Response to reviewer # 2, Anonymous Referee
P. R. Lindgren et al.

Comment on "Detecting methane ebullition on thermokarst lake ice using high resolution optical aerial imagery"

We are very grateful to the reviewer for giving the time to read the manuscript in detail and for providing very valuable feedback. We have revised our manuscript based on the reviewer's comments. Below is our response to all the comments.

General comments:

The methods section would benefit from a summary paragraph, particularly one that describes the sampling strategy with which methods were used where and how. The methods is long and difficult to follow at times. I feel portions of it could be placed in a supplemental methods section. See specific comments for some suggestions. I also suggest how to split some sections for easier reading.

Thank you for your valuable feedback. We realize that our method section has a lot of information and it can be difficult follow. We have now provided a summary paragraph in the Methods. We have re-arranged and sub-divided sections to make this section easier to understand. We have also moved some portions of methods to the supplementary section to make the paper more concise and easy to follow. We have incorporated changes into the revised manuscript based on your suggestions. Our replies to specific sections are below in specific comments.

'Tiny-type' seeps do not add much to your story at all. Is this necessary?

We agree that introducing the Tiny-seep class in the Methods section is confusing to the readers since very little research has been done on this seep class. We have removed Tiny-type seep from the Methods. Since it was a late finding in the study, we have kept the discussion to explain the findings and the implications of Tiny-type seep in section 4.1 of the revised manuscript.

The results/discussion section has some very long sections that can be re-classified into more self-standing sections to help the reader follow along. I make specific suggestions below as to how to do this. I strongly urge the authors to consider these suggestions as the reader does tend to get bogged down with many details and perhaps lose the main point of each paragraph.

We appreciate your feedback. We have re-classified the Results and Discussion as suggested.

Section 5 should start with the positives, then discuss the negatives.

Thank you for your suggestion. We have rearranged this section. It starts with the positives.

Section 6 (conclusions) should lose the values and not repeat the abstract and results. The conclusion could be more concise and simply highlight the author's main points and their role in the big picture.

We agree that the Conclusion section is long and repeats the results. We have now shortened the Conclusion section by removing result summary and made it concise to highlight the major findings and significance of this study.

Specific comments:

1. **P7450, L5 – what does 'multi-temporal' mean exactly?**

   In this line, 'multi-temporal' refers to data acquired over more than a year. We have now removed 'multi-temporal' since we already mention years when data was acquired at the end of this sentence.

2. **P7450, L9-11 – 'Our aerial imagery thus. . .' sentence is confusing. How does the aerial imagery capture the events that occurred before image acquisition? I guess you mean that since the bubbles are frozen in ice that the image is capturing those events, but I think you should make this clearer. However, I think this sentence could also be left out.**

   We have mentioned that gas bubbles are trapped in lake ice as lake ice impedes the release of gas to the atmosphere in L8-9.

3. **Why is 'hotspot' capitalized? I think this is unnecessary and looks strange.**

   We understand your point that the capitalized hotspot looks strange. Hotspot is a name given to the highest flux methane ebullition seep in our study. We use it here as described and used by Walter Anthony et al. (2010; Limnology and Oceanography Methods) and other related studies.

4. **P7454, L13-end – It is not usual to reference a figure in the introduction already. Is this necessary? I believe this whole paragraph could be moved to the methods as a sort of summary of your very complicated methods section. And you can replace this paragraph here with a much shorter version of what you will describe without the use of the figure.**

   We felt important to reference a figure in the introduction to familiarize the readers how ebullition bubble patches look in high-resolution aerial images. So far as we know, there is no published study that uses high-resolution aerial images to understand methane ebullition dynamics on a lake.

5. **P7456 – Your methods are highly complicated to follow and I strongly suggest starting with a summary paragraph. You should list what the next methods sub-sections will be describe and be very specific as to the sampling strategy as you used multiple methods at different times and different years.**

Here you can specific in regards to when you sampled in terms of ice on/off and snow cover as this was not immediately obvious throughout the methods. A summary paragraph here will really help the reader through the methods.

We have added a summary paragraph in the Methods. Please see the reply above in general comment.

6. **P7456, L6 – how did you survey here? By plane?**

   We surveyed the lake perimeter and reference markers on the lake using Differential Global Positioning System (DGPS). We have now made it clear in the text.

7. **P7456, L18 – 'Tiny-type' sounds a bit informal. I understand that since you already have an 'A-type' that going smaller requires a new term. However, you also don't quantify the emissions from this tiny-type so you can use what you like in terms of a name. How about 'sub A-type' or 'diffuse' or 'mm-sized'? And again, the 'tiny-type' bubbles were not used much at all in the analysis and perhaps it can be left out entirely.**

   We have removed Tiny-type seep from the Methods. Please see the reply #2 above.

8. **P7456, L27 – the 60-80% CH4 in the bubbles is from the unpublished citation too, I presume. You should cite 'unpub' again.**

   We have cited 'unpub'.

9. **P7457, L4 – 'of the lake area' – add the 'a' at the end of 'are'**

   'a' is added at the end of 'are'.

10. **P7458 – In general, I think these few paragraphs are very difficult to follow. I strongly urge the authors to perhaps shorten it to only the most useful information and put the rest in a supplemental methods section. I found Fig. S1 to be very useful in understanding the classification system; however, the figure caption for S1 is much easier to understand than the text in the manuscript. I suggest using the figure caption wording and expanding to what is necessary in the main text of the manuscript.**

    Thank you for your feedback. To make it clear, we have now simplified the section by expanding the figure caption and moved some information to the supplementary section. Please see the reply in general comments.

11. **P7460-7462 – I suggest splitting section 3.4 into three sub sections. There is too much information in this whole section, which requires subdivision to**

help the reader follow and there are natural places where this could occur. The first section should still be 'interpretation of image classification results'. The second section will discuss how you determined spatial patterns and start at P7461, L14 and could be expanded a bit most likely. The third section will discuss how you determined temporal patterns and starts at P7461, L21. However, this section definitely has too much information. It could shortened and details moved to a supplemental with a flow chart figure to help support the reader in understanding the methods.

Thank you for this helpful advice. As per the suggestion we have subdivided section 3.4 into
3.4.1 Interpretation of image data results
3.4.2 Classification of bubble patches
3.4.3 Analysis of spatial distribution of bubble patches
3.4.4 Analysis of temporal pattern of bubble patches

12. **P7461 – better explain 'training samples' and 'field-collected seep location data' – I was not sure what you meant by this.**

    We have made it clear.

13. **P7461, L17 – cite 'Fig. 1' after '1949 aerial image'**

    We have cited Fig. 1 after '1949 image'.

14. **The results/discussion section 4.1 is difficult to follow even with the subdivisions. I believe sections 4.1.1 and 4.1.2 can be divided into three separate sections (4.1, 4.2 and 4.3) with further subdivisions when necessary. Section 4.1 should keep the title 'Relationship between bubble patch brightness and field-measured methane flux' and could be divided into four sub-sections (4.1.1, 4.1.2, 4.1.3) potentially. First is the first paragraph. Second would be the second paragraph where you discuss the limitations of the classification method. The third section would be the third paragraph (P7464, L3) discussing individual seep type difficulties, but di- vided into two paragraphs with the first paragraph discussing A and B-types and the second paragraph discussing C-type. The fourth section would be the last paragraph of the section discussing Tiny-type seeps, but perhaps this paragraph is not necessary at all since this is more or less the only time it is discussed or used.**

    Thank you for this helpful suggestion. We have divided section 4 into 5 sub-sections.
    4.1 Relationship between bubble patch brightness and field-measured methane flux
    4.2 Classification of bubble patches
    4.3 Estimation of whole-lake methane flux
    4.4 Spatial distribution of bubble patches in relation to thermokarst-lake margin

4.5 Multi-year comparison of bubble patch characteristics: 2011 and 2012

15. **P7463, L18-19 – I do not really understand how you were able to come to any final numbers or conclusions if 'an absolute discrimination of individual seep type was difficult'. So how did you overcome this then? You must have in order to report final values but I am lost trying to figure out exactly how. It should be made immediately aware to the readers; otherwise, your method appears not to work based on this statement.**

    Here we are trying to explain our post-hoc analysis results. HSD test shows that only C- and A-type, Hotspot and A-type, Hotspot and B-type seeps are distinct based on PC 1 brightness. We understand the confusion rising from our statement 'An absolute discrimination of individual seep type was difficult to achieve due to overlapping brightness ranges….'. Therefore, we have reworded our statement: 'An absolute discrimination of individual seep type based on brightness was not shown in post-hoc analysis due to overlapping brightness ranges…'. Later we also integrated bubble patch size information in addition to brightness information to classify bubble patches into different seep classes, which we have explained in the manuscript (sections 3.4.2)

16. **P7464, L8 – 'B-type seeps were also difficult to map' – is this because it was difficult or because they were not there? You should qualify this statement by explaining briefly at the end of this sentence why it was difficult, which leads to the next sentence/topic.**

    Individual B-type seeps were also difficult to map since they had not expressed completely and were not distinct like A-type seep under the given spatial resolution of our data. We have stated this in the revised manuscript in section 4.1.

17. **Section 4.2 would then begin with current section 4.1.2 discussing 'classification of bubble patches'.**

    As per the suggestion this section has been revised in the new version of manuscript. Please see reply # 19.

18. **But then Section 4.3 should deal with the 'estimation of whole-lake methane flux' and begin at P7466, L16.**

    This section has been revised. Please see reply # 19.

19. **P7465, L7-8 – This first sentence is very confusing. How does 2012 have two accuracies?**

    The sentence is now modified to make it clearer.

20. P7465, L9-11 – How did the classifier work best for A-type seeps when B-type or C-type seeps were misidentified as A-types? What is 'commission'? You mean 'omission'? Is any of this misidentification/omission data anywhere to be seen in the manuscript? Did you correct for these errors? How? It is fine that the method doesn't work perfectly, but if you had to do manual corrections, then you should state how you did here as well as how you even knew that the seeps were misidentified. I am still not clear on that.

Overall accuracy for A is higher. Error of commission is associated with overestimation, i.e. in our case B- and C-type seeps are overestimated (high commission error) since many A-type and Hotspot seeps were misclassified as B- and C-type seep. And therefore, A has high error of omission, i.e. many actual A-type seeps were classified incorrectly as other type of seeps. We did not correct for errors. These are the results from our MLC classification steps.

We have provided the accuracy assessment table with commission and omission errors in the Supplementary (Table S3 in the new version of manuscript).

21. P7466, L13-15 – Did you correct for this potential misidentification of hotspots as C- types? It is fine if you did not, but you should state that in regards to your final numbers.

We did not correct for misidentification of Hotspots as C-types.

22. Section 4.4 would be 'spatial distribution of bubble patches in relation to thermokarst- lake margin'

This section has been revised. Please see reply # 19.

23. P7467 – I really like this relationship with emission and the distance from the lake margin; however, I kept wondering what the depths were from the margin to the center as well. Can you also put that data in the text?

We did not conduct analysis related to lake depth and ebullition bubbles. Sonar-based measurements of lake water depth on the surveyed polygons and another linear transect (east-west in the center part of the lake) on the lake show that the lake depth depicts baydjarkah pattern on the lake bed (Walter Anthony and Anthony, 2013; JGR Biogeosciences). Walter Anthony and Anthony (2013; JGR Biogeosciences) have conducted detail study on the relationship between lake bed morphology and ebullition bubbles. They found that ebullition seeps are clustered around baydjarakhs on Goldstream Lake. We have included this as additional information in the revised manuscript in section 4.4.

24. Section 4.5 would be 'Multi-year (2011-2012) comparison of bubble patch characteristics'

As per the suggestion this section has been revised. Please see reply # 19.

25. **P7468, L7-10 – You use '(a), (b)' etc here in the text, which is confusing when looking at Figure 6, which has two panels labeled 'a' and 'b' but what you want the reader to see are the images labeled '(i)' and '(ii)', etc. . .. so you should change this in the text.**

    The labels in the figure and the text are same in the revised manuscript.

26. **Figure 6 – why is 2012 so much brighter than 2011? When first reading this section, that question stuck with me unanswered for a while. I believe later you give an explanation but I think you should address it sooner.**

    We have provided the reason for brighter bubbles in 2012 in the first paragraph of section 4.5 'Multi-year comparison of bubble patch characteristics: 2011 and 2012'.

27. **Figure 7 – I feel the panels should be reversed (i.e., panel C should be A and then A and B should become B and C, respectively). Then you can reference the figure panels in the text. P7468, L26 – you should reference the pressure time series, and P7468, L 28, you should reference the bubble-patch images.**

    The panels are reversed.

28. **P7469, L7 – I believe a sub-section of 4.5 should start here (4.5.1) where you discuss these deviations and Figure 8. In general, this paragraph was a bit difficult to follow. It could use some re-writing. I also feel a new paragraph should start at P7469, L20 with sentence 'Based on our DGPS data'.**

    As per the suggestion this section has been revised. Please see reply # 19.

29. **P7470, L15-18 – 'Increased brightness' sentence is difficult to understand. How does the increased brightness of 2012 matter to the 2011 data?**

    We have removed this line. After reading it again we felt that it was unnecessary and confusing. We were referring to very bright bubble patches in 2012, which is already explained in line 2 in that paragraph.

30. **P7470, L22 – what hypothesis are you referring to?**

    We have explained the hypothesis in the revised manuscript (Section 4.5, paragraph 5).

31. **Section 5 is a nice section outlining the benefits and limitations of your method; how- ever you should reverse the order in which you discuss things. You should discuss the benefits first (it's always good to start positive and the**

title of the section also states 'benefits' first) and the limitations/challenges second. Therefore, start the section with L25 of P7471 with the sentence 'Despite these challenges', but of course delete the 'Despite these challenges' part because you will not have discussed them yet in this new order. Also, The second paragraph on P7472 (L19) can be added to the first paragraph to make just one paragraph for benefits. As well, the second paragraph discussing challenges could also simply be one paragraph by combining sentences on P7471,L22-25 with the previous lines.

Thank you for your suggestion. We have started the section with benefits, later we discuss the limitations and we also made additional suggested changes.

32. **Conclusions – I feel this section should be shortened. I was tempted to say to even forget it since you could sum up everything in the previous section. However, since your method is complicated and the results and discussion are combined, I feel that a conclusion section summing your main points is necessary. Although, I suggest that you leave out any numbers, particularly ones that are already in the abstract and the results/discussion section. Try to keep to the main points without values, but then discuss how your results and the method fit into the big picture. Why is this method necessary? This is already discussed in the last paragraph, I believe. But you also must be careful not to make this section redundant with the benefits of the previous section. The conclusion should focus on how the results from this method will help advance knowledge in the big picture (i.e., global methane budgets), while the previous section focused on the immediate benefits of the method in terms of evaluating flux.**

This is a very helpful comment. We have shortened this section. Please see reply # 5 above.

33. **Table 1 – Why are the references there? Is it that the ground surveys are from the previously published work? IT should be made clearer in the caption.**

Yes, the ground surveys are from previous published work. We have made it clear.

34. **Table 2 – clarify in the caption what 'overlapping threshold', 'total', 'as one patch', 'in a cluster of patches' means. Put in the column headings that these are 'N'.**

We have removed Table 2 since the same information is already in the text. We felt that this is redundant and more confusing to the readers.

35. **Figure 3 – change the caption text slightly to be clearer: 'Significant differences ($p < 0.05$ at 95% CI) based on PC1 mean brightness values were**

found between C- and A-type seeps, Hotspot and A-type seeps,. . .. For 2011 and . . .. For 2012.'

We have changed the caption text to be clearer. And since $p < 0.05$ and 95% CI is redundant, we are only using $p < 0.05$ in the revised manuscript.

36. **Figure 4 – the descriptions of the (i), (ii), etc images are somewhat better here in the caption than in the main text. Consider aligning the text and caption somehow.**

    The labels are aligned.

37. **Figure 6 – descriptions in the caption for (i), (ii) etc are also better here in the caption than in the main text. Again consider aligning the two descriptions.**

    The labels are aligned

38. **Figure 7 – reverse panels – Make C become A.**

    We have reversed the panels in Figure 7.

39. **Figure 8 – This figure is slightly difficult to understand. The main text might describe it better than the figure caption. Make sure the reader can understand both.**

    We have shortened the graph details in the main text and added more details in the figure caption to make it understandable.

40. **Supplemental figures in the supplemental should be labeled 'S1', 'S2', 'S3', as is written in the manuscript text, and Table should be labeled 'T1' and placed before the figures in the supplemental.**

    Supplemental figures and table are re-labeled and re-arranged. We have additional supplemental text and therefore, instead of using different labels (such as 'S1' for figure and 'T1' for table) we decided to use Text S#, Figure S#, Table S# to label text, figures and tables. As in the manuscript text, we have placed supplemental text and tables before figures. We have referenced supplemental figure as Figure S#, supplemental table as Table S# and supplemental text as Text S# for text in the main manuscript.