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Lateglacial and Holocene climate, disturbance and permafrost peatland dynamics on the Seward Peninsula, western Alaska

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ABSTRACT

Northern peatlands have accumulated large carbon (C) stocks, acting as a long-term atmospheric C sink since the last deglaciation. How these C-rich ecosystems will respond to future climate change, however, is still poorly understood. Furthermore, many northern peatlands exist in regions underlain by permafrost, adding to the challenge of projecting C balance under changing climate and permafrost dynamics. In this study, we used a paleoecological approach to examine the effect of past climates and local disturbances on vegetation and C accumulation at a peatland complex on the southern Seward Peninsula, Alaska over the past ~15 ka (1 ka = 1000 cal yr BP). We analyzed two cores about 30 m apart, NL10-1 (from a permafrost peat plateau) and NL10-2 (from an adjacent thermokarst collapse-scar bog), for peat organic matter (OM), C accumulation rates, macrofossil, pollen and grain size analysis.

A wet rich fen occurred during the initial stages of peatland development at the thermokarst site (NL10-2). The presence of tree pollen from *Picea* spp. and *Larix laricinia* at 13.5–12.1 ka indicates a warm regional climate, corresponding with the well-documented Bølling–Allerød warm period. A cold and dry climate interval at 12.1–11.1 ka is indicated by the disappearance of tree pollen and increase in Poaceae pollen and an increase in woody material, likely representing a local expression of the Younger Dryas (YD) event. Following the YD, the warm Holocene Thermal Maximum (HTM) is characterized by the presence of *Populus* pollen, while the presence of *Sphagnum* spp. and increased C accumulation rates suggest high peatland productivity under a warm climate. Toward the end of the HTM and throughout the mid-Holocene a wet climate-induced several major flooding disturbance events at 10 ka, 8.1 ka, 6 ka, 5.4 ka and 4.7 ka, as evidenced by decreases in OM, and increases in coarse sand abundance and aquatic fossils (algae *Chara* and water fleas *Daphnia*). The initial peatland at permafrost site (NL10-1) is characterized by rapid C accumulation (66 g C m^{-2} yr^{-1}), high OM content and a peak in *Sphagnum* spp. at 5.8–4.6 ka, suggesting the lack of permafrost. A transition to extremely low C accumulation rates of 6.3 g C m^{-2} yr^{-1} after 4.5 ka at this site suggests the onset of permafrost aggradation, likely in response to Neoglacial climate cooling as documented across the circum-Arctic region. A similar decrease in C accumulation rates also occurred at non-permafrost site NL10-2. Time-weighted C accumulation rates are 21.8 g C m^{-2} yr^{-1} for core NL10-1 during the last ~6.5 ka and 14.8 g C m^{-2} yr^{-1} for core NL10-2 during the last ~15 ka. Evidence from peat-core analysis and historical aerial photographs shows an abrupt increase in *Sphagnum* spp. and decrease in area of thermokarst lakes over the last century, suggesting major changes in hydrology and ecosystem structure, likely due to recent climate warming.

Our results show that the thermokarst–permafrost complex was much more dynamic with high C accumulation rates under warmer climates in the past, while permafrost was stabilized and C accumulation slowed down following the Neoglacial cooling in the late Holocene. Furthermore, permafrost presence at local scales is controlled by both regional climate and site-specific factors, highlighting the challenge in projecting responses of permafrost peatlands and their C dynamics to future climate change.

1. Introduction

Northern (boreal and subarctic) peatlands contain approximately 500 gigatons of carbon (Gt C) that has accumulated since the Last Glacial Maximum (Gorham, 1991; Yu et al., 2010; Yu, 2012).

Abbreviations: C, carbon; OM, organic matter; LOI, loss-on-ignition; HTM, Holocene Thermal Maximum; BA, Bølling–Allerød; YD, Younger Dryas.

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Many of these peatlands in the subarctic regions are underlain by permafrost (Tarnocai et al., 2009; Grosse et al., 2011). The long-term ability of peatlands to sequester CO_2 from the atmosphere means that they play a critical role in modulating global climate (Turunen et al., 2001; Frolking and Roulet, 2007). High-latitude regions have been experiencing much greater warming than the global average in recent decades (IPCC, 2007), and the effect of these warmer temperatures on the permafrost and peatland C pools and the feedback potential of these ecosystems to climate change remains debated. An additional concern in high-latitude regions is how permafrost thaw (and thermokarst lake formation) will affect the global C balance. Permafrost occupies 22% of the exposed land surface of arctic and boreal regions in the northern hemisphere (Zhang et al., 1999), with an estimate of 277 Gt C stored in permafrost peatlands (Schuur et al., 2009). These landscapes are highly dynamic and can change rapidly due to internal factors and/or climate (Camill et al., 2001; Jorgenson et al., 2001; Turetsky et al., 2002; Seppälä, 2006; Schuur et al., 2008; Tarnocai et al., 2009; Jones et al., 2012), with permafrost thaw and aggradation having profound effects on local hydrology and ecosystem C balance. Understanding how these ecosystems have responded to past climates and climate-induced disturbance is crucial for developing accurate climate and ecosystem models used to project possible future changes.

Peat C accumulation occurs when primary production exceeds decomposition. Warmer temperatures stimulate peatland vegetation production, but can also increase decomposition rates. Whether peatlands will continue to act as C sinks under a warmer climate is highly debated (Roulet et al., 2007; Beilman et al., 2009; McGuire et al., 2009; Yu et al., 2009). During the early Holocene, corresponding with the warm Holocene Thermal Maximum (HTM) at ~11–8 ka in many northern high-latitude regions, northern peatlands spread rapidly on the basis of >1500 basal peat dates (MacDonald et al., 2006), and vertical C accumulation rates in northern peatlands also show a peak during the HTM based on 33 sites across the circum-Arctic region (Yu et al., 2009). Some peatlands in Alaska also show increases in C sequestration during the Medieval Warm Period about 900 years ago (Hunt, 2010). These records indicate that peatlands are capable of increasing C sequestration under a warmer climate, but whether the net effect of C sequestration from peatlands coupled with CH_4 and old C release from thawing permafrost will lead to a negative feedback to climatic warming is highly debated (Schuur et al., 2009; Jones and Yu, 2010).

In the discontinuous permafrost zone, regional temperatures are not low enough to sustain permafrost everywhere. As a result patterns of permafrost distribution are largely controlled by local factors such as topography, hydrology, vegetation, snow cover, and subsurface material properties (Schuur et al., 2008), which in turn affect C dynamics in these ecosystems. In permafrost landscapes, ground ice can occupy up to 80% of the soil volume, and thus thawing of ice-rich soils can trigger major changes in surface topography and ecosystem dynamics, including C release and uptake (Brown et al., 1998; Yershov, 1998; Oksanen et al., 2003; Schuur et al., 2008). Where permafrost is ice-rich, permafrost thaw leads to the formation of thermokarst lakes, which in turn can act as a positive feedback to permafrost thaw at the edges and bottom of the lake due to the higher heat capacity of water than air (Schuur et al., 2008). Permafrost thaw that occurs where ice content is lower leads to the formation of collapse-scar bogs or fens. On the other hand, permafrost formation causes volume expansion of the freezing water, which raises the surface of a peatland well above the water table, thus creating drier conditions. If surface conditions become too dry, peat accumulation can cease because oxidation of the surface peat increases (Vitt et al., 1994). At a fen–bog complex in northern Alberta, Canada, high accumulation rates in the early Holocene declined markedly after 4 ka due to permafrost aggradation (Bauer and Vitt, 2011). However, there may be little difference in net primary productivity (NPP) before and after permafrost thaw due to tradeoffs between long-term woody tissue growth on permafrost plateaus and rapid moss growth in permafrost collapse areas (Camill et al., 2001).

In this paper we present a multiple proxy record of ecosystem change over the last 14.8 ka from a permafrost–thermokarst complex to better understand environmental and ecological controls on C accumulation in peatlands and to gain insight into how climatic changes and disturbance affect peatland ecosystem dynamics. This study also fills a gap in peat C accumulation records from the Seward Peninsula, which is of particular interest due to its sensitive location near the forest-tundra ecotone and within the discontinuous permafrost zone. Furthermore, this is a region close to the Bering Sea, so there is the potential for this region to respond sensitively to change in sea-ice extent, which is expected to decrease with a warmer climate. Therefore, a high-resolution record of ecosystem change and C accumulation from this region would provide a valuable dataset for large-scale synthesis of climate and ecosystem change at regional and circum-Arctic scales and for understanding the importance of climate and moisture variability on hydrological and ecosystem processes in the recent past.

2. Regional setting

The study region is on the southern Seward Peninsula, western Alaska (Fig. 1A). The glacial history of the Seward Peninsula is limited to the small glaciers of the Kigluaik Mountains, which lie ~80 km northwest of the study site. The glaciers have recessed during recent warming, and moraine evidence indicates glacier stagnation during the Little Ice Age (Calkin et al., 1998). The study area appears to be an old or possibly current floodplain of the Niukluk River. It is currently located near the confluence of the Niukluk and Fish rivers (Fig. 1B), and lies at the border of two drainage basins: the eastern basin drains approximately 3280 km^2 while the western basin drains approximately 2305 km^2 (Fig. 1B). In addition, the study region is in the discontinuous permafrost zone (Fig. 2); therefore, permafrost dynamics exert a strong control on local hydrology.

The study region experiences a semi-maritime climate that is controlled by the Bering Sea and sea surface conditions (especially sea-ice extent). The closest weather station to the study region is located in Nome, AK, which is about 100 km southwest of the site. The mean annual temperature (MAT) in Nome is −2.74 °C, mean annual precipitation is 420.6 mm, and mean annual snow depth is 1.45 m for the period 1971–2000 (NOAA; Fig. 3). The area around the study region supports both tundra and forest vegetation types. Lichen-dominated tussock tundra is abundant in the lowland areas, which are largely underlain by permafrost. Forests dominated by *Picea glauca* and *Larix laricina* occur in the upland areas (Hinzman et al., 2005). In addition, the study region is located near present-day treeline (CAFF, 2001), and therefore, is well positioned to show treeline shifts during past climatic changes or species migrations.

Two study sites are located near Niukluk Lake (unofficial name; Figs. 1D and 2). Site NL10-2 is a thermokarst peatland at the edge of Niukluk Lake below a nearby permafrost peat plateau (coring site: 64° 49.645′ N, 163° 27.235′ W; elevation = 16 m asl; Fig. 1C). Site NL10-1 is located on the permafrost plateau (coring site: 64°49.648′ N, 163° 27.265′ W; elevation = 18 m asl; Fig. 1C); which is about 2 m above coring site NL10-2. The active layer depth of coring site NL10-1 was 63 cm in August 2010. These two sites are