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 #1

Received and published: 21 May 2015

General Comments:

This paper presents data and analysis of the thermal regimes of five thermokarst lakes located on the Lena River Delta in Siberia over a three year period. This is a worthwhile contribution because 1) there is relatively few studies of lakes in Siberia despite their very high abundance and potentially rapidly changing condition, 2) many such lake studies only collect summer data from single years, whereas year round and multiannual data are presented in this work, and 3) the collection of water level and bathymetry data in addition to thermal data presents additional opportunities to understand these systems.

Many of the observed aspects of thermal regimes such as release heat from the sediment following ice cover development and warming the water column prior to ice out appear correctly interpreted yet are not widely reported in other analyses of lake thermal regimes though I believe these are common processes. Good support for the value of year-round monitoring of lakes. This paper is very descriptive however and it seems there are many opportunities for comparison and analysis the authors elude to but never pursue.

Some examples are comparison of thermal regimes by 1) landscape setting (river terraces vs. Pleistocene Ice Deposit Complex) or source waters (subject to river flooding vs. more isolated), 2) bathymetric characteristic, or 3) interannual variation in relation air temperature, radiation, or wind regimes. I think all of these potential controls on lake thermal regimes are qualitatively addressed to some degree but not analyzed in any meaningful way and thus the paper lacks potential understanding of these relationship that could be use predict changes in lake thermal regimes in time or space. The use of the FLAKE model is somewhat unclear as well. Some unmeasured parameters were simulated but it is not entirely clear what the value of these are to the analysis and questions of interest.

Additionally the figures are mostly time series plots of different climate, water temperature or heat budget components and not always that insightful. I would simply recommend analyzing the collected data in a way that helps understand how these thermal processes vary in some meaningful way. I think that in addition to the importance of this lake type in this region would make this a valuable paper.

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 his/her valuable comments. We agree with the reviewer that the data and processes discussed in this paper are not (widely) reported and have, to our knowledge, not been reported for Arctic thermokarst lakes at all. We see the strength and novelty of this paper in presenting data and quantitative analysis of new processes, such as warming of bottom temperatures (following ice cover development) and warming of the under the ice that were speculative in the past. Furthermore, we provide modeled biogeochemical indices that are indices of summer stratification in thermokarst lakes. While commonly reported for non-Arctic lakes, we report and discuss these numbers and processes for the first time for North East Siberian thermokarst lakes.

To address the major comment on the potential controls on the lake thermal regimes in a quantitative way, we have performed additional numerical modeling analysis. In particular, we have explored the relationship between the morphometry (depth) and summer stratification duration as one of the most morphometry-sensitive characteristics of the thermal regime of these northern lakes. Furthermore, we have added quantitative statistics to the model validation that will aid the clarification of the use of the model. Overall, we sharpened the objectives of the paper, including why we chose the FLake model. We have generally revised the description of the modeling in the aims and method section. Furthermore, we have moved the section 3.3 "Lake Morphometry" to the appendix of the paper.

Please find the specific comments below.

The revised method section now includes the following additions:
The model was used for:

- Validation of the 1d modeling approach and qualification of the main mechanisms governing such features of the lake thermal regime as summer stratification, water-sediment heat exchange, ice melting

- Characterization of the water-sediment heat exchange on the annual time scales as a key effect of lakes on the permafrost thawing

- Establishing a relationship between the morphometry and summer stratification duration as one of the most morphometry-sensitive characteristics of the thermal regime.

The first two points are addressed in the paper, while the third point has been suggested by the reviewer, and has now been added to this study. We performed a sensitivity study by keeping all model parameters and just changing the morphometry (depth) since this a fundamental parameter for 1 dimensional models. For Sa_Lake_1, lake depths were varied for the range of 2-12 m with increments of 0.5 m. From all these results a single characteristics--the number of days with summer stratification, Sum(Ns) where Ns =1 if (Ts-Tb)>0.5°C was calculated and put on the line vs. depth (Fig. R1). Discussions on the stratification importance for the biogeochemistry and its dependence on the lake morphometry have been added to the revised manuscript in the discussion section 5, pp.6659 L22:

Our observations revealed, and the model was able to simulate, appearance of short stratification periods in summer in the studied lakes (Figs. 4& 5). While this has importance of these stratification events for the lake biogeochemistry is not quantified yet, though the seasonal mixing regime is apparently the major physical factor affecting all biogeochemical processes in lakes. In particular, duration of the thermal stratification in summer affects immediately the amount and the vertical distribution of *dissolved oxygen: longer summer stratification provokes deep anoxia and favors by this methanogenesis in the deep water column and in the upper sediment (Golosov et al. 2012). Under equal climatic forcing, lake depth is the primary factor determining duration of summer stratification (the second one being the water transparency, Kirillin 2010). Sensitivity model runs with the lake depth varying in the range 2-12 m using the same meteorological input data from Samoylov demonstrate that lakes in this climatic zone with mean depths >5 m should have dimictic stratification regime, i.e. develop continuous stratification in summer with duration of 1 month or longer (Fig. R1). This also supports the observation of summer stratification in deeper (> 6 m) Alaskan thermokarst lakes (Sepulveda-Jáuregui et al., 2015). In deeper lakes of ~8 m depth or more, the summer stratification duration significantly increases on account of high thermal inertia resisting to vertical mixing during the autumn cooling in August-September (Fig. R2).*

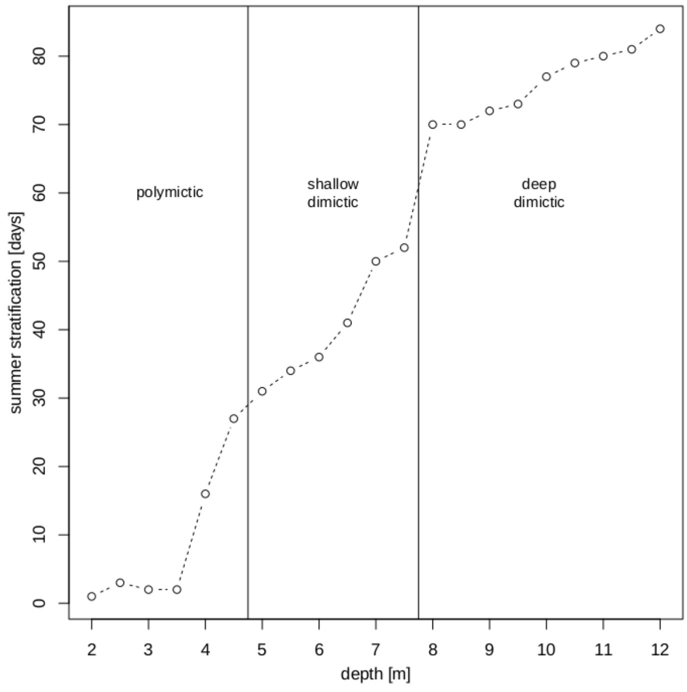

Fig. R1. Total number of days with summer stratification in lakes of varying depths modeled with FLake driven by the meteorological forcing from Samoylov Station for 2010. Existence of stratification was determined by the criterion (Ts-Tb)>0.5°C, where Ts and Tb are the modeled temperatures at lake surface and lake bottom, respectively.

While the majority of thermokarst lakes are shallow, our results suggest that stratification events can be sufficiently long in lakes with depths > 4 m with corresponding effects on biogeochemical processes within the water column and on the lake-atmosphere exchange of dissolved gases. Hence, relatively deep lakes might play the role of ‘hot spots’ in the tundra landscape, where decomposition of organic matter in the deep water column and in the upper sediment is accelerated by the isolation from the atmospheric oxygen.

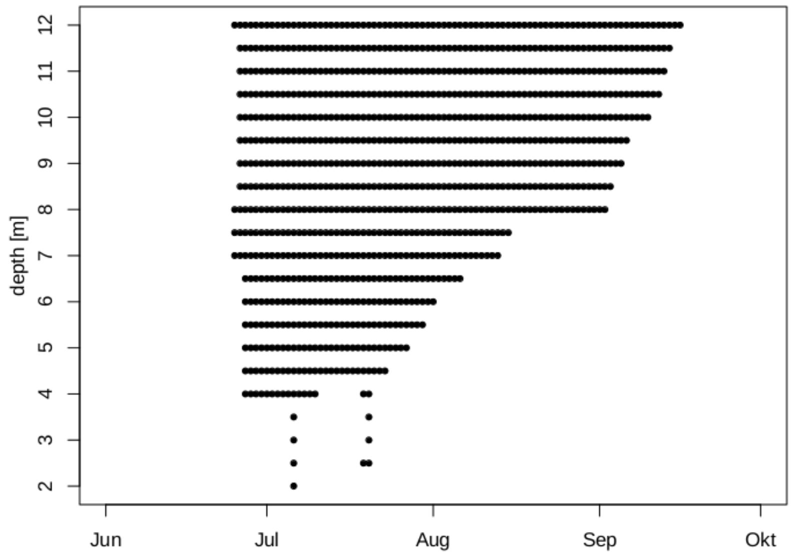

Fig. R2. Summer stratification duration in lakes of varying depth (see Fig. R1 for definitions).

Added to references:

Sepulveda-Jauregui, A., Walter Anthony, K. M., Martinez-Cruz, K., Greene, S., and F. Thalasso (2015). Methane and carbon dioxide emissions from 40 lakes along a north–south latitudinal transect in Alaska, Biogeosciences, 12, 3197-3223, doi:10.5194/bg-12-3197-2015.

Reply to specific comments:

Title: I would replace “Physical Processes” with either “Thermal Processes or Regimes” because it doesn’t seem like other physical processes were analyzed or considered.

Agreed and changed.

Abstract: 6639 L16 – might just say what Wedderburn number mean as many readers might not be familiar with this term.

Agreed and added:

.., a quantitative measure of the balance between wind mixing and stratification that is important for describing the biogeochemical cycles of lakes.

6639 L19-20 – Not sure naming the model is necessary

Agreed and changed.

6640 L30 – Seem abstract should follow with some treatment of ideas in the Summary and Conclusions section.

We assume that the reviewer refers to the abstract (page 6640, L1-3, since Line 30 does not exists on this page)?

We have revised the abstract by including the results of the new modeling results, as well as further details from the summary and conclusion section.

Introduction 6641 L12 – Toolik Lake is a Long Term Ecological Research (LTER) station, not a Long Term Experimental (LTE) site (though the latter might be more fitting). Also, if there are long-term data from this site that are truly exceptional they should be noted here.

Corrected.

We assume that the reviewer refers to long-term data collected from lakes at this site. Initial limnological work at the Arctic LTER began at Toolik Lake in 1975, but time-series of temperature data have been collected routinely in Toolik Lake starting in 1998 (http://ecosystems.mbl.edu/ARC/). This data record is already noted in the paper (pp 6641, L10-14).

Last paragraph on aims; ii) doesn't appear to have been done, but it is a very good idea, and iii) it is unclear to what end this modeling part is for.

We assume that the reviewer refers to i) and ii) of aims (page 6642)?

i) thermal processes have been addressed qualitatively in sections 4.6.1-4.6.3 of the manuscript. ii) validation of FLake has been addressed in section 4.6. The results of the new statistical analysis have been added to section 4.6 Modeled seasonal lake thermal dynamics, pp. 6656. L 2:

To quantify the model performance for thermokarst lakes we applied standard measures (e.g. Thiery et al. 2014) of the model's ability to reproduce the observed mean temperature (Tm), the standard deviation ratio (SD_{model}/SD_{obs}), the centered Root Mean Square Error (RMSEc), and the Pearson correlation coefficient (r). Please note we use Tm (no temperature probes in the surface because of the seasonal forming ice cover) while other lake model evaluations use surface temperature Ts (for example, from African and West European lakes). The FLake demonstrated good performance with regard to the mean lake temperature. The statistics—Pearson correlation coefficient r = 0.97, SD_{model}/SD_{obs} 1.28, RMSE 1.49 °C are slightly worse than those reported previously for temperate lakes (r = 0.988; Stepanenko et al. 2010) and better than FLake performance on deep tropical lakes (r = 0.78, SD_{model}/SD_{obs} 1.25, RMSE 0.75 °C; Thiery et al. 2014). The model reproduced summer stratification during the ice free period (r = 0.93, SD_{model}/SD_{obs} 1.25, RMSE 1.82 °C). Solar heating of the water below the ice is not included in the model and thus the agreement between model and observations is lower during the ice covered period (r = -0.42, SD_{model}/SD_{obs} 0.37, RMSE 0.66 °C). Furthermore, this period comprise the winter ice-covered period, as well as the ice break up period in early summer, thereby including uncertainties in the ice breakup prediction and in the lake heat content at the beginning of the open water period (Fig. 8). As the thermal dynamics under the ice cover is, as a rule, crudely reproduced by the one-dimensional lake models used in coupled climate modeling systems (Stepanenko et al. 2010), estimation of the role played by thermokarst lakes in regional climate requires integration of a cost-effective and physically sound sub-model of winter lake thermodynamics into lake parameterization schemes for climate models (e.g. Oveisy and Boegman 2014).

Added to references:

Thiery, W., V. M. Stepanenko, X. Fang, K. D. Jöhnk, Z. Li, A. Martynov, M. Perroud, Z. M. Subin, F. Darchambeau, D. Mironov and N. P. M. van Lipzig (2014). LakeMIP Kivu: evaluating the representation of a large, deep tropical lake by a set of one-dimensional lake models. Tellus A, 66. 10.3402/tellusa.v66.21390.

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., and D. Mironov (2010). First steps of a lake model intercomparison Project: lakemiP. Boreal environment research, 15, 191-202.

Oveisy, A. and L. Boegman, (2014). One-dimensional simulation of lake and ice dynamics during winter. Journal of Limnology 73, no. 3.

Site Description:

6644 L13-15 This statement that lake source water is ground ice has a reference, but this seems unlikely. More likely its snow-water which has a similar isotopic signature to ground ice (suggest removing this).

The statement is taken from the article by Abnizova et al. (2012) who conducted water balance measurements, as well as detailed analysis of stable isotopic signatures of waters at this site. In addition, ongoing research at this site confirms thawed ground ice as one main source of lake water with potential mixing with precipitation. The isotopic compositions of snow and ice wedges are isotopically much “colder” compared to lakes and ponds. The isotopic composition of ice wedges ranges between δ^{18}O -27 und -21 ‰, with slopes close to the GMWL (Meyer et al. 2015). Snow shows a large spread in its isotopic composition (δ^{18}O 36.1 to -16.1 ‰), with an average of about δ^{18}O -27.5 ‰ and with slopes close to the GMWL (pers. Communication T. Opel).

Other publications of Siberian thermokarst lakes also point to ground ice as an important source for thermokarst lake water, for example by Fedorov et al. (2014).

Changed:

The stable isotopic ratios indicate that the thermokarst lake water is sourced mainly from thawed ground ice *mixed with precipitation* and the water in shallow ponds is sourced mainly from summer precipitation (Abnizova et al., 2012).

Meyer, H., Opel, T., Laepple, T., Dereviagin, A. Y., Hoffmann, K., and Werner, M.: Long-term winter warming trend in the Siberian Arctic during the mid- to late Holocene, Nature Geosci, 8, 122-125, 10.1038/ngeo2349

Fedorov, A.N., Gavriliev, P., Konstantinov, P., Hiyama, T., Iijima, Y., and Iwahana, G., 2014. Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia, Ecohydrology, 7, 188-196.

Methods 6645 L25 – 6646 L6 – How were the buoys relocated and retrieved if they are located well below the water surface? Just curious as this seems challenging.

The reviewer recognizes the difficulties since only sometimes the yellow buoys are visible through the upper m of the water column! We have established a system of land based markers that together with GPS coordinates, as well as “catch method” by rowing in circles around the GPS position with a rope on the bottom sediment.

6648 L7 – This section is interesting, but seems more rational is needed as to why this is a good way to present lake thermal data.

Changed:

Starting Section 3.3 with ``The ability of lakes to store and redistribute additional heat at seasonal time scales and to affect by this the heat budget of permafrost areas on the landscape level is the major factor related to the thermal regime of tundra lakes. Therefore..."

6648 L19-20 – Since latent heat of freezing and thawing aren’t the same, why should this necessarily be the case.

To our best knowledge the latent heat of fusion and freezing for freshwater is essentially the same and both terms are interchangeable. For some high Artic lakes, however, the ice cover does not thaw completely during some years and thus multiyear ice cover can form (though rare, for example on Color Lake on Axel Heiberg Island, Nunavut, Canada; Adams et al., 1989).

Adams, W. P., Doran, P. T., Ecclestone, M., Kingsbury, C. M and C. J. Allan (1989). A Rare Second Year-Lake Ice Cover in the Canadian High Arctic, Arctic, 42(4), 299-306.

6649 – L19-21 – How certain are you that lakes are snow- free most winters? Have multiple lakes been observed throughout multiple winters? Are there other studies or observations to back this up?

We have field observations for several spring field seasons in 2009, 2011 and 2013 for a number of lakes on both islands (Samoylov and surrounding island, such as Kurungnakh). The larger lakes had almost no snow cover, only isolated patches along ice cracks show snow accumulation. These field observations are also supported by optical satellite images. Likely, the (little) snow is blown away by high winter winds. On the smaller lakes (ponds), with slight topographic depression, a snow cover exists and varies between years.

Results:

6657 L16-22 – This lake sediment data is very interesting, but not from this study so why is it in the results.

We prefer to keep these in results as they are directly related to model application for estimating the typical ranges of the water-sediment heat fluxes in seasonal cycle.

For clarification, we have moved and added further information on this data set in the method section 3.4. “Modeling of lake thermodynamics” (pp 6650, L4):

Two temperature profiles were obtained in June 1984 for one shallow (1 m) and one deeper (5 m) lake, down to a sediment depth of up to 20 m. These temperature profiles are used as input for the model experiments since the assumption of thermal equilibrium does not necessarily exist for the lakes in the permafrost landscape.

Furthermore, the following information was added to the Introduction section:

(ii) *to make use of measured data to validate the freshwater model FLake*, *as well as estimate water sediment heat exchange. FLake offers a good compromise between computational efficiency and physical reality, and has been coupled to several regional and global climate models (Thiery et al. 2014; Martynov et al. 2010) and has* *been tested for a wide range of lakes, including tropical lakes in lake model intercomparison projects. However, it has not been used for Arctic lakes and thus, for the first time, the ability of FLake is tested to reproduce the temperature regimes of thermokarst lakes in northern Siberia.*

Discussion:

6659 L2 – What is CALON?

We explain CALON on page 6641, L28:
CALON is a new Circum-Arctic Lakes Observation Network initiative, see also (http://www.arcticlakes.org/calon-lakes.html)
6659 L10 – I believe that (lake depth > winter ice cover depth) should be (lake depth > maximum ice thickness)

Changed.

6660 L22-27 – Not sure I follow the comparison of fall and spring thermal dynamics here.

For clarification, we revised this paragraph the following:

The warming of lake-bottom temperatures with the onset of ice cover was initially attributed by Brewer (1958) to net shortwave radiation warming and by Mortimer and Mackereth (1958) to the heat release from the lake sediment. Our observational results clearly demonstrate increase of the near-bottom temperature right after onset of the ice cover and the modeling experiments suggest them to be produced solely by the heat flow from sediment with typical rates of < 10 W m^2*. However, the heat flux from the sediment in tundra lakes appears to decay within less than one month, which is much faster than in ice-covered lakes of the temperate and boreal climates (cf. Rizk et al. 2014), and is followed by gradual decrease of the deep water temperatures. The latter appeared to be not well reproduced by the parameterized sediment module of the FLake. Another process missing in the modeling results is the lake temperature increase, which starts in spring 1-2 months before the ice-off and is apparently attributed to the heating by solar radiation. This temperature increase takes place down to the lake bottom that supports an important contribution of solar heating in the heat budget of the water column 25 under ice, especially in spring, and suggests that radiation can also make a significant direct contribution to* *sediment heating in shallow and clear-water thermokarst lakes – a contribution that is usually neglected in lake models.*

Added to references:

Mortimer, C. and F. Mackereth (1958). Convection and its consequences in ice-covered lakes. Verh Int Ver Limnol 13:923–932.

Rizk, W., Kirillin, G., and M. Lepparanta (2014). Basin-scale circulation and heat fluxes in ice-covered lakes. Limnol. Oceanogr. 59: 445–464. doi:10.4319/lo.2014.59.2.0445.

6661 – L19-23 – I didn't see data presented to support this statement (may have missed it) but would be interesting to see this and focus more on such question with data presented in results (and figures) and discussed. All time series figures should have y-axis title in addition to units and x-axis dates are hard to read.

Flooding of river water and the effect on the thermal regimes of the lakes was discussed in section 4.3 (page 6653, L13). To clarify and highlight the river flooding events, we have added arrows in the revised figures 4 and 5.

Furthermore, all figures were redrawn with a reformatted x-axis and titles were added to the y-axes.

Figure 6 – Which months are which and why the interannual variation?

Starting with colder mean bottom temperature in July after ice break up, gradual warming creates warmest mean bottom temperatures in the deepest lake Sam_Lake_4 always in August and in the shallowest lake Sam_Lake_3 in July. For all other lakes, maximum bottom temperatures occur either in July or August, depending on the lakes's seasonal energy balance. Maximum air temperature usually during July, but net radiation can be quiet variable (Fig. 3 c). Interannual variations are mostly due to the differences in timing of ice cover break up which is determined by a combination of factors (thickness of ice, wind forces that break up the ice, surface energy balance, turbidity of the water influencing the light transmission and absorption). As listed in Table 1, the start of ice cover break up and complete melt can range over several weeks in its length and annual variability.

We added the following information to the results section 4.4, page 6654, L19:

Starting with colder mean bottom temperature in July, gradual warming creates warmest mean bottom temperatures in the deepest lake Sam_Lake_4 always in August and in the shallowest lake Sam_Lake_3 in July. For all other lakes, maximum bottom temperatures occur either in July or August, depending on the timing of ice break up and the lake's seasonal energy balance.

We will also supply a summary table on monthly air and bottom lake temperatures in the supplementary material of this paper, since the figure would otherwise be too crowded.

Lake bathymetry figures – Can you show were sensors were located in each?

The lake bathymetry figures have been revised and now include the location of the sensors.