Interactive comment on "Physical processes of thermokarst lakes in the continuous permafrost zone of northern Siberia – observations and modeling (Lena River Delta, Siberia)" ***by J. Boike et al.***

Anonymous Referee #2 Received and published: 26 June 2015

General comments:

In general, the paper seems worth publishing. Lakes are frequent phenomena in arctic landscapes, yet still not many studies have been published on their thermal behaviour, namely for multiannual periods including cold seasons. The purpose of observing them but also designing a model and evaluating it with the observed data is important. It is well pointed out that albeit similar studies are around on lakes in these landscapes, a lack of data is addressed with the present study located in northern Eurasia. However, while the study specifically investigates a small number of lakes in the Lena delta in northern Siberia, I somewhat miss a statement on how applicable the results are for Siberia in general, or how specific the lakes in this study are. It was not so clear to me why specifically the FLake model was used. This could be motivated actually when hinting to the possibility of implementing/coupling it (in)to regional or global climate models, as in fact these large scale models often still very much simplify lake physics, in contrast to what is stated in the introduction (see specific comments). Is there any conclusion on the usability of the FLake model for such a purpose? I would also recommend some statement on the applicability of the FLake concept of self-similarity for such complex systems, and/or e.g. where reasons might be for the disagreement between model and observations during winter time. An advantage of the study is that the measurements of the lake, e.g. water depth, ice break up, and temperatures, are related to data from the surroundings, as river flooding events and river temperatures; the description of the observed phenomena in the lakes is conducted in context with these supplementary observations.

Our reply (marked in green) is structured the following:

- *Italic indicates that text has been revised or added to paper*
- References are given with full citations when not included in paper already
- Page (pp) and Line (L) numbers refer to current online discussion paper

Reply to general comments:

We thank the reviewer for the valuable comments. As outlined in our response to reviewer #1, we have sharpened/tightened the manuscript by performing additional model runs with FLake. Overall, we sharpened the objectives of the paper, including why we use the FLake model, we have generally revised the description of the modeling in the aims and method section. In particular, we have refined the description of the modeling section in the aims and methods and the applicability of the FLake is addressed in the discussion/conclusion section.

Please find our answers to the specific comments below.

Why was the FLake model used?

We added an explanation why we used the FLake model at the end of the introduction section 1, pp 6642:

FLake offers a good compromise between computational efficiency and physical reality, and has been coupled to several regional and global climate models et al. 2014; Martynov et al. 2010) and has been tested for a wide range of lakes, including tropical lakes. FLake has been used in various 1 d lake modeling studies, including the lake model intercomparision project (LakeMIP; Thiery et al. 2014; Stepanenko et al. 2010). However, it has not been used for Arctic lakes and thus, for the first time, we test the ability of FLake to reproduce the temperature regimes of thermokarst lakes in northern Siberia.

How applicable are the results for Siberia in general, or how specific are the lakes in this study?

The lakes presented in this paper are of thermokarst origin which is common for the lowland tundra permafrost areas of North East Siberia. These areas were not ice-covered during the latest glacial period (70,000-10,000 years ago) and are characterized by high to moderate ground ice content and thick sediment cover. Arctic lowlands with similar landscape characteristics and lake distributions can be found in Central and East Siberia, Interior and Northern Alaska as well as Northwest Canada (Grosse et al., 2013).

Added to section 2 “Site description”

The lakes presented in this paper are of thermokarst origin which is common for the lowland tundra permafrost areas of North East Siberia. These areas were not ice-covered during the latest glacial period (70,000-10,000 years ago) and are characterized by high to moderate ground ice content and thick sediment cover. Arctic lowlands with similar landscape characteristics and lake distributions can be found in Central and East Siberia, Interior and Northern Alaska as well as Northwest Canada (Grosse et al., 2013).

Added to section 6 “Summary and conclusion”, pp. 6662, L 13

The investigated thermokarst lakes are representative of Arctic tundra lowlands characterized by thermokarst processes that are common for large regions in Central and East Siberia, Interior and Northern Alaska as well as Northwest Canada.

Is there any conclusion on the usability of the FLake model for such a purpose? I would also recommend some statement on the applicability of the FLake concept of self-similarity for such complex systems, and/or e.g. where reasons might be for the disagreement between model and observations during winter time.

We revised the paper and added to the discussion on the model performance as this was also requested by reviewer #1. Please find a detailed response to this in the “Reply to general comments” to reviewer #1.

Furthermore, we added the following text to address the applicability of the FLake concept of self-similarity for the complex thermokarst lake system in the discussion section :

The concept of self similarity cannot account for the permafrost-talik specific lake processes, such a (ii) instantaneous warming of bottom waters with onset of ice formation and (ii) phase change in the lake’s frozen sediment, i.e. annual freeze thaw processes and thawing at the talik-permafrost boundary.

Specific comments:

Abstract: Why the FLake model? Is it necessary to mention here the specific model?

We would like to mention FLake once in the abstract, but remove the additional ones.

We added an explanation why we used the FLake model at the end of the introduction section 1, pp 6642:

FLake offers a good compromise between computational efficiency and physical reality, and has been coupled to several regional and global climate models et al. 2014; Martynov et al. 2010) and has been tested for a wide range of lakes, including tropical lakes. FLake has been used in various 1 d lake modeling studies, including the lake model intercomparision project (LakeMIP; Thiery et al. 2014; Stepanenko et al. 2010). However, it has not been used for Arctic lakes and thus, for the first time, we test the ability of FLake to reproduce the temperature regimes of thermokarst lakes in northern Siberia.

'Wedderburn number': if mentioned, please shortly explain it.

Added:

.. *a quantitative measure of the balance between wind mixing and stratification that is important for de scribing the biogeochemical cycles of lakes*.

Introduction: Caution: 'thermal dynamics [of lakes] are often incorporated in RCMs and GCMs' is not fully true, as still the representation of lakes is rather simple in large scale models. –

Changed to:

..*but their thermal dynamic represented in RCMs and GCMs is rather simple, not covering all physical processes that are necessary for reproducing atmosphere-lake interaction.*

3.2 Lake morphometry: P6647 L 8-10: if not treated here, why mentioned?

– many details on the morphometry, but are these related later to the results?

The section is shortened and moved to the appendix.

3.4 Modelling of lake thermodynamics: P 6649, L 13-15: Golosov and Kirilin and Mironov et al. applied this concept to observations? Not clear to me whether this was also modelling or observations.

Golosov and Kirillin developed the sediment model, Mironov et al. developed the ice model. Both references contain model comparisons to observations.

4.4 Summer: interesting points with the Wd number: ’monthly bottom Ts for some lakes were also warmer than the corresponding monthly air Ts’ reasoning given is that radiative heating as well as mixing is at work.

To highlight this point, we added the following in section 6 “Summary and conclusion”:

The lakes were shown to receive substantial energy for warming from net shortwave radiation *during the summer.* Warming also occurs during the ice cover period in spring, resulting in convective mixing…

4.5 Lake heat content: P 6655, L 11: annually, the energy fluxes should be more or less balanced - I had problems with approaching the energy balance by summing up all terms into an ’annual heat budget [...] up to 1 GJ/mˆ2’, in other words neglecting the sign of a term. Latent heat of fusion, e.g., is consumed in spring/summer, yet released in fall and winter. Is the interesting point in that as to how strong the consumption of incoming energy through these lakes is (the sales, so to say)?

We calculated the lake heat content (described in 3.3, equation 1, page 6646 L10-16) following Wetzel (2001). Following this method, the heat content is divided for the periods of summer, winter, and annually. Though the latent heat of fusion of the formation/thawing of the ice equals out on an annual basis (in case of a complete thawing of lake ice cover), this amount is included in the annual heat content in this method (Wetzel, 2001). This allows also direct comparison with the heat content numbers given for a worldwide variety of lakes (Wetzel, 2001, Table 6-2). We compare our heat content numbers with numbers given by previous calculations in section 5 (pp 6659, L23 to pp 6660 L1).

For clarification we added the following text at the end of the method section 3.3 “Heat content” where the heat content calculation is explained:

The annual heat budget is the total amount of heat necessary to raise the water from the minimum temperature to maximum summer temperature. The winter heat income and the annual heat budget must include the latent heat of fusion for the ice cover, especially for high latitude lakes (Wetzel, 2001).

The “sales point” here is that these studies lakes process much larger amounts of energy compared to lakes in temperature environments. Furthermore, their heat storage is much larger compared to their frozen environment (please also see reply to the following comment).

4.6.3 Thermal properties of the lake sediments and water-sediment heat flux: really interesting: how much warmer these lakes are than both the underlying ground and the atmosphere.

The „thermal offset“, i.e. difference between the mean annual temperature of permafrost and air is a result of the thermal influence of snow cover and active layer, As a result, the permafrost soil is several degrees warmer than the mean annual air temperature (MAAT) at this site of about -12.5°C. The lake with mean annual positive water temperatures is significantly warmer than MAAT, and with a higher thermal capacity resulting in a much higher annual energy density.

The energy density for measured mean annual temperatures for a lake (3°C) and permafrost soil at 2 m depth (-7°C) using the respective volumetric heat capacities for water (c_W= 4.2 MJ/m^{3}K) and frozen soil (c_S=1.8 MJ/m^{3}K; Langer et al., 2011b) and a MAAT of -12.5°C. The calculated energy density for the lake is 65.1 MJ/m^3, thus more than six times compared to the amount for the permafrost soil of 9.9 MJ/m^3.

Added to Section 4.6.3

The calculated energy density for the lake with mean annual water temperature of 3°C is about 65 MJ/m^3, thus more than six times compared to the amount for the permafrost soil of about 10 MJ/m^3. This demonstrates the importance of lakes in terms of energy storage compared to the frozen landscape.

5. Discussion: P 6660, L 9: where does this specific number come from, and for which region/landscape?

This number is the measured reported maximum thaw depth of active layer from the polygonal tundra landscape of this area using a 150 point grid (Boike et al. 2013).

Changed:

In contrast, progressive deepening of the seasonally thawing upper layer of permafrost (the active layer) of the polygonal tundra landscape at this site takes several months and only reaches a maximum thaw depth of about 0.6 m (Boike et al. 2013).

– Is it possible to state that the effect of lakes on PF below is still somewhat unclear, that is, whether a talik necessarily thaws the PF below?

Below the talik permafrost will degrade as long the vertical heat flux is not balanced by the lateral heat flux which depends on lake size and the thermal state of the surrounding soil.

We would like to point out that the bottom lake temperatures are highly relevant for talik development underneath; a difference in mean annual bottom lake temperature of 2°C would change the heat flux by a factor of two. Thus, our data aid constraining future numerical modeling experiments for talik development. For example, the numerical study of talik development for shallow lakes on the Alaskan Arctic Coastal Plain (Ling and Zhang, 2003) uses a range between 1-3°C, and thus about twofold modeled talik thickness.

We added to the discussion in section 5, pp. 6659, L9:
Mean bottom lake temperatures (range between 2.7 and 4, depending on lake depth) and are important for constraining future numerical modeling experiments addressed for talik development.

P 6660, L 15-21: If a still downward directed heat flux at the lake bottom during winter really implies PF degradation/warming can only be stated if heat fluxes during warm periods are also mainly downwards. Couldn’t it be that lakes, through their much larger heat capacity as they freeze and melt, exert a larger phase lag on temperature variations of the ground as the surroundings? –

The average bottom temperature is always larger than the freezing point which is the temperature at lower boundary of the talik. Thus, there is on an annual average a net downward ground heat flux no matter of the annual air temperature variations. However, this heat flux linear decreases with talik depth and will equilibrate at a certain point with lateral heat fluxes resulting from heat budget differences to the surrounding soils.

P 6661, L 6-8: Is it really the case that heat transfer to the atmosphere is of minor importance during winter? Ice has a large thermal conductivity, and the temperature gradient between ice (/water below) and atmosphere is large. Are there any references for that?

The reviewer is absolutely right. The heat flux from lakes to the atmosphere is much higher than the heat flux from snow covered soils (for example, shown by Langer et al. 2011b for ponds and Jeffries et al. 1999 for Alaskan lakes; both cited in this paper). In particular during winter the subsurface heat flux becomes an essential component in the surface energy balance due to the lag of incoming short wave radiation. The sub surface heat flux balances up to 90% of the radiative losses. Thus, lakes could play an important role in the atmosphere heat budget during winter.

Technical:

P 6646, L 3: ’were reinstalled’

Corrected.

P 6647, L 8: ’obtained for additional ...’

Corrected.

- generally, visibility in Fig.s 4b, 5b, 8c may be improved

We will supply higher resolution figures with the final manuscript version.

P 6652, L 21: replace ’with a light extinction of ...’ with ’assuming light extinction to be ...’

Corrected.

P 6652, L 23: ’radiative’ instead of ’radiation’

Corrected.

P 6658, L 2: ’release of heat’

Corrected.

P 6659, L 10-11: ’ice cover thickness’

Corrected.

P 6661, L 11: ’...such as thawing.’

Corrected.