Journal of Hydrology 561 (2018) 751–763

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Spatial and temporal variations of thaw layer thickness and its controlling factors identified using time-lapse electrical resistivity tomography and hydro-thermal modeling

Anh Phuong Tran*, Baptiste Dafflon, Gautam Bisht, Susan S. Hubbard

Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, United States

ARTICLE INFO

This manuscript was handled by Emmanouil Anagnostou, Editor-in-Chief, with the assistance of Pierre-Emmanuel Kirstetter, Associate Editor

Keywords:
Electrical resistivity
Permafrost
Thaw layer thickness
Land community model
Arctic
Spatiotemporal variation

ABSTRACT

Quantitative understanding of controls on thaw layer thickness (TLT) dynamics in the Arctic peninsula is essential for predictive understanding of permafrost degradation feedbacks to global warming and hydro-biochemical processes. This study jointly interprets electrical resistivity tomography (ERT) measurements and hydro-thermal numerical simulation results to assess spatiotemporal variations of TLT and to determine its controlling factors in Barrow, Alaska. Time-lapse ERT measurements along a 35-m transect were autonomously collected from 2013 to 2015 and inverted to obtain soil electrical resistivity. Based on several probe-based TLT measurements and co-located soil electrical resistivity, we estimated the electrical resistivity thresholds associated with the boundary between the thaw layer and permafrost using a grid search optimization algorithm. Then, we used the obtained thresholds to derive the TLT from all soil electrical resistivity images. The spatiotemporal analysis of the ERT-derived TLT shows that the TLT at high-centered polygons (HCPs) is smaller than that at low-centered polygons (LCPs), and that both thawing and freezing occur earlier at the HCPs compared to the LCPs. In order to provide a physical explanation for dynamics in the thaw layer, we performed 1-D hydro-thermal simulations using the community land model (CLM). Simulation results showed that air temperature and precipitation jointly govern the temporal variations of TLT, while the topsoil organic content (SOC) and polygon morphology are responsible for its spatial variations. When the topsoil SOC and its thickness increase, TLT decreases. Meanwhile, at LCPs, a thicker snow layer and saturated soil contribute to a thicker TLT and extend the time needed for TLT to freeze and thaw. This research highlights the importance of combination of measurements and numerical modeling to improve our understanding spatiotemporal variations and key controls of TLT in cold regions.

1. Introduction

Thaw layer dynamics and its feedbacks to climate change in permafrost regions are a focus of intensive investigations (e.g., Schuur et al., 2009). Thaw layer dynamics may influence the decomposition of the enormous carbon pool contained in the subsurface, releasing CO_2 and CH_4 to the atmosphere, and therefore, potentially increasing global warming. Thaw layer thickness (TLT) also influences the groundwater direction, surface topography and ecological landscape in the permafrost regions (e.g., Turetsky et al., 2002; Hinzman et al., 2005) as well as the groundwater storage capacity. In turn, the changes in topography and landscape affect the partitioning of precipitation into runoff and infiltration (e.g., Kane et al., 2008). As a result, it is crucial to quantitatively characterize the thaw layer and its controlling factors to increase our predictive understanding of permafrost system behavior.

Thaw layer dynamics can be explored using numerical simulations or field investigations. Numerical approach considers near-surface atmospheric forcing (e.g., air temperature, precipitation, radiation, wind speed, humidity, and air pressure), vegetation characteristics and soil properties (e.g., porosity, water retention curve, hydraulic conductivity, thermal conductivity, and heat capacity) to simulate the surface-subsurface hydro-thermal processes and thaw layer spatiotemporal variability, often in high resolution. Development of these models is often challenging due to the complexity of hydro-thermal processes that need to be included, such as radiation exchange, evapotranspiration, root water uptake, and snowmelt, as well as water phase transition and its associated landscape deformation (Painter et al., 2013). In addition, the common lack of model input data (e.g., vegetation, soil properties, and bedrock location) and system states (e.g., liquid/ice content, soil temperature, and groundwater table) inhibits calibration and validation of these models.

* Corresponding author.
E-mail address: aptran@lbl.gov (A.P. Tran).

https://doi.org/10.1016/j.jhydrol.2018.04.028
Received 3 October 2017; Received in revised form 3 April 2018; Accepted 8 April 2018
Available online 21 April 2018
0022-1694/ Published by Elsevier B.V.

Combining hydro-thermal modeling with multi-scale observations can lead to improved understanding of the thaw layer dynamics and its drivers. Thaw layer dynamics can be characterized using a range of field-based techniques. Traditional techniques include mechanical probing, vertical soil temperature measurements and visual observations (e.g., Brown et al., 2000). While these traditional techniques provide the relatively accurate measurements of TLT, they are labor – intensive and often do not provide dense spatiotemporal information. Several noninvasive geophysical techniques have demonstrated utility for TLT estimation. For example, Arcone et al. (1998); Hinkel et al. (2001); Jørgensen and Andreasen (2007) and Léger et al. (2017) employed ground-penetrating radar (GPR) to characterize the thaw layer. Schaefer et al. (2015) used Interferometric Synthetic Aperture Radar (InSAR) to estimate the thaw depth at Barrow. You et al. (2013) employed electrical resistivity tomography (ERT), ground temperature monitoring, frost table probing and coring to detect the permafrost depth. Hubbard et al. (2013) combined Lidar data with multiple geophysical (ERT, GPR, electromagnetic) and point measurements to characterize the thaw layer and permafrost variability over a large area. However, the time span of most of these studies were limited, taking place from few measurements to one growing season. There is a lack of data tracking the spatiotemporal variations of TLT over the course of a year, or many years. There have been only few studies that cover several years. For example, Hilbich et al. (2008) used ERT and temperature observations in seven years to explore the long-term and short-term variations of the freezing/thawing process in alpine permafrost and its links to the atmospheric temperature. Dafflon et al. (2017) used one-year multiple datasets obtained from autonomous above- and below-ground measurements, including ERT, to monitor the annual cycle of freezing/thaw dynamics (winter – growing season – freezing) and its link to surface processes.

Besides monitoring TLT, identifying the factors that control TLT dynamics is important as well. Hubbard et al. (2013) found that TLT co-varied with several parameters, including vegetation, soil physical properties, soil water content, polygon morphology and seasonal temperature. Hinzman et al. (1991) and Tran et al. (2017) identified soil organic carbon (SOC) as a main factor that governs the hydro-thermal and thaw layer dynamics in the Alaskan Arctic. Nelson et al. (1998) stated that topography, via near-surface hydrology, is closely linked to the variations of TLT. Wright et al. (2009) reported that the spatial pattern of TLT strongly correlates with the soil moisture distribution, and found that its temporal variations are influenced by air temperature and precipitation. Hinkel and Nelson (2003) analyzed data collected at seven circumpolar active layer monitoring (CALM) sites in northern Alaska during the 1995–2000 period and found that the annual maximum thaw depth is controlled by air temperature. Meanwhile, its spatial variations depend on vegetation, substrate properties, snow cover and soil surface topography. Blok et al. (2010) observed that the shrub expansion in the Arctic region may increase soil temperature and TLT. McClymont et al. (2013) showed that soil temperature in winter in the peat plateau is considerably lower than that in the bog. Dafflon et al. (2017) showed that subsurface soil moisture and thaw depth in the Arctic tundra exhibit a strong correlation with the vegetation greenness. Using numerical simulations, Nicolsky et al. (2007) showed that inclusion of surface SOC in the land surface model could improve the TLT estimation. In a study at Barrow, Alaska, Atchley et al. (2016) performed a sensitivity analysis and found that TLT is the most sensitive to top organic layer thickness and snow depth, but relatively insensitive to water saturation.

The above studies indicate the need to simultaneously investigate the spatiotemporal variations of TLT and identify the factors that control these variations in permafrost regions. Our study addressed this requirement using the following model-data integration approach. We first estimated TLT variations in time and space using time-lapse subsurface electrical resistivity images, which were obtained by inversion of ERT measurements in an ice wedge polygon dominated tundra in Barrow, Alaska. Secondly, we used the probe-based TLT measurements and co-located soil electrical resistivity to determine the electrical resistivity thresholds that separate the thaw layer from the permafrost layer using the grid search optimization algorithm. Then, these thresholds were used to derive TLT from soil electrical resistivity images over a period from 2013 to 2015. Next, we analyzed the annual and multiannual variations of the soil electrical resistivity and TLT. Finally, we performed numerical hydro-thermal simulations to explore TLT dynamics and to investigate the factors that govern these dynamics, including soil properties, morphology and atmospheric forcing. Compared to previous studies, this study advances the knowledge of how to use long-term measurements to provide a more comprehensive picture of the spatiotemporal variability of TLT and its controlling factors. In addition, the joint interpretation of measurements and numerical modeling provides new insights and decreased uncertainty about the controls of TLT dynamics.

2. Description of study site and data availability

Our study site is associated with the Department of Energy's Next-Generation Ecosystem Experiment (NGEE) Arctic project and is situated at the Barrow Environmental Observatory in Alaska (Fig. 1). The NGEE site is characterized by ice-wedge polygons, which include low-centered polygon (LCP), flat-centered polygon (FCP) and high-centered polygon (HCP) morphologic features (Hubbard et al., 2013). The polygon morphology largely controls the spatial distribution of snow thickness (Wainwright et al., 2017) and TLT (e.g., Gangodagamage et al., 2014). In the summer season, while the centers of the LCPs are

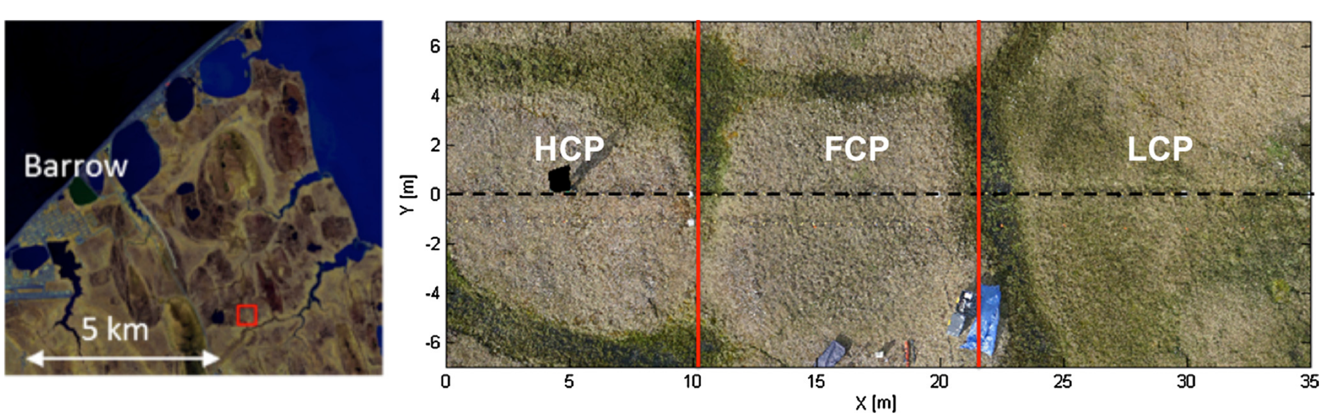

Fig. 1. (Left panel) Location of the study site (red square) near Barrow, Alaska, USA. (Right panel) Aerial view of the ERT transect (dashed line), which traverses a high-centered polygon (HCP, $0 < X < 10$ m), a flat-centered polygon (FCP, $10 < X < 22$ m) and a low-centered polygon (LCP, $22 < X < 35$ m). The red lines separate these three polygons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)