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Modelling present and future permafrost thermal regimes in Northeast Greenland

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A R T I C L E I N F O

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A B S T R A C T

Permafrost is vulnerable to rapid changes in climate, and increasing air temperatures have recently resulted in the increase of active layer thickness, thaw subsidence and warming of the underlying permafrost. Such changes have important implications for geotechnical properties and the stability of infrastructures in permafrost-affected areas. Many studies focus on the sensitivity of the active layer with respect to changes in climate conditions, but few assess the sensitivity of active layer thermal properties in relation to sediment types and soil water contents, and the importance of direct measurements of thermal property sensitivity with respect to soil water content compared to default physical relationships incorporated in process-based models. In this study, we use on-site data and samples to measure thermal conductivity (TC) at different gravimetric water/ice contents (GWC) in frozen and thawed permafrost. The samples, obtained from an emerged delta and an alluvial fan in the Zackenberg Valley, NE Greenland, are characterized by contrasting grain-size distribution and mineralogy. We calibrated a coupled heat and water transfer model, the "CoupModel", to simulate permafrost temperatures at two sites on the delta. The sites have different snow depth characteristics and were simulated using both observed and default values of TC, and observed liquid soil water content. The results show that depth- and sediment type-specific TC values are crucial for a successful model simulation, and that transfer function derived values of TC are useful for modeling permafrost temperatures as long as site- and depth-specific grain size distribution and ice contents are defined. A thicker snow pack increased ground surface temperatures and resulted in a 1 °C higher annual mean ground temperature at the depth of zero annual amplitude. Permafrost temperatures increased by 1.5 °C and 3.5 °C at the depth of 18 m with 3 °C and 6 °C ground surface warming, but warming combined with increased soil water content had no important additional effect on the thermal regime when ground surface temperatures were prescribed as upper boundary conditions. Precipitation in the form of snow, however, may have a larger effect on ground temperatures directly, due to the surface temperature changes, than will the subsequent changes in thermal properties following increase in soil water content.

1. Introduction

The Arctic has warmed more than twice the rate of the global-average since the 1980s (International Panel on Climate Change (IPCC), 2013; Screen and Simmonds, 2010). Global climate models suggest that the amplified increase in mean annual air temperatures will continue the next decades (Bintanja and van der Linden, 2013). Climate warming is considered a key attributor to the changes currently observed in permafrost regions across the circumpolar north, such as changes in vegetation dynamics and permafrost degradation (Post et al., 2009; Schuur et al., 2015; Westermann et al., 2015). Permafrost is defined as soil, sediment or rock not exceeding temperatures of 0 °C for at least two consecutive years (Müller, 1947). A seasonal cycle of thawing and freezing occurs in the active layer and buffers the energy exchange between atmosphere and the underlying permafrost (e.g. Boike et al., 1998). Thus, the physical, chemical and biological processes in the active layer play a critical role for the permafrost thermal regime.

Global Climate Models predict that air temperatures in Greenland could increase by up to 5–7 °C by 2100 (International Panel on Climate Change (IPCC), 2013). Model investigations (Daanen et al., 2011; Westermann et al., 2015) and in situ measurements (Hollesen et al., 2011) indicate that the upper permafrost in many periglacial areas of

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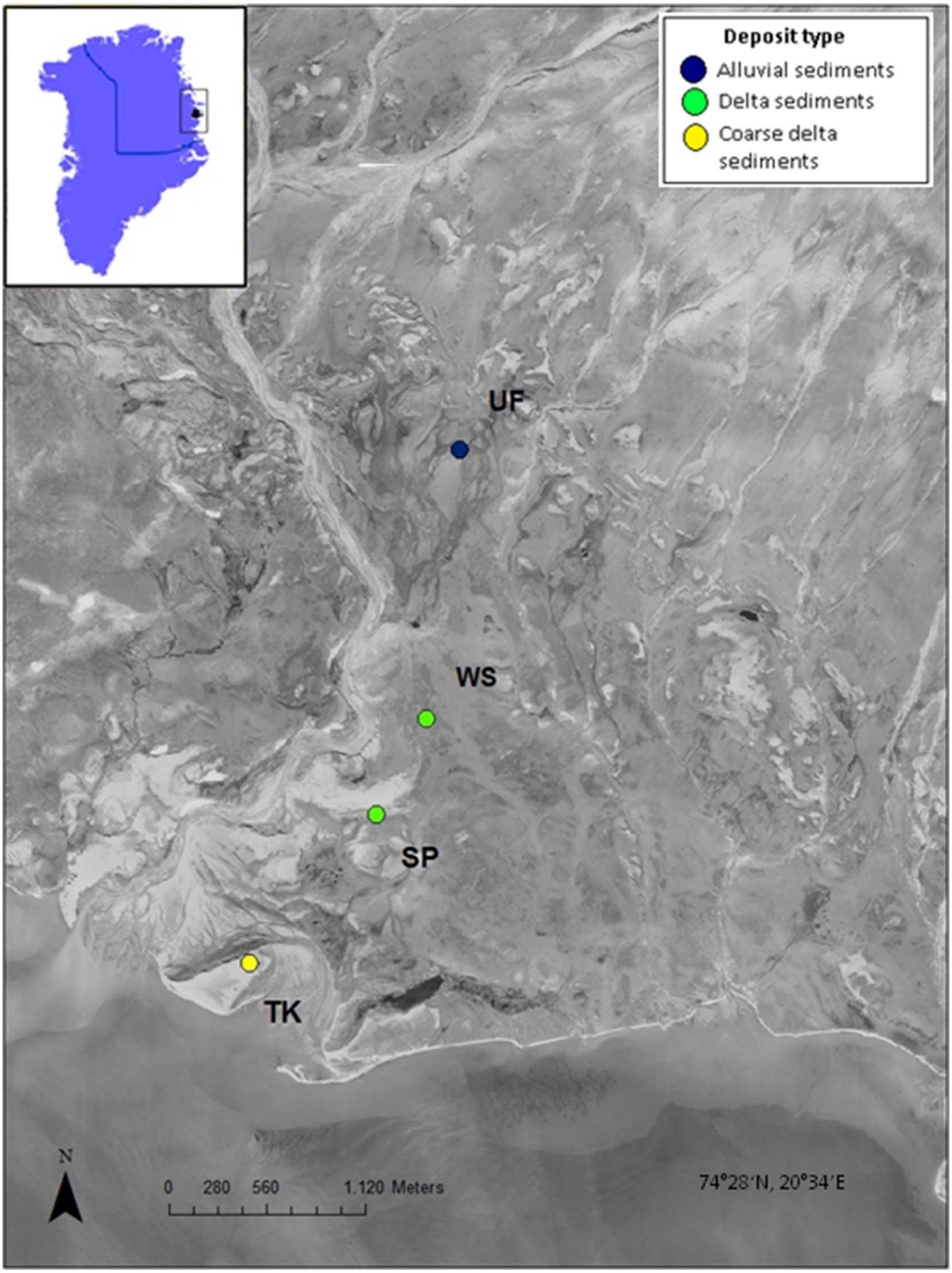

Fig. 1. Location of the Zackenberg Valley and ortho photograph with location of studied boreholes (high-resolution map from http://zackenberg.dk/maps/high-resolution/). The boreholes are marked with coloured dots, specifying the sediment type subsampled from the core (blue: alluvial, green: fine sandy delta sediment and yellow: gravelly delta sediments) and abbreviations: Delta bar TK (Trekanten), delta bar with snowpatch SP (Snow Patch), delta bar WS (Weather Station) and alluvial UF (Upper Fan). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Greenland is at risk of degradation before the year 2100.

The thermal stability of the upper permafrost is influenced by the thermal regime of deeper layers (Riseborough et al., 2008), and it is therefore important to include the physical conditions of permafrost below the depth of zero annual amplitude in model studies.

Air temperature is the key factor controlling the distribution of permafrost (French, 2007). In addition, the timing and duration of snow cover, lithology and permafrost ice content have an important impact on the thickness and stability of permafrost at local scales (Lawson, 1986; Juliussen and Humlum, 2007; Westermann et al., 2015). The depth to which surface temperature change influences ground temperatures is determined by below-ground processes of heat and mass transfer, and the soil thermal properties. Detailed experimental studies of how soil thermal properties depend on soil water content, mineralogy and bulk density were conducted by Kersten (1949), and the importance of unfrozen water content in cold regions was underlined by Farouki (1981) and Gavrilév (1989). The physical relationships obtained from such investigations are used widely in process-based