Geomorphology 323 (2018) 80–97

Contents lists available at ScienceDirect

Geomorphology

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

Decadal topographic change in the McMurdo Dry Valleys of Antarctica: Thermokarst subsidence, glacier thinning, and transfer of water storage from the cryosphere to the hydrosphere

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ARTICLE INFO

Article history:
Received 29 May 2018
Received in revised form 9 September 2018
Accepted 10 September 2018
Available online 13 September 2018

Keywords:
Antarctic
Permafrost
Glaciers
Lidar

ABSTRACT

Recent local-scale observations of glaciers, streams, and soil surfaces in the McMurdo Dry Valleys of Antarctica (MDV) have documented evidence for rapid ice loss, glacial thinning, and ground surface subsidence associated with melting of ground ice. To evaluate the extent, magnitude, and location of decadal-scale landscape change in the MDV, we collected airborne lidar elevation data in 2014–2015 and compared these data to a 2001–2002 airborne lidar campaign. This regional assessment of elevation change spans the recent acceleration of warming and melting observed by long-term meteorological and ecosystem response experiments, allowing us to assess the response of MDV surfaces to warming and potential thawing feedbacks. We find that locations of thermokarst subsidence are strongly associated with the presence of excess ground ice and with proximity to surface or shallow subsurface (active layer) water. Subsidence occurs across soil types and landforms, in low-lying, low-slope areas with impeded drainage and also high on steep valley walls. Glacier thinning is widespread and is associated with the growth of fine-scale roughness. Pond levels are rising in most closed-basin lakes in the MDV, across all microclimate zones. These observations highlight the continued importance of insolation-driven melting in the MDV. The regional melt pattern is consistent with an overall transition of water storage from the local cryosphere (glaciers, permafrost) to the hydrosphere (closed basin lakes and ponds as well as the Ross Sea). We interpret this regional melting pattern to reflect a transition to Arctic and alpine-style, hydrologically mediated permafrost and glacial melt.

1. Introduction

Changes to Earth's terrestrial cryosphere (glaciers, snow, permafrost, and ground ice) can rapidly reorganize landscapes, leading to changes in energy balance, runoff, and ecosystem functioning. These perturbations to topography drive further changes in glacial and ground ice stability, generating positive feedbacks in frozen landscapes. For example, lidar and topographic studies of glacier surfaces in Arctic and alpine regions have shown that ablation can drive sediment mobilization and enhance melting (Irvine-Fynn et al., 2011), roughening of supraglacial channels can lead to enhanced melting (Rippin et al., 2015), and steepening of exposed glacier surfaces can enhance ablation and melt at low sun angles (Mölg, 2004). Hydrological and sediment mobilization feedbacks are thought to be disintegrating the terminal regions of several Antarctic glaciers (Fountain et al., 2014).

Such positive melting feedbacks are also associated with permafrost degradation, where changes in drainage, the geometry of thermokarst ponds, channel stability, and active layer thermal properties can rapidly alter the distribution of soils, ice, and carbon (Jorgenson et al., 2006; Gooseff et al., 2011; Arp et al., 2015; Kanevskiy et al., 2016; Levy and Schmidt, 2016; Strauss et al., 2016). Hydrologically mediated melting of ground ice has led to thermokarst subsidence over broad study areas containing continuous permafrost. For example, ~35% of tussock tundra sites in the Eight Mile Lake, a research watershed in Alaska, have experienced water-mediated subsurface thaw and subsidence (Belshe et al., 2013) similar to widespread thawing impacts at permafrost research sites in Siberia (Czudek and Demek, 1970).

In the Arctic, mechanisms driving permafrost degradation are well-understood and include i) surface warming caused by warmer air

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https://doi.org/10.1016/j.geomorph.2018.09.012
0169-555X/© 2018 Published by Elsevier B.V.

temperatures, ii) reduction in albedo and ponding of surface waters, which is most pronounced in glacial drifts and eolian soils (Farquharson et al., 2016), and iii) land cover disturbance (e.g., Shur and Jorgenson, 2007). The magnitude and pattern of thermokarst subsidence is strongly controlled by where ground ice is abundant and subject to melt (cryolithology) (French and Shur, 2010). In addition, enhanced thermokarst erosion occurs in lower-slope watersheds where ponding occurs, implying surface slope may play a controlling role in subsidence (Farquharson et al., 2016). Finally, landscape age plays a key role in the distribution of Arctic thermokarst-enhanced thermokarst reworking is most prevalent on older landscapes (Jorgenson and Shur, 2007). Surface- and groundwater mediated permafrost thaw are hypothesized to now be occurring in the ice-free polar deserts of Antarctica (Schmidt and Levy, 2017).

In contrast to rapidly changing Arctic and alpine cryosphere landscapes, Antarctica's largest ice-sheet-free region, the McMurdo Dry Valleys (MDV) (Fig. 1), has been mostly shielded from abrupt change due continually cool, and in cases cooling, air temperatures during the 1990s to early 2000s (Doran et al., 2002a; Shindell and Schmidt, 2004). Counterintuitively, during this period, solar radiation had been increasing significantly (Fountain et al., 2014; Obryk et al., 2018). A notable summer thaw in 2001–2002 coincided with a pivot in the cooling/brightening climate trajectory; since 2002, summer air temperatures and elevated solar flux (Fig. 2) have remained largely constant, leading

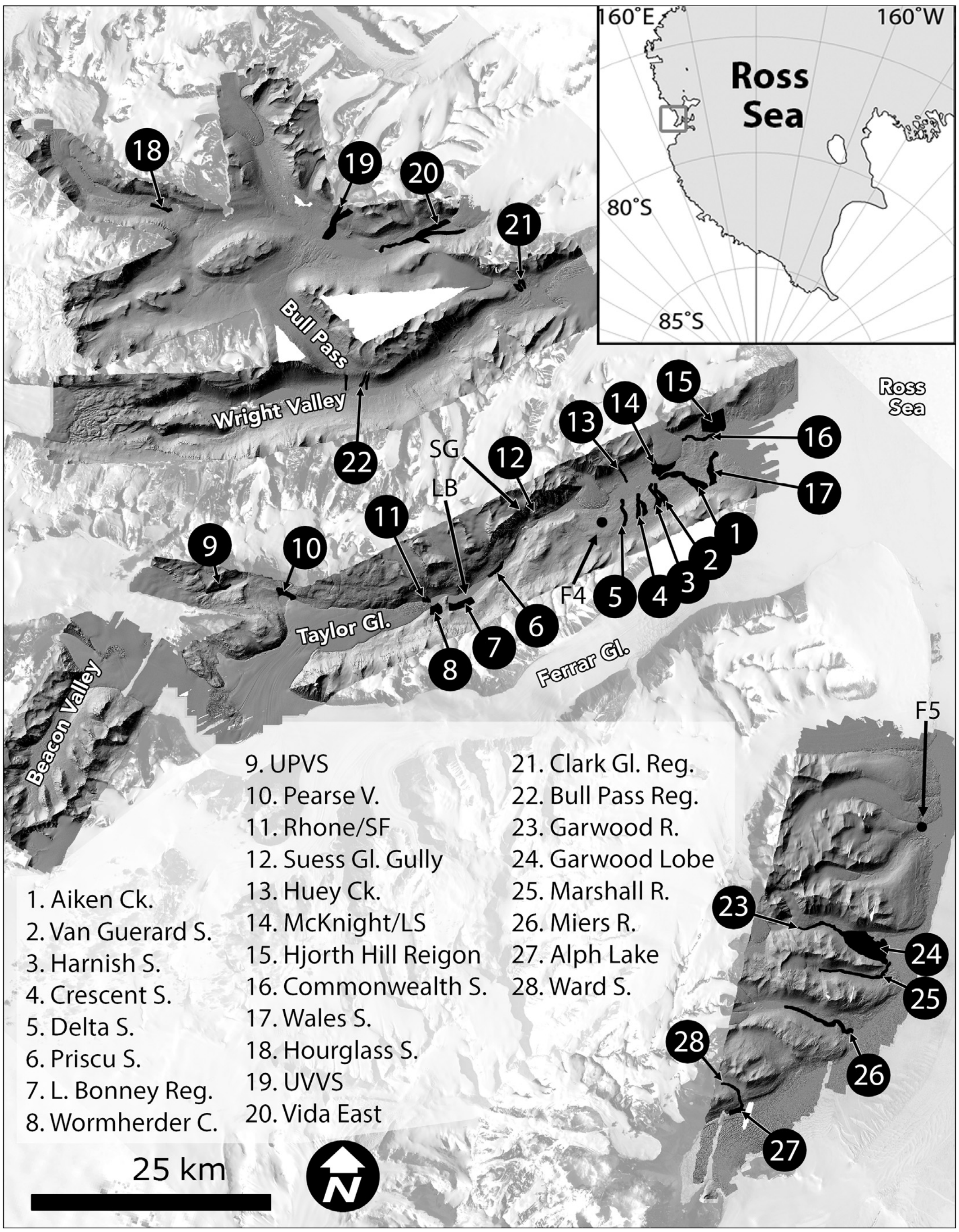

Fig. 1. Context map and hillshade of the lidar data set over Landsat Image Mosaic of Antarctica (LIMA) data. Features of interest for the erosion/volume-change analyses are highlighted in black. Note, feature area has been exaggerated one pixel to enhance visibility. Feature area and GIS shapefiles are available as supplementary files. Dot marked F5 indicates the location of Fig. 6. Dot marked F4 indicates the location of soil roughness analyses shown in Fig. 5. LB indicates Lake Bonney. SG indicates Seuss Glacier.