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Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia

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[1] The hydrology of the Lena and its tributaries is characterized by an extremely episodic flow regime. Here we report recent climatic change in Central Siberia, and its impact on the fluvial thermal erosion. We point out three major changes since the 1980s: a marked reduction of the river ice thickness in winter, a pronounced increase of the water stream temperature in spring and a slight increase of the discharge during the break up (May–June). A GIS analysis based on aerial pictures and satellite images highlights the impact of the water warming on the frozen banks. The vegetated islands appear to be very sensitive to the water temperature increase, showing an acceleration of their head retreat (+21–29%). This suggests that recent global warming directly affects the fluvial dynamics and the erosional process of one of the largest arctic fluvial system.

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1. Introduction

[2] It is now well-known that Arctic regions are very sensitive to the global warming and those arctic hydrological systems are quite receptive to the temperature rise. The Yakutia region is a particularly interesting region for its extremely low temperature, and its thick permafrost (up to 1,500 m). The Lena river is one of the largest arctic rivers located in a permafrost environment. The total length of the Lena river exceeds 4,400 km, and the width of the floodplain can reach 25 km downstream of Yakutsk [*Antonov*, 1960]. Due to its large basin (2.49 million km^2), the Lena river conveys 525 km^3 of water to the Laptev Sea annually. At the latitude of Yakutsk (62°N), the fluvial forms of the floodplain exhibit a large number of shallow and wide channels. The width of the channels varies between several hundred meters and three kilometers (Figure 1). These multiple channels enclose large forested islands from 1 to 5 km long and large sandy bars (Figure 1). The hydrology of the Lena and its tributaries is characterised by high discharge variations [*Gordeev and Sidorov*, 1993; *Gautier and Costard*, 2000]. The break up starts on May 15 for the Lena (at the latitude of Yakutsk), corresponding an increase of the water stream temperature up to 18°C from May to July and to a rise of the water level up to 8–10 m, which inundates the floodplain and the islands. Highest floods occur in June and can be 50,000 m^3.s^{-1} at Tabaga gauging site, near Yakutsk. During the break up period, the joined elevation of the water level and stream temperature contribute to a thermal and mechanical erosion [*Walker and Hudson*, 2003; *Randriamazaoro et al.*, 2007; *Costard et al.*, 2003], followed by exceptional high recession of river banks, up to 19 to 24 m.year^{-1} [*Jahn*, 1975; *Are*, 1983; *Gautier et al.*, 2003].

[3] In spite of a relatively good understanding of the initial stage of the break up period of these periglacial rivers [*Beltaos and Burrell*, 2002; *Shen*, 2003; *Billfalk*, 1982], only a few studies report on the role of thermal erosion during the flood season [*Walker*, 1983]. During the last few years, various papers have documented a significant impact of the recent global warming at the Lena basin [*Yang et al.*, 2002; *Fedorov and Konstantinov*, 2003]. In Yakutia, meteorological studies show an increase of the permafrost temperature up to 1°C and an increase of the thickness of the active layer since the end of the 1980s [*Fedorov and Konstantinov*, 2003; *Pavlov*, 1994].

[4] The main objective of this study is to evaluate the impact of the climatic change on the fluvial dynamics of the middle Lena river. We quantified the fluvial thermal erosion rates measured on river banks from satellite images during the last three decades and we examined their correlation with various hydrometeorological variables (discharge, stream water temperature, river ice thickness). The main result of this study demonstrates the impact of the recent global warming, by means of an increase of the water stream temperature, and an acceleration of the thermal erosion along the frozen river banks. In the current study, parameters affecting fluvial thermal erosion were collected in the middle valley at the Tabaga gauging station, south of Yakutsk city, by 61° 4′N and 129° 3′E, where active fluvial thermal erosion on islands have been recorded [*Costard et al.*, 2003; *Are*, 1983; *Gautier et al.*, 2003]. At the Tabaga station, anthropic influence remains weak, probably because there is no large reservoir in the upper part of the basin. These hydrological observations over the Siberian regions including the Tabaga gauging site in the Lena river, such as discharge, stream temperature, river-ice thickness have been carried out by the Russian Hydrometeorological Services and have been quality-controlled and archived by the same agency. These data have been widely used for hydro-

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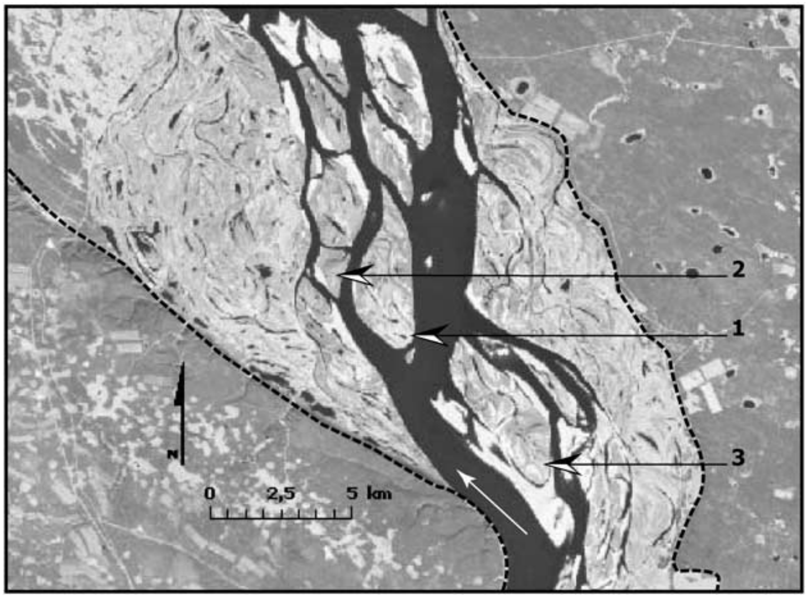

Figure 1. Example of fluvial forms of the middle Lena River (just downstream of Yakutsk 61°5′N–129°5′E). Three types of islands are distinguished: type 1: islands located in the central part of the channel; type 2: islands located near the river bank, and type 3: islands located downstream of an unvegetated bar. Landsat image.

climatic change analyses [*Yang et al.*, 2004, *Ye et al.*, 2003] over the Russian Arctic.

2. Complexity of the Hydroclimatic Change

[5] The recent climatic change exerts different effects on climatic and hydrologic variables. The maximum thickness of the river ice cover in the middle valley near Yakutsk shows a general decrease during the last three decades in relation to the global warming. Before 1987, the river ice thickness during winter exceeded 1.5 m every two years. Since 1987, we calculated that the river ice exceeded this value only four times near Yakutsk. This observation agrees with the evolution on the Lena river northerly near Kusur: according to *Yang et al.* [2002], the winter temperature (November–March) increased by 1.9–3.8°C over the last six decades, and the ice cover was 20–30 cm thinner for the 1970–1980 decade than during the 1950s–1960s. This is also in agreement with the increase up to 1°C of the permafrost temperature for the last three decades [*Fedorov and Konstantinov*, 2003].

[6] Concerning the water discharge during the flooding (May and June), a general but moderate increase of 3% can be noticed at Tabaga since the 1980s (Figure 2). These results partially differ from the observations obtained on the low Lena river where the hydrological change seems to be more significant. *Peterson et al.* [2002], studying the six largest Eurasian Arctic rivers (including data from the lower Lena at Kusur), calculated an annual average rate of discharge increase of 7%. The spring discharge at Kusur on the river outlet increases strongly [*Yang et al.*, 2002]. But, the reservoir regulation on the Villiou river (an important tributary of the Lena river) has a strong influence on the water temperature and discharge on the low Lena river [*Liu et al.*, 2005; *Ye et al.*, 2003].

[7] An important change concerns the significant trend of water stream temperature of the Lena river. During 1950–2002, water stream temperature at Tabaga station is characterized by a progressive increase of its trends during the flood season (May and June) up to 2°C (Figure 3) in relation with previous measurements of increase of the air temperature [*Fedorov and Konstantinov*, 2003]. The correlation between air temperature, water temperature and river discharge was previously underlined by *Yang et al.* [2002] and *Liu et al.* [2005]. The relative importance of

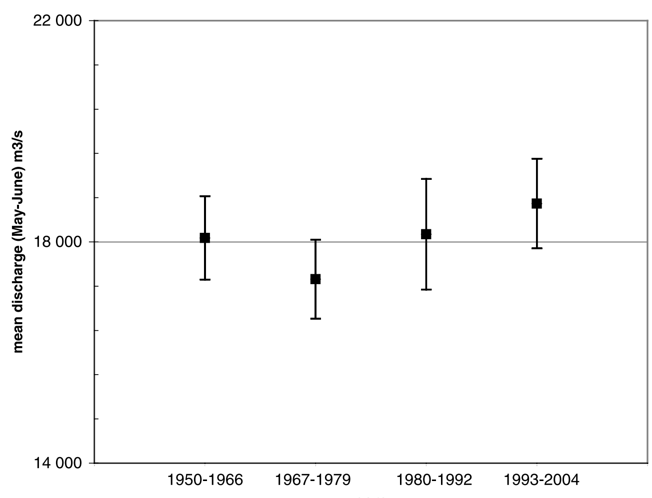

Figure 2. Long-term evolution of the May and June mean discharge between 1950–1966, 1967–1979, 1980–1992 and 1993–2004 at Tabaga station. Data from Yakutsk Navigation Service.

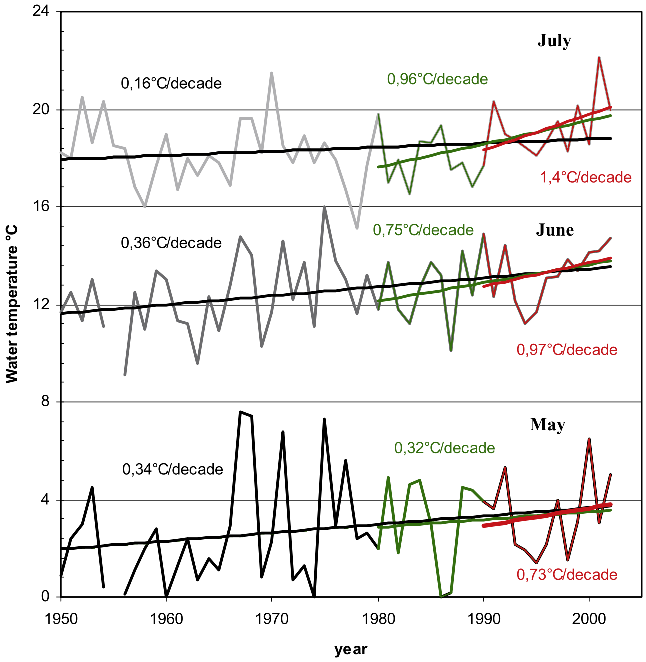

Figure 3. Long-term variation of the water stream temperature and its trends of the Lena River at Tabaga gauging site (near Yakutsk) for the periods 1950–2002 (in black), 1980–2002 (in green), and 1990–2002 (in red). (Data from Yakutsk Navigation Survey.)

the permafrost temperature, ice content, discharge and water stream temperature affecting the efficiency of thermal erosion process were studied quantitatively on the basis of laboratory simulation coupled with a numerical approach [*Costard et al.*, 2003; *Randriamazaoro et al.*, 2007]. Our modelling has been applied to the Lena river case study and demonstrated than thermal erosion is strongly influenced by the water temperature. The water temperature increase is 4 times more efficient than the discharge increase, and the influence of the permafrost temperature remains low. Furthermore, during the last decade, the river discharge increase was associated with positive anomalies of water temperature (excepted for 1996 and 1998).

3. Increase of Fluvial Thermal Erosion

[8] A 35 years diachronic GIS analysis (1967–2002) of the middle Lena River fluvial forms was conducted in order to evaluate the effects of the recent global warming on the mobility of the fluvial units. The delineation on the one hand, of the channel banks and on the other hand, of the vegetated islands was measured on every aerial picture (Corona satellite, 1967 and 1980) and on satellite images (Landsat 4 to 7: 1992, 1999 and 2002) for a 300 km-length of the river, upstream and downstream of Yakutsk (Figure 1). This diachronic study clearly underlines the unequal efficiency of thermal erosion. Actually, for the 1967–2002 period, the mean retreat of the channel banks is low or moderate, with an average value of 2 m per year, that represents only 0.05–0.1% of the main channel width. Maximal values of 14–18 m per year were registered locally.

[9] In contrast, island heads undergo a stronger erosion with mean values of 15 m per year. Three types of vegetated islands are distinguished on the basis of the images analyses coupled with field observations (Figure 1): i) T1: islands located in the central part of the channel; ii) T2: islands located near the river bank and iii) T3: islands located downstream of an unvegetated bar. The two first types are characterized by the greater instability (Figure 4), with maximal head retreats exceeding 40 m per year; furthermore, these islands are subjected to a greater head retreat since 1992 (+29% for T1 and +21% for T2). In that typical situation, the thawed sediments are swept away by the current of the flood, and the water of the Lena river is in permanent contact with the frozen river banks; therefore thermal and mechanical erosion are jointly at work, explaining

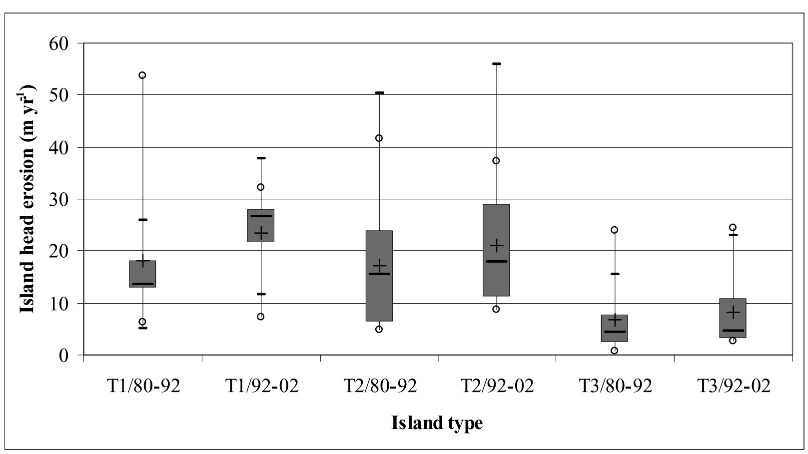

Figure 4. Increasing erosion of the island heads on the middle Lena river (1980–1992 and 1992–2002). Box and whiskers plot for 33 islands. Data from GIS method using Corona, Landsat TM et Landsat ETM images. (See types of islands on Figure 1) Crosses: mean value; horizontal bar: median; grey box: first and third quartile; points: minimal and maximal values. The highest increase of the thermal erosion since the last three decades occurs on type 1 islands, which undergo the most severe impact.

the rapid migration of the form. In the third type, lower erosion rates were registered (6–8 m per year) because of the protection created by the bar located just upstream, but we also observed an acceleration of the island head erosion (+21%). The comparison of the island head retreat before the temperature increase (1980–1992) and since 1992 clearly highlights a strong acceleration of erosion of 24.5% (Figure 4).

4. Discussion and Conclusions

[10] Our study demonstrates that the increase of the fluvial thermal erosion since the beginning of the 1980s is positively correlated with the increase up to 2°C of the water stream temperature during the flood season. To investigate the potential impact of such warming on fluvial thermal erosion, we used our ablation model [*Costard et al.*, 2003; *Randriamazaoro et al.*, 2007]. The result reveals that the measured increase up to 2°C of the water stream temperature alone could increase the erosion rate respectively by 26% and 16% in May and June and easily explains the acceleration of the fluvial thermal erosion rate.

[11] The observed acceleration of the fluvial erosion is correlated with an increased sediment deposition on the downstream part of islands and active deposition on bars. We compared the change of total area of the islands between 1967 and 2002. A decrease of the total area would have indicated a net erosion, which is not supported by the data. In fact, the thermal and mechanical erosion on the island heads provide a sediment load that exceeds the flow capacity because of i) the relatively low specific stream power (10 $W.m^{-2}$) and ii) the brevity of the morphogenic discharges during the break up. Therefore, the sediment load (mainly sand deposits) provided by the thermal erosion process does not migrate over long distances downstream to accumulate on wide bars and long islands [*Gautier and Costard*, 2000].

[12] This study identifies the first response of the fluvial forms of the Lena river, that is marked by a greater mobility of the islands. The fluvial form destabilization is mainly controlled by the water stream temperature increase. It can be hypothesized that the continuation of the warming could induce a general destabilization of river banks and amplify the sediment supply in the riverbed. The stream temperature increase over the last three decades have a major influence on the erosional processes and a direct impact on the settlement of villages (Yakutsk, Villiousk city), generally located on the riverside. Future research will pay more attention to the interaction between fluvial dynamics and spatial variation of the underlying permafrost by means of geophysical sounding. A closer cooperation of researchers with a multi-disciplinary approach should be promoted for the understanding of the impact of the recent climatic warming on these periglacial rivers.

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