Reply to reviewer 2:

We like to thank the reviewer for the constructive comments on our manuscript. The review helped to enhance the quality and improve the comprehensibility of our study. We carefully considered all comments of the reviewer. The answers are highlighted in bold and changes done in the manuscript are marked in italic.

– Introduction: The bubble paragraph is rather long and it is a jumping the style of writing. It also does not integrate well with the rest of the chapter. Do you need to describe all bubble types in detail?

We have shortened introduction and removed the extensive description of bubble types.

Define what you mean by pond, and initial stage and late stage pond. I'm missing that in the introduction. Nothing about in in section 1, but its mentioned in the abstract.

The abstract summarizes the entire study and highlights the main results. Thus, it is sometimes unavoidable to use terminology which is explained later in the adequate sections. We believe that the right place to explain and defined the used terminology is the method section and not the introduction. However, in order to avoid confusion we have changed the wording in the Abstract as follows:
Results revealed marked differences in early winter net CH4 production among various ponds. Ponds situated within intact polygonal ground structures yielded low net production rates, of the order of 10−11 to 10−10 mol m−2 s−1 (0.01 to 0.14 mgCH4 m−2 d−1). In contrast, ponds exhibiting clear signs of erosion yielded net CH4 production rates of the order of 10 mol m s (140 mgCH4 m d). The net per square meter CH4 production rate of ponds with signs of erosion exceeded the per square meter emission rate of the average tundra landscape which was measured at the study site during summer.

P11066, L4-10: "These polygonal structures are present in different stages of degradation. Initial degradation often leads to the accumulation of surface water, either in the depressed polygon centers (intra-polygonal ponds) or along the troughs between the polygon rims above the ice-wedges (ice-wedge ponds) (Wetterich et al., 2008; Helbig et al., 2013; Negandhi et al., 2013).... Both intra-polygonal ponds and ice-wedge ponds are usually very shallow, with water depths ranging from just a few centimeters to a few tens of centimeters."
Typically ponds in the center of low-centered polygons are not formed due to degradation, but rather the opposite (ice wedge growth that pushes the soil, e.g. rims, up). See Lachenbruch 1962 for details.

We agree with the reviewer that ice wedge growth, as well as thermal expansion are responsible for the formation of polygons (Lachenbruch et al. 1962). At this study site, the initial degradation of the polygonal walls strongly controls the water level of the polygon center (e.g. Helbig et al. 2012). However, water accumulation within intact polygonal structures is possible due to the accumulation of snow and rain water. Nevertheless, the vertical water balance is usually neutral to negative so that these ponds would dry out sooner or later without a connection to a larger catchment area. For clarification, we simplified the concerning paragraph to:
Ponding water is often found in the depressed polygon centers (intra-polygonal ponds) or along the troughs between the polygon rims above the ice-wedges (ice-wedge ponds) (Fig. 2 a, b) (Wetterich et al., 2008; Helbig et al., 2013; Negandhi et al., 2013).

The authors have not described their particular study ponds in detail. Based on the very general description, which certainly is not specific to their study ponds, it is impossible to clearly understand what types of ponds they are investigating and whether or not their geomorphological assessment is realistic.
A general pond description is not given until page 11067. It is OK, especially with fig 2, but it is too late in the manuscript.

Following the reviewer's suggestion we have placed references to Fig. 2 now already in the study site description in order to facilitate the visualization.

P 11067, L12: Figures should be referred to in order. Fig 2b is discussed before Fig 2a.

Not longer applicable in the revised version (see comment above).

L 15-16: "ISPs can be interconnected with other ISPs or with larger waterbodies, but the individual polygon shape is still preserved." Grouping ice wedge ponds and polygon center ponds into ISP makes this statement confusing. Fig 2 does effectively show the interconnectedness between ice wedge ponds, but certainly not for polygon center ponds (Fig 2 says they are ASP). Therefore, it is difficult to envision how connected pond of the latter still maintain the individual polygon shape (especially by looking at fig 2c).

The aim of the performed classification is to distinguish between different degrees of degradation of the polygonal ground structures within which ponds occur. The grouping was done due to fact that ice-wedge ponds (Fig.2a) and intra-polygonal ponds (Fig.2b) occur within almost intact polygonal ground structures. Intact polygonal ground structures means that individual polygons can be recognized from aerial images. Nevertheless, it is possible that these polygonal structures show local signs of degradation along the polygon wall. This often leads to a hydrological connection between intra-polygon ponds and ice-wedge ponds. Merged ponds as show in Fig.2c are clearly classified as (ASPs) since the individual polygonal structures are degraded. We modified the entire paragraph in order to clarify our classification scheme:
We were able to loosely distinguish three types of ponds within the study area (Fig. 2). On the basis of morphology we distinguish between ice-wedge ponds (Fig. 2 a), intra-polygonal ponds (Fig. 2 a), and merged ponds (Fig. 2 c). These ponds are further grouped into initial state ponds (ISPs) and advanced state ponds (ASPs) according to the degrees of degradation of the polygonal ground structures within which the ponds occur. ISPs are defined as ponds that occur within almost intact polygonal structures; they include both ice-wedge ponds located between polygon rims (Fig. 2a) and intra-polygonal ponds located in polygon centers (Fig. 2b). ISPs are shallow with water depths of less than 0.5 m. Their horizontal extent typically ranges from a few meters up to about 10 m, which is a typical diameter for the polygonal structures. Due to initial degradation ISPs can be hydrologically interconnected with other ISPs or with larger waterbodies, but the individual polygon shape is still preserved.

P11068, L7-8: "The pond was transitional between ISPs and ASPs in its level of degradation."
What do the authors mean here?

ISPs and ASPs are end members in terms of degradation of the polygonal ground structures within which the ponds occur. Thus, ponds can exist in between the state where the polygonal ground structure is completely intact or completely lost. This fact is stated at the end of section 3.1: "Transitional forms between the three waterbody types are also common."

L5-7: “The first temperature profile was from an intra-polygonal pond, based on measurements from four temperature sensors over a depth of 0.4 m.” Be specific. At what depths were the temp sensors? When was the water depth 0.4 m? I would think you see some variability in water level over the summer season. Same concerns regarding the other ponds.

A more detailed description of the water temperature profiles is provided in the revised version of the manuscript:
The first temperature profile was from an intra-polygonal pond, based on measurements from four temperature sensors. The first three temperature sensors were installed at depths of 0 m, 0.15 m, and 0.33 m. The lowermost sensor was fixed directly on the ground at a depth of 0.4 m. The pond was transitional between ISPs and ASPs in its level of degradation. Temperature profiles were also obtained for two typical ASPs, in each case using six temperature sensors over a depth of about 0.8 m. In ASP1 the temperature sensors were deployed at depths of 0 m, 0.20 m, 0.35 m, 0.53 m, 0.67 m, and 0.76 m. In ASP2 the sensors were mounted at depths of 0 m, 0.20 m, 0.33 m, 0.50 m, 0.71 m, and 0.75 m. With exception of the lowermost senors which were fixed to the ground, all sensors were hold in place relative to the water surface on a floating metal wire.

P11067-11068: No discussion at all about the different types of bubbles.

We agree with the reviewer that the detailed description of the different bubble types in the introduction is desirable, but might also be misleading. This study focuses on CH4 storage in freeze-out bubbles in order to derived CH4 production rates from concentration profiles. It is out of the scope of this study to provide a detailed analysis of all bubbles types that can occur besides freeze-out bubbles. Therefore, the introduction was shortened and rephrased (see comment above).

P 11070, L27-28: ” Thus, the obtained ice profiles were analyzed for occurrence of bubble layers that were related to air pressure changes.” During modeling or measurements?

Sentence changed to:
Thus, the obtained ice profiles were analyzed for occurrence of bubble layers that were related to air pressure changes before they were used for modeling.

P11071,L11-12: “: : :the net CH4 production rate and effective bubble cross-section can be inferred by fitting the model to measured CH4 concentration profiles.” Please clarify. Profiles of what? The ice via the collected ice samples?

The term CH4 concentration profile is defined and explained in detail in the first sentences of section 3.3 (P. 11068 L15): *"Thirteen CH4 concentration profiles were obtained from ice blocks cut from eight ponds ..."*

L16-17: “The model was fitted to the measured CH4 profiles using a non-linear fitting routine provided by MATLAB.” Same issue here. The measured CH4 profiles form the ice samples?

Sentence changed to:
The model was fitted to the measured CH4 profiles form the ice samples using a non-linear fitting routine provided by MATLAB.

Again, no mention about the classification of bubble types, which were extensively

discussed in the introduction.

Please see comment above.

Fig 3: Only water bodies <1500 m2 are represented, but on page 11067 (L8) you write that you studies ponds up to 10,000 m2. Why this inconsistency? Is Fig 3 then really representative of your other results and vise versa??

Thanks for the comment. Originally, we excluded waterbodies larger 1500m² in Fig.3a in order to enlarge the information contained in the histogram. We changed Fig. 3 to a cumulative histogram in order to include waterbodies up 10.000m².

Fig 4: What is the depth of each pond?

Water depth of each pond is now added to the legend of Fig. 4.

Fig 4 and P11072, L12-onwards: For the purpose of finding an average ice growth rate, I do not find it effective to compute a linear average based upon all three ponds, especially if the onset of ice growth varies between each pond (see Fig 4a). Instead, compute the linear regression for each pond or normalize the onset of the start of ice growth. As presented now, you are not presenting average ice growth rate, but rather the average start and end of freeze amongst ponds.

We agree with the reviewer that it would be better to infer the average ice growth rate by calculating linear averages for the individual ponds. We follow the suggestion of the reviewer and correct the ice growth rates accordingly. Since the ice growth rate is used as input for the fitting procedure of the mass balance model, new calculations with modified ice growth rate are performed as well. The impact of the changed ice growth rate on the results of the fitting procedure is found to be negligible. At maximum the CH4 production rates and effective bubble areas are corrected by about 10% which is smaller than the uncertainties introduced by the other input factors and the calculated 95% confidence intervals. This additional check confirms the result of the performed sensitivity test which reveals a high robustness of the model towards uncertainties in ice growth rate (cp. Sect. 5.2). The modified ice growth rates do not affect the results of this study, since differences in CH4 production between the ponds are evaluated on the basis of orders of magnitudes.
Corrected statement:
During the winter of 2010-2011 the average growth rate of the ice cover was 0.91 ± 0.11 cm d−1 (Fig. 4a).

Why the difference in pond-to-pond variability between the two winters?

A possible explanation could be the observed spatial differences in snow depth. However, to clarify this question multi annual measurements of the energy balance of different waterbodies would be necessary. Thus, it is out of the scope of this study to clarify the observed variations in ice growth rate.

P11072, L26-30 and onwards: It is unclear what periods the authors are referring to. I suggest highlighting the different periods in Fig 4.

Done.

P11073: “During the field campaign clear differences in snow cover thickness of about 20 to 30 cm were observed between the ponds.” Unclearly written. Was snow 20 cm at one place and 30 at the other, or?? Which ponds had deeper snow? If you are to mention/discuss snow cover, then provide details or simply do not discuss it at all.

Statement on snow cover deleted.

P11073, L5: Did you study these lakes? If not, write so. And what does “larger” entitle?

Statement on snow cover deleted (see comment above).

P 11073, L21: Bottom of what? Clarity please.

Statement clarified:
... did not reach the bottom of the ponds and hence the presence or absence of a possible layer of abundant bubbles ...

P11073: The paragraph describing bubbles needs a supporting figure that shows the bubble distribution, especially if this bubble distribution is important to the rest of the paper.

This very short paragraph on the bubble distribution in the ice samples is necessary to clarify possible error sources (e.g. due admixture of ebullition bubbles and pressure change bubbles). However, this paragraph provides ancillary information which is not directly used for the modeling. We believe that an additional figure would not provide any further information and value for the results of this study.

P11073, L10: ISP2 and ISP3 pond?? This is the first time ISP 2 and 3 pond are mentioned. There is only an ISP1 pond in Fig 4.

We add the following information to the method section:
Thirteen CH4 concentration profiles were obtained from iceblocks cut from eight waterbodies using a chainsaw (STIHL, Germany) with a 40 cm guide bar during a field program in April 2011. Three waterbodies were ponds with maximum water depths of less than 0.5 m. The morphology of these ponds still placed them within the ISP category, despite some early signs of degradation. In the following, these ponds are named ISP1, ISP2, and ISP3. Four waterbodies had maximum depths greater than 0.5 m (up to 1.2 m) and occurred within clearly degraded polygonal ground structures. The four ponds fell into the ASP category and are named ASP1 to ASP4 in the following. One of the sampled waterbodies fell into the category of a thermokarst lake with a maximum water depth of 5.3 m. Temperature chains were installed in ISP1, ASP1, and ASP2 in order to observe ice cover growth (cp. Sect. 3.2).

L16-18: “The consistent occurrence of these thin bubble layers in similar depths and different ponds indicates a formation related to air pressure changes.” Needs clarity. Are all these three ponds of similar water depth? Looking at Fig 4, there is quite a difference in both onset of ice formation and timing of complete freeze-up, eg bubbles at the same depth between ponds may not represented the same date.

We have added the following information:
The three ISPs feature similar water depths of 30 to 45 cm and we expect similar freezing rates.

L6-27: Lack of consistency. Use either the bottom of the pond (sediment-water interphase) as the reference or use the top of the water (ice) surface as the reference. As written, it is unclear at places.

In the manuscript all depths are consistently given relative to the water/ice surface.
P11074, L23-24: What does "close to the bottom" mean? In cm.

Done. We have changed the sentence to:
An exponential increase in CH4 concentration was recorded for all ponds in which the acquired ice columns reached close (about 30 cm) to the bottom of the waterbody.

P 11074, L24-26: "The lowest CH4 concentrations were recorded in the ice columns from large thermokarst lakes. In these lakes only the uppermost part of the ice cover was sampled relative to the maximum lake depths." Isn't there a bias introduced to Fig 4 and the results if the larger lakes only had the top part of the ice cover analyzed for CH4? If only the top ice was sampled at larger (what does "larger" mean??) lakes, then you need to be careful in how you refer to the results.

The samples from the thermokarst lake are not used for modeling the CH4 production rates in ISPs and ASPs. The samples from the thermokarst lake are presented for comparison only. A clear definition of what is considered a thermokarst lake is given in Sect. 3.1.

P11075: How ponds were divided into different categories (ISP versus ASP) is a definition that should be provided earlier, not wait until this time. Also, the wording is a bit funny, making it read like a circular statement.

This paragraph has been removed in the revised version and is now part of Sect. 3.3 in order to introduce the ponds earlier (see also comment above).

L 7-8: "The maximum CH4 concentrations measured in the ISP1, ISP3, and ASP3 samples were about one order of magnitude higher than those from the other profiles." What does "other" refer to? If it is "larger lakes", then I do not find the claim justified as the "larger lakes" only had the top ice measured for CH4. Why were not the entire ice column measured for CH4 in the larger lakes?

We changed the statement to:
The maximum CH4 concentrations measured in the ISP1, ISP3, and ASP3 samples were about one order of magnitude higher than those from ISP2, ISP3, ASP1, ASP2, and ASP4.

Fig 6: Is each sub-figure supposed to be an individual pond?? Or are they all "ASP 3"??

The reviewer is right, the sub-figures are supposed to represent individual ponds. There was a label error which occurred due to the conversion from the original pdf to eps figures. This error is corrected in the revised version.

Fig 7: Suddenly there is an ASP4 pond. It is frustrating to read the manuscript when new ponds and new results keep appearing without the pond being introduced and described.

All ponds are now introduced on the method section (please see comment above).

P11076-11077: A larger portion of the discussion is devoted to future changes. Nowhere does the

manuscript address any future changes and studies of future conditions. The manuscript addresses the current system and the variability in ice growth rate and CH4 production during the ice growth period of differing ponds. I find it a stretch to devote a large portion of the discussion to future changes and conditions. It comes across as hand-waving. A large portion of this first section in the discussion reads as a literature review too. Focus on the results in this manuscript!

All parts which were not directly related to the results of this study are removed in the revised version of the manuscript. The discussion concerning possible future changes is excluded.

P11079, L1-2: Poorly written. Should state "uniformly distributed CH4 concentrations and a constant rate of bubble accumulation, could also affect the simulated net CH4 production rates."

Changed.

P11079-11080: "This is half an order of magnitude less than the winter net CH4 production rates from ASPs: : :" No sediment temperatures were provided. The study did not include the entire winter. I find it inappropriate to refer to this study as representing "winter net CH4 production"

We agree with the reviewer the study only focuses on the early winter period as explained in the introduction. Thus, we change the statement to:
... early winter net CH4 production rates ...

P11080, L12-13: Why does the CH4 increases exponentially with depth?

This fact is clearly demonstrated in the result section and explained in the discussion (see Fig. 5 and 6). However, we have added the following statement for clarification:
Extensive measurements in the ice cover of different ponds have revealed that the CH4 concentrations increase exponentially with depth, indicating intensive CH4 production under the growing ice cover. The measured CH4 concentration profiles were successfully reproduced by 1D mass balance model demonstrating that the exponential shape results from the dynamic balance between net CH4 production, freeze-degassing, and storage of CH4 within the ice cover.

L15-16: "..in ponds showing signs of erosion in the surrounding permafrost.." What does "surrounding" refer too? Lateral/pond sides? Below pond etc?

In order to be more consistent with the definitions and explanations in the method section, we changed the statement to:
Inverse modeling has revealed high net CH4 production rates in ponds showing signs of erosion in the surrounding polygonal ground structures, which contrasts with the low net production rates observed in ponds located within almost intact polygonal ground structures.

L20-21: "..Ponds therefore make a significant contribution to the greenhouse gas emission budget of the tundra" This is just thrown out from nowhere. Add a justification how important its contribution is to the rest of the tundra if you are writing "significant contribution".

Due to comments from reviewer 1 this statement has been removed.

L23-24: "thermal state and stability of the permafrost" Nowhere are we presented with proof of degradation (change in soil (permafrost) temperature over time etc). How can you then state that these

ponds are degrading?

We agree with the reviewer and changed the statement to:
Ponds are abundant in lowland tundra landscapes and their occurrence is closely related to the state of degradation of surface structures in permafrost landscapes. Hence, further degradation of surface structures due to thawing permafrost may affect the occurrence of ponds and thus the CH4 emissions from tundra landscapes.

L25-26: "..show signs of thermal erosion in the surrounding permafrost.." Again, the authors are making statements that are not supported by data.

Statement changed to:
The net production of CH4 from ponds that show signs of erosion in the surrounding polygonal ground structures is observed to be two to three orders of magnitude ...

P11081, L4-6: This conclusion is not supported by any data in this manuscript. Remove.

Removed in agreement with the comments of reviewer 1.