

## **Final response to referee comments**

*We thank both referees for the thorough revision of our manuscript and their constructive comments that helped to improve the paper. Our replies to the comments are written in italics.*

### **Anonymous Referee #1**

I greatly enjoyed reading this article describing thermokarst lakes and basins of the Lena Delta region of Northern Yakutia of Siberia.

*Thank you.*

This is a fascinating area to study post-glacial landscape-scale degradation of permafrost and thermokarst processes. The authors conducted a comprehensive analysis using geospatial techniques applied to Landsat imagery to calculate lakes and basin shape metrics, with statistical analysis comparing morphological characteristics of lakes and basins of the third Lena Delta terrace and subgroups. The study was supplemented by a more intensive and comprehensive terrain analysis of the smaller key area of Kurungnakh Island using a high-resolution DEM (5-m horizontal resolution) and bathymetric data from several lakes.

The data sources were appropriate for the stated objectives, although the ~6m vertical accuracy of the ALOS PRISM DEM seemed rather large for this low-relief terrain.

*The lack of high resolution digital elevation data in arctic tundra regions is a major limitation for detailed relief analyses. We decided to use ALOS PRISM data for DEM generation, because one scene covers the whole key site of Kurungnakh Island with a footprint of 35 x 35 km. As standard procedure, the ALOS PRISM forward and backward scenes are used for stereo analyses because of the large base-to-height ratio of 1. In our case also the nadir scene was used to enhance the accuracy of the DEM. It was generated using all three possible stereo pairs of the PRISM triplet and averaging them. Then the full DEM editing procedure of the PCI module Focus was applied (Günther, 2009). Especially within thermokarst basins, which are situated on a height level close to the boundary between the two sedimentary units Ice Complex and fluvial sands and exhibit a larger lake coverage, the effect of averaging lake levels and subsequent hydrological correction led to a better representation of the thermokarst terrain. This is confirmed by comparing a high resolution field survey DEM from 2008 (Ulrich et al., 2010) with the ALOS PRISM DEM used in this study over a 7.5 km<sup>2</sup> large thermokarst basin, where the root-mean-square error of the*

*vertical difference raster over the whole area is only 3.5 m (Günther, 2009). We agree with the reviewer that the calculated vertical accuracy for the whole DEM of about 6 m is still rather large for the thermokarst terrain, but this value is rather conservative and refers to singular height GCPs taken mainly from trigonometric points of topographic maps of the 1970s. Altogether, the DEM is the currently best available DEM for the study area and proved sufficient to clearly distinguish the different relief units (Yedoma uplands, thermokarst basins, thermo-erosional valleys) and to allow for the analysis of their position (see profile line in fig. 11 as an example).*

Data processing and the analytical methods used were appropriate and clearly explained, the writing was concise, and the overall presentation is well organized. Although I am not familiar with the Russian-language literature, the references cited are appropriate.

The authors derive several substantial conclusions. First, they clearly demonstrate the importance of stratigraphic (cryolithological) control on thaw susceptibility. At Kurungnakh Island, an ice-poor sand unit of fluvial origin underlies thick (30m) Yedoma deposit with excess ground ice. The contact is at 17m asl. The younger Ice Complex has experienced thermokarst since the early Holocene, and large thermokarst lakes developed at the surface where low slopes promoted water detention and ponding. In time, as the lakes grew in size and the talik penetrated the ice-rich sediments, the lakes deepened. However, once the talik reached the ice-poor lower unit, further ground subsidence was halted. This is evidenced by the concordance of basin and lake bed elevations at ~17m in Figure 11; about 70% of the lakes and basins on Kurungnakh Island have subsided to the base of the Ice Complex. The authors present a useful conceptual model (Figure 13) that describes lake, basin and landscape evolution.

*Thank you.*

Unlike large areas of Arctic North America, thermokarst lakes are not extremely abundant and cover only ~5% of the study area. By contrast, total basin area exceeds lake area by about a factor of four. From this and other evidence, the authors conclude that lakes in the past were much larger owing to the uniformly flat terrain lacking integrated surface drainage.

Although thermokarst development on the Ice Complex is ongoing, there have been changes to the landscape that affect future rates of degradation. As basins coalesced and streams developed in this dynamic deltaic environment, the local relief increased. Thermo-erosion channels have developed on basin slopes that enhance drainage of the thaw-susceptible uplands. Over the Holocene, the extension and integration of the stream drainage system,

combined with thermal degradation of the landscape, has reduced the overall potential for ponding across the region; it is largely limited to higher elevations with slopes  $< 2^\circ$ . Currently, only about 1/3 of Kurungnakh Island is vulnerable to future thermokarst and associated mobilization of old soil organic carbon.

The authors have presented a compelling case for thermokarst evolution over time and space. Some of the observational data could not be definitively explained (e.g., inconsistencies in lake and basin orientation, the consistent displacement of pingos and residual/secondary lakes to the north or south of the basin center), and warrant further research. This manuscript is so professionally prepared that I have only a few very minor suggestions:

Use of the term “Island” to describe the Yedoma uplands is somewhat misleading and should be clearly noted early in the paper.

*We added the following sentence in the first paragraph of section 2 Study area and regional setting (p. 1498, l. 27):*

*“These insular remnants of Ice Complex deposits will be termed islands in the following and named after the delta island they belong to.”*

Figures 1b, 4 and 10 are busy, with labels and boundaries somewhat difficult to discriminate.

*We agree that the figures contain much information, but in our opinion no important information is compromised by the figure arrangements. Figure 4 is not intended to show all single thermokarst features, but to give an overview of the distribution of the different types in the study area. We improved the readability of the labels in figures 1b and 4 by highlighting them. We also increased the font size in figure 10.*

## **Referee 2: L. Smith**

This informative, careful, and well-written paper provides a valuable contribution to a growing literature that is using satellite remote sensing, geoinformatics and, when possible, field work to understand how long-term environmental changes influence the size, distribution and morphology of Arctic lakes.

*Thank you.*

While attributions to past and current climate changes have dominated this field as of late, the authors also incorporate the widely appreciated yet understudied importance of stratigraphy, geomorphology and relict landscapes as controls on lake characteristics and their evolution over time.

Perhaps the most significant idea advanced in the paper is that on Russia's carbon-rich Yedoma uplands, many modern lakes reside within larger, abandoned lake basins, that are relicts from ~12 ka when conditions for large thermokarst lake expansion were more favorable than today. At that time, the Arctic Ocean lay several hundred kilometres further north, the region was a broad plain rather than the dissected, geomorphologically complex river delta of today, and – as becomes important in this paper – the landscape was generally less disturbed by prior lake activity. In such an environment, thermokarst lakes had greater capacity to expand to very large sizes (several km) before intersecting a channel or other low-lying surface feature, at which point the shoreline breaches thus triggering lateral drainage. Another important argument of the paper is the role of underlying ice-poor fluvial sands as a limiting factor on thermokarsting. While some nice work partitioning relict from contemporary lake basins has previously been done for Alaska's North Slope, it's new for Russia where few previous studies have distinguished between thermokarst lakes on Yedoma uplands and those residing within older relict basins.

The paper provides a good literature review, tracing back to early Soviet-era work by Soloviev, Katasonov, Romanovskii and others. Another strength is its close attention to geology and permafrost ice properties in the uppermost stratigraphic units (two Pleistocene, one Holocene) of its Lena River delta study area. The paper incorporates new and prior field work to supply relevant details like the influence of terrain slope on presence of ice-wedge polygons (apparently, slopes of ~0 to 2 degrees support polygons whereas steeper slopes do not) and lake bathymetry. The importance of coalesced (vs. single) lakes is recognized, as the former are less likely to regrow after drainage owing to better integration with local surface drainage networks.

Other findings include discovery of statistically significant differences between lakes located on the Yedoma uplands (smaller, smoother shorelines) and basins, and identifying differences in prevailing lake orientation. The latter will add to a small ongoing literature, again rooted mainly in North America, debating the roles of wind direction, limnology and other processes on thaw lake orientation.

The study area focuses on only ~1700 km<sup>2</sup> but the benefit of this is a process- and landscape-level understanding of controls on lake formation, stability, and drainage. The authors display good appreciation of the influence of RS pixel size on derived lake metrics, a power-law lake size distribution (heavily skewed towards tiny ponds), and other problems

that plague efforts to map Arctic lakes from satellite imagery. To help mitigate them 2,327 "water bodies" (1 pixel) initially mapped in the Landsat ETM+ classification are culled to 514 lakes of size > 14,400 m for further morphometric analysis.

As mentioned earlier, the authors specifically consider stratigraphy in their analysis. A shrewd attempt to estimate the stratigraphic penetration of lake beds is based on its elevation, i.e. all lakes and basins located at or below 17 m a.s.l. are assumed to have beds in fluvial sands of the lower stratigraphic unit. The importance of this arises in later discussions in the paper (pp. 1511-1512) and has to do with low thermokarst potential in this material. I wonder if some independent validation of this approach might be enabled by examining the visible bands of the ETM+ mosaic. I know from previous experience that sand bars are clearly visible along Siberian rivers, at least, using ETM+, and the photograph in Figure 2 suggests sizable sand outcrops are visible in the study area. The authors might get lucky if any lakeshores and/or bottom reflectance (if water is clear enough) lend some independent, if qualitative support for their stratigraphic estimates.

*It is true that the sand bars are well distinguishable in the satellite data along the margins of the islands. However, sandy sediments cannot be used as indicators of lake position in relation to stratigraphy. Even if a lake had subsided to the fluvial sand unit, the lake bed and/or lake shores would not reveal the sandy sediments, because these are inevitably covered by a layer of taberites. The taberites are up to several meters thick depending on the thickness of the original Ice Complex and its ice content. In addition, lake sediments should be present on top of the taberites. Strong erosion of lake shores or on basin floors that would remove the taberites and lake sediments and expose the underlying sands in an extent that would make them detectable in Landsat data is not occurring in the study area to our best knowledge.*

Section 5.3 is one long paragraph and quite indigestible in its present form, especially the latter part (discussion of taberites). I recommend separating this section into distinct paragraphs with an eye towards improving the reading flow.

*We followed the suggestion and divided the original section into five paragraphs. The part that discusses the three different types of permafrost sediments that have developed in thermokarst basins including taberites is now the fourth paragraph of section 5.3. We think that further dividing the paragraph (for example one distinct paragraph for each horizon) would rather lead to incoherence than better readability.*

*In addition, after personal discussion with T. N. Kaplina (Industrial and Research Institute for Engineering Survey in Construction, Moscow, Russia), a leading Russian expert on thermokarst, we clarified statements related to taberites. It is not plausible that the lake*

*and/or basin floors are situated right at the Ice Complex base, because there always has to exist a layer of taberites on top of the Ice Complex base, even if thermokarst has completely thawed the original Ice Complex. We therefore deleted the following sentences (p. 1512, l. 8ff.):*

*“Soloviev (1962) also describes central Yakutian basin floors situated just above the Ice Complex base. Therefore, we assume that basin depth in our study area approximately corresponds to Ice Complex thickness, and the position of the basin floors marks the position of the Ice Complex base. This is confirmed by our analysis of the relief on Kurungnakh Island, where lake bottoms are situated at the Ice Complex base and lake surfaces and basin floors are located a few meters higher (Fig. 11).”*

*and also on page 1513, l. 9ff.:*

*“Taberites in a thermokarst basin on Kurungnakh Island have been calculated to be 2.3 m thick, assuming a total ice content of 90 vol% in the original Ice Complex (Ulrich et al., 2010).”*

*In return, we changed the last sentence of the section (p. 1513, l. 26) and added the following text that should further clarify the intended information:*

*“The present lake floor is situated directly at the 17 m level, which we defined as the generalized Ice Complex base. In fact, the Ice Complex base should be situated a few meters lower here, because a layer of taberites necessarily exists underneath the lake bottoms. Its thickness depends on the original ice content of the Ice Complex; the lower the ice content, the thicker the taberal layer.*

*Figure 11 shows lake bottoms situated at the assumed Ice Complex base and lake surfaces and basin floors located only a few meters higher. This suggests that the taberal layer is only a few meters thick and the original ice content was very high. For the large thermokarst basin with lakes 1 to 3, taberites have been calculated to be 2.3 m thick, assuming a total ice content of 90 vol% in the original Ice Complex (Ulrich et al., 2010). Soloviev (1962) also describes central Yakutian basin floors situated just above the Ice Complex base. Therefore, basin depths can be used as indicators of ice content and total thickness of Ice Complex deposits.”*

If possible, the conclusion and abstract could be strengthened by better addressing the "so-what" question. The key, take-home message of this paper is that undisturbed, upland permafrost landscapes that have not already experienced widespread thermokarsting in the past have more potential to experience lake expansion in the future under a warming climate; whereas landscapes that previously experienced lake expansion in the past are limited as to

how much lake expansion can occur, mainly confined to small 2nd- and 3rd- generation lakes trapped within larger relict basins. This important finding would have even broader impact if the authors could posit how much of the Russian north (i.e. in continuous permafrost) falls into this "restricted" category of landscape. Do previously disturbed Yedoma areas represent only a small fraction of the overall landscape, or are the prospects of widespread thermokarst lake expansion – together with all of its carbon cycle ramifications - dimmed by the findings of this study? Because changing surface hydrology is highly relevant to soil carbon and trace gas exchange, placement of this paper's central conclusion into an even broader context would expand its appeal to researchers in other fields.

*Thank you for this important comment. It is indeed the case that a large portion of Siberian Yedoma landscapes has experienced extensive thermokarsting in the past and that future thermokarst development in these regions is restricted in a similar way as in our study area. So the implications drawn from this study regarding the magnitude of impact of thermokarst lake expansion on changes of landscape, hydrology, climate, carbon cycle, etc. are undeniably transferrable to most of Siberian Yedoma landscapes. We therefore added the following paragraph at the end of section 5.4 Impact of future thermokarst development:*

*“The implications of significantly reduced thermokarst potential in large parts of the study area are also highly relevant for most other Yedoma landscapes in Siberia, which are estimated to occupy an area of  $10^6$  km<sup>2</sup> (Zimov et al., 2006a). Environmental changes at the transition between Pleistocene and Holocene led to extensive thermokarst activity in Siberian Ice Complex deposits (Kaplina, 2009). The percentage of thermokarst affected terrain as well as the morphology of thermokarst lakes and basins varies between different Yedoma regions. Precise calculations of Yedoma and thermokarst area percentages are rare, but old thermokarst basins generally exist in nearly all Yedoma regions and restrict future thermokarst lake expansion. In the Kolyma lowlands, for example, Kaplina et al. (1986) report different degrees of Yedoma dissection by thermokarst basins from weak (<25 %) to very high (>75 %). In a subset of this area, Veremeeva and Gubin (2009) calculated that 65 % are covered by thermokarst basins and only 26 % represent Yedoma uplands. For the Yedoma region of the Bykovsky Peninsula, Grosse et al. (2005) find that about 53 % of the area is affected by thermokarst. For the Lena-Anabar lowland, which is similar in geological composition to the Lena Delta study area with Ice Complex deposits underlain by fluvial sands, about 49 % of the area is covered with thermokarst landforms (Grosse et al., 2006). Kaplina (2009) points out two types of Yedoma territories in north Yakutian lowlands, where thermokarst has no potential to develop. The first type corresponds to the situation in our study area representing drained Yedoma massifs and remnants where water accumulation is impeded. The second type are areas, where coalesced thermokarst basins form extensive alas plains underneath which the former Ice Complex almost completely underwent taberal*

*reworking. This shows that investigations of modern and possible future thermokarst lake development in Siberian Yedoma regions in the context of changes in landscape, hydrology, climate, carbon cycle, etc. always have to consider the history of former thermokarst evolution and permafrost degradation.”*

*In the conclusion, the last part now reads as follows (beginning on p. 1519, l. 3):*

*“Developing thermokarst lakes on undisturbed Yedoma uplands have the highest impact on the alteration of Ice Complex deposits and Yedoma landscapes. However, past thermokarst activity and erosion have severely diminished original Yedoma surfaces, not only in the study area, but in Siberian Yedoma regions in general, so future thermokarst lake expansion in these landscapes may be considerably restricted. Therefore, it is necessary to differentiate between the various developmental stages of thermokarst and landscape units in order to assess the degradation of very ice-rich permafrost due to thermokarst, for example to quantify organic carbon inventories and the potential for future carbon fluxes.”*

*We also changed the last sentence of the abstract:*

*“Future thermokarst lake expansion is similarly limited in most of Siberia’s Yedoma regions covering about  $10^6$  km<sup>2</sup>, which has to be considered for water, energy, and carbon balances under warming climate scenarios.”*

Figure 10 label font is a bit small/hard to read.

*We increased the font size of all labels in figure 10.*

Figure 13 right-hand legend is outsized. Rather than shrink it, perhaps fix by horizontally stretching the 5 schematic diagrams in the right-hand column to match the dimension of the legend.

*We changed the figure following the suggestion.*

### **Further changes made to the manuscript**

*We exchanged the reference Grosse et al. (2011, EOS) with Grosse et al. (2011, JGR) and added a reference to Grosse et al. (in press) for a review book chapter on thermokarst lakes and drained lake basins in the introduction.*

*In addition, we added the citation of Sher et al. (1987) in the second paragraph of the introduction (p. 1497, l. 10), because this is a more appropriate reference for the late*



*Pleistocene age of the Ice Complex in Northern Siberia. With its review on Siberian Ice Complex, Schirrneister et al. (2011b) is still a valuable reference for this issue.*

*Futhermore, we noticed that in figure 10 some basins were not color coded correctly. One large basin that intersects the 17 m isoline was coded as being situated above 17 m a. s. l., whereas several small basins well above 17 m a. s. l. were coded as being situated below that threshold. We corrected for that in the revised figure 10. This mistake concerned only the color coding in the figure, not the areal calculations in the text.*

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