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Coupling of sedimentological and limnological dynamics in subarctic thermokarst ponds in Northern Québec (Canada) on an interannual basis

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ABSTRACT

Landscapes are changing at fast rates in subarctic regions due to recent climate warming and related permafrost thaw. As a consequence, thermokarst lakes and ponds are forming and their properties are changing rapidly. Here, we report on the interannual (2012-2014) variability of sedimentological and limnological conditions in a recently formed thermokarst pond in discontinuous permafrost terrain in Northern Quebec, and we discuss various aspects of pond sedimentation processes. Sediment samples from collecting traps and a short core were analyzed for particle size, organic matter content and geochemical composition, as well as ^{14}C dating of a peat sample from the core. Results reveal the preponderance of silts containing 2 to 13% organic matter and an age of 1825–1950 cal. yr. BP for the peat sample. A hypoxic hypolimnion formed in the pond during the short summers. Apparent sedimentation rates (up to 5.5 mm/d) varied in relation to local meteorological conditions and snow cover. The results also reveal major parameters associated with sediment composition, most notably dissolved oxygen in the water column, sampling depth and the year of sampling. Microplankton (20–200 μm) is likely the main source of organic matter, which represents up to 10 to 13% of sediment trap samples, considering its size matching a major grain size mode (44.9–59.0 μm). Using sedimentation rates and an estimation of long-term sediment compaction, the pond's "life span" was calculated at 370 to 600 years. This represents a baseline for the general understanding of the development of young (15–20 years) subarctic thermokarst ponds overlying impermeable soils, and provides an approximate time frame for the potential response of such systems to climate change impacts on northern landscapes.

1. Introduction

Studying past and present climate variations is essential to design and validate reliable climate models which are crucial to the understanding of future climate evolution and its various impacts on the landscape. Some regions are more susceptible to climate change than others, and show fast evolution under changing conditions. It is critical to study these "sentinel" regions where impacts of climate change are more immediate and more readily recognizable. Among these is the Subarctic, a transition zone between the Arctic and temperate regions where landscapes are contrasted depending on latitude and where the transition from discontinuous to continuous permafrost is located. The discontinuous permafrost zone is highly climate-sensitive since temperature and precipitation are among the controlling factors of permafrost stability and thickness (Buteau et al., 2010; Smith et al., 2010). Many studies report increasing ground temperatures and permafrost degradation within this zone over the past 50 years, leading to the northward displacement of the discontinuous-continuous permafrost boundary in eastern Canada (e.g., Beaulieu and Allard, 2003; Vallée and Payette, 2007; Chouinard et al., 2007; Beck et al., 2015) and worldwide (e.g., Romanovsky et al., 2010a, 2010b; Smith et al., 2010, 2012).

In the discontinuous permafrost zone, ice-rich landforms are usually dominated by mounds formed by frost heave when segregated ice lenses grow in the soil (Allard et al., 1996; Calmels et al., 2008b; Fortier et al., 2008; Iwahana et al., 2012). Thawing of ice-rich permafrost leads to ground subsidence and formation of thermokarst ponds and lakes in the depressions (Czudek and Demek, 1970). The development, expansion and drainage of these ponds and lakes are controlled by lateral and vertical permafrost degradation, so they reflect the spatial distribution and depth changes of the permafrost (Chen et al., 2014). Thermokarst aquatic systems also affect the energy balance and thermal dynamics of the surrounding permafrost and can further increase its degradation (Yi et al., 2014). Strong erosive processes associated with permafrost thawing usually create high turbidity in the pond waters,

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associated with high sedimentary charges (Jolivel and Allard, 2013). With the recent accelerated permafrost degradation in the discontinuous zone due to climate change (Vallée and Payette, 2007; Jones et al., 2011), the number and size of thermokarst lakes increase rapidly, especially in poorly drained soils such as clays and peatlands (Jolivel and Allard, 2013; Bouchard et al., 2014), although it decreases in some regions, mainly due to drainage (Smith et al., 2005; Jones and Arp, 2015). This results in widespread release of mineral and organic sediments, formerly trapped in permafrost, into aquatic systems (Jolivel and Allard, 2013; Hugelius et al., 2014). Organic matter (OM) that is present in both particulate and dissolved form in thermokarst ponds is involved in the biogeochemical production and emission of methane (CH_4) and carbon dioxide (CO_2) into the atmosphere (Phelps et al., 1998; Walter et al., 2006; Schuur et al., 2009; Laurion et al., 2010). These greenhouse gas (GHG) emissions from thermokarst lakes and ponds thus have the potential to contribute to known positive feedback mechanisms thereby enhancing climate warming (Walter et al., 2006; Schuur et al., 2008; Laurion et al., 2010). Aquatic thermokarst systems have a high impact potential on global climate because of their extended distribution among permafrost regions; Holocene thermokarst basins have been assessed to be a major organic carbon reservoir and thus a potential carbon source upon permafrost thaw (Walter Anthony et al., 2014). Actual thermokarst basins potentially have an equally important impact on modern carbon pool, and an improved understanding of the sedimentary dynamics of these systems is needed.

The aim of this study was to determine the variability of sedimentological and limnological conditions of a thermokarst pond in Northern Québec (Nunavik, Canada) throughout a year, and between different years. An appropriate way to study modern sedimentary processes and dynamics in thermokarst lakes and ponds is the use of sediment traps. This approach has only recently been used in thermokarst ponds (Bouchard et al., 2014) and this study further develops its application. It is part of the broader research program ADAPT (Arctic Development and Adaptation to Permafrost in Transition), aimed at assessing various aspects of permafrost degradation at northern latitudes. More specific objectives of the study were to determine the amplitude and dynamics of sedimentation processes in the pond, and to characterize the relationships between sediment properties, its limnological parameters, and meteorological conditions. Furthermore, the study aimed at identifying patterns that could provide a more generalized understanding of thermokarst pond sedimentological dynamics and a first estimation of their “life span”.

2. Study area

2.1. Geological setting, climate and vegetation

The study was conducted in subarctic Québec, on the eastern shore of Hudson Bay, in Nunavik, Canada (Fig. 1). The transition from isolated (< 10% of land surface) to sporadic permafrost (< 50%) and then from discontinuous (> 50%) to continuous (> 90%) permafrost stretches along a south–north gradient/transect between 55° and 58°N. Two sub-zones related to the presence of postglacial Tyrrell Sea deposits (see below) can also be distinguished: plateaus and mounds (lithalsas) in clayey silts (B^1), and palsas overlying fine postglacial sediments (C^1) (Bhiry et al., 2011) (Fig. 1).

Nunavik bedrock is mainly composed of Precambrian granito-gneissic rocks belonging to the Superior geological province (Thériault and Beauséjour, 2012). The Wisconsin glaciation ended around 8000 cal yr. BP in the Hudson Bay region (Hillaire-Marcel, 1976; Dyke and Prest, 1987) and following glacial retreat, the postglacial Tyrrell Sea submerged the landscape up to an elevation of between 244 and 315 m above present-day sea-level (a.s.l.) (Hillaire-Marcel and Fairbridge, 1978; Allard and Séguin, 1985). Due to rapid postglacial isostatic rebound, the sea has receded near its present-day level around 6000 cal yr. BP (Bhiry et al., 2011; Lavoie et al., 2012). Along the present-day coastline of Hudson Bay, permafrost has therefore developed postglacially in marine sediments of the Tyrrell Sea and peatlands (Hillaire-Marcel, 1976; Allard and Seguin, 1987; Bhiry et al., 2011; Lamarre et al., 2012).

In the sporadic and discontinuous permafrost zones, numerous palsas and lithalsas have formed, mostly at the beginning of the so-called Neoglacial cool episode about 3000 years ago and the onset of the Little Ice Age (LIA) (Beaulieu and Allard, 2003; Vallée and Payette, 2007; Bhiry et al., 2011). Permafrost degradation following the LIA led to widespread thawing and the formation of thermokarst ponds during

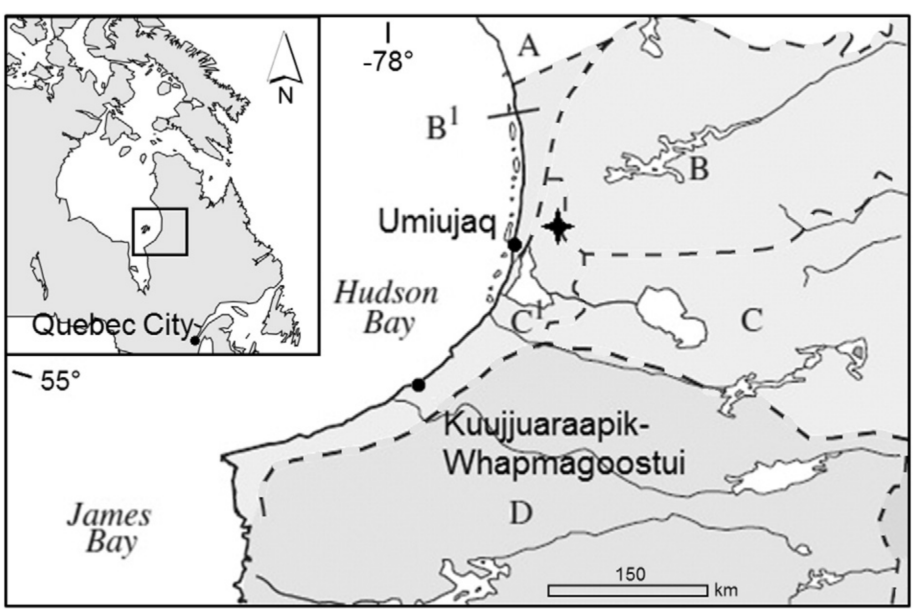

Fig. 1. Study site location (star) and permafrost distribution in subarctic Quebec. (A): Continuous permafrost (> 90% of land surface). (B): Discontinuous permafrost (50–90% of land surface). Sub-zone **B¹**: Major concentration of permafrost area plateaus and mounds in clayey silts of Tyrrell Sea. (C): Sporadic permafrost (10–50% of land surface). Sub-zone **C¹**: Area characterized by palsas overlying fine Tyrrell Sea sediments. (D): Isolated permafrost (< 10% of land surface). Modified from Bhiry et al., 2011.