more concise write-up, and possibly (some of) Figures 11-15 could be combined into one larger panel Figure. I also recommend moving the analysis at the end of 4.4 (the two box calculation and its *discussion) into a separate paragraph/section, where both the enhanced chemical tracers as well as the temperature depressions and humidity enhancements are simultaneously addressed after a clearer description of how the box calculations are performed, what assumptions are made, and what questions it can address. Can you state that you solve the temporal increase of a given tracer over a given depth by the surface flux, and be more clear about what you mean with the different heights of the two boxes (line 23, P 11043). Since it is such a simple calculation, why don't you do it separately for the decoupled layers and the coupled layers, that have different mean mixed layer heights? (first paragraph section 11044)*

Regarding a more concise write-up, we have gone through the manuscript again to see how the writing may be tightened up, but found that the descriptiveness is necessary to address why and how certain atmospheric state variables were composited across the cold pool.

We agree with the reviewer that the two box model calculations should be given a separate section, which we have put under Section 4.5. We have also state early in the section that '**We are interested in testing whether the differences [in DMS and coarse mode aerosol concentrations] can be obtained over time scales that are comparable to the lifetime of cold pools.**'

The height pertains to the mixing height in the two boxes. We have replaced the existing sentence with the following sentence:

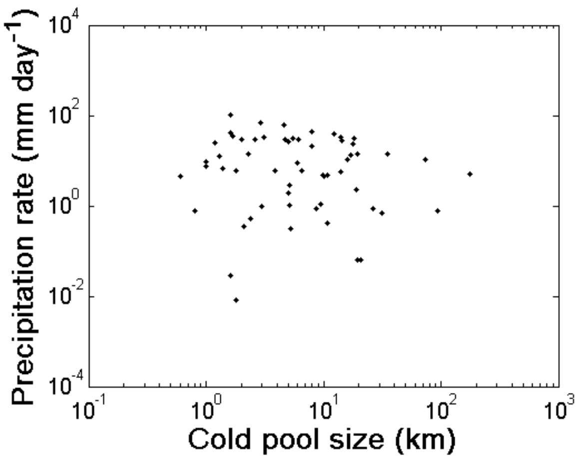
~~Therefore, the different heights of the two boxes drive any concentration differences and these differences grow linearly with time.~~ **Therefore, differences in the rate of concentration increase between the two boxes will be driven by differences in the height of the two boxes over which the surface fluxes are mixed.**

In regards to separating the calculation, we do not think that doing the calculation separately for decoupled and coupled layers will be informative. Aside from using different mixed layer heights to obtain the time scales, the calculation requires different observable inputs (CDP concentration, RH, wind speed, and cold pool depths) for the two BL cases. For example, the relative humidity in the coupled boundary layer outside the cold pool is 67%, compared with 76% in the decoupled boundary layer. The CDP therefore measured a different dry aerosol size range in the two cases. This makes it difficult to disentangle the factors that lead to the different timescales that would be obtained from looking at coupled and decoupled boundary layers.

Specific comments

- Figure 7 and Figure 8: Would it be interesting to scale the size of the individual markers by the mean size of the cold pools along each leg? This would bring out relationships between the cold pool size and drizzle rates respectively cloud top heights or depth, and would provide an interesting link between the analysis shown in Figure 4 and 5 and those in the subsequent figures.

Although it would be interesting to connect cold pool size with other variables, we find that the correlations are weak. To see whether a correlation existed between the cold pool size and precipitation rate, we plotted the mean precipitation rate inside the cold pool against the size of the cold pool, much like Fig. 5, but for precipitation rate instead of temperature difference. The plot is shown below. As we can see from the figure, there exists a very weak anti-correlation. Therefore, we find that scaling the size of the markers according to the mean size will not be as informative. We also are reluctant to change the size of the markers, since larger markers would imply more importance, when our intent is to treat each leg with the same weight and ask how cold pool occurrence correlates with environmental conditions.



- P. 11027, line 26: It would be interesting if the authors can provide a few short notes of the largescale conditions experienced during this period and in this region, e.g. by how much do large-scale parameters such as SST and LTS change across the region used?

On P. 11027 after, 'This dataset is appropriate for studying cold pools in a large range of potential stratocumulus conditions,' we have included the following sentence. '**Along 20S, sea surface temperatures from 75W to 85W increase from approximately 17.5 to 18.5C (Bretherton et al., 2010), while lower tropospheric stability over the same distance decreases from approximately 26 to 23K (Toniazzo et al., 2011).**'

Toniazzo, T., Abel, S. J., Wood, R., Mechoso, C. R., Allen, G., and Shaffrey, L. C. (2011). Large-scale and synoptic meteorology in the south-east Pacific during the observations campaign VOCALS-REx in austral Spring 2008. *Atmos. Chem. Phys.*, 11(10), 4977-5009.

_ *P. 11032, line 24: What is meant by outside the cold pool? Is it just outside the edge of the cold pool (mentioned later in section 4.1), or some average over a certain distance outside the cold pool?*

By outside, we mean the mean quantity just outside the cold pool over the 2.5 km segment from the edge. Because the cold pools have two edges, we have taken the outside temperature to indicate the mean temperature of the 2.5km segment surrounding the cold pool on either side. To clarify, we have included the following sentence: '(Spearman rank correlation of -0.76, Fig. 5). **To obtain the temperature outside of**

cold pools, we take the mean temperature from the 2.5 km segments on either side of the cold pool.'

_ P. 11032, line 25: The authors write that larger cold pools require sustained cooling. What is their thought on the causality of the relationship between cold pool size and cooling? Would it be better to write that more cooling leads to larger cold pools?

Because the larger cold pools are associated with embedded cold pools, we believe that the large cold pools form from having multiple cold pools forming on top of each other. The larger cold pools are colder not because the precipitation rates in the larger cold pools are higher, but because they are associated with cold pools forming on top of each other and forming cold pools in an existing larger cold pools. This requires the mesoscale feature of the cloud field overlying the cold pools to consist of multiple precipitation cells, which may indeed be the causal link between the cold pool size and cooling.

To clarify this point, the paragraph has been rewritten such that it reads:
We find a strong negative correlation between the cold pool size and the mean temperature difference between inside and outside (2.5 km mean temperatures from both sides of the cold pool) the cold pool (Spearman rank correlation of -0.76, Fig. 5). **This strong correlation suggests that more cooling leads to larger cold pools. When taken with the finding above that large cold pools are associated with clusters of cold pools (Fig. 3), however, we speculate that large cold pools are not formed from larger or more intense precipitation cells, but from the clustering of multiple cells. Indeed, the mean precipitation rate over the cold pool and its size do not correlate well.**

_ P. 11034, line 6-10: The fact that precipitation and cold pools not necessarily need to be correlated (i.e., there is a time lag involved) is an interesting one that is not mentioned again when studying the composite precipitation characteristics inside and outside the cold pools in section 4.3. One could even imagine that precipitation rates and temperature depressions are de-correlated because once most of the precipitation has evaporated (low precipitation rates) the air is the coldest. The authors do not correlate precipitation rates and temperature depressions alone, which would be interesting to see, and is not evident from the composites per se.

We have correlated the difference in radar reflectivity and temperature depressions below. The correlations are based on looking at the temperature and reflectivity differences between 2.5 km segments inside and outside of the cold pool from the edge. The correlation plot shows that larger temperature depressions are not indicative of stronger precipitation rates.

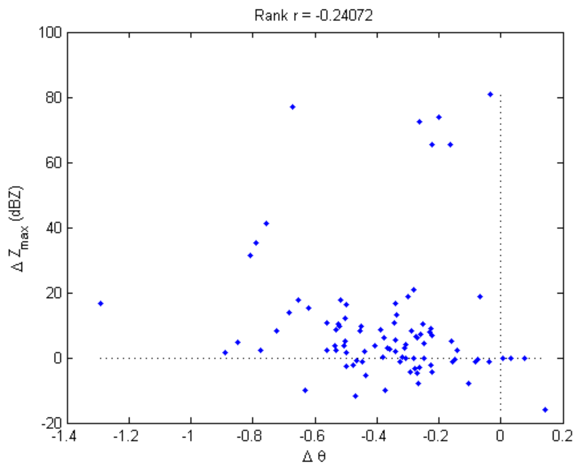


Figure: Correlation between potential temperature and radar reflectivity differences between inside and outside of the cold pools. 2.5km segment-means from the cold pool edge are used to indicate inside and outside.

_ *P. 11035, section 3.4: The authors have clearly stated that regions with higher cloud tops are characterized by more rain (and thus more cold pools). The obvious question here in finding out what makes certain areas more prone to cold pool formation than other regions is thus what (large-scale parameters) allow for clouds to become deeper initially? The authors do not mention factors such as lower tropospheric stability, SST or subsidence rate, and although that goes beyond the scope of this study, it would be a good question to mention when discussing explanations of why one region has more cold pools than others.*

As discussed by Bretherton et al. (2010), the westward increase in inversion height can be explained by a westward decrease in tropospheric temperature, while increased radiative cooling to west and decreased divergence can also play a role in increasing the BL height. Temporally, the boundary layer height can change over synoptic time-scales from caused by ridging and troughing in the free troposphere over the VOCALS region (Toniazzo et al., 2011).

We mention the connection of BL characteristics and large-scale parameters in the discussion section, which is pasted below.

_ *P. 11040, line 1-8: How I interpret the writing in this section is that the vertical velocity field can have perturbations or anomalies that are as large as the differences in mean vertical velocities between different flight legs. But I may be misinterpreting this. The authors may want to specify what is the standard deviation of vertical velocity within one flight leg, which as I read it can be quite small ("negligible ascent or descent away from the edge").*

The vertical wind speeds in the surface legs are not negligible. As stated, the standard deviation of the vertical wind speed is 0.37 ms^{-1}, which is larger than the anomaly we see at the edge in the Fig. 12c. Because the sentence, 'There is negligible

ascent or descent away from the edge,’ causes confusion, we have combined the sentence with the next sentence so that it now reads:
In the composite mean, there is no systematic ascent or descent away from the edge, but it should be noted that the vertical wind anomaly exists in a background where the standard deviation of vertical wind speed is 0.37 ms^{-1}.

_ P. 11040, line 23-27: I do not follow this train of logic entirely. Do the authors mean that the lower cloud base could be due to the radar misinterpreting drizzle below clouds as cloud base? Probably not, because they use the lidar to derive cloud base height. If the authors mean that the lowered cloud base could be a thermodynamic effect of the cold pools produced by heavy drizzle (lowered LCL), then they should say so, or is there another effect that I am missing?

The explanation we gave may have been confusing. What we are addressing here is that the cloud base height may be lower over the cold pool because cold pools tend to form over heavier precipitation, and heavier precipitation form under thicker clouds. Therefore, we can observe thicker clouds over cold pools just because cold pools tend to form over heavily precipitating clouds thicker clouds and not because cold pools tend to lower cloud bases. From the data alone we cannot distinguish between the two.

To clarify, we have stated the following:
From the composites along we cannot conclude that the decrease in cloud base height over the cold pool is a sign of the dynamical impact of cold pools on the clouds. **Because cold pools tend to form under heavier precipitation, the thickening that we see may just indicate that cold pools form under thicker clouds that tend to precipitate more.**

_ P. 11045, discussion: it would be nice to have the discussion aligned according to the investigation of cold pools on large scales and on small scales. Line 16-17: ”we first examined the large-scale environment that accompanies cold pools”, i.e., what makes a region more prone to cold pool formation, and then investigate the cloud and environmental properties across the cold pool edge in more detail.

Our intent was to divide the first two paragraphs of the discussion section into the large-scale features that accompany cold pool formation and the small-scale changes that were observed across the cold pool edge, as is suggested by the reviewer. Because some results from the small-scale analysis had made its way into the first paragraph, we rearranged parts of the discussion such that the separation was more apparent. The discussion now reads:
Modeling and observational studies have suggested that cold pools initiate transitions from closed to open cellular stratocumulus clouds (Savic-Jovcic and Stevens, 2008; Xue et al., 2008; Wang and Feingold, 2009; Feingold et al., 2010; Berner et al., 2011). This study systematically examines cold pools that form in the southeast Pacific using aircraft data. We first examined the range of MBL and cloud conditions that accompany cold pools, finding that cold pools form preferentially under heavily drizzling clouds (>1 mm d^{-1}). This explains why cold pools are common further offshore where the MBL is deeper, clouds are thicker, and the aerosol concentrations are lower. Satellite microwave data show high values of cloud LWP during the night prior to the observed cold pools, but do

not show high values of LWP during the previous afternoon. This suggests that understanding the factors controlling how high values of LWP are produced overnight will be important for predicting heavy precipitation and cold pool formation. In terms of size, the observed cold pools in this study have horizontal extents that are roughly lognormally distributed with 50% of them between 2 and 16 km. Some cold pools are larger than 100 km and these tend to be associated with **cold pools clustered and embedded in other cold pools, as found within** POCs. Instead of forming separately, these cold pools tend to cluster together with new ones often forming on top of older ones, stressing the importance of understanding how cold pools interact with each other to affect boundary layer processes.

Although we have examined the MBL conditions that correlate with cold pool occurrence, we are limited by a single snapshot from the time of cold pool sampling and have not addressed the relationship between cold pool occurrence and **large scale parameters, such as tropospheric temperatures, sea surface temperatures, and subsidence rates, which all act to modify the geographic and temporal variations in MBL depth and conditions over the VOCALS region. Because cold pools preferentially form where large scale parameters favor the stratocumulus-to-cumulus transition, it remains to be seen whether and to what extent the cold pools play a role in the cloud break-up.**

Composite cold pools show that numerous variables change between the cold pool air and its environment, as summarized in Table 1 and Fig. 16. **Whereas the analysis of leg-averages shows that cold pools tend to form under heavier precipitation, the composites further demonstrate that precipitation near the surface is a better indicator of cold pool formation than precipitation at cloud base. Unlike in the analysis of leg-averages, however, we do not see a drastic change in the composite of cloud top height across cold pool edges, indicating that not all large scale parameters that make the MBL prone to cold pool formation are reflected in the changes at the smaller scales.** The composites do show that consistent with previous measurements of cold pools under marine stratocumulus, drops in temperature are accompanied by increased water vapor, convergence and associated uplift at the edges, and enhanced θ_e values inside the cold pool. Additionally, we find an increase in DMS and coarse-mode aerosol concentrations, both of which provide important evidence that cold pool-induced stratification concentrates surface fluxes in the cold air near the surface. From the observations alone, we cannot address whether the dynamic or thermodynamic effects of the cold pools are more important for changing MBL structure. We do find, however, that the significant drop in LCL inside the cold pool is largely due to the q_v increases instead of the θ decreases. This means that if cold pools form where clouds are thicker and cloud bases are lower due to lower LCL, then the lowered cloud bases is a result of the cold pool trapping surface fluxes near the surface. The modeling study of Savic-Jovcic and Stevens (2008) point out this importance of cold pools in transitioning from closed-cell to open-cell convection. Furthermore, the dynamic and thermodynamic effects of the cold pool can be thought of as how cold pools vertically and horizontally concentrate moisture (thermodynamic) and how that gets lifted into the cloud layer (dynamic). We also find that unlike cold pools that form under deeper cumulonimbus clouds (Goff, 1976), wind gusts associated with the cold pools under stratocumulus are almost always smaller than the mean wind speed in the SEP. This means that, by themselves, cold pools cannot drive upstream propagation of POC boundaries (Fig. 2 of Wood et al., 2011a). It also means that changes in surface fluxes inside the cold pool that are driven by changes in wind speed are small.

There remain a number of questions that cannot be addressed from observations alone. We find that cold pools indeed exert dynamic and thermodynamic effects on the MBL. What then is their role in organizing and influencing further precipitation? **Is the clustering of cold pools that we observe just an imprint of environmental conditions, or do cold pools play a role in the clustering?** Can the dynamic effect of cold pools alone increase precipitation in a cloud field? Modeling studies of Xue et al. (2008), Feingold et al. (2010), and Wang et al. (2010) have tackled this using a variety of experiments, but it remains to be seen whether a dynamic or thermodynamic feedback between precipitation and cold pools is necessary to transition from overcast stratocumulus to one of broken cumulus clouds.

One interesting difference that does not come out that clearly in the discussion, is the fact that clouds are deeper (which I interpret as clouds having greater cloud top heights) in regions with cold pools offshore, from a large-scale perspective. From a small scale perspective, there is however no discernible difference in cloud top heights.

To address this point we have included in our discussion that certain factors like cloud top height do not vary as much over smaller spatial scales as others (see discussion section pasted above).

Typo's/errors/graphics
_ P. 11044, line 4: strange sentence: rewrite to: "... and qv is lower in the cloud layer than in the surface layer"

We have applied the suggested rewrite.

_ Figure 3: why are not all cold pool edges marked by a red triangle? is the yellow cold pool an example of a cold pool that gets excluded from the analysis because its rightmost edge is not detected?

The red triangles indicate all edges detected by the θ threshold criteria. The other edge of the cold pool was determined by the method described in Sect. 3.1. The size of the yellow cold pool was included in the analysis because the temperature recovered to the given temperature. An example of a cold pool size that was not reported is shown below. In this example, the temperature never recovered to that at the edge before the end of the flight leg, therefore we do not have any knowledge of how much further the cold pool extended, and hence its partial size is not included in obtaining the size distribution.

_ Figure 5: y-axis reads "di erence" instead of "difference"

We have checked the figure, and find that the 'ff' are visible.

_ *Figure 11-15: It may be helpful to put: "Inside cold pool" and "Outside cold pool" on the top of each figure.*

We have added them to the figures.