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Thermal regime of permafrost at Varandey Settlement along the Barents Sea Coast, North West Arctic Russia

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ABSTRACT

Soil temperature variation is one of the governing factors of mechanical properties of frozen soils and has a large effect on the stability of soil masses in regions affected by permafrost. The understanding of the thermal regime is critical for planning, designing, constructing, and maintaining infrastructure needed to sustain communities and/or industries in these regions. Detailed studies on the effects of thermal variations based on field data measured in permafrost are limited due to the high cost and high risk associated with field investigations in these remote areas. This study will contribute to bridge the current knowledge gap through an investigation of the thermal regime in permafrost at Pesyakov Island in the Varandey settlement along the Barents Sea coast, in northwest Arctic Russia. Samples were collected and thermistor string was installed at a series of 6 boreholes along a 500 m transect. The transect crosses a coastal barrier island from the beach margin through a dune belt to the laida zone. Continuous measurement of the ground temperature over a period of two years reveals a strong correlation between the surface conditions (air temperature, vegetation, snowfall) and the variation of soil temperature above the permafrost. Numerical modelling of the transect, calibrated with the measured soil temperature, shows important features of the thermal profile, including the existence of frozen soil lenses within unfrozen soil masses and vice versa.

1. Introduction

The distribution and variation of ground temperature in permafrost soils, referred to as “thermal regime” in this study, is one of the key factors influencing soil strength. In permafrost-affected coastlines, the soil strength governs the stability of coastal bluffs where destabilized soil masses can be carried away by waves and sea currents, adding to erosion problems. Understanding of the thermal regime of these coastal areas is therefore instrumental to plan, design and construct sustainable infrastructure in such areas. This topic has become particularly important in recent decades due to increased erosion rates observed at several locations in the Arctic. Some of the most dramatic losses have been observed along the coasts of the Laptev and Beaufort Seas (Fritz et al., 2017) and in the area of Varandey settlement on the coast of the Barents Sea, in northwest Russia (Novikov and Fedorova, 1989; Guégan et al., 2016; Sinitsyn et al., 2017). This study will focus on the thermal regime of Pesyakov Island, one of the three geographical sectors of the Varandey coastline.

The Varandey region is located in northwest Russia on the shore of the Barents Sea (Fig. 1). Interests in the region have risen strongly over the years following the establishment of a key oil and gas development. The 90 km coastline, from Pesyakov Island in the southwest to the Medynskiy Zavorot Cape in the northeast, is underlain by permafrost. The coastline of the Varandey area also suffers from erosion, which has accelerated over the years at the central and north-eastern sectors due to climate change and human activities (Ogorodov, 2005; Sinitsyn et al., 2017). Pesyakov Island experiences local erosion in separate areas within its coastline, but over the last 50 years is on average relatively stable (Sinitsyn et al., 2017).

Decreasing extent and duration of sea ice that protects the coasts, and increasing air temperatures caused by global warming can lead to an increase in the rate of coastal erosion in permafrost-affected coastlines (Jones et al., 2009). It is believed that these factors can potentially accelerate the rate of erosion on Pesyakov Island in the future, similar to the current situation of the other arctic coastlines, which are all composed from loose/Quaternary sediment.

The threat to the oil and gas infrastructure due to coastline erosion stimulates special interest in the thermal regime of the soils in the

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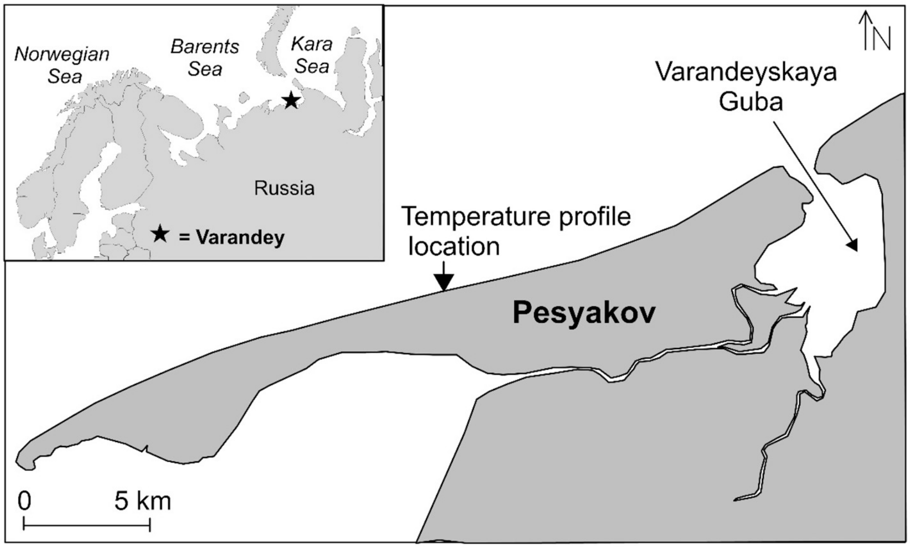

Fig. 1. Map of the Pesyakov Island (main figure) at the Varandey site and location of the Varandey site in a map of northern Europe and Russia (sub-figure).

Varandey settlement. There have been a limited number of published studies that contain information about the permafrost conditions at this site (e.g. Novikov and Fedorova, 1989; Ogorodov, 2004; Ogorodov, 2005; Ivanova et al., 2008; Guégan et al., 2016; Sinitsyn et al., 2017). These studies focused on the geomorphological and geocryological conditions and erosion rates at Varandey. Some studies reported limited field measurement of soil temperatures using thermistor strings (Ivanova et al., 2008; Guégan et al., 2016).

This paper focuses specifically on the thermal regime of Pesyakov Island using field measurements and numerical modelling. Long-term monitoring of ground temperature in permafrost-affected areas is often performed by deploying a thermistor string in a borehole to record the ground temperature over time. Thermistor strings are specially designed to operate under extreme temperature conditions, and have been used frequently for monitoring roads, embankments and pipelines in regions with permafrost (Heuer et al., 1982; Goering, 2003; Kristensen et al., 2008; Flynn et al., 2016; Guégan and Christiansen, 2016).

Soil temperature measured by thermistor strings is limited in time and space. It is therefore quite often supplemented with numerical modelling to extrapolate in space and time. Many studies have demonstrated the potential of numerical models to compliment field temperature data e.g., (Goering, 2003; Kristensen et al., 2008; Flynn et al., 2016). Numerical models can be used as a tool to predict thickness of the active layer and soil temperatures in permafrost. The active layer refers to the relative thin surface ground layer above the permanently cryotic soil. The active layer undergoes freezing and thawing every season. Predictions of active layer thickness and soil temperature can be utilized in designing foundations, pavements, buried pipelines, pipeline crossings in coastal zones, and other infrastructure. The object of this study is to combine field investigation and numerical modelling to reconstruct the thermal regime of Pesyakov Island (Fig.1).

Pesyakov Island is a coastal barrier island about 33 km long, with a spit of 350 m attached to the western end (Fig. 1). The island was formed by cross-flow of fine sand from submarine coastal slopes during the period of climatic optimum (i.e. warm period) at the final stage of the Holocene transgression (Ogorodov et al., 2014). The topsoil layers are therefore characterised by relatively homogeneous medium to fine sands. Mixed organic grass remains and peaty materials can be found in soil samples at distances of > 100 m inland from the beach.

A typical cross-section of Pesyakov Island, from the beach to the lagoon, is shown in Fig. 2. The cross-section is perpendicular to the coast and can be subdivided into four parts: beach, dune belt, barrier and laida (i.e. coastal wetland formed behind the barrier terrace), listed from the coast moving inland (Fig. 2). These parts are relatively distinct in geological and geomorphological characteristics. The beach is covered with well-washed medium to fine sands with some pebbles, gravels, fragmented rock debris and single bivalve shells. The beach ranges between 80 and 100 m wide, bordered by the dune belt separating the beach from the barriers and the laida (Fig. 2). The dune belt is formed by numerous sand dunes, which lie adjacent to the beach and parallel to the coastline. The sand dunes of aeolian-marine genesis are composed of fine-grained sands and devoid of any pebbles, gravel and other coarse-grained materials. The dune width is in the order of tens of meters while the dune height is around 5 to 12 m relative to the sea level.

The relatively flat and wide barrier lies adjacent to the dune belt. The barrier is between 3 and 8 m high relative to sea level. The barrier materials consist of fine sand with some grass remains and appear to have increasing organic content with depth. The laida deposits formed under the influence of storm surges and consist of swampy areas up to 3.5 m above sea level. The laida deposits are characterised by fine sands with an abundance of grass remains and/or interbedded with thin layers of peaty organic materials. The laida can be separated into two morphological levels: upper laida corresponding to wind surges of sporadic catastrophic events (i.e., storms) and lower laida corresponding to fair weather conditions.

2. Methods

A soil investigation was carried out around the middle of the summer in two consecutive years (3–20 July 2012 and 9–16 August 2013).

2.1. Borehole drilling

Boreholes with depths ranging from 3 to 10 m were drilled at nine locations along an approximately 500 m long cross-section perpendicular to the shoreline. The cross-section is located close to the middle of the island. The drilling work was performed with a UKB 12/25 portable rig that consists of a petrol engine mounted on a collapsible metal frame. In most boreholes an auger was employed to drill through the active layer first, followed by the retrieval of ice-bonded frozen cores with a conventional (single-tube) core sampler. The sampler was able to retrieve ice-bonded sand sediments, but no sand sediment unbonded by ground ice (either noncryotic, thawed, or unfrozen) (Harris et al., 1988) could be sampled. On the dune belt, the active layer was thick and the