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Identifying permafrost slope disturbance using multi-temporal optical satellite images and change detection techniques

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A B S T R A C T

Active layer detachments (ALDs) are a common form of permafrost slope disturbance that pose a serious risk for infrastructure and can impact environmental and ecological stability in Arctic regions. Effective recognition and detection of slope disturbances are critical for future hazard analysis. Historically, this has primarily been done through manual image interpretation and field mapping, both of which are cost-intensive. Semi-automatic detection techniques have been successfully applied in more temperate regions to identify slope failures, however, little work has been done to map permafrost disturbances. In this paper we present a methodology to detect and map ALDs using multi-temporal IKONOS satellite imagery in combination with vegetation index differencing and object-based image analysis, to semiautomatically identify landscape change associated with ALDs. A normalized difference vegetation index (NDVI) was computed for each of the two dates (2004 and 2010) and then subtracted generating a NDVI difference surface. Using areas where vegetation was removed as a proxy for the presence of ALDs, a multi-resolution segmentation algorithm was used to threshold the NDVI difference map into objects to demarcate regions of similarity (i.e., potential ALDs). To discriminate between disturbed and undisturbed zones a NDVI threshold was applied removing false positives. The thresholded image was then verified with a disturbance inventory collected from the field. These methods were successfully applied to the study area achieving 43% detection accuracy when identifying all ALDs. Morphometric characteristics were used to separate ALDs into two forms, elongate and compact, with accuracies assessed for each. Elongate ALDs, with a detection accuracy of 67%, are typically more destructive, moving substantially more material downslope over longer distances and posing a greater risk for infrastructure. By contrast, compact ALDs are associated with minimal downslope sliding distances (<1 m to several meters) and result in little to no extension in the scar zone and thus limited downslope material movement. The method used in this study detected only 7% of compact disturbances indicating that morphology and size are important variables when detecting ALDs. These results collectively show promise for the semi-automated detection of slope disturbances (i.e., elongate ALDs) in permafrost settings and a cost-effective method to delineate areas for more detailed hazard assessment methods.

1. Introduction

Permafrost related hazards are of growing concern in Arctic regions where the effects of climate change are rapidly resulting in unstable landscapes (ACIA, 2005; Nelson et al., 2002). Thawing of near surface ground ice on slopes can lead to instabilities in the substrate, resulting in exposures of ice bodies and/or ice-rich sediments that generate rapid mass movements such as active layer detachments (ALDs) (Lewkowicz, 1992). Permafrost slope disturbances have been documented across the Arctic (Lamoureux and Lafrenière, 2009; Lantz and Kokelj, 2008; Lewkowicz and Harris, 2005) and constitute a hazard for infrastructure and a source of environmental degradation. Knowledge of landslide distribution and geological associations are an important first step in hazard and risk assessment. Mapping permafrost-related hazards is labor and cost intensive due to the vast size and remoteness of many Arctic regions. Visual interpretation of remote sensing data is time consuming and thus not an optimal method, and while automatic and semi-automatic detection techniques have been applied in more temperate regions to identify landslides (Barlow et al., 2006; Lu et al., 2011; Martha et al., 2010; Nichol and Wong, 2005), little work has been done in cold regions to automatically map permafrost disturbances.

When dealing with any form of mass movement, effective hazard and risk management begins with comprehensive detection and mapping, providing insight into their spatial and temporal occurrence (Carrara and Merenda, 1976; Guzzetti et al., 2000). Until recently, most hazard inventory mapping was completed manually by combining field investigations with visual interpretation of aerial photographs or satellite imagery (Kaab, 2008; vanWesten and Getahun, 2003). Many researchers have used satellite imagery and various detection strategies with mixed success. Pixel based change detection methods using digital number (DN) values (McDermid and Franklin, 1994; Nichol and Wong, 2005) have been moderately successful but are limited in that DN alone

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will not characterize the entirety of the landslide. Contextual analysis techniques applied by Barlow et al. (2006) achieved good detection accuracy but only considered very large landslides (>10,000 m^2). Martha et al. (2012) increased the accuracy of these detection techniques through the utilization of expert knowledge and object-oriented analysis; however, the methods have not been applied to permafrost-related settings.

The main objective of this study was to identify permafrost disturbances, specifically ALDs, using IKONOS satellite imagery and a combination of semi-automatic change detection techniques including image differencing and object-oriented analysis. ALDs are a common form of permafrost disturbance that represent translational landslides of soil, vegetation, and other surface materials in the seasonally thawed or thawing active layer. This study is based on an area of recent and well-documented ALD activity in the Canadian High Arctic where ground-based field mapping of disturbances was conducted. During the summers of 2007/8, higher than normal air temperatures and several major July rainfall events resulted in extensive slope failures throughout the study area at Cape Bounty, Melville Island, Nunavut (Lamoureux and Lafrenière, 2009). The ALDs that formed at Cape Bounty have a mean area of 2000 m^2 and varied considerably in morphology.

The removal of vegetation within disturbances results in spectrally different zones and is best represented in terms of spectral indices, specifically, the normalized difference vegetation index (NDVI). Using areas devoid of vegetation as a proxy for the presence of ALDs, NDVI differencing and object-based methods were used to detect change associated with ALDs. Further research objectives included examining the influence of disturbance size and morphology on the accuracy of automatic change detection analysis to represent the potential for applying this method to areas without prior ground-based mapping of disturbance.

2. Study area

This study was carried out at Cape Bounty, located on the south-central coast of Melville Island, Nunavut (74°55′ N, 109°35′ W) (Fig. 1). Cape Bounty is the location of multidisciplinary research focused on aquatic and terrestrial systems operating within paired High Arctic watersheds (East and West watersheds, unofficial names). Water, sediment, carbon, nutrient, and contaminant fluxes have been integrated with studies of soil biogeochemical, vegetation, and trace gas processes. Many of these processes have been monitored since 2003 as a part of the overall Cape Bounty Arctic Watershed Observatory (CBAWO).

Bedrock in this region is composed of upper Devonian sandstone and siltstone of the Weatherall, Griper Bay, and Hecla Bay formations (Hodgson et al., 1984). Glacial and early Holocene marine sediments drape the region resulting in a landscape characterized by incised low elevation plateaus and gentle hills (Hodgson et al., 1984). The region is underlain by continuous permafrost and forms an active layer that is 0.5–1 m deep by late summer. Vegetation cover is organized into three categories largely based on moisture regimes and includes: polar semi-desert, mesic tundra, and wet sedge (Gregory, 2011).

Extensive slope failures were observed at Cape Bounty during the summers of 2007/8. Substantially higher than normal air temperatures and intense precipitation resulted in a thickening of the active layer which destabilized slopes and resulted in ALDs (Lamoureux and Lafrenière, 2009). These ALDs were subsequently documented and mapped annually on foot using a handheld GPS

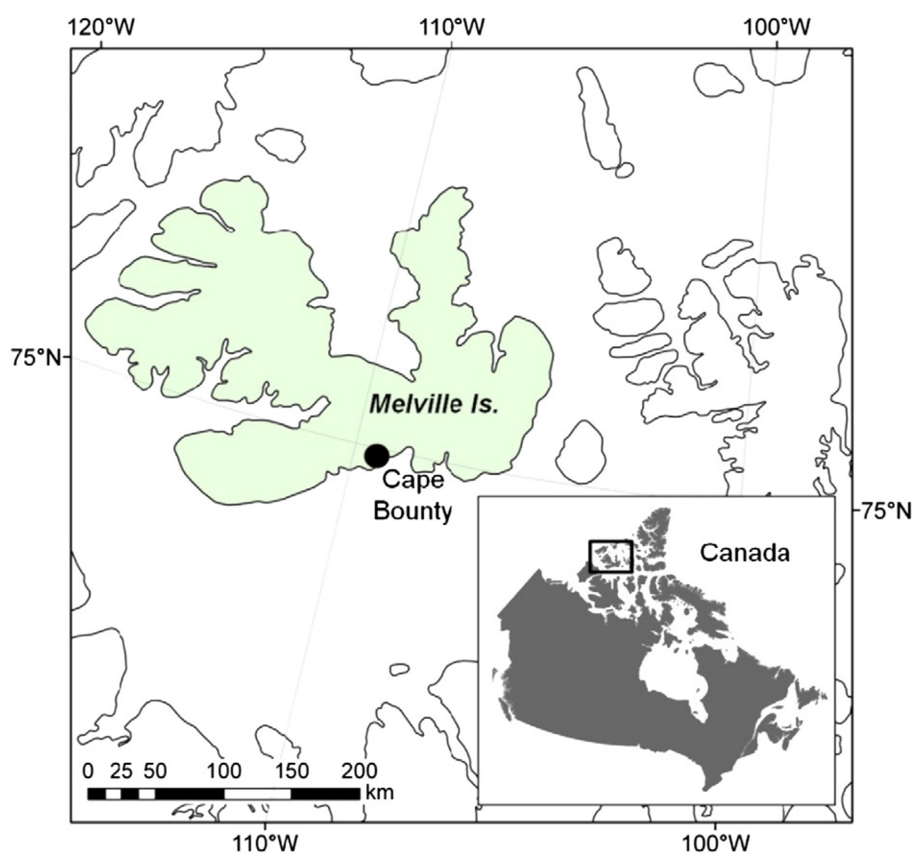

Fig. 1. Map of study area.