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1 **Thermal regime variability of islands in the Lena River near Yakutsk, eastern Siberia**

2

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8

9 **Abstract**

10 Recent evidence has shown that Arctic regions have warmed about twice as much as elsewhere on the
11 planet over the last decades, and that high-latitude permafrost-periglacial processes and hydrological
12 systems are notably responsive to rising temperatures. The aim of this paper is to report on thermal
13 regime of islands located along the Lena River floodplain, upstream of the city of Yakutsk (eastern
14 Siberia). Four islands were monitored using waterproof dataloggers and continuous monitoring of
15 frozen soil in contact with ice breakup of the Lena River. For each of these islands, we measured: i)
16 ground surface temperature, air and frozen soil temperatures at different depths; ii) submersion
17 duration during the flood. Our results show that within a zone of thick and continuous permafrost, the
18 Lena floodplain is notably heterogeneous, with a combination of permanently and seasonally frozen
19 islands. The ice breakups seem to have a negligible impact on the ground thermal regime. Our study
20 confirms that relatively young (less than 30 years old) islands, composed of fine sand material, appear
21 less prone to permafrost formation compared to older islands with ice-rich silty material.

22

23 **1. Introduction**

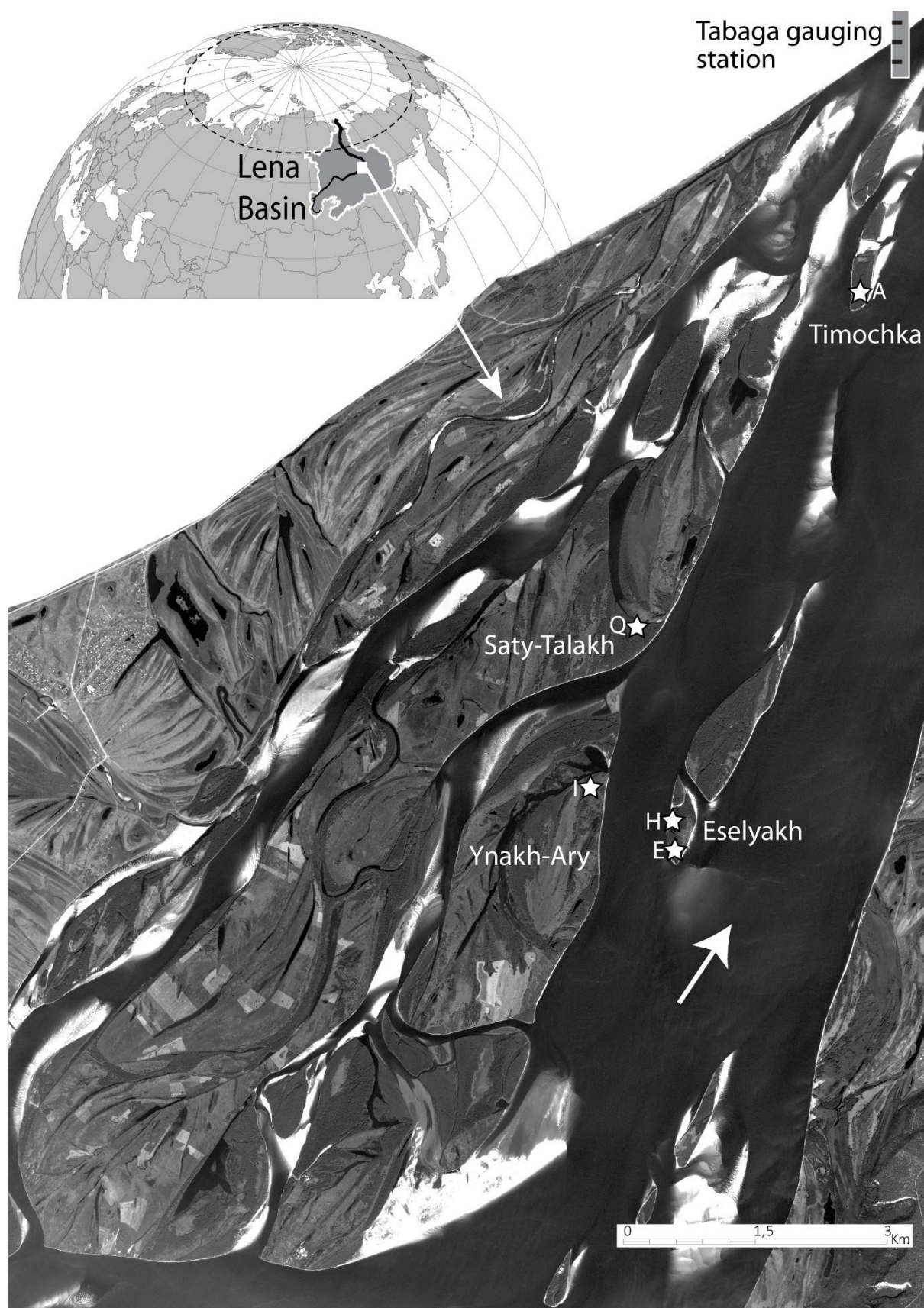
24

25 Permafrost has been warming at the global scale over the last decade, following the Arctic
26 amplification of air temperature increase in the Northern Hemisphere (Biskaborn et al., 2019). Recent
27 work has shown a significant increase in air and ground temperatures in central Yakutia (Eastern
28 Siberia) since the late 1980s (Fedorov et al., 2014; Iijima et al., 2016, Zhang et al., 2012). In the Lena
29 River valley (Figure 1), according to Iijima et al. (2010), the mean annual ground temperature at a depth
30 of 3.2 m has increased by about 1.3°C since 1930. The mean annual air temperature at Yakutsk was -
31 9.9°C and it ranged between -8°C and -12°C for the period 1936-199. The mean annual air temperature
32 has increased to -8.4°C between 2000 and 2007 and to -7.4°C after 2008 (the last period ranging
33 between -6.7°C and -7.8°C). A wetter period is registered between 2002 and 2008 (mean annual value
34 for the period: 276 mm), however the precipitation has decreased after (about 220 – 230 mm). Very

35 wet conditions occurred in 1999, 2003, 2005, 2006, 2007 and 2013, with storms affecting Siberia
36 resulting in more abundant late summer precipitation and early winter snow (Fedorov et al., 2014b;
37 Iijima et al., 2016).
38 Furthermore, active layer deepening results in an increase in river discharge (Peterson et al., 2002).
39 More recently, Gautier et al. (2018) reported a strong water discharge increase since the beginning of
40 the 21st century for the Lena River at Tabaga (just upstream of Yakutsk city, at 61° 4'N and 129° 3'E,
41 Figure 1): the 2000-2017 discharge was 15% higher than the discharge for 1936-1999. Furthermore,
42 floods are also changing, with more frequent flood peaks and longer recorded flooding durations
43 (Gautier et al., 2018). Recent exceptional flood events are reported (Shiklomanov and Lammers, 2009;
44 Costard et al., 2014; Gautier et al., 2018; Tei et al., 2020). There has also been a decrease in winter
45 river ice cover, used as road. Winter thawing/melting events, as well as spring ice jam floods during
46 the ice breakups represent major risks for riverside residents, road and river infrastructures. All these
47 factors lead to permafrost instability and consequent changes in forest, wetland, lake and river
48 ecosystems.

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51
 52 Figure 1: A: Location of the Lena basin and the study sites (upstream of Yakutsk). B: Observation points.
 53 Star with letters: Data loggers; Background image: Spot 2008 (CNES, France).

54 Very few studies have focused on permafrost in floodplains and little is known on geomorphological
55 impacts of ice breakups and floods on major Arctic rivers. Most of the geomorphological studies report
56 on river dynamics of breakup for Canadian Arctic rivers (Beltaos and Burrell, 2002). Specifically, studies
57 have shown the role of the ice cover and its thickness on the intensity of ice jams produced by ice packs
58 along the Yukon River (Shen, 2003; Walker and Hudson, 2003). With increasing discharge, the ice cover
59 under pressure locally cracks and starts to move (Shen, 2003). This is the beginning of the "breakup"
60 phase where ice rafts accumulate at the head of islands (Figure 2); ice breakup usually occurs in spring,
61 between May 20th and early June on the middle Lena River, and in Mid-June or late June downstream,
62 in the low valley (Gautier and Costard, 2000). The flow often carries these ice blocks along with tree
63 trunks (Walker and Hudson, 2003). Ice jams produce local dams, resulting in a sudden rise of water
64 levels (Billfalk, 1982; Beltaos and Burell, 2002; Costard et al., 2014). During the flood season from May
65 to July, the stream water warms the frozen soils, leading to accelerated erosion of the banks (Are,
66 1983; Jahn, 1975; Walker, 1983). Melting of the ice contained in the porous sediment of the riverbank
67 reduces its strength, and produces removable unconsolidated material (Costard et al., 2003).
68 Furthermore, when the water level is above the bankfull level, the overbank water submerges the
69 island soil that is still frozen. The effects of the submersion have never been studied.

70
71 Breakups and floods are strongly heterogeneous, as numerous factors control their starting date,
72 duration and intensity (Costard et al., 2014; Gautier et al., 2018). The flood wave coming from the
73 upper basin can occur on a floodplain that is still frozen or not (depending on the local temperature).
74 Moreover, analysis of climatic and hydrological data near Yakutsk showed a very clear thinning trend
75 in winter ice thickness and a significant increase in water temperature of the Lena River near Tabaga
76 (gauging station upstream section of Yakutsk, Figure 1). We have also demonstrated the impact of
77 recent warming on increasing erosion rates of the islands by thermal erosion (Costard et al., 2007;
78 Gautier et al., 2021).

79 Only a few studies report on permafrost thermal regime in Arctic floodplains, and in spite of a relatively
80 good understanding of the initial stage of the breakup period of these periglacial rivers [Beltaos and
81 Burrell, 2002; Shen, 2003; Billfalk, 1982], little is known regarding the influence of ice breakup and
82 flooding on ground thermal regime during the flood season (Are, 1983; Walker, 1983). The major
83 influence of water stream temperature on the thermal regime of frozen ground has already been
84 demonstrated using cold room experiments (Costard et al., 2003), but only for river bank erosion.

85 Moreover, breakup and large flooding events represent an important risk in Arctic regions and can
86 threaten infrastructures. In May 2001 and 2010, catastrophic breakup events linked to an early spring
87 season following a severe winter strongly impacted the cities of Yakutsk and Lensk (Gautier et al.,
88 2018). Recently, a project of a 6 km-long bridge across the Lena floodplain at Tabaga site is projected

89 and it implies accurate knowledge of the formation, and especially of the causes of the variable
90 intensity of these ice breakups.

91



92

93 Figure 2: Beginning of the ice breakup on the Lena River, May 15th, 2010. Flow from right to left. During
94 the first days, drifting ice blocks on the river formed thick ice accumulations at the head of Timochka
95 Island, which led to a frontal erosion of up to 40 m within a few days.

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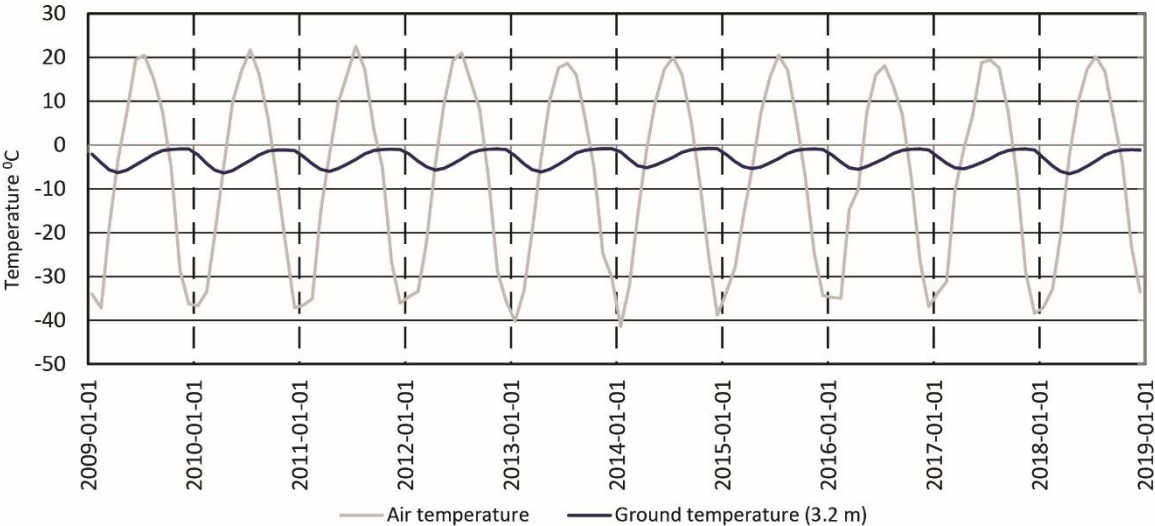
97 The main objective of this paper is to analyze the near-surface thermal regime of four islands in the
98 Lena River floodplain, eastern Siberia, and to determine to what extent it is affected by island dynamics
99 and ice breakup/flooding events. We investigate the thermal influence of the water stream
100 temperature by a vertical variation of the ground thermal regime during a typical submersion of the
101 islands affected by ice breakups and flooding events.

102

103 2. Study area

104 Central Yakutia (eastern Siberia) is characterized by a continental periglacial climate with extreme
105 variations in air temperatures, ranging from +30°C in summer to -50°C in winter (Fedorov et al., 2014)
106 (see Figure 3 for the period 2009-2018). The region is characterized by a thick continuous ice-rich
107 permafrost of late Pleistocene age, called “Yedoma” (Antonov, 1960; Schirrmeister et al., 2013). The
108 mean air temperature at Yakutsk is -8.5 °C since the beginning of the 21st century. The winter
109 temperature (October to April) ranged between -10°C and -40°C (Figure 3). The temperature becomes
110 positive at the beginning of May and the mean monthly temperature can exceed +20°C from mid-June
111 to mid-August. The low annual precipitation (230 mm near Yakutsk), together with a high evaporation
112 rate, induces a dry climate (Antonov, 1960). Most of the precipitation occurs in summer, with 140 mm
113 distributed between June and September. Snow cover thickness remains low (30 to 40 cm), which
114 favors efficient frost penetration and the existence of a deep permafrost, especially underneath the
115 taiga. The mean annual temperature of the permafrost at depths of 10 m to 20 m ranges from -2°C to

116 -4°C (Fedorov and Konstantinov, 2003). Since the end of the 1980s, it has undergone a warming of
 117 almost 1.5°C (at a depth of 3.2 m), together with a deepening of the active layer, with values ranging
 118 from 0.8 to 1.2 m at the latitude of Yakutsk (Fedorov and Konstantinov, 2003; Fedorov et al., 2014).
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 123 Figure 3: Mean monthly air and ground (3.2-m depth) temperature at Yakutsk (NOAA data) – July 2009
 124 – July 2018.

125
 126
 127 The Lena River is one of the largest fluvial hydrosystems within the periglacial zone (Figure 1), with
 128 thick and continuous permafrost that covers 77% of the basin (Soloviev, 1973). During the winter
 129 season (October to April), the river flows under an ice cover with an average thickness of 1.4 m (min:
 130 0.3 m; max. 2 m). The river discharge is then extremely low (less than $1500 \text{ m}^3 \text{ s}^{-1}$ at the Tabaga station,) and reaches its lowest discharge of $870 \text{ m}^3 \text{ s}^{-1}$ in April, at the end of the winter (Gautier and Costard, 2000; Gautier et al., 2018). The breakup and the flood occur between May 20th and June 10th. However, the recent years showed earlier or later events (Gautier et al., 2018). The overbank discharge (about $30\,000 \text{ m}^3 \cdot \text{s}^{-1}$ at Tabaga) inundates the forested islands and the floodplain with a great irregularity: the inundation can last from a few days to one month. After the flood, the water level rapidly drops in July. On the Lena River, ice breakups are controlled by the meridian course of the river, with a 30- to 50-day lag between basin upstream and downstream (Gautier et al., 2003). As a result, when snow and ice covers melt, a flood wave propagates from the southern regions further to the still-frozen regions in the north. Therefore, the water discharge increases abruptly and massive ice and log jams can be formed on the island heads (figure 2). Within a few days, the volume of water flow increases 20 to 45 times (Gautier et al., 2018). The peak flood can reach up to $50,000 \text{ m}^3 \text{ s}^{-1}$ (Antonov, 1960, Liu et al., 2005; Gautier et al., 2018). At the latitude of Yakutsk, the water level during the flood season can be

up to 8 to 10 m higher than during the winter low water level (Costard et al., 2007; Gautier et al., 2018). During high floods, the Lena flood spreads over a width of 15 km. The water stream temperature, about 0°C in the winter and up to 8°C at the beginning of the flooding season, increases rapidly to reach 17-18°C in July and August (Costard et al., 2014).

For the purpose of our study, a site upstream of Yakutsk (Figure 1) have been chosen, in order to avoid the urban heat flow. In addition, the upstream Lena River is not impacted by dams. Ten islands were preselected in the riverbed upstream of Tabaga gauging station, and four of them were instrumented and are discussed further in this paper (Figure 1). Eselyakh and Timochka islands (0.2 and 0.7 km² are located in the central part of the active channel, whereas Ynakh-Ary and Saty-Talakh are two much larger lateral islands, sizing 5 km² and 20 km², respectively (Table 1). The island elevation ranges between 92 masl for the highest parts (levees and center of old islands) and 88 masl for the depressions that generally correspond to abandoned channels. 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 their abundance, young trees trap the sediment load, causing rapid vertical accretion of the island (Gautier et al., 2021). Hence, the base of the island stratigraphy is mainly composed of homometric ($D_{50} = 200 - 250 \mu\text{m}$) sandy material organized in horizontal beds several tens of centimeters thick. The sandy deposits are often covered with layers of fine sand and silt ($D_{50} = 50 - 100 \mu\text{m}$) deposited by overbank flows. On the oldest islands, overbank deposits can be 2 m thick. Fine-grained deposits mixed with organic matter are found in abandoned channels. For a detailed description of the sedimentary sequences of these islands, see Gautier and Costard (2000), Costard et al. (2014), and Gautier et al. (2021).

Bank erosion of the Lena river 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 process explains the relative efficiency of bank retreat (Walker and Arnborg, 1963; Jahn, 1975; Walker, 1983; Costard et al., 2014).

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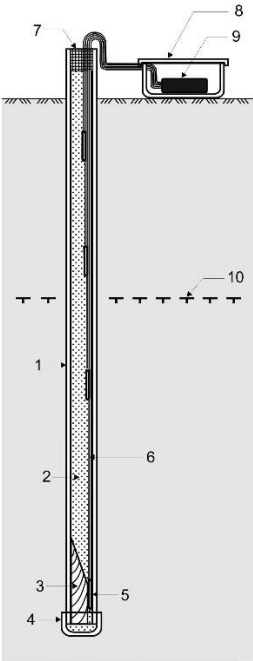
173 3. Methods

174 In order to determine the ground temperature and to evaluate the active layer thickness on the islands,
175 various methods were integrated. First, a drilling campaign (2008) enabled the installation of several
176 temperature sensors at different depths and a precise measurement of the active layer with a steel
177 stick. Thus, topographic conditions do not change a lot in the proximity of the sensors. We used HOBO

178 4-channels dataloggers (model U12-008) to record variations in the thermal profile. Each datalogger,
179 previously calibrated in the laboratory, includes 4 thermistor sensors (TMCx-HD) that produce a
180 temperature-dependent voltage, which is then converted to temperature and stored in the datalogger,
181 every hour, with an accuracy of $\pm 0.25^{\circ}\text{C}$, in the soil, at 0 m (soil surface), 1 m, 2 m and 3.2 m depth
182 (Figure 4). On Saty-Talakh island, the sensors have been installed at 2 m, 3 m and 4 m depth (plus the
183 surface). The annual periods are delimited from July to July. Once a year, after the ice breakup, we
184 went to the instrumented sites to collect data from the dataloggers and to ensure the equipment
185 maintenance on site. During the first year (2008) on Timochka and Eselyakh islands, only two among
186 the four sensors worked well and the others were broken by the strong ice breakup. They were
187 modified to ensure waterproof conditions and to improve the robustness of the equipment in order
188 to control the mechanical effect of ice breakups (e.g., internal pressure). Thus, we had to develop a
189 new system (Figure 4) that is much more efficient and could resist the repeated impacts of ice rafts
190 and water pressure (Konstantinov et al., 2011). Unfortunately, because of the extremely rough
191 conditions, the duration of measurements of the temperature sensors is very variable (Table 1): some
192 of them have been working for more than 10 years, whereas others disappeared during a flood or were
193 buried under meters of sediment and woody debris. Due to some severe breakups, some ground
194 temperature sensors were broken during the first year. In the present study, we present the data of
195 the devices that were installed several dozen meters away from the riverbank and that were preserved
196 from erosion and/or thick sediment deposition during floods.

197

198



199

Figure 4: Sketch on the left: Drilling in the frozen soil for the installation of thermistor sensors placed at 0 m (soil surface), 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 resist flooding of the island during spring breakup. Note the two weights on the box and the wooden support holding the datalogger in the waterproof box. (Figure modified from Konstantinov et al., 2011). Every sensor position was precisely determined with a GPS and a total station.

The water levels and the daily discharge were recorded at Tabaga (gauging station, 8 km north from the sites, see Figure 1). The overbank discharge and the submersion duration of the islands have been determined during field observations during the flooding season. Island inundation begins when the river discharge reaches about 30 000 m³.s⁻¹ (Costard et al., 2014 and Gautier et al., 2001; Tananaev, 2016). The lowest parts of the islands can be inundated for a discharge a bit lower and the highest parts need about 32 000 m³.s⁻¹ to be flooded.

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

Island Name	Area (m ²)			Age	Dataloggers			Geomorphic Unit
	1967	2008	2017		Mean temp. at -3.2 m (°C)	Duration of measurement	Sediment	
Eselyakh – Upstream part Downstream part	486,726 416,877	198,256 790,189	105,520 675,931	> 60 yr	E: -2.2 H: -0.4	2008 – 2011 2008 – 2011	Mixed sed. Sand	Abandoned channel Bar/island
Timochka - Upstream part Downstream part	216,239 0	135,560 70,300	107,161 79,164	< 30 yr	A: 1.2	2008 – 2014	Sand	Bar/island
Ynakh-Ary	5047,718	5338,126	50294,298	> 70 yr	I:-3.9	2009 – 2016	Mixed sed.	Abandoned channel
Saty-Talakh	18 247,279	20 125,713	19 685,946	> 70 yr	Q: -0.6	2009 – 2018	Sand	Bar/island

We estimated the age of the islands based on the year of their appearance from a previous pluri-decadal analysis of aerial pictures and satellite images (Figure 1 and Table 2) used by Gautier et al. (2021). We also used the dendrochronology method to precisely measure the age of the oldest trees. Our objectives were to determine whether the thermal regime is related to the age (and/or size) of the islands. For each of these sites, we also did an analysis of the sediments and stratigraphy using a soil moisture sensor and grain-size was determined with a laser granulometer (see Supplementary material S1). The

224 depth of the permafrost table and its ice content were obtained by sampling with a drilling machine
225 down to 3.2 m; the permafrost table was also measured every year with a stick. The analysis of the
226 sediments was done at the Melnikov Permafrost Institute in Yakutsk.
227

228 **4. Results**

229 The analysis reveals an important inter-annual variability, which underscores the heterogeneity of the
230 thermal regime of islands within the Lena floodplain. On the basis of field surveys and soil temperature
231 data, we are able to distinguish two main types: islands with a perennially frozen soil (*i.e.* with a
232 permafrost), and islands with a seasonally frozen ground only.

233

234 4.1. Islands with permanently frozen soil

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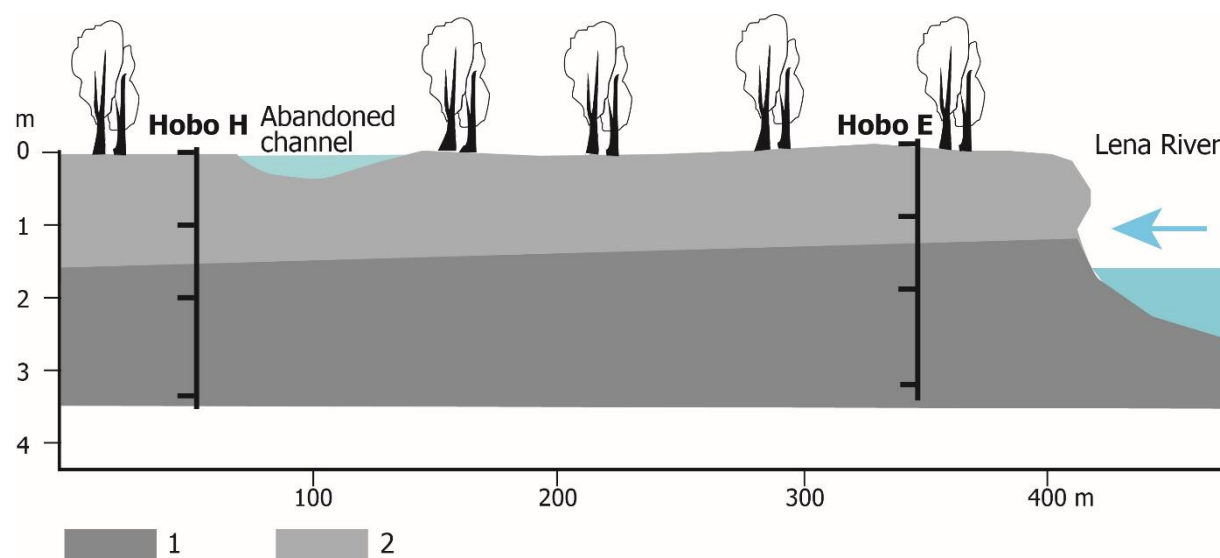
236 *Eselyakh Island*

237

238 The Eselyakh Island (Figure 5) has a permanently frozen soil. According to Hobo E (Figure 6), the annual
239 average temperature at 3.2 m depth was -2.2°C for 2009-2010 and -3°C for 2010-2011. At 1 m and 2
240 m depths, the Hobo recorded a slightly lower mean temperature and a higher intra-annual variability
241 (1m: -2.5°C in 2009-2010 and -4.3°C in 2010-2011; 2m: -2.4°C in 2009-2010 and -3.5°C in 2010-2011).
242 Hobo measurements coupled with successive field campaigns have shown that the active layer is
243 thinner on the upstream section (1.2 m depth) of the island than on the downstream section (1.5 m
244 depth) (Figure 5). The active layer is composed of peaty sandy loam with a volumetric moisture content
245 of 25% to 53%. Based on drilling operations, the permafrost table at Hobo E site is located at 1.5 m and
246 contains ice-rich sandy loam materials with 19% to 50% ice content by volume.

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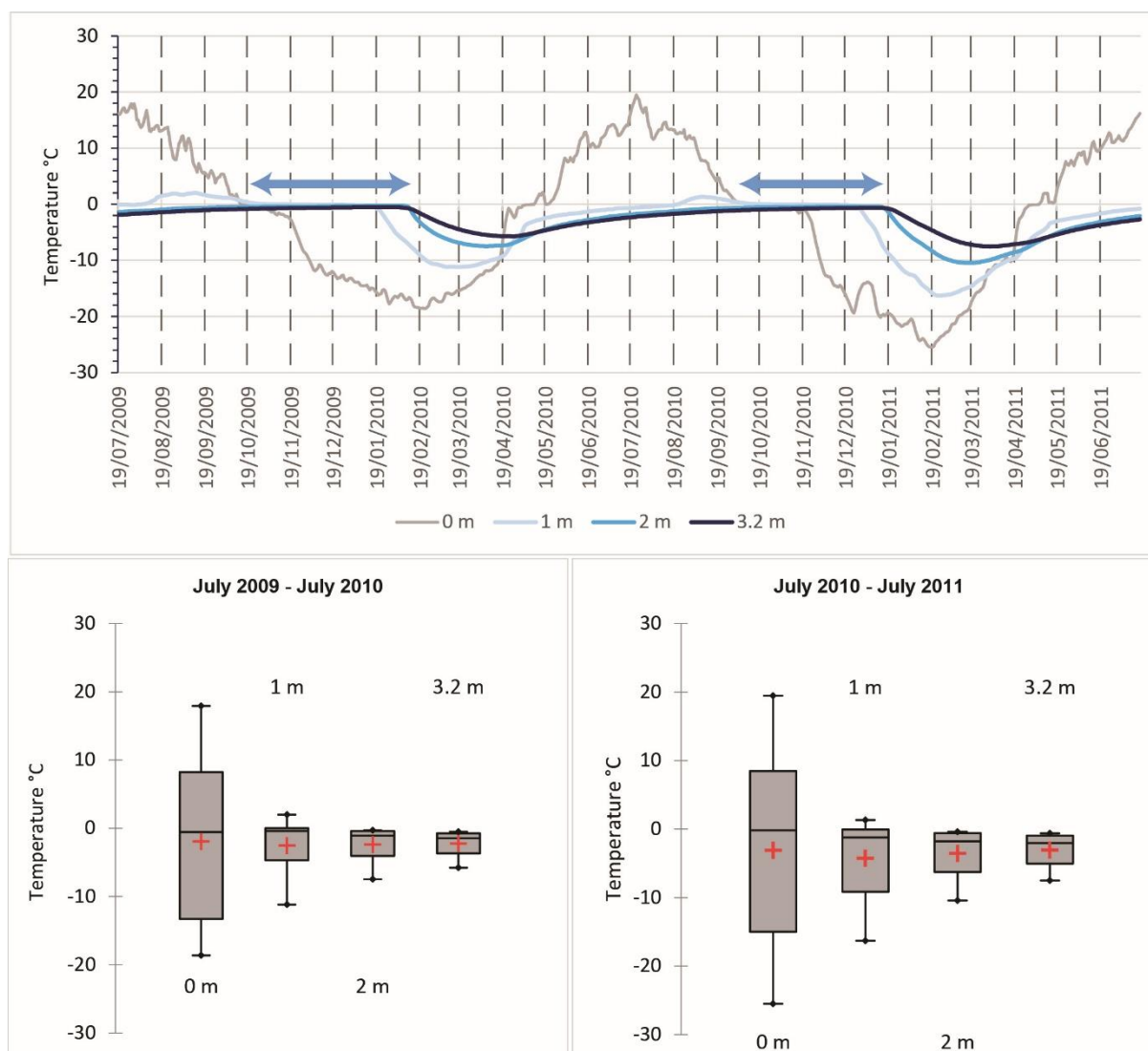


249
 250 Figure 5: Schematic longitudinal section of Eselyakh Island. 1: permanent frozen soil; 2: active layer.
 251 Blue arrow indicates flow direction (to the North). Hobo H is located near a 30 m wide abandoned
 252 channel.
 253

254 According to the thermal profile of HOBO E (Figure 6), underneath the active layer, there is
 255 permanently frozen soil with temperatures ranging from -0.3°C to -10.4°C at a depth of 2 m during the
 256 two consecutive years (2009 – 2010 and 2010 – 2011). At 3.2m depth, the variability of frozen soil
 257 temperature was even less pronounced, ranging between -0.5°C and -7.5°C . We note a downward
 258 propagation of the winter freezing wave and a time lag with depth for reaching minimum temperature
 259 due to the thermal inertia of frozen ground (Figure 6). For example, the minimum annual temperature
 260 was reached in mid-February at the soil surface, in early March at a depth of 1 m, in late March at 2 m,
 261 and in mid-April at 3.2 m, during the first winter. The second winter was harsher and a colder weather
 262 occurred earlier with -20°C in December and -25°C in February, at the soil surface. Consequently, this
 263 ~ 20 -day time lag between different depths was also observed during the second winter, although
 264 nearly three weeks earlier than the previous year (in mid-February, early March and late March,
 265 respectively). For the October – December period, temperatures were stabilized (70 to 80 days) just
 266 below 0°C at a depth of 1 m due to the effect of latent heat (zero curtain effect on Figure 6). At 2m and
 267 3.2m-depth, temperature began to decrease at the end of January.

268

269



270
 271 Figure 6: Ground thermal profiles on Eselyakh Island at 1 m, 2 m and 3.2 m depth for HOBO E
 272 datalogger; 0 m: soil surface temperature (July 2009 – July 2011). Blue arrows correspond to the zero-
 273 curtain effect during phase change of the water-ice in winter season.

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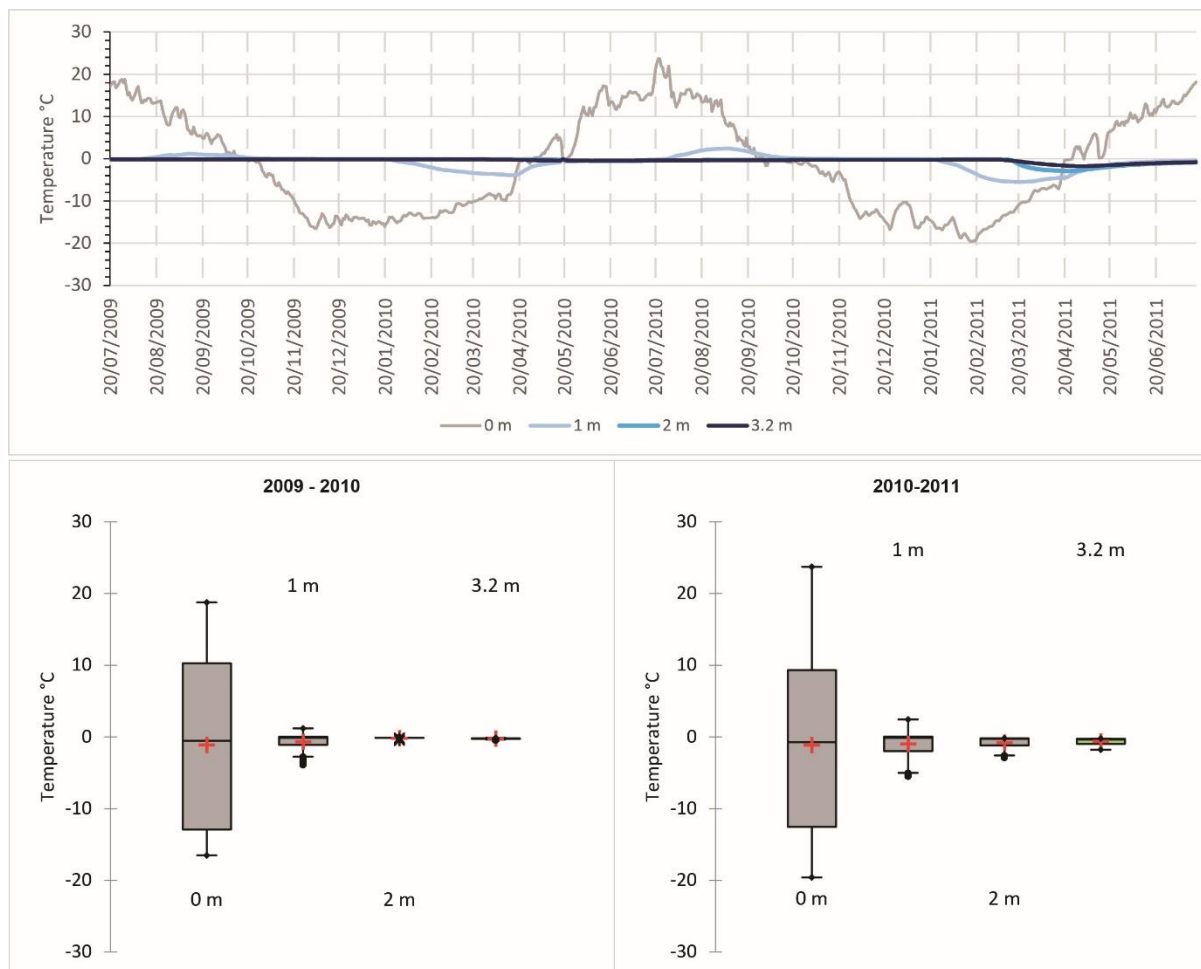


Figure 7: Ground thermal profiles on Eselyakh Island at 1 m, 2 m and 3.2 m depth for HOBO H datalogger; 0 m: soil surface temperature (July 2009 – July 2011).

Contrastingly, the thermal profile of HOBO H, located further downstream on the island (Figure 7), shows a notably warmer frozen soil. For 2009-2010, the mean temperature was -0.67°C , -0.18°C and -0.24°C at 1 m, 2 m and 3.2 m, respectively. In 2010-2011, the mean temperature was lower (-1°C , -0.8°C , -0.6°C at 1 m, 2 m and 3.2 m). Furthermore, the temperature ranged between $\sim 0^{\circ}\text{C}$ and -5.5°C (1 m), between -0.1°C and -2.9°C (2 m) and between -0.2°C and -1.7°C (3.2 m) during the second (colder) winter. The temperature did not vary substantially during the first winter and decreased a bit more during the second winter. The lowest temperature was registered in April before the breakup (-1.8°C at 3.2m). The lowest temperatures are not as cold as the one registered by Hobo E (-7.5°C in April 2011 at 3.2 m). The sediment is identical, with the same composition and grain size characteristics as on the previous site.

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 (1 m) -1.2°C and -11.1°C (2 m) and between -1.2°C and -8.9°C (3.2 m depth). When comparing the same years (2009 to 2011), Ynakkh – Ary has a colder soil than Eselyakh: -2.98°C for 2009-2010 (at 3.2 m) and -3.97°C for 2010-2011 mean value. We also observed a two month-time-lag separating the beginning of continuous negative temperature on the soil surface (October) and the start of the cooling within the frozen soil: beginning of January at 1 m and 2 m depths, end of January or early February at 3.2m depth.

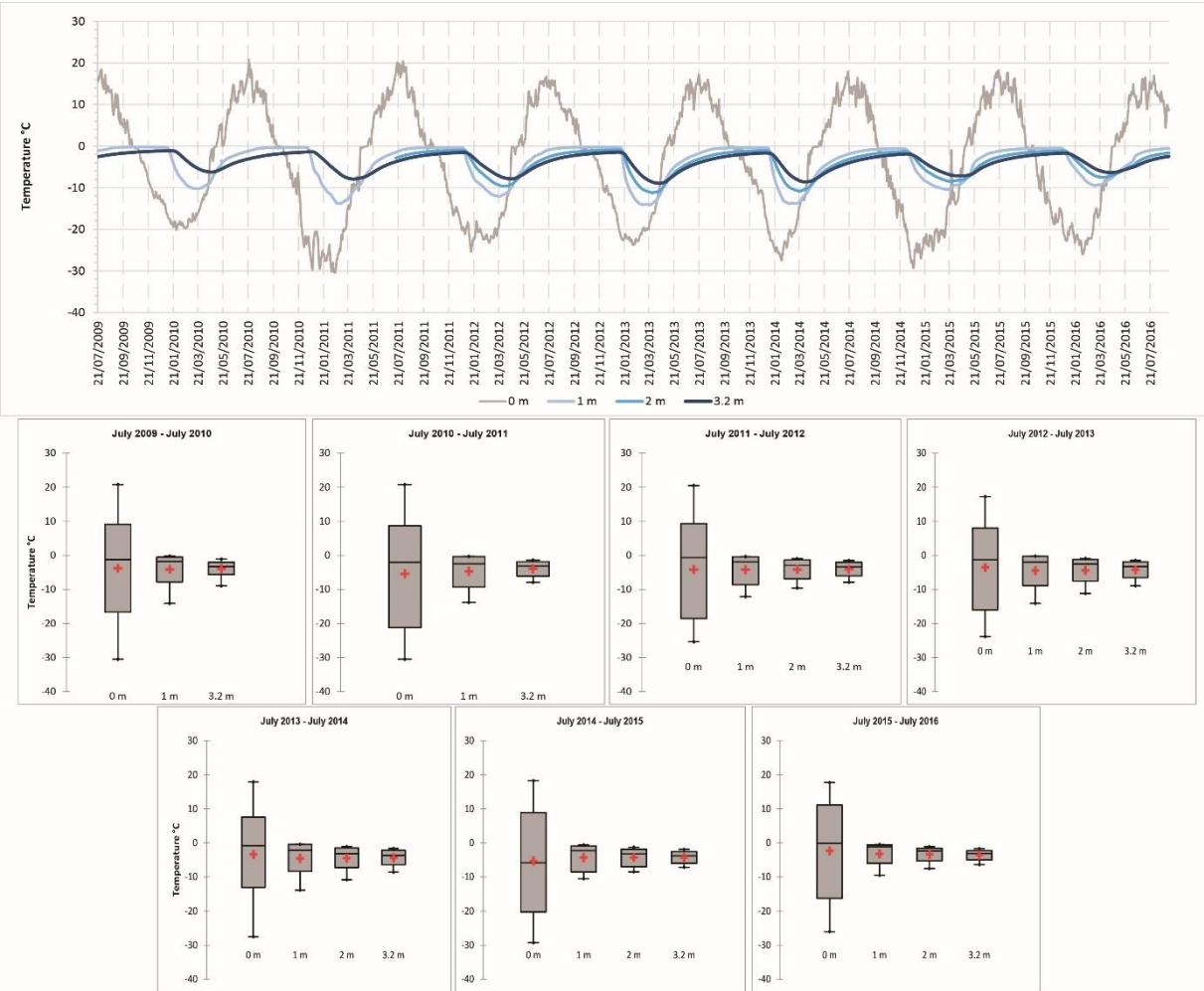
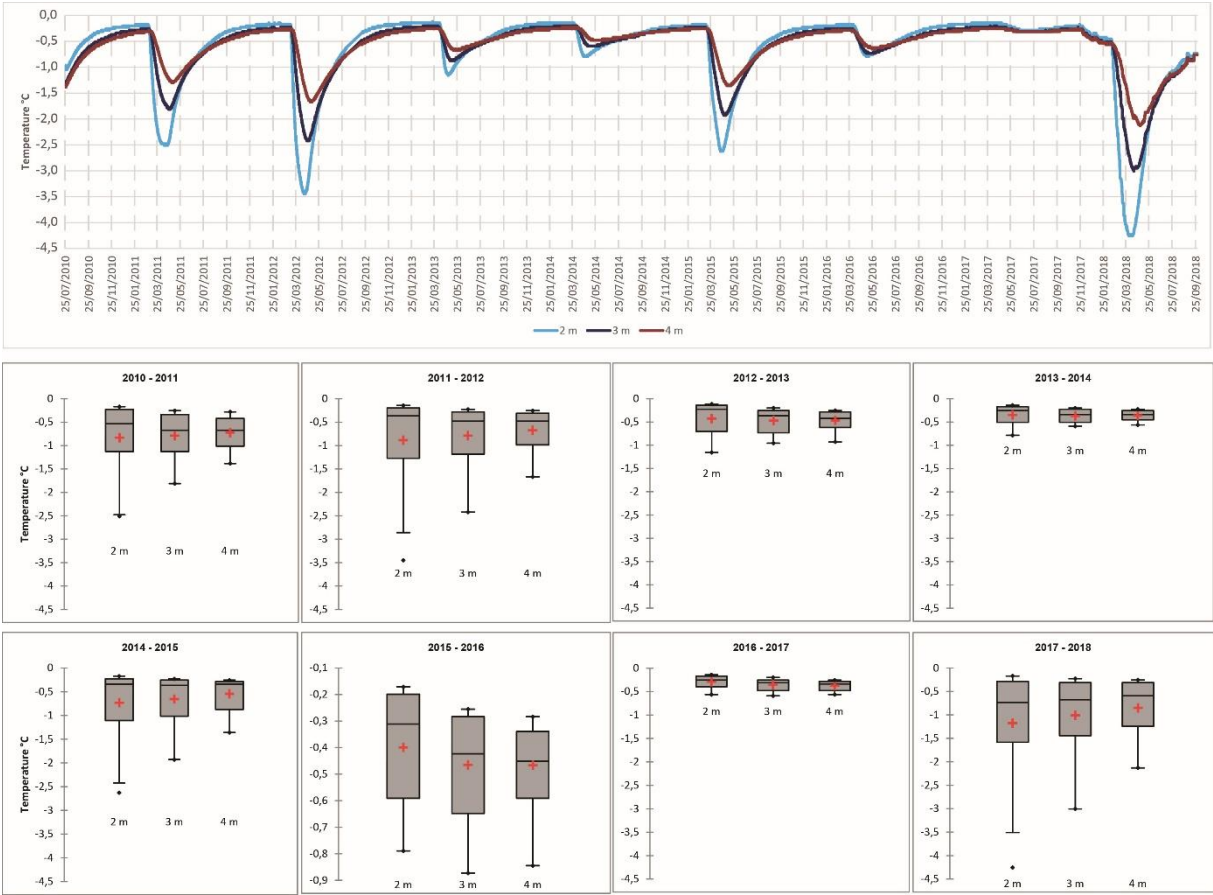


Figure 8: Ground thermal profiles on Ynakh-Ary island, at 1 m, 2 m and 3.2 m depth for Hobo I datalogger; 0 m: soil surface temperature (July 2009 – July 2016).

On Saty-Talakh, which is also a large lateral island, Hobo Q has been working from 2010 to 2018 (Figure 9). The thermal profile differs from the data registered on Ynakh-Ary. The temperature regime is similar

310 to Hobo H on Eselyakh island, because of a relatively warm permafrost at 3.2 m depth. For 2010-2011,
311 the mean temperature (3.2 m) was -0.79°C and dropped to -1.81°C at the end of the winter. The cold
312 winter 2017 – 2018 induced a stronger cooling; the 3 m Hobo recorded -3°C in mid-April.
313
314



315
316 Figure 9: Ground thermal profiles on Saty-Talakh island, at 2 m, 3 m and 4 m depth for Hobo Q
317 datalogger (July 2010 – September 2018). No data logger at the soil surface for Hobo Q.
318
319

320 4.2. Islands with seasonally frozen ground

321 *Timochka Island*

322 Timochka Island has a seasonally frozen ground; negative temperature is observed from November to
323 the end of April at 1m depth. At 3.2 m depth, the average annual temperature ranges between +1°C
324 and +1.5°C. Thus, temperatures remain constantly above 0°C even at a depth of 3.2 m (Figure 10). This
325 island is mostly composed of fine sand, and the willows are relatively younger than those on Eselyakh
326 Island (Gautier et al., 2021). The volumetric soil moisture content ranges from 4% at 0.1 m depth to
327 40% at 1 m depth. Similarly to other Hobo sites on the other islands, however, ground temperature

variability is notably larger near the surface (at 1 m deep) compared to several meters deep (Figure 10, lower graphs).

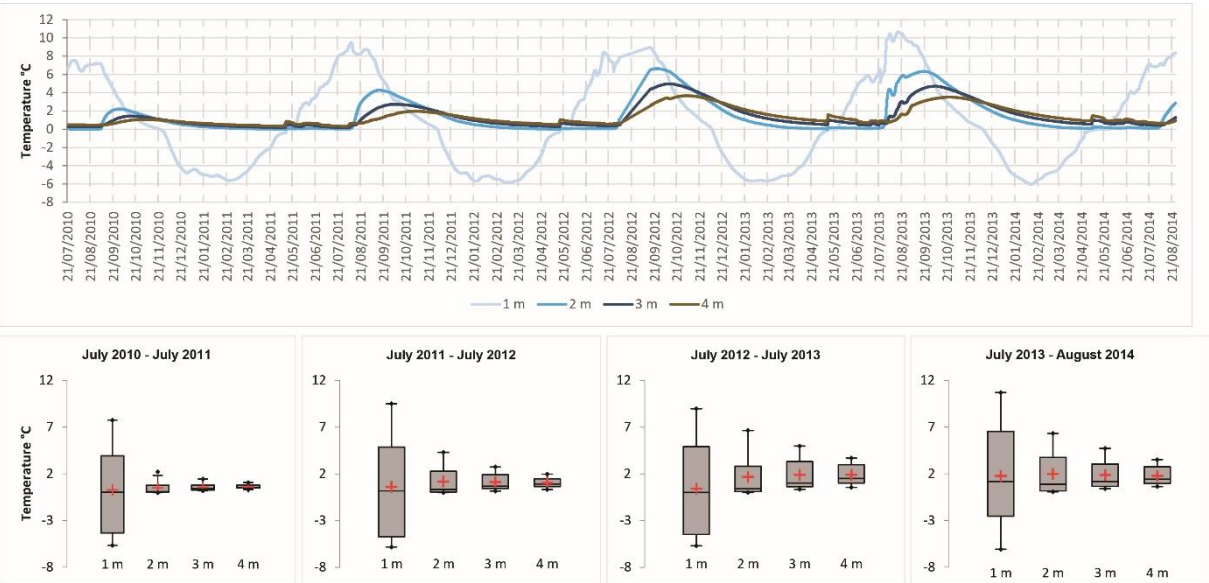


Figure 10: Ground thermal profiles on Timochka Island at 1 m, 2 m, 3 m and 4 m depths for HOBO-A (July 2010 – August 2014), without a permanently frozen soil. No data logger at the soil surface for Hobo A.

5. Discussion

Our results demonstrate that, even in an area of thick continuous permafrost, the ground is not permanently frozen everywhere within the Lena floodplain. This study also highlights not only a strong inter-annual variability in ground temperature, but also the spatial heterogeneity of the thermal regime of frozen soils. On the one hand, some sites along the islands show a colder permafrost conditions that vary little throughout the years, and on the other hand, other sites are underlain by a notably warmer seasonally frozen ground affected by strong thermal variability. Two main factors are inferred to influence permafrost dynamics in the Lena floodplain: the age of the islands and the thermal effect of spring breakups.

Age and thermal state of the islands

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 Eselyakh and Timochka islands that are located in the central part of the active channel (Figure 1). Thus, they rapidly

352 migrate downstream, as the head is progressively eroded, whereas the tail (downstream) progresses
353 by deposition (Figure 11). Island sides are also exposed to erosion, explaining the reduction in form
354 size (Table 1). The two other islands (Ynakh-Ary and Saty-Talakh) are much larger lateral islands, and
355 are more stable. As they are located at the margins of the river active channel, they are subjected to a
356 reduced reshaping (sediment drift) with a local erosion of their bank (Figure 11).

357 Eselyakh and Timochka are relatively small islands with surface area of 0.2 km² and 0.13 km²,
358 respectively (Table 1). They are bisected with a secondary channel between the two parts (Figure 1,
359 Table 1). Eselyakh is older than Timochka, as its two parts were already formed in 1967 and a
360 dendrochronological analysis of a willow puts its age at 56 years in 2010. It suggests the stabilization
361 of a sand bar during the 1950's. The upper part of Eselyakh is progressively shrinking due to head and
362 side erosion, whereas the lower part is growing by sedimentation. Timochka is an elongated island that
363 is migrating very rapidly since its formation. Hence, the present-day island is young: the upper part
364 corresponds to a deposition zone formed between 1980 and 1996.

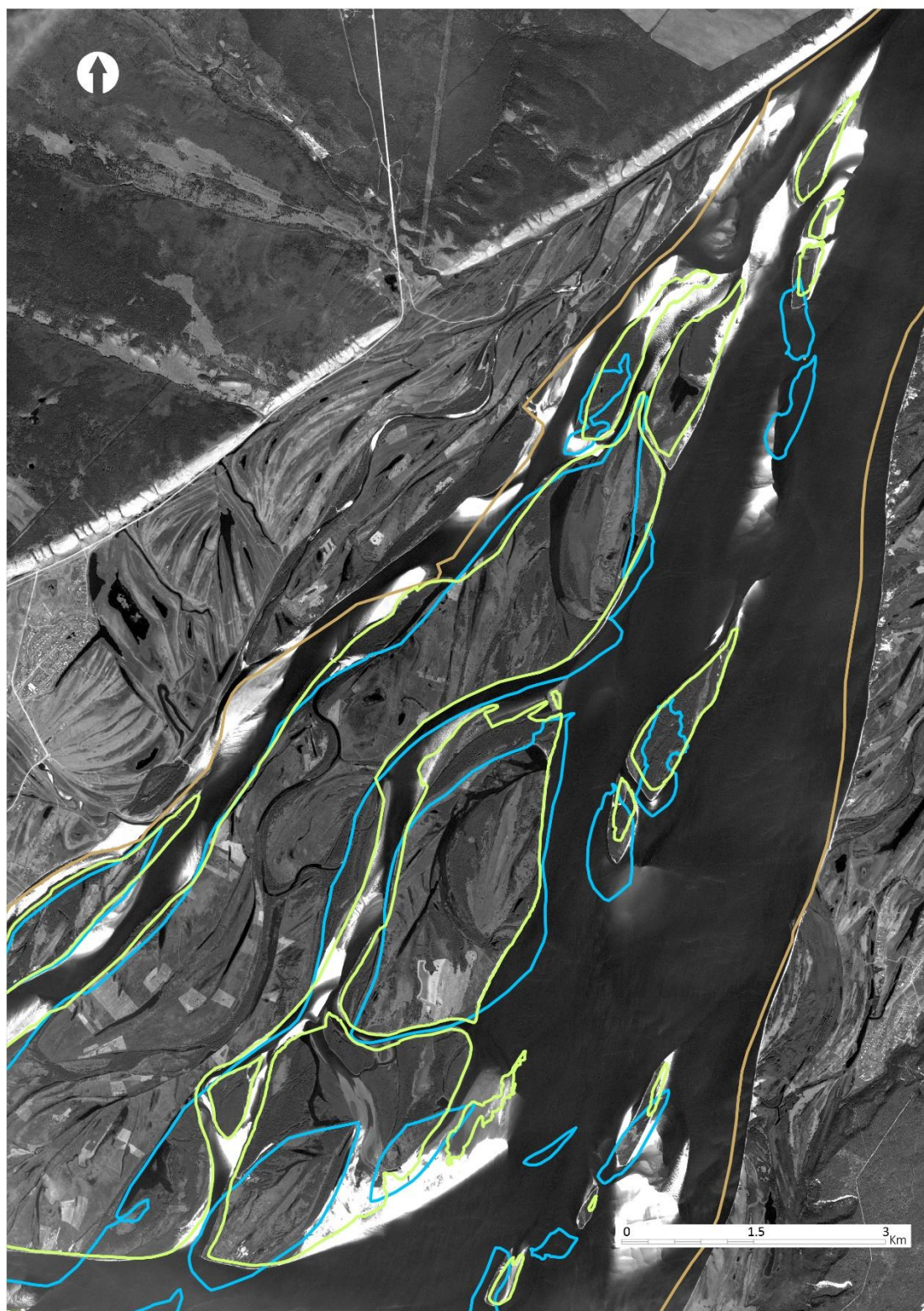
365 Ynakh-Ary and Saty-Talakh are large islands with surface area of 5 km² and 20 km², respectively. They
366 had the same general shape in 1967 (Figure 11). According to local inhabitants, they are very old
367 islands. They were formed by merging of different islands, and lakes and swamps occupy the former
368 inter-island channels.

369 It appears that the oldest islands are thus at least 70 years old in our selected study area (Gautier et
370 al., 2021). The Ynakh-Ary, Saty-Talakh and Eselyakh islands are old islands with a permanent frozen soil
371 developed in fine-grained material (silt-clay) deposited by overbank flows overlaying a sandy base.
372 Timochka Island is much younger, with only seasonally frozen ground and mostly sand deposits, as the
373 island has been formed by the colonization of a former sand bar by willows. This apparent relationship
374 between the age of deposition/formation and the thermal regime of the ground can also be extended
375 to the much older permafrost near Yakutsk (Figure 3), where ground temperatures at 3.2 m can remain
376 below -1°C at the end of the summer and below -4°C at the end of the winter. Contrastingly, ground
377 temperatures barely or never attain such low values at Eselyakh (Figures. 6 and 7), Ynakh-Ary (Figure
378 8) or Saty-Talakh (Figure 9), which are nevertheless underlain by frozen ground. Permafrost obviously
379 had much less time to develop at these sites and is in equilibrium with current climate conditions,
380 which is not the case 'onshore' near Yakutsk.

381 However, the age of the island is not the only parameter explaining the observed differences. Local
382 parameters, and more precisely, abandoned channels, also seem to explain the observed thermal
383 heterogeneity. Hobo H is located not far from a 30 m-large abandoned channel (Figure 5), which
384 obviously induces a thermal effect by heating the upper part of the frozen soil. Widespread along the
385 floodplain, such abandoned channels are watered more frequently and they are located on lower

386 topographic levels. These depressions are humid and occupied by swampy vegetation. Eselyakh (Hobo
387 E) and Ynakh-Ary dataloggers are installed on higher topographic levels.

388



389
 390 Figure 11: Island migration of the study reach upstream of Yakutsk city from GIS study. Blue line: island
 391 shape in 1967 (Corona photographs); Brown line: channel bank in 1967; Green line: island shape 2017

392 (Pleiade images © CNES, 2017, Distribution Airbus DS, all rights reserved). Background image: Spot
393 2008 (© CNES, Freance)

394
395 *Thermal effect of spring breakup: the example of 2010*
396 During spring floods, the islands along the Lena River channel are submerged and this induces an
397 additional thermal imprint. Our dataloggers were able to record this specific stage on Eselyakh and
398 Ynakh-Ary islands (Figure 12). It can be seen that the temperature variations on the ground are
399 suddenly interrupted on May 19, 2010 with a temperature dropping and remaining at 0°C until May
400 25 (Figure 12; Table 2). This is due to the inundation of the islands when the flooding begins (for a
401 discharge exceeding about 30,000 m³.s⁻¹). The submersion duration greatly varied during the study
402 period (Table 3).
403 Furthermore, the sensor installed at the soil surface (0 m on Figure 12) registered the water stream
404 temperature. At the beginning of the flooding, temperatures close to 0°C confirm the existence of a
405 mixture of water and ice during the breakup. Then, after a few days, the water temperature slightly
406 increases (1°C to 3°C) as the islands are inundated by water only.

407
408 Table 2. Flood duration, number of flood peaks and temperature range of the study sites along the
409 Lena River

410		Flooding duration (Days)	Flood peaks	Stream water temperature range (°C)
	2009	26	June 3 rd – June 28 th	ND
	2010	9	May 19 th – May 27 th	0°C – 0.9°C
	2011	6	May 13 th – May 18 th	0.2°C – 1.4°C
	2012	36	May 17 th – May 26 th June 5 th – June 19 th July 5 th – July 9 th July 28 th – August 4 th	0°C – 3°C 9.5°C – 12°C 15°C – 15.5°C 15°C – 16.5°C
	2013	14	May 14 th – May 21 st July 23 rd – July 29 th	5°C – 5.5°C 18°C – 19°C
	2014	0		
	2015	7	May 13 th – May 19 th	0.3°C – 3°C
	2016	10	June 10 th – June 16 th	11.6°C – 13.3°C

		July 31 st – August 3 rd	14.6° – 15°C
2017	5	July 20 th – July 24 th	19°C – 19.5°C
2018	17	May 5 th – May 10 th July 19 th – July 25 th	ND

411

412 However, the observed effect of island submersion at the time of breakup appears to have a relatively

413 moderate impact on thermal profile at depth (i.e. more than 1 m deep). This can likely be explained by

414 1) the duration of submersion, which in that case is too short to have a long-term thermal impact in

415 the ground, and 2) the water temperature, still near 0°C, again precluding major thermal disturbance

416 within the ground, at least below the surface. Figure 12 clearly shows that the ground temperature

417 regime for the two islands (Eselyakh and Ynakh-Ary) did not change, even during the 10-day

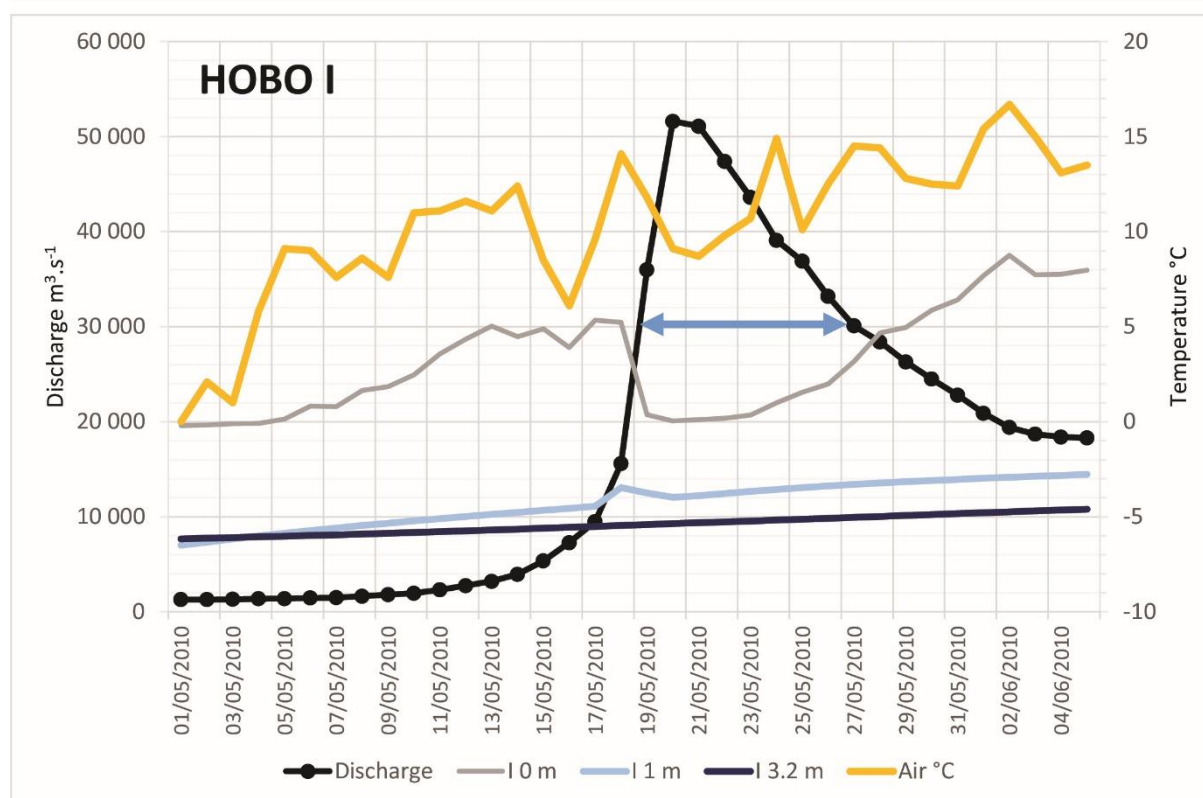
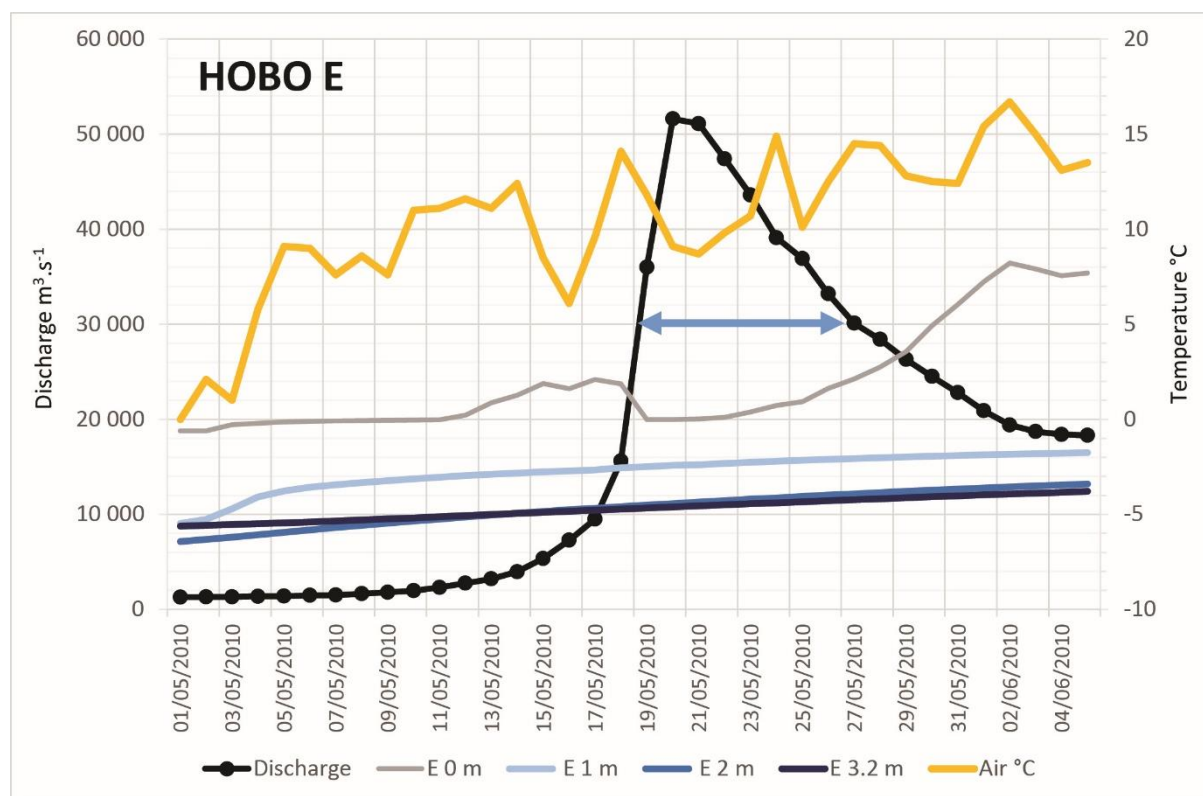
418 submersion of the island during the ice breakup in May.

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420

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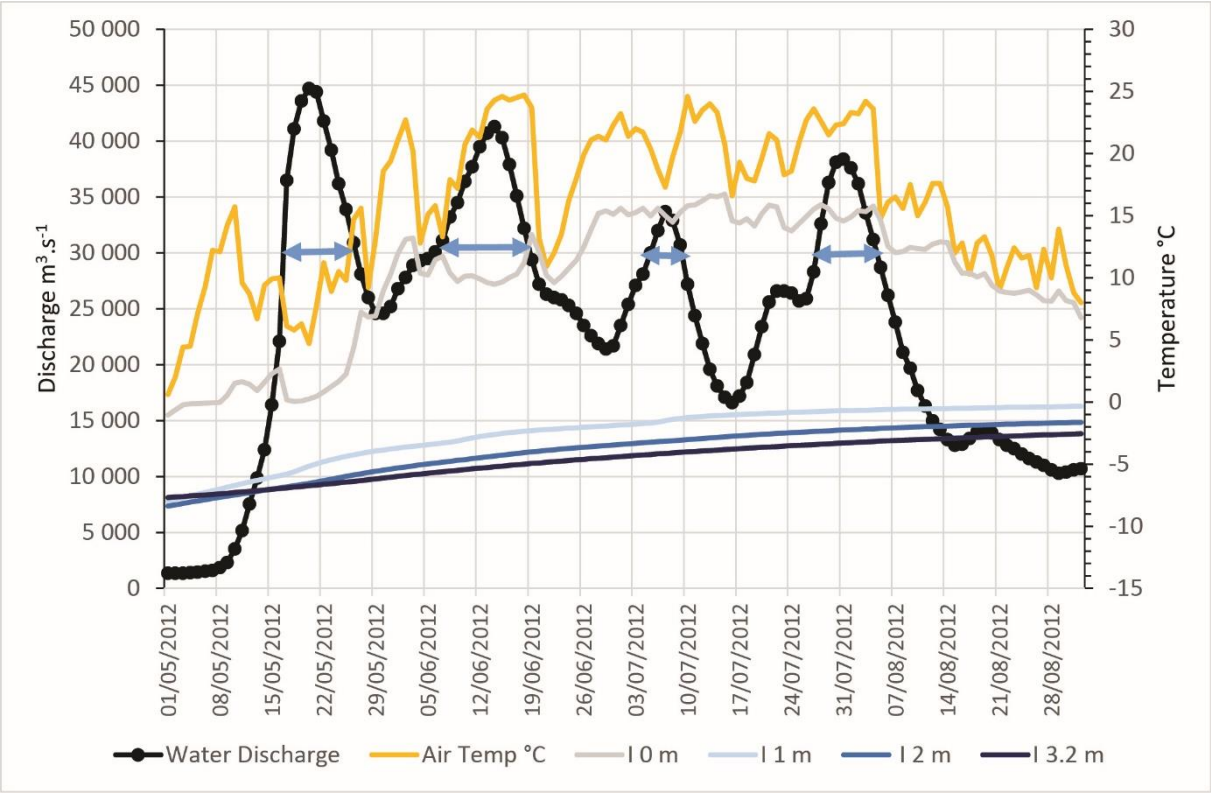
423
 424 Figure 12: Mean daily discharge and temperature on islands with a permanent frozen soil (2010, May
 425 1 – June 5). Eselyakh Island (HOBO E), Ynakh-Ary Island (Hobo I). Water Discharge at Tabaga gauging
 426 station (Roshydromet data); 0 m: soil surface temperature; ground temperature at different depths (1

427 m, 2 m and 3.2 m); air temperature at Yakustk (NOAA, NASA data). The blue arrow corresponds to the
428 submersion duration of the islands in relation with a discharge > 30,000 m³.s⁻¹.

429
430 Interestingly, multiple water level increases during the warm seasons have occurred in the Lena River.
431 During some years, the islands can be inundated twice or more often. For example, in 2012, the Lena
432 River underwent four flood peaks (Figure 13) with 36 days of total flood duration (Table 2). The
433 repeated inundations and warm stream water did not significantly affect, however, the ground
434 temperature regime of the islands.

435 Regarding the surface temperature recorded in 2010 and in 2012 for Eselyakh Island (HOB0 E) and
436 Ynakh-Ary Island (Hobo I), we can observe a systematic decrease of the surface temperature (0 m)
437 during each of these breakups and flood seasons (Figures 12 and 13). The water stream temperature
438 is systematically lower than the air temperature due to the water/ice mixture of the breakup that
439 decreases the surface temperature of the islands during the submersion phase. We also observed that
440 the initial phase of the breakup in May is accompanied by a net decrease in air temperature (yellow
441 curve on figure 12 and figure 13). Finally, regardless of the water stream temperature or the thermal
442 state and water/ice content of the subsoil, the thermal regime of the subsoil at 1 m depth (Figure 13)
443 does not appear to be affected.

444
445



446

447 Figure 13: Mean daily discharge, air temperature and thermal regime of subsoil of Ynakh-Ary (HOBO I)
448 between May and August 2012. Water Discharge at Tabaga gauging station (Roshydromet data); 0 m:
449 soil surface temperature; ground temperature at different depths (1 m, 2 m and 3.2 m); air
450 temperature at Yakutsk (NOAA, NASA data). Blue horizontal line corresponds to a water discharge >
451 30,000 m³.s⁻¹ in relation with the submersion of the island.

452

453 **6. Conclusion**

454 For a first time, we were able to instrument a large Arctic fluvial system in order to acquire new data
455 on frozen ground development within a large floodplain. Our measurement campaigns revealed that
456 the floodplain of the Lena River, upstream of Yakutsk, does not everywhere contain permanently
457 frozen soil, and that some highly mobile and young islands have (only) a seasonally frozen ground.
458 Even in old islands, where frozen ground is present, a marked variability is noticeable. We also conclude
459 that the ice breakups and floods seem to have a negligible impact on the ground thermal regime. Our
460 study confirms that relatively young (less than 50 years old) islands, composed of fine sand material,
461 appear less prone to permafrost formation compared to older islands with ice-rich silty material. Thus,
462 the Lena floodplain is notably heterogeneous, with a combination of permanently and seasonally
463 frozen islands. The observed disparity between these islands is significant and unexpected, because it
464 confirms that the Lena River floodplain is far from being thermally and geomorphologically
465 homogenous. It rather consists of a juxtaposition of seasonally frozen islands and permanently frozen
466 islands in the regional context of a floodplain affected by thick and continuous permafrost. The
467 heterogeneity could also induce differential responses of the frozen and unfrozen parts of the
468 floodplain to global warming.

469

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