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Abstract

Recent evidence has shown that Arctic regions have warmed about twice as much as elsewhere on the planet over the last decades, and that high-latitude permafrost-periglacial processes and hydrological systems are notably responsive to rising temperatures. The aim of this paper is to report on permafrost thermal regime of islands located along the Lena River floodplain, upstream of the city of Yakutsk (eastern Siberia). Four islands were monitored during two consecutive years (July 2009 to July 2011) to characterize their frozen soil thermal regime using waterproof dataloggers and continuous monitoring of permafrost in contact with ice breakup of the Lena River. For each of these islands, we measured: i) river water, air and frozen soil temperatures at different depths; ii) height of ice jams; iii) submersion duration and height during the flood; iv) erosion and sedimentation. The results show that within a zone of thick and continuous permafrost, the Lena River floodplain is far from being homogeneous: it rather shows notably heterogeneous thermal regimes, with some islands composed of permafrost and others with only seasonally frozen ground. Our study highlights the complexity of ecosystem responses across Arctic environments.

1. Introduction

Permafrost has been warming at the global scale over the last decade, following the Arctic amplification of air temperature increase in the Northern Hemisphere (Biskaborn et al., 2019). Recent work has shown a significant increase in air and ground temperatures in central Yakutia since the late 1980s (Fedorov et al., 2014; Iijima et al., 2016, Zhang et al., 2012). In the lower Lena River valley (Figure 1), according to Yang et al. (2002), the mean annual ground temperature has increased by about 1.3°C since 1930. The mean annual air temperature at Yakutsk, which was ranging between -10.3°C and -9.9° for the period 1936-1999, has increased to -7.4°C for the period 2008-2017. The warming is characterized by a marked inter-seasonal evolution: a strong increase (+3°C since 2000) in winter temperatures (November-March) is observed, while spring temperatures (April and May)

have increased by 2.3°C. The precipitation (about 230 mm per year at Yakutsk) does not show the same trend, however. Very wet conditions have occurred more frequently since 1998 (1999, 2005, 2006, 2007 and 2013), with storms affecting Siberia resulting in more abundant late summer precipitation and early winter snow (Fedorov et al., 2014b; Iijima et al., 2016).

Furthermore, active layer deepening results in an increase in river discharge. At the beginning of the 21st century, Peterson et al. (2002) reported an average increase of 7% in water discharge volumes delivered by the seven main sub-arctic rivers, including the Lena. More recently, a study (Gautier et al., 2018) reported a strong water discharge increase since the beginning of the 21st century for the Lena River at Tabaga (just upstream of Yakutsk): the 2000-2017 discharge was 15% higher than the discharge for 1936-1999. Furthermore, floods are also changing, with more frequent flood peaks and longer recorded flooding durations (Gautier et al., 2018). Recent exceptional flood events are reported (Shiklomanov and Lammers, 2009; Costard et al., 2014; Gautier et al., 2018; Tei et al., 2020). There has also been a decrease in winter river ice cover, used as road. Winter thawing/melting events, as well as spring ice jam floods during the ice breakups represent major risks for riverside residents, road and river infrastructures. All these factors lead to permafrost instability and consequent changes in forest, wetland, lake and river ecosystems.

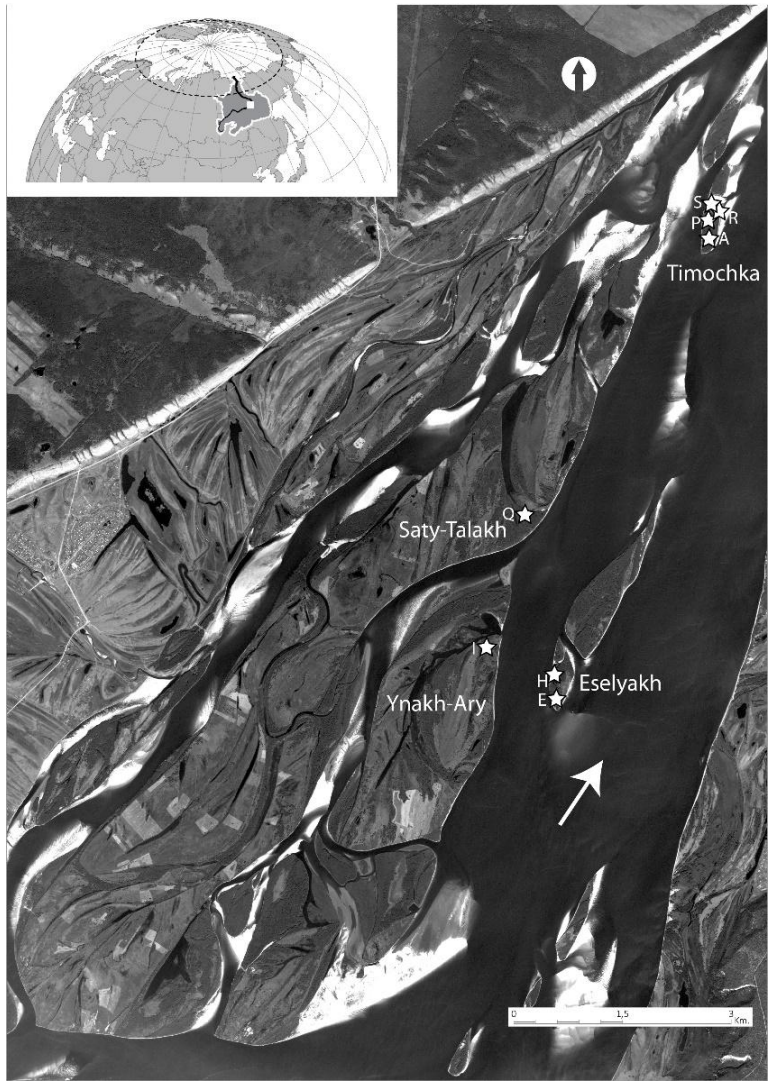


Figure 1: A. Location of the Lena basin (grey-shaded area). B. Study area (upstream of Yakustk). Background image: Spot 2008; Star with letters: Temperature sensors.

Very few studies have focused on geomorphological impacts of ice breakups and floods on major Arctic rivers. Most of the geomorphological studies concern river dynamics of breakup for Canadian Arctic rivers (Beltaos and Burrell, 2002). Specifically, studies have shown the role of the ice cover and its thickness on the intensity of ice jams produced by ice packs along the Yukon River (Shen, 2003; Walker and Hudson, 2003). With increasing discharge, the ice cover under pressure locally cracks and starts to move (Shen, 2003). This is the beginning of the "break up" phase where ice rafts accumulate at the head of islands (Figure 2). The flow often carries these ice blocks along with tree trunks (Walker and Hudson, 2003). Ice jams produce local dams, resulting in a sudden rise of water levels (Billfalk, 1982; Beltaos and Burell, 2002; Costard et al., 2014). During the flooding season, a typical

heat exchange takes place between the water and the frozen islands, leading to accelerated erosion of the banks (Are, 1983; Jahn, 1975; Walker, 1983).

Breakup is strongly heterogeneous, as numerous factors control its starting date and intensity (Costard et al., 2014; Gautier et al., 2018). These events can depend on temperature and precipitation within the watershed, but also on ice cover thickness, starting date and duration of the break-up phase, and spring and/or winter temperatures. In Siberia, the conditions for the onset of break-up events, as well as their intensity or efficiency on erosion, remain poorly characterized. Moreover, analysis of climatic and hydrological data near Yakutsk showed a very clear thinning trend in winter ice thickness and a significant increase in water temperature of the Lena River near Tabaga (gauging station upstream section of Yakutsk, Figure 1). We have also demonstrated (Costard et al., 2007) the impact of recent warming on increasing erosion rates of the islands by thermal erosion. .

Figure 2: Beginning of the ice breakup on the Lena River in 2010. The Eselyakh Island is submerged. Flow from right to left. During the first days, drifting ice blocks on the river form thick ice accumulations at the Eselyakh Island head, together with a frontal erosion of up to 40 m within a few days.

Break-up and large flooding events represent an important risk in Arctic regions and can threaten infrastructures. In May 2001 and 2010, catastrophic breakup events linked to an early spring season following a severe winter strongly impacted the cities of Yakutsk and Lensk (Gautier et al., 2018). Recently, a project of a 6 km-long bridge across the Lena floodplain at Tabaga site is projected and it implies accurate knowledge of the formation, and especially of the causes of the variable intensity of these ice breakups. Specifically, there is a clear need to analyze the conditions that triggered these ice breakups and their subsequent geomorphological impacts on the Lena river banks. Interestingly, some key parameters remain unresolved, such as the thermal state of these frozen islands. In order

to document the thermal profiles of these islands and to clarify the thermal impact of these ice breakups on Lena floodplain permafrost, we started a joint research program between GEOPS and LGP laboratories near Paris and the Melnikov Permafrost Institute in Yakutsk. The main objective of this paper was to investigate the hypothesis that some of these islands contain permanently frozen soil (permafrost), while others are affected only by seasonal frost.

2. Study area

Central Yakutia (eastern Siberia) is characterized by a strongly continental climate with extreme variations in air temperatures, ranging from +40°C in summer to -60°C in winter (Fedorov et al., 2014). The region is characterized by a thick continuous ice-rich permafrost of late Pleistocene age, called “Yedoma” (Antonov, 1960; e.g., Schirrmeister et al., 2013). Figure 3 and Table 1 show the contrasted ground surface temperature range between July 2009 and July 2011, as recorded within the Lena River floodplain upstream of Yakutsk at the Eselyakh Island (for location see Figure 1). The average annual ground surface temperature is around -10°C. The low annual precipitation (230 mm near Yakutsk), together with a high evaporation rate, induces a dry climate (Antonov, 1960). The wet season occurs in the summer, with 140 mm distributed between June and September. Snow cover thickness remains low (30 to 40 cm), which favors efficient frost penetration and the existence of deep permafrost, especially underneath the taiga. Locally, permafrost has an average temperature of -5°C and a maximum depth of 1500 m (Fedorov and Konstantinov, 2009). Since the end of the 1980s, it has undergone a warming of almost 1.5°C (at a depth of 3.2 m), together with a deepening of the active layer, with values ranging from 0.8 to 1.2 m at the latitude of Yakutsk (Fedorov and Konstantinov, 2003; Fedorov et al., 2014).

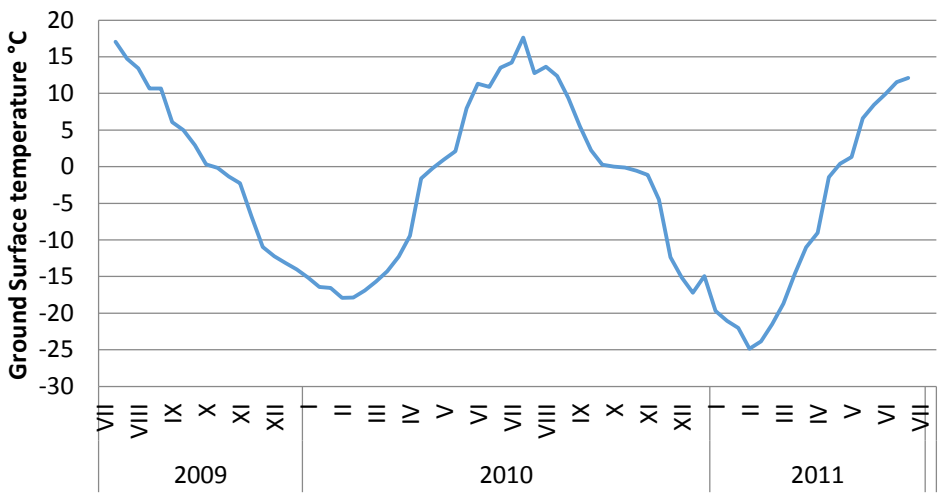


Figure 3: Recorded ground surface temperatures of Hobo E between July 2009 and July 2011 on the Lena River floodplain at Eselyakh Island.

In Yakutia, the Lena River is one of the largest fluvial hydrosystems within the periglacial zone (Figure 1), with thick and continuous permafrost. From its large watershed (2.49 million km²), the Lena annually brings 525-537 km^3 of water to the Laptev Sea (Antonov, 1960; Shiklomanov et al., 2009), representing 15 % of total freshwater flow into the Arctic Ocean. During the winter season, the river flows under an ice cover of 1.4 m thick on average (min: 30 cm; max. 2 m). The river discharge is then extremely low (less than 1500 $m^3 s^{-1}$ at the Tabaga station, south of Yakutsk city, by 61° 4'N and 129° 3'E) and reaches its lowest discharge of 870 $m^3 s^{-1}$ at the end of the cold season (Gautier and Costard, 2000; Gautier et al., 2018).

The four instrumented islands present various configurations. Two islands (Eselyak and Timochka) are located in the central part of the active channel, whereas Ynakh-Ary and Saty-Talakh are two very large lateral islands, sizing 5 km² and about 20 km², respectively (Figure 1). The islands are colonized by a homogeneous alluvial forest mainly composed of willows. On the Lena River, islands are formed by stabilization of sand bars by pioneer sequences. Because of the short duration of flooding in the spring, sand bars are dewatered during two or three months (July-September), allowing young willows to grow. Because of their abundance, young trees trap the sediment load, causing rapid vertical accretion of the island (Gautier et al., 2021). Hence, the basis of the island stratigraphy is mainly composed of sand, i.e. homometric (D_{50} = 200 - 250 µm) sandy material organized in horizontal beds several tens of centimeters thick. The sandy deposits are often covered with layers of silt (D_{50} between 50 and 100 µm) deposited by overbank flows. Thicker fine-grained deposits can be found in abandoned channels. For a detailed description of the sedimentary sequences of these islands, see Gautier and Costard (2000) and Costard et al. (2014).

On the Lena river, ice breakups are controlled by the meridian (i.e. from south to north) course of the river, with a 30- to 50-day lag between basin upstream and downstream (Gautier et al., 2003). As a result, a flood wave propagates from the southern regions further to the still-frozen regions in the north. In spring, when snow and ice covers melt, the flow increases abruptly. Massive ice and log jams can be formed on the island heads (figure 2). The ice break-up at the latitude of Yakutsk occurs during the second half of May and within a few days, the volume of water flow increases by 20 to 45 times. The peak flood can reach up to 50,000 $m^3 s^{-1}$ (Antonov, 1960, Liu et al., 2005; Gautier et al., 2018). At the latitude of Yakutsk, that water level during the flood season can be up to 8 to 10 m relative to the winter low water level (Costard et al., 2007; Gautier et al., 2018). During high floods, the Lena flood spreads over a width of 25 km. The water temperature, very low in the winter and at the beginning of the flooding season, increases rapidly to reach 17-18°C in July and August (Costard et al., 2014).

Preliminary studies based on the analysis of satellite images had been conducted, which enabled us to identify the locations with the highest erosion rates on a 100-km long transect of the Lena River in Yakutia (Costard et al. 2007). Furthermore, more than one hundred islands have been surveyed on the basis satellite images (1967 – 2017) and erosion – sedimentation was surveyed for several years on five islands (Costard et al.., 2014; Gautier et al., 2021). Thermal erosion of river banks ranges on average between 11 and 18 m yr^{-1} on island head (upper part) and 5 to 10 m on island side. In localized areas, erosion rates of 25 to 40 m yr^{-1} could be observed (Gautier et al., 2003; Costard et al., 2007, 2014; Tananaev, 2016; Dupeyrat et al., 2018; Gautier et al., 2021). The thermo-mechanical erosion efficiency implies that the water is permanently in contact with permafrost (Walker and Arnborg, 1963; Jahn, 1975; Walker, 1983; Costard et al., 2014).

For the purpose of our study, a site upstream of Yakutsk (Figure 1) have been chosen, which allows to avoid the urban heat flow. In addition, the upper Lena River is not impacted by dams. Ten islands were preselected, and four of them have been instrumented and discussed further in this paper (Figure 1). Two islands are lateral old islands and two are located in the center of the river channel.

Table 1. Main features of the 4 study islands. Letters: temperature sensors

	Area (m^2)				Dataloggers			
Island Name	1967	2008	2017	Age	Temp. at -3 m Mean – Max (°C)	Duration of measurement	Sediment	Geomorphic Unit
Eselyakh Upstream part Downstream part	486,726 416,877	198,256 790,189	105,520 675,931	>60 yr	T4 E: -2.3/-3.1 H: -0.3/-0.6	2008 – 2011 2009 – 2011 2008 – 2011	Mixed sed. Sand	Abandoned channel Bar
Timochka Upstream part Downstream part	216,239 0	135,560 70,300	107,161 79,164	<30 yr	A: 0.7/2.1 P: 0.6/1.6 R: 1.1/1.6 S: 1.1/1.6	2008 – 2014 2010 – 2014 2010 – 2015 2016 – 2018	Sand Sand Sand Sand	Bar/island Bar/island Bar/island Bar/island
Ynakh-Ary	5 047,718	5 338,126	5 0294,298	>70 yr	I:-3.1/-3.4	2009 – 2016	Mixed sed.	Abandoned channel
Saty-Talakh	18 247,279	20 125,713	19 685,946	>70 yr	Q: 0.3/-1.2	2010 – 2018	Sand	Bar/island

3. Methods

In order to determine the ground temperature of the islands with and without permafrost, and to evaluate the active layer thickness on the islands, various methods were integrated. First, a drilling campaign (2008) enabled the installation of several temperature sensors at different depths and a precise measurement of the active layer. We used HOBO 4-channels dataloggers (model U12-008) to record variations in the thermal profile of the frozen soil at different depths. Each datalogger, previously calibrated in the laboratory, includes 4 thermocouples that automatically record, every hour, permafrost and water temperature with an accuracy of +0.1°C, on the soil surface, at 1m, 2m and 3.2 m depth (Figure 4). On Saty-Talakh island, the sensors have been installed at 2 m, 3 m and 4 m depth. Once a year, after the ice break-up, we went to the instrumented sites to collect data from the dataloggers and to ensure the equipment maintenance on site. During the first year (2008) on Timochka and Eselyakh islands, only two among the four sensors worked well and the others were broken by the strong ice breakup. They were modified to ensure waterproof conditions and to improve the robustness of the equipment in order to support the mechanical effect of ice breakups (e.g., internal pressure). Thus, we had to develop a new system (Figure 4) that is much more efficient and could support the repeated impacts of ice rafts and water pressure (Konstantinov et al., 2011). Unfortunately, because of the extremely rough conditions, the duration of measurements of the temperature sensors is very variable (Table 1): some of them have been working for more than 10 years, whereas others disappeared during a flood or were buried under meters of sediment and woody debris.

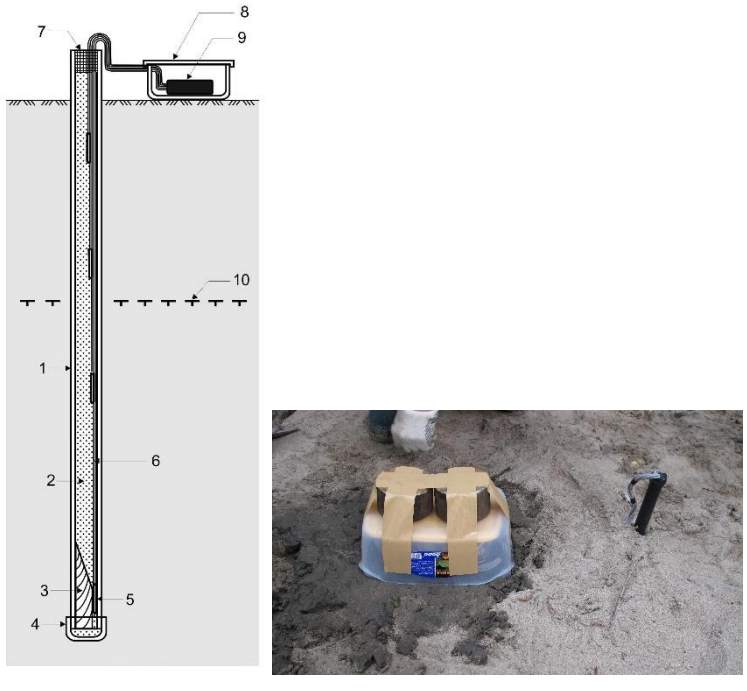


Figure 4: Photo on the left: Drilling in permafrost for the installation of thermocouples placed at 0 m, 1 m, 2 m and 3.2 m depth. 1- polypropylene tube; 2- dry sand; 3-wooden bloc; 4- tube plug; 5-sensor; 6-cable; 7- waterproofing compound; 8-protective box; 9-data logger; 10-bottom of active layer. Photo on the right: HOBO datalogger modified to support flooding of the island during spring breakup. Note the 2 weights on the box and the wooden support holding the datalogger in the waterproof box. (Figure modified from Konstantinov et al., 2011).

Other Progres-Plus Thermo-Buttons iBTag (model 22L with a ± 0.5°C accuracy) sensors were installed on *Salix* trunks of two instrumented islands (Timoshka and Eselyakh islands) to estimate the height and duration of submersion and variations of water temperature (Costard et al., 2014; Gautier et al., 2018). These thermobuttons were installed from the ground surface and every 50 cm up to a height of 3 m. The water levels are correlated to the daily discharge measured by the navigation services at Tabaga (gauging station at 8 km from the sites). Every sensor position was precisely determined with a GPS and a total station.

We estimated the age of the islands based on the year of their appearance (Gautier et al., 2021) from a diachronic analysis of satellite images (Figure 10). We also used the dendrochronology method to precisely measure the age of the oldest trees. Our objectives were to identify a possible difference in their thermal regime between perennially-frozen islands and islands without permafrost (only frozen in winter).

We also quantified the variability of erosion and sedimentation rates over a year using field surveys (total station topographic measurements and sediment traps) and we realized various grain-size

analyses of the deposits (Costard et al., 2014). Here, we focus our study on the thermal regime of four islands (Figure 1).

4. **Results**

4.1. Islands with permafrost

Thermal subsoil profiles on Eselyakh Island

Based on datalogger data, we present the thermal profiles of the four islands over two consecutive years between July 2009 and July 2011. The upper part of Eselyakh Island (Hobo E & H, Figures 6 and 7) has a permafrost with an annual average temperature of -1.3°C at 3.2 m depth. Hobo measurements from successive field campaigns have shown that this permafrost is thicker on the upstream section of the island (Figure 5). The soil is composed of silty-clay material.

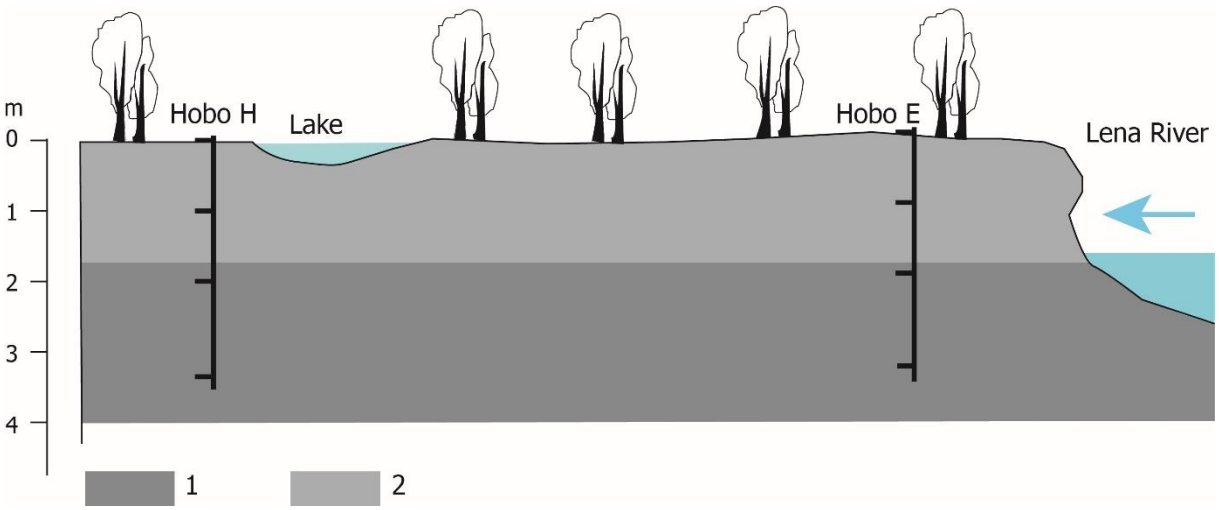


Figure 5: Schematic longitudinal section of Eselyakh Island. 1: permafrost; 2: active layer. Blue arrow indicates flow direction (to the North). Hobo H is located near a 30 m-diameter thermokarst lake.

For this island, according to the thermal profile of HOBO E (Figure 6), permafrost temperatures ranged from -0.1°C to -16.1°C at a depth of 1 m and from -0.3°C to -10.4°C at a depth of 2 m during the two consecutive winters (2009 – 2010 and 2010 – 2011). At 3.2m depth, the variability of permafrost temperature was even less pronounced, ranging between -0.5°C and -7.5°C. The second winter was harsher: the surface temperature dropped to -25°C, and ground temperatures at 1 m, 2 m and 3.2 m deep reached their lowest values during this winter. The active layer is 1.6 m thick. We note a downward propagation of the winter freezing wave and a time lag with depth for reaching minimum temperature due to the thermal inertia of frozen ground (Figure 6). For example, the

minimum annual temperature was reached in early March at a depth of 1 m, in late March at 2 m, and in mid-April at 3.2 m during the first winter. This ~ 20-day time lag between different depths was also observed during the second winter, although nearly three weeks earlier than the previous year (in mid-February, early March and late March, respectively). For the October – December period, temperatures were stabilized for several weeks (from 70 to 80 days) at 0°C at a depth of 1 m at the time of freezing due to the effect of latent heat (zero curtain effect on Figure 6). At 2m- and 3.2m-depth, temperature began to decrease at the end of January. The lowest temperatures were registered in April 2010 and in March and April 2011. The permafrost here is composed of ice-rich silty clay materials (ice content around 40% by volume)

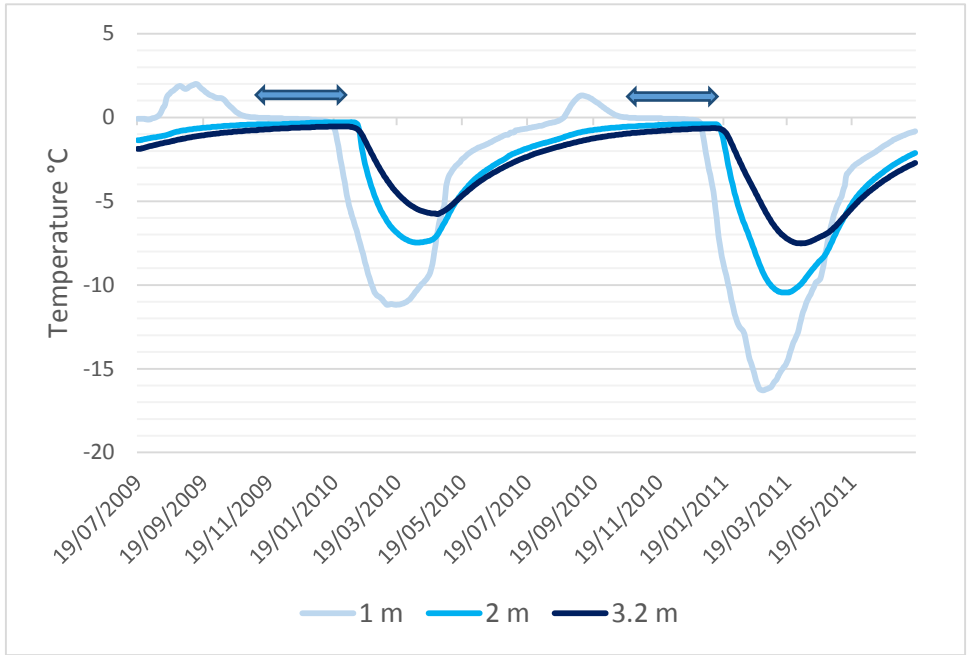


Figure 6: Ground thermal profiles on Eselyakh Island at 1 m, 2 m and 3.2 m depth for HOBO E datalogger (July 2009 – July 2011). Blue arrows correspond to the zero curtain effect during phase change of the water-ice flow during breakup.

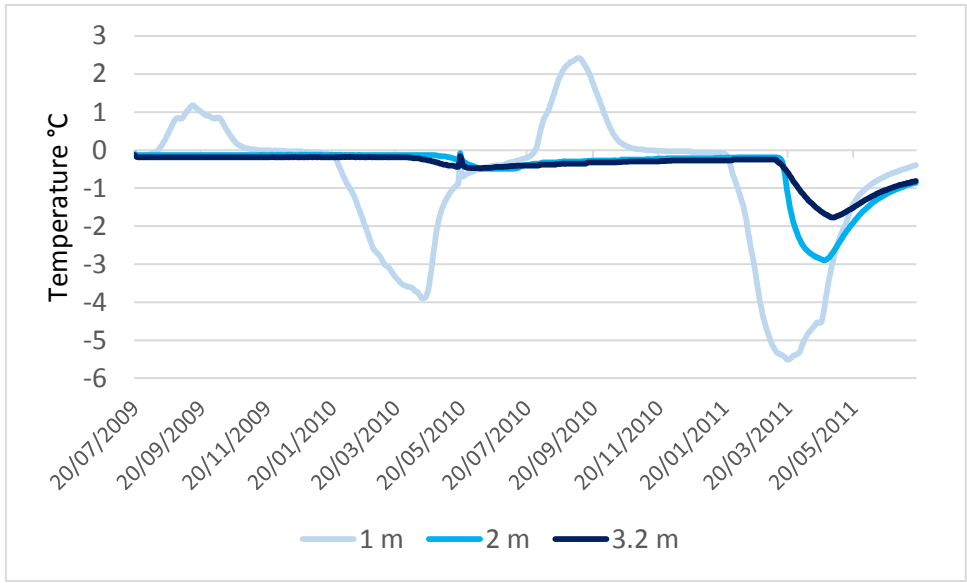


Figure 7: Ground thermal profiles on Eselyakh Island at 1 m, 2 m and 3.2 m depth for HOBO H datalogger. (July 2009 – July 2011).

Contrastingly, the thermal profile of HOBO H, located further downstream on the island (Figure 7), shows the presence of a notably warmer permafrost. The temperature ranged between ~ 0°C and -5.5°C (1m), between -0.1°C and -2.8°C (2m) and between -0.2°C and -1.7°C (3.2m) during the second (colder) winter. Contrastingly, temperature reached -4°C at 1m and stayed around 0°C at 2 and 3.2m deep during the first (warmer) winter. In fact, this recorder is located not far from a 30 m-diameter thermokarst lake (Figure 5) corresponding to an abandoned channel, and indicates an average annual ground temperature of -0.5°C. The temperature did not vary a lot during the first winter and decreased a bit more during the second winter. The lowest temperature was registered at the end of the cold season (April, beginning of May), just before the breakup. The sediment is identical, with the same composition and grain size characteristics as on the previous site. The lake obviously induces a thermal effect by heating the upper part of permafrost, and its presence alone can explain the observed difference in the thermal regime between HOBO E and HOBO H.

Thermal subsoil profiles on large lateral islands (Ynakh-Ary and Saty-Talakh)

On Ynakh-Ary, Hobo I has been working from 2009 to 2016 (Figure 8). The temperature varied between -0.1 and -14°C (1m) -1.2°C and -11.1°C (2m) and between -1.2°C and -8.9°C (3.2m depth). The same progressive temperature decrease is observed, with a 2 month-time-lag separating the beginning of continuous negative temperature on the soil surface (October) and the start of the cooling within the permafrost: beginning of January at 1 m and 2 m depths, end of January or early February at 3.2m depth.

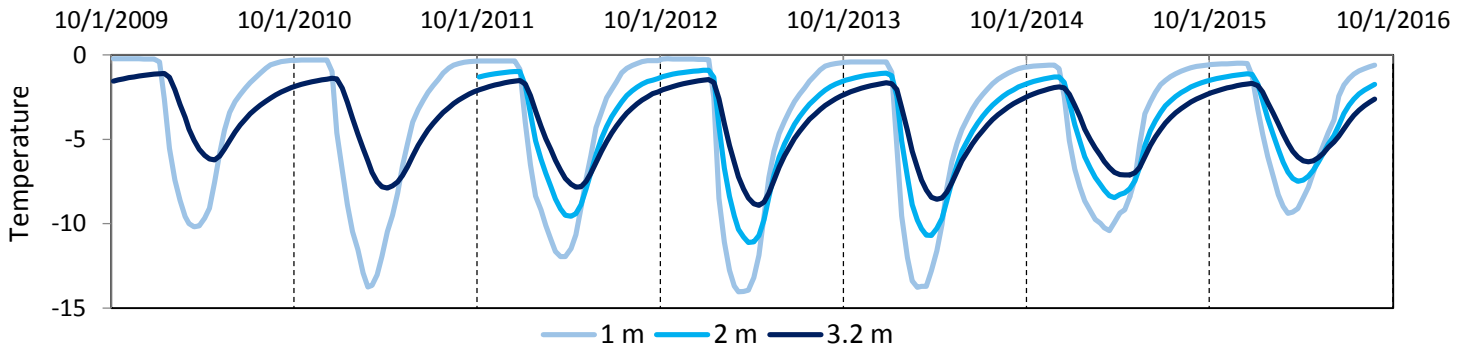


Figure 8: Ground thermal profiles on Ynakh-Ary island, at 1 m, 2 m and 3.2 m depth for Hobo I datalogger. (October 2009 – October 2016).

4.2. Islands with seasonally frozen ground

Thermal subsoil profiles on Timochka Island

The second instrumented island "Timochka" has a seasonal frozen ground, because the average annual temperature varies between +1°C and +1.5°C at 3.2 m depth. Temperatures even remain constantly above 0°C at a depth of 2 m (Figure 9). This island is mostly composed of fine sand, and the willows are relatively younger than those on Eselyakh Island (from dendrochronology measurements; Gautier et al., 2021).

These results confirm that islands like Timochka, with mainly sandy material (20% ice content by volume) are less prone to the inception and development of ice-rich permafrost, whereas islands like Eselyakh, containing ice-rich clay materials, are much more likely to contain ice-rich permafrost in the form of segregated ice, with a much higher ice content (40% ice content by volume).

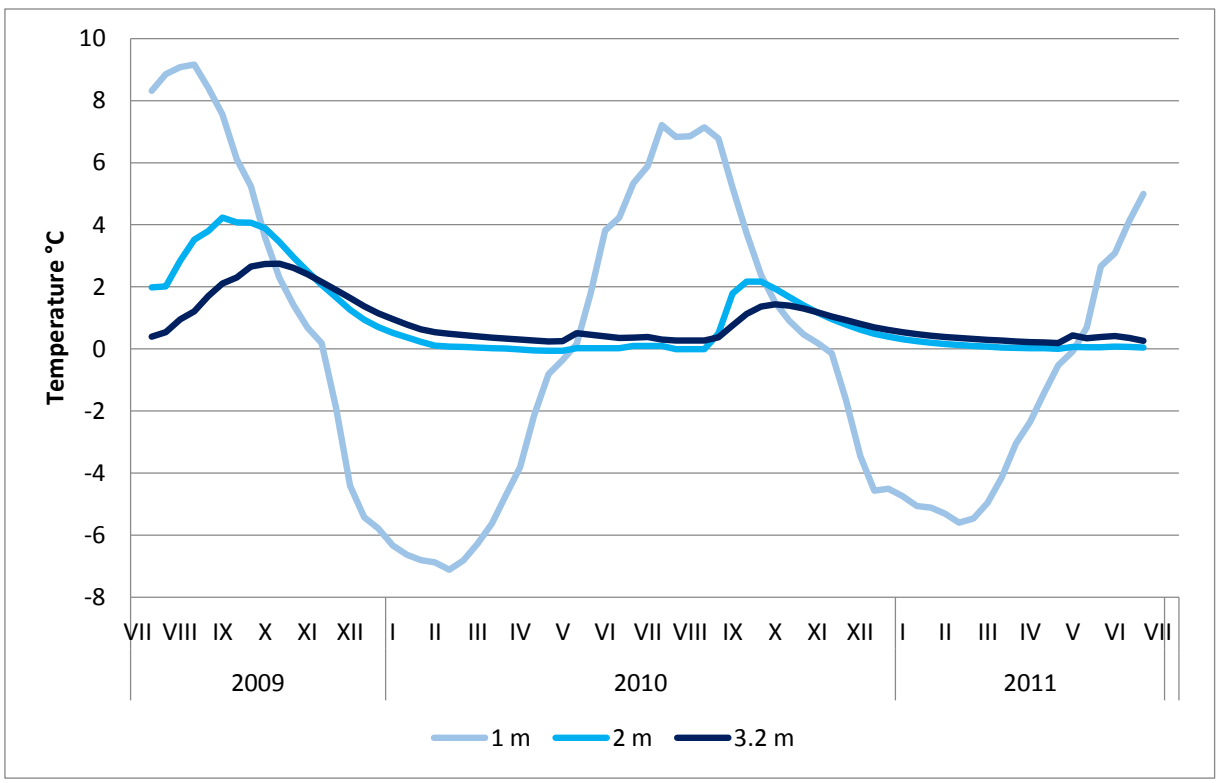


Figure 9: Ground thermal profiles on Timochka Island at 1 m, 2 m and 3.2 m depths for HOBO-A, with no permafrost.

Discussion

Age of the islands and permafrost

The middle Lena River develops a multiple-channel pattern with large forested islands (Costard et al., 2000; Gautier et al. 2008). The anabranching fluvial pattern implies relative stability of the channels and islands, although some islands quickly migrate downstream. This is the case for two islands (Eselyak and Timochka) that are located in the central part of the active channel (Figure 1). Thus, they rapidly migrate downstream, as the head is progressively eroded, whereas the tail (downstream) progresses by deposition (Figure 10). The two other islands (Ynakh-Ary and Saty-Talakh) are large lateral islands, and are more stable.

Eselyakh and Timochka are bisected islands with a secondary channel between the two parts (Figure 1, Table 1). Eselyakh is older than Timochka, as its two parts were already formed in 1967 (Corona pictures) and a dendrochonological analysis allows to precisely determine the age of an old willow (56 years old in 2010). This is due to the stabilization of a sand bar during the 1950's. The upper part of Eselyakh is progressively shrinking due to head erosion, whereas the lower part is growing by sedimentation. Timochka is an elongated island that is migrating very rapidly since its formation.

Hence, the present-day island is young: the upper part corresponds to a deposition zone formed between 1980 and 1996.

Ynakh-Ary and Saty-Talakh are large islands with surface area of 5 km² and 20 km², respectively. According to local inhabitants, they are very old islands. They were formed by the merging of different islands, and lake and swamps occupy the former inter-island channels. From our study, it appears that the oldest islands are thus at least 50 years old in our selected study area (Gautier et al., 2021). The Ynakh-Ary, Saty-Talakh and Eselyakh islands are old islands with permafrost developed in fine-grained material (silt-clay) accumulated in lower energy sections of the river, whereas Timoshka Island is relatively young, with only seasonally frozen ground and mostly sand deposits accumulated near the main channel, with high energy.

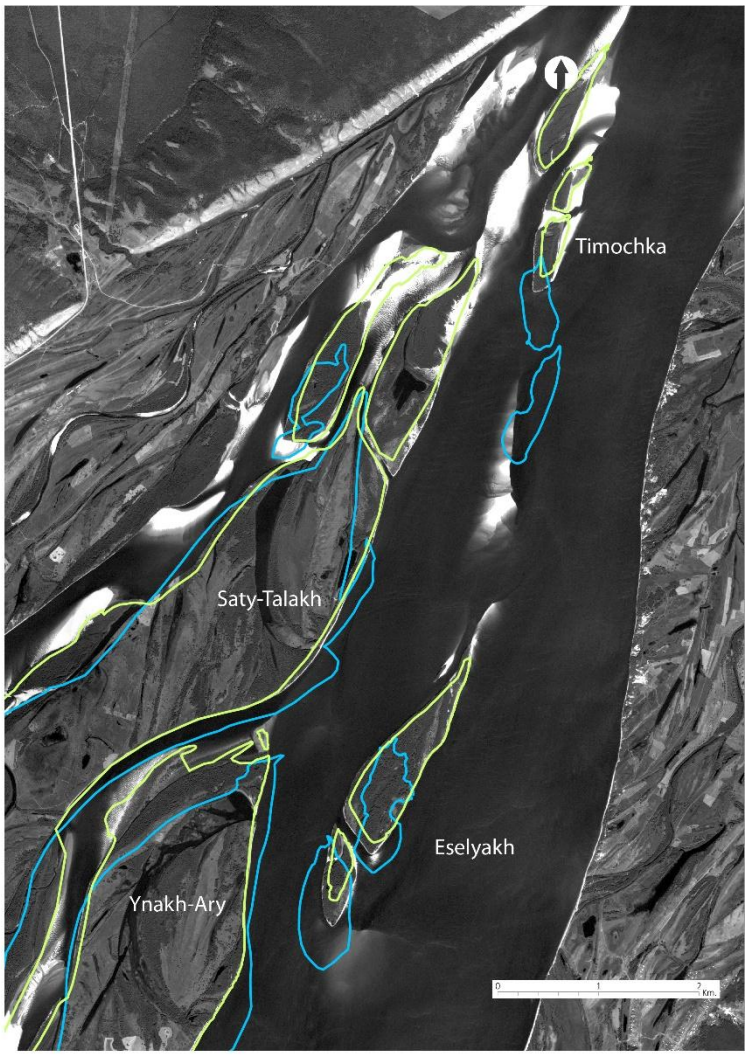


Figure 10: Main island migration on the Lena river upstream of Yakutsk city) from GIS study. Blue line: island shape in 1967 (Corona photographs); Green line: island shape 2017 (Pleiade images).

Thermal effect of spring breakup: the example of the 2010 breakup

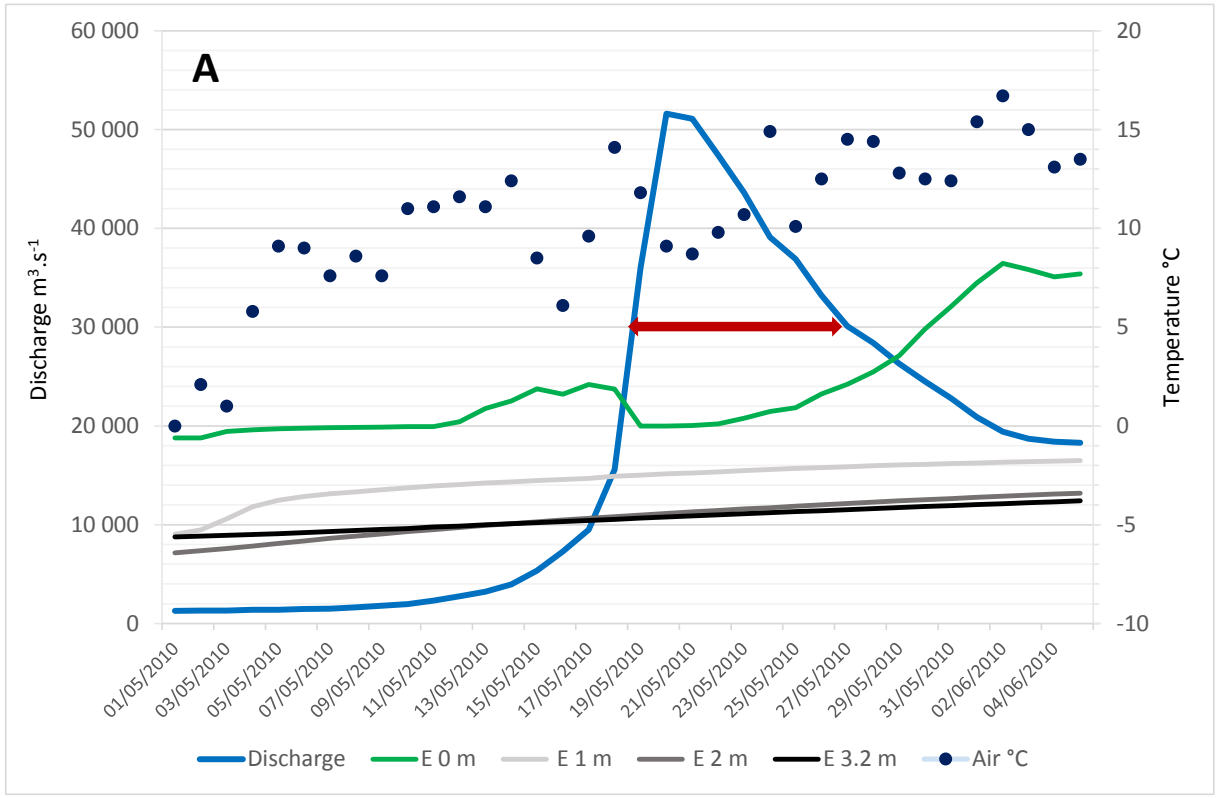
During spring floods, the islands along the Lena River channel are submerged and this induces an additional thermal imprint. Our dataloggers were able to record this specific stage on Eselyakh and Ynakh-Ary islands (Figure 11). It can be see that the temperature variations on the ground are suddenly interrupted on May 19, 2010 with a temperature dropping and remaining at 0°C until May 25, 2010 (Figure 11). This is due to the inundation of the islands where the flooding begins when the water discharge exceeds 30,000 $m^3.s^{-1}$. The submersion duration greatly varied during the study period (Table 2).

Furthermore, the sensor installed at the soil surface (0 m on Figure 11) registered the water temperature. At the beginning of the flooding, temperatures close to 0°C confirm the existence of a mixture of water and ice during the break-up. Then, after a few days, the water temperature slightly increases (1°C to 3°C) as the islands are inundated by water only.

Table 2. Flooding characteristics

	Flooding duration (Days)	Number flood peaks	Mean water temperature
2009	26	June 3rd – June 28th	ND
2010	9	May 19th – May 27th	0°C – 0.9°C
2011	6	May 13th – May 18th	0.2°C – 1.4°C
2012	36	May 17th – May 26th June 5th – June 19th July 5th – July 9th July 28th – August 4th	0°C – 3°C 9.5°C – 12°C 15°C – 15.5°C 15°C – 16.5°C
2013	14	May 14th – May 21st July 23rd – July 29th	
2014	0		
2015	7	May 13th – May 19th	0.3°C – 3°C
2016	10	June 10th – June 16th July 31st – August 3rd	11.6°C – 13.3°C 14.6° – 15°C
2017	5	July 20th – July 24th	ND
2018	11	May 5th – May 10th July 19th – July 25th	ND

However, the observed effect of island submersion at the time of break-up appears to have a relatively moderated impact on permafrost thermal profile at depth (i.e. more than 1 m deep). This can likely be explained by 1) the duration of submersion, which in that case is too short to have a long-term thermal impact in the ground, and 2) the water temperature, still near 0°C, again precluding major thermal disturbance within the ground, at least below the surface. Figure 11 clearly shows that the thermal regime of permafrost for the two islands with permafrost (Eselyakh and Ynakh-Ary) did not fluctuate, even during the 10-day submersion of the island during the ice breakup in May.



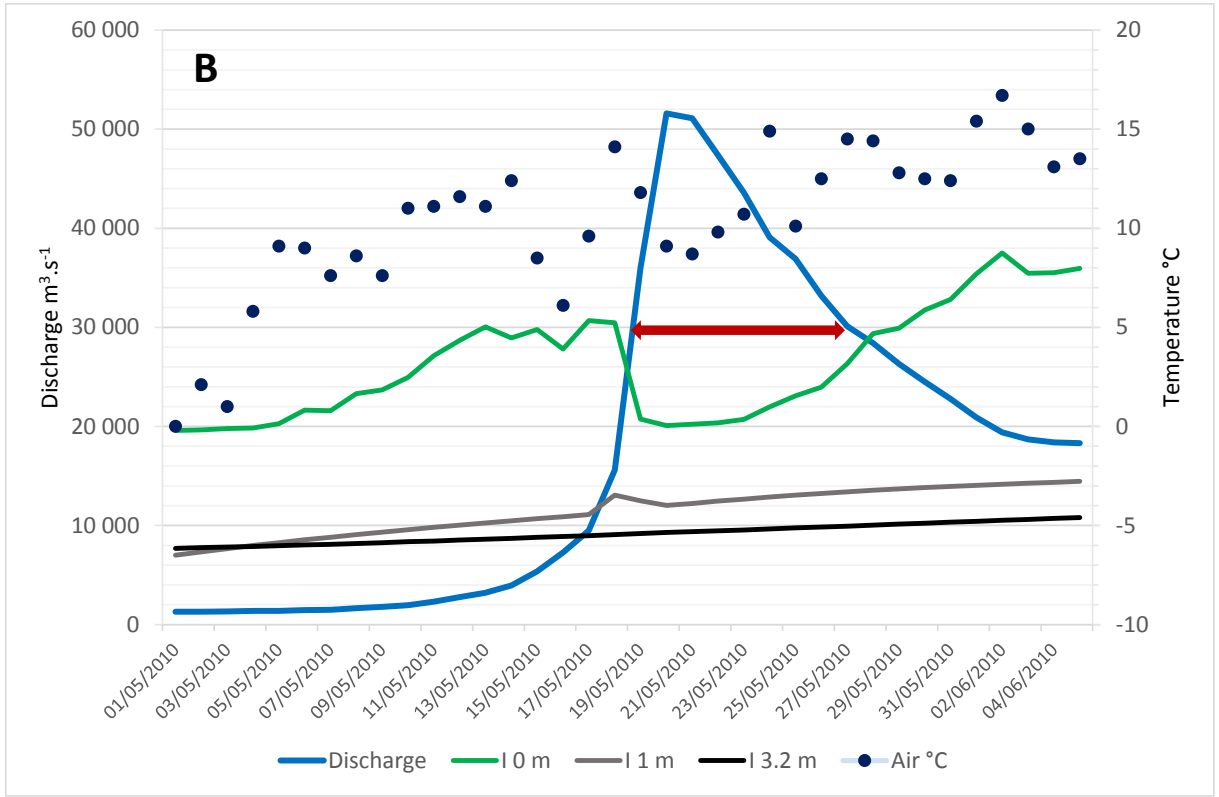


Figure 11: Water discharge and temperature on islands with permafrost (2010, May 1 – June 5). A: Eselyakh Island (HOBO E), B: Ynakh-Ary Island (Sensor I). Water Discharge at Tabaga gauging station (Roshydromet data); 0 m: soil surface temperature; permafrost temperature at different depths (1 m, 2 m and 3.2 m); air temperature at Yakustk (NOAA, NASA data). The red arrow corresponds to the duration of the submersion of the islands in relation with a discharge > 30,000 $m^3.s^{-1}$.

During some years, the islands can be inundated two times or more. For example, in 2012, the Lena River underwent four flood peaks (Figure 12). This offers the possibility to examine the effect of repeated inundations and warm stream water. Even if the water temperature strongly increased from May to August, reaching 15°C – 16°C at the end of the summer, the submersion does not seem to have caused a marked increase in permafrost temperature (Figure 12).

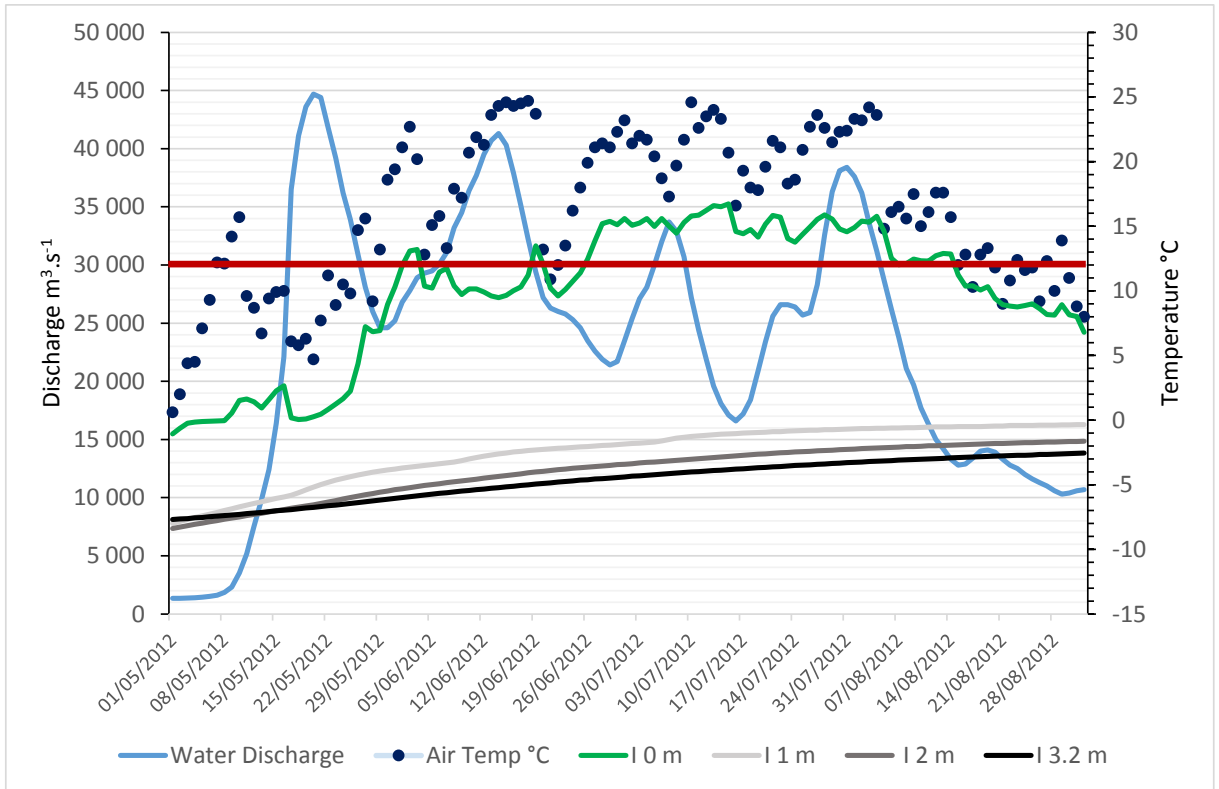


Figure 12: Water discharge, air temperature and permafrost temperature of Ynakh-Ary (HOBO I) between May and August 2012. Water Discharge at Tabaga gauging station (Roshydromet data); 0 m: soil surface temperature; permafrost temperature at different depths (1 m, 2 m and 3.2 m); air temperature at Yakutsk (NOAA, NASA data). Red horizontal line corresponds to a discharge > 30,000 $m^3.s^{-1}$ in relation with the submersion of the island.

Conclusions

For a first time, we were able to instrument a large Artic river in order to acquire new data on the thermal impacts of ice break-up (intensity, duration, ice thickness) and flooding (water temperature, duration of submersion) on ground thermal regime. Our measurement campaigns revealed that the floodplain of the Lena River, upstream of Yakutsk, did not always contain permafrost, and that some highly mobile islands have (only) seasonally frozen ground. The Lena floodplain is notably heterogeneous, with a combination of permanently and seasonally frozen islands. The observed disparity between these instrumented islands is significant and unexpected, because it confirms that the Lena River floodplain is far from being thermally and geomorphologically homogenous. It rather consists of a juxtaposition of seasonally frozen islands and permanently frozen islands in the regional context of a floodplain affected by thick and continuous permafrost. Further surveys of 10 more islands confirm that relatively young (less than 30 years old) islands, composed of fine sand material

accumulated in higher energy sectors, appear less prone to permafrost formation compared to older islands with ice-rich silty material deposited in lower energy environment.

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References :

Antonov, S., 1960. Delta reki Leny. Trudy Okeanographitcheskiy Comissyi. Ak. Nauk. SSSR, 6: 25-34.

Are, F.E. (1983), Thermal abrasion on coasts, Proceedings, Fourth International Conference on Permafrost, Fairbanks, Alaska, National Academy Press, Washington DC, 24-28.

Beltaos, S. and B. C. Burrell (2002), Suspended sediments concentrations during the spring breakup of river ice.. In Ice in Surface Waters, Proceedings of the 14th IAHR Ice Symposium, 27-31 July 1998, Postdam, N.Y. Edited by H.T. Shen. A.A. Balkema, Rotterdam, 2, 793-800.

Billfalk, L. (1982), Breakup of solid ice covers due to rapid water level variations. CRREL Report 82-3, US Army CRREL, Hanover, N.H.

Biskaborn et al. 2019. Permafrost is warming at a global scale. Nature Communications, 10, 264. doi: s41467-018-08240-4.

Costard F., E. Gautier, D. Brunstein, J. Hammadi, A. Fedorov, D. Yang, L. Dupeyrat (2007). Impact of the global warming on the fluvial thermal erosion over the Lena river in Central Siberia. Geophys. Res. Lett., 34, (14), doi:10.1029/2007GL030212

Costard F. and Gautier E. (2007). The Lena River: main hydromorphodynamic features in a deep permafrost zone. In Large rivers: Geomorphology and Management, Gupta A (ed.). John Wiley & Sons; 225-232.

Costard F., E. Gautier, A. Fedorov, P. Konstantinov and L. Dupeyrat. (2014). An assessment of the erosional potential of fluvial thermal process during ice breakups of the Lena River (Siberia). Permafrost and Periglacial Processes, Vol. 25, 162-171, doi:10.1002/ppp.1812

Dupeyrat, L., Hurault, B., Costard, F., Marmo, C., Gautier, E., (2018). Satellite image analysis and frozen cylinder experiments on thermal erosion of periglacial fluvial islands. Permafr. Periglac. Process. doi:10.1002/ppp.1973

Fedorov, A. and P. Konstantinov (2003), Observations of surface dynamics with thermokarst initiation, Yukechi site, Central Yakutia. Proceedings of International Permafrost Conference, Zurich, In Permafrost, Philips M., Springman S. Arenson L.U. (eds), 239-243.

Fedorov, A.N., Ivanova, R.N., Park, H., Hiyama, T., Iijima, Y., 2014. Recent air temperature changes in the permafrost landscapes of northeastern Eurasia. Polar Sci. 8, 114–128. doi:10.1016/j.polar.2014.02.001

Gautier, E. and F. Costard (2000), Les systèmes fluviaux à chenaux anastomosés en milieu périglaciaire: la Léna et ses principaux affluents en Sibérie Centrale. Géographie Physique et Quaternaire, 54/3, 327-342.

Gautier, E., D. Brunstein, F. Costard and R. Lodina (2003), Fluvial dynamics in a deep permafrost zone: the case of the middle Lena river (Central Yakutia). Proceedings of International Permafrost Conference, Zurich, Philips M., Springman S. Arenson L.U. (eds), 271-275.

Gautier E., A. Fedorov, F. Costard and D. Brunstein (2011). Impact of climate change on the dynamics of a large Russian Arctic river, the Lena in Central Siberia. In Le changement climatique. Fourth Evian European Dialogues. EURCASIA Ed. pp. 65-73.

Gautier, Emmanuèle, Dépret, T., Costard, F., Virmoux, C., Fedorov, A., Grancher, D., Konstantinov, P., Brunstein, D. (2018). Going with the flow: Hydrologic response of middle Lena River (Siberia) to the climate variability and change. J. Hydrol. 557, 475–488. doi:10.1016/j.jhydrol.2017.12.034

Gautier E., Depret Th., Cavero J., Costard F., Virmoux C., Fedorov A., Konstantinov P., Jammet M., and D. Brunstein (2021). Fifty-year dynamics of the Lena river islands (Russia): spatio-temporal pattern of large periglacial anabranching river and influence of climate change. Science of the Total Environment. In review.

Iijima, Y., Nakamura, T., Park, H., Tachibana, Y., Fedorov, A.N., 2016. Enhancement of Arctic storm activity in relation to permafrost degradation in eastern Siberia. Int. J. Climatol. 2007. doi:10.1002/joc.4629

Jahn, A. (1975), Problems of the periglacial zone, Washington D.C., Warzawa, 223 p.

Konstantinov, P.Y. , A.N. Fedorov, T. ?achimura, G. Iwahana, H. Yabuki, Y. Iijima, F. Costard (2011). Use of automated recorders (data loggers) in permafrost temperature monitoring. Kriosphera Zemli, 1, 23-32, in russia.

Liu B., D. Yang, B. Ye, and S. Berezovskaya (2005), Long-term open-water season stream temperature variations and changes over Lena River Basin in Siberia. Global and Planetary Change, 48, 1-3, 96-111.

Peterson, B.J., R. M. Holmes, J. W. McClelland, C. J. Vörösmarty, R. B. Lammers, A.I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf, (2002), Increasing River discharge to the Arctic Ocean. Nature, 298, 2171-2173. doi:10.1126/science.1077445

Shen, H.T. (2003), Research on river ice processes: progress and missing links. J. Cold Regions Engineering, 135-142.

Schirrmeister, L., Froese, D., Tumskoy, V., Grosse, G., and Wetterich, S. (2013). “Yedoma: late Pleistocene ice-rich syngenetic permafrost of Beringia,” in The Encyclopedia of Quaternary Science, ed. S. A. Elias (Amsterdam: Elsevier), 542–552. doi: 10.1016/b978-0-444-53643-3.00106-0

Shiklomanov, A.I., Lammers, R.B., (2009). Record Russian river discharge in 2007 and the limits of analysis. Environ. Res. Lett. 112, 1–14. doi:10.1029/2006JG000352

Tananaev, N.I., (2016). Hydrological and sedimentary controls over fluvial thermal erosion, the Lena River, central Yakutia. Geomorphology 253, 524–533. doi:10.1016/j.geomorph.2015.11.009

Tei, S., Morozumi, T., Nagai, S., Takano, S., Sugimoto, A., Shingubara, R., Fan, R., Fedorov, A., Gavrilyeva, T., Tananaev, N., Maximov, T., 2020. An extreme flood caused by a heavy snowfall over the Indigirka River basin in Northeastern Siberia. Hydrol. Process. 34, 522–537. doi:10.1002/hyp.13601

Walker, H.J. (1983). Erosion in a permafrost dominated delta, Proceedings Fourth International Conference on Permafrost, Alaska. National Academy Press, Washington DC, 1344-1349.

Walker, H.J. and P. F. Hudson (2003), Hydrologic and Geomorphic Processes in the Colville Delta, Alaska. Geomorphology, 56, 291-303. doi:10.1016/S0169-555X(03)00157-0

Yang D., D. Kane, L. Hinzman, X. Zhang, T. Zhang, and H. Ye (2002), Siberian Lena River hydrologic regime and recent change. J. of Geophys. Res. , 107 (D23), 4694-4703. doi:10.1029/2002JD002542

Zhang, X., He, J., Zhang, J., Polyakov, I., Gerdes, R., Inoue, J., Wu, P. (2012). Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. Nat. Clim. Chang. 3, 47–51. doi:10.1038/nclimate1631