AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL069688

Key Points:
- The first inventory of wastes in the Greenland ice sheet at the abandoned military base Camp Century
- Regional climate modeling suggests that these wastes can no longer be considered “preserved for eternity”
- The potential remobilization of wastes previously deemed sequestered represents a new pathway to political dispute due to climate change

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Citation:
Colgan, W., H. Machguth, M. MacFerrin, J. D. Colgan, D. van As, and J. A. MacGregor (2016), The abandoned ice sheet base at Camp Century, Greenland, in a warming climate, *Geophys. Res. Lett.*, *43*, 8091–8096, doi:10.1002/2016GL069688.

Received 27 MAY 2016
Accepted 6 JUL 2016
Published online 4 AUG 2016

The abandoned ice sheet base at Camp Century, Greenland, in a warming climate

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Abstract In 1959 the U.S. Army Corps of Engineers built Camp Century beneath the surface of the northwestern Greenland Ice Sheet. There they studied the feasibility of deploying ballistic missiles within the ice sheet. The base and its wastes were abandoned with minimal decommissioning in 1967, under the assumption they would be preserved for eternity by perpetually accumulating snowfall. Here we show that a transition in ice sheet surface mass balance at Camp Century from net accumulation to net ablation is plausible within the next 75 years, under a business-as-usual anthropogenic emissions scenario (Representative Concentration Pathway 8.5). Net ablation would guarantee the eventual remobilization of physical, chemical, biological, and radiological wastes abandoned at the site. While Camp Century and four other contemporaneous ice sheet bases were legally established under a Danish-U.S. treaty, the potential remobilization of their abandoned wastes, previously regarded as sequestered, represents an entirely new pathway of political dispute resulting from climate change.

1. Historic and Climatic Context

The advent of long-range aircraft capable of deploying nuclear bombs drew military attention to the Arctic, the shortest route between the U.S. and USSR, during the Cold War. In April 1951, the U.S. and Denmark signed the Defense of Greenland Agreement. Three air bases, including Thule Air Base (AB) in northwestern Greenland, opened later that same year. In 1959, after several years of intensive ice sheet research, the U.S. Army Corps of Engineers (USACE) built Camp Century 204 km east of Thule Air Base on the main divide of the Greenland Ice Sheet (GrIS) [*Clark*, 1965]. Camp Century was excavated at 8 m depth in the ice sheet’s porous near-surface firn using a cut-and-cover trenching technique (Figures 1 and S1 in the supporting information) [*Abele*, 1964]. The subsurface base provided year-round accommodation for between 85 and 200 soldiers, was powered by a portable nuclear generator, and logistically supported by pulling supplies across an over-snow trail from Thule AB. At Camp Century the USACE studied the feasibility of Project Iceworm, which sought to deploy ballistic missiles within the ice sheet but was never realized [*Weiss*, 2011].

Because firn deformation is accelerated by the latent heat associated with meltwater, Camp Century was deliberately established in the dry snow zone of the ice sheet, where virtually no surface melting occurs [*Clark*, 1965]. In 1962, following the successful installation of an experimental subsurface railway at Camp Century, the U.S. Army proposed Project Iceworm to U.S. Joint Chiefs of Staff [*Weiss*, 2011]. The project envisioned subsurface railway beneath $1.3 \cdot 10^5$ km^2 of the GrIS to support 600 ballistic missiles. However, Project Iceworm was rejected in 1963 and year-round operations at Camp Century ceased in 1964. Seasonal operations continued until 1967, when the base was abandoned with minimal decommissioning, as engineering design of the era assumed that the base would be “preserved for eternity” by perpetual snowfall [*Clark et al.*, 1962]. The last reported USACE visit to the abandoned Camp Century site was in 1969 [*Kovacs*, 1970]. Aside from the reaction chamber of the portable nuclear generator, which was removed for destructive testing [*Clark*, 1965], all infrastructure remained in the collapsing tunnel network after the 1969 survey.

Since the 1960s, however, the scientific community has recognized the GrIS to be more sensitive to climate forcing than previously thought. The GrIS lost 75 ± 29 Gt a^{-1} of mass between 1900 and 1983, and recent anthropogenic climate change has accelerated this mass loss, especially since circa 1990 [*Kjeldsen et al.*,

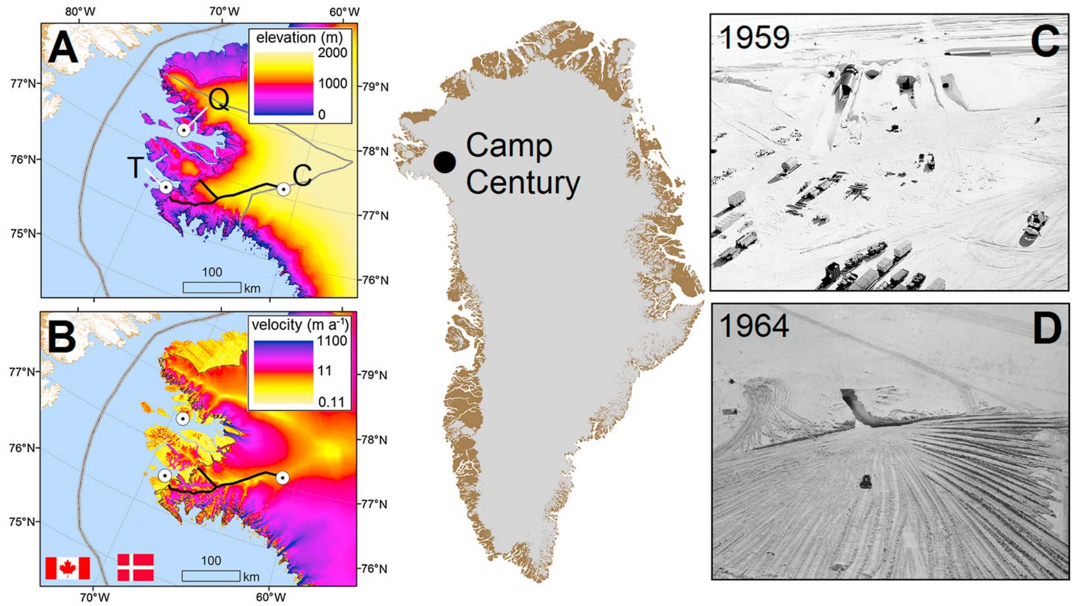

Figure 1. (a) Surface elevation [*Howat et al.*, 2014] and (b) surface velocity [*Joughin et al.*, 2010] in the vicinity of Camp Century ("C"). Thule Air Base ("T"), Qaanaaq ("Q"), and the over-snow trail (black line) shown for context. The grey boundary denotes GrIS Basin 8.2 [*Andersen et al.*, 2015]. The velocity color bar is logarithmic. Both color bars saturate at extreme values. The northeast portal to Camp Century during construction in 1959 (C) and again in 1964 (D; U.S. Government Photos). Inset: The location of Camp Century in Northwest Greenland.

2015]. The ice sheet lost 262 ± 21 Gt a^{-1} between 2007 and 2011, with the majority of this ice loss due to declining surface mass balance (SMB), meaning enhanced melt and runoff, rather than increased iceberg discharge [*Andersen et al.*, 2015]. Ice loss due to recent climate change is readily observable in northwestern Greenland. The ice drainage system downslope of Camp Century ("Basin 8.2") lost 14 ± 2 Gt a^{-1} of ice between 2007 and 2011, and the majority (80%) of this ice loss was due to decreasing SMB [*Andersen et al.*, 2015].

Increasing meltwater production is also having a profound effect on the melt distribution and firn structure of the ice sheet [*Humphrey et al.*, 2012; *Machguth et al.*, 2016]. The ablation zone of the ice sheet, where annual meltwater runoff exceeds snowfall (negative SMB), is expanding in the present-day climate. Given the approximately parabolic profile of the ice sheet surface, upslope migration of the equilibrium line altitude (ELA) results in a nonlinear increase in ablation area. Ascent of the ELA in western Greenland has already doubled the width of the ablation zone there from 1996 to 2012 [*McGrath et al.*, 2013]. At higher elevations, projections suggest that by 2025 there is a 50% chance that the ice sheet will no longer have a dry snow area [*McGrath et al.*, 2013]. In July 2012, 98% of the GrIS surface area was melting during an extreme event [*Nghiem et al.*, 2012]. Over the coming decades, increased surface melting will affect higher ice sheet elevations, where melt previously did not regularly occur.

2. Abandoned Wastes

We first inventory the nature and quantity of abandoned wastes buried at the Camp Century site (supporting information). Physical waste, such as buildings and railway, is approximately $9.2 \cdot 10^3$ t. Chemical waste is an estimated $2.0 \cdot 10^5$ L of diesel fuel and a nontrivial quantity of polychlorinated biphenyls (PCBs). Biological waste consists of at least $2.4 \cdot 10^7$ L of grey water, including sewage, disposed in unlined sumps. Previously acknowledged radiological waste (coolant for the portable nuclear generator) had a bulk radioactivity of $1.2 \cdot 10^9$ Bq at the time of its disposal (1960–1963) in an unlined sump. While nontrivial in absolute terms, this radiological waste is small compared to the $>4.6 \cdot 10^{12}$ Bq accidentally dispersed in the vicinity of Thule AB in 1968 [*Christensen*, 2009].

Persistent organic pollutants (POPs), including PCBs, are one of three broad classes of chemical toxins of global significance [*Noyes et al.*, 2009]. Due to relatively low air temperatures, which favor persistent POP

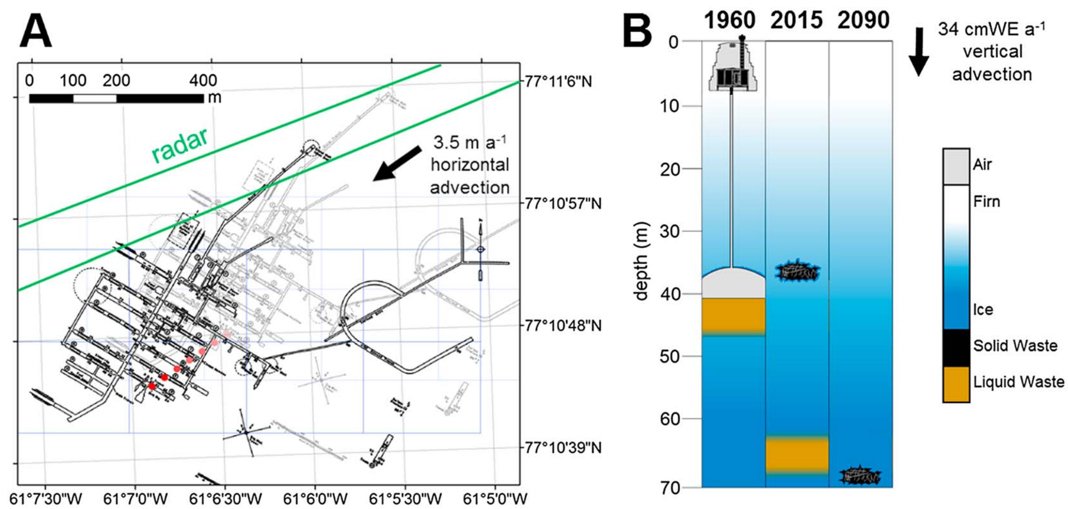

Figure 2. (a) Camp Century "as built" map georeferenced to 1960 (grey) and 2020 (black) locations [*Kovacs*, 1970], based on past surveys of the borehole location and horizontal advection associated with ice flow (Supplementary Methods). The red points denote decadal borehole location from 1960 to 2020. The green lines denote radar profiles shown in Figure 3. (b) Estimated Camp Century solid and refrozen liquid waste depths in 1960, 2015, and 2090, based on vertical advection rates (Figure S3). The horizontal extent of the liquid waste, while large relative to tunnel width, is small relative to camp width.

deposition, the Arctic has so far been a global sink for POPs released at lower latitudes. Glacierized regions are now poised to become a POP source; however, as rapid warming there remobilizes POPs that have been stored in the cryosphere [*Grannas et al.*, 2013; *Sharma et al.*, 2015]. While substantial PCB remediation efforts have been undertaken at the majority of 63 former Distant Early Warning (DEW) bases built along the Arctic Circle in the 1960s [*Poland et al.*, 2001], Camp Century is only one of five abandoned and unremediated ice sheet bases in the vicinity of Thule AB [*Lufkin and Tobiasson*, 1969]. PCBs were well suited for Arctic use in insulating fluids and paints, given their high heat capacity, low flammability, and physical flexibility, and the PCB concentration in some paints used by DEW bases exceeds 5% by weight [*Poland et al.*, 2001]. We therefore speculate that PCBs are the most consequential waste at Camp Century.

We next assess the extent and depth of these abandoned wastes. The Camp Century tunnel network covers an area of 1.1×0.5 km (55 ha; Figure 2). Based on modeled vertical advection rates, the majority of solid waste is now likely buried at approximately 36 m depth (supporting information). Due to the relatively efficient movement of liquids within permeable firn, the burial depth of refrozen sumps is less certain, but it is unlikely they are now shallower than 65 m depth. A notable exception is diesel fuel, which was stored in rigid tanks at tunnel depth, and may even remain liquid to date, although the tanks have likely ruptured. Independent airborne ice-penetrating radar observations [*Gogineni*, 2012] record strong, anomalous reflections at locations and depths consistent with inferred tunnel positions and modelled waste depths (Figure 3). Unfortunately, these observations alone are insufficient to delineate the extent and depth of all abandoned wastes at Camp Century. Our inferred vertical advection rate profile suggests that solid and liquid wastes will reside at depths of 67 and 93 m, respectively, in 2090.

3. Climatic Projections

We now evaluate GrIS SMB using the regional climate model MAR3.5 [*Fettweis et al.*, 2013] to assess whether increased surface melting associated with climate change could remobilize abandoned wastes at Camp Century. We use simulations that are forced by the Canadian Earth System Model version 2 (CanESM2) and Norwegian Earth System Model version 1 (NorESM1) global circulation models, using historical simulations for 1950–2005 and Representative Concentration Pathway (RCP) 8.5 for 2006–2100. The RCP8.5 climate scenario may be regarded as a business-as-usual scenario that assumes little deviation from recent trends in anthropogenic greenhouse gas emissions [*Church et al.*, 2013]. Both simulations, which are calibrated to observed mean SMB during 1950–1999 to correct for systematic biases (supporting information), predict increased surface melting in northwestern Greenland through 2100 (Figure 4). At Camp Century, MAR3.5 forced by NorESM1 projects that increases in snowfall will exceed increases in melt, maintaining consistently

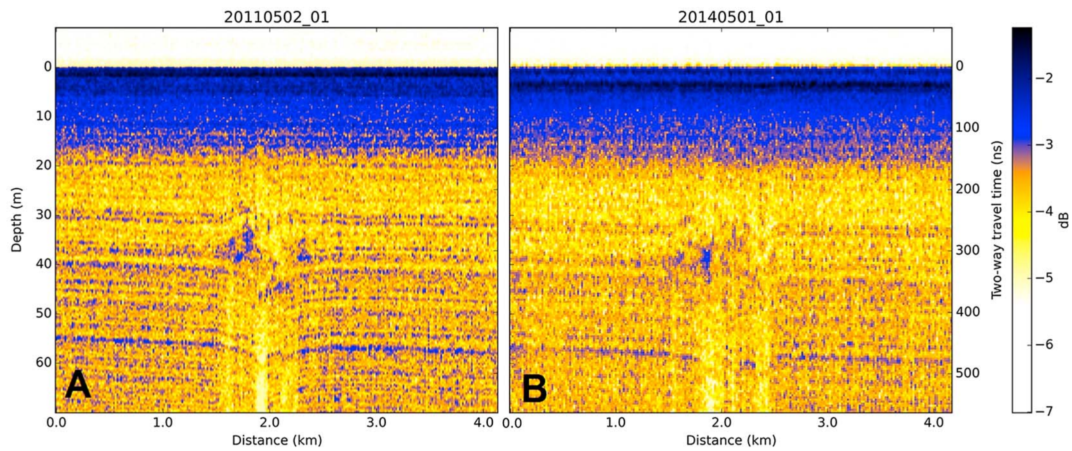

Figure 3. Airborne UHF accumulation radar profiles across Camp Century, acquired (a) 2 May 2011 and (b) 1 May 2014 by NASA Operation IceBridge [*Gogineni*, 2012]. Locations of the radar profiles are shown in Figure 2. Strong, anomalous reflections indicate the presence of buried physical wastes at depths consistent with those predicted for the Camp Century tunnels.

positive SMB (net accumulation) through 2100. Conversely, MAR3.5 forced by CanESM2 projects that increases in surface melt will not be offset by increases in snowfall, resulting in a transition to negative SMB (net ablation) around 2090.

While these two simulations highlight the uncertainty associated with SMB projections at Camp Century, the key result is that at least one such simulation (CanESM2 forced) now suggests that the ELA will migrate inland of Camp Century within the next 75 years under a business-as-usual scenario. Even the NorESM1 forced scenario predicts a substantial inland migration of the ELA, and thus should not be interpreted as suggesting net accumulation (positive SMB) in perpetuity (Figure S2). As the NorESM1 and CanESM2 forced scenarios have systematic biases of +179 and −49 mmWE a^{-1} relative to the 50 year mean observed SMB, the CanESM2 forced

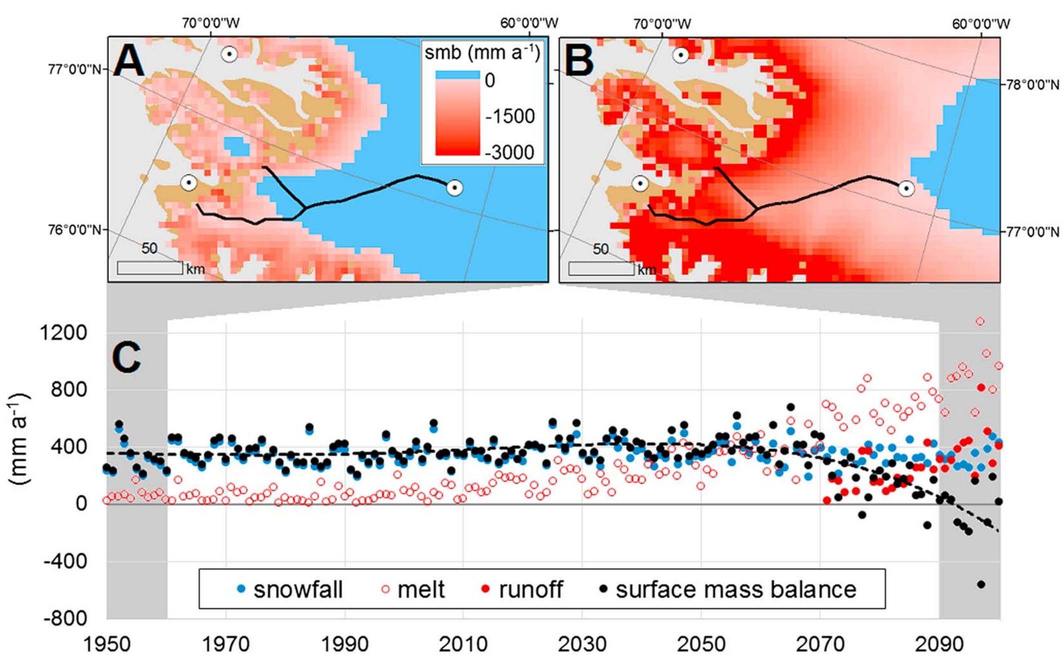

Figure 4. (a) Surface mass balance in Northwest Greenland during the 1950s (1950–1959) and (b) 2090s (2090–2099) as simulated by MAR v3.5 forced by CanESM2 under RCP8.5 [*Fettweis et al.*, 2013]. The color bars saturate at minimum and maximum values. The blue shading denotes the accumulation area where surface mass balance is positive. (c) Surface mass balance, and its components, at Camp Century during 1950–2100 as simulated by MARv3.5 and forced by CanESM2. The dashed line denotes polynomial trend. The NorESM1 simulation is shown in Figure S2.

historical simulation appears to represent recent SMB at Camp Century more accurately than the NorESM1 forced historical simulation. A transition to net ablation at Camp Century would make the eventual coastward remobilization of abandoned wastes inevitable by either surface exposure of abandoned wastes via persistent ablation of overlying firn and ice or subsurface hydrology via meltwater percolation through overlying firn.

Given an anticipated 2090 solid waste depth of 67 m (44 m water equivalent, WE), 88 years of persistent 0.5 mmWE a^{-1} ablation (or 44 years at 1.0 mWE a^{-1}) would be required to melt all overlying firn and expose wastes at the ice sheet surface. However, meltwater can interact with deep firn more rapidly via vertical percolation. Observations indicate that surface meltwater can percolate downward 10 m through firn in a single summer melt season [*Humphrey et al.*, 2012]. Liquid meltwater can also persist year-round within GrIS firn, forming an active englacial aquifer that saturates pore space below 20 m depth [*Forster et al.*, 2014]. PCBs could therefore be remobilized from Camp Century by englacial water flow decades before surface runoff is observed at the site [*Pavlova et al.*, 2015]. Such hydrologic remobilization, primarily via dispersion, and subsequent englacial flow would transport these toxins down hydraulic gradient from Camp Century, deeper into the ice, before eventually reaching proglacial regions [*Sharma et al.*, 2015].

4. Political Context

The general existence of Camp Century was understood by both the Danish and U.S. governments, which together signed the 1951 Defense of Greenland Agreement under the auspices of the North Atlantic Treaty Organization (NATO) [*Petersen*, 2008]. USACE reports acknowledge the presence of Danish liaisons involved in the planning and environmental monitoring of Camp Century. These reports, for example, suggest Danish permission for the operational disposal of $1.9 \cdot 10^9$ Bq of radiological waste in the ice sheet [*Nicoll et al.*, 1962; *Clark*, 1965]. However, it is unclear whether Denmark was sufficiently consulted regarding the specific decommissioning of Camp Century, and thus whether the abandoned wastes there remain U.S. property. Article XI of the 1951 treaty states that "All property provided by the Government of the United States of America and located in Greenland shall remain the property of the Government of the United States of America. … [it] may be removed from Greenland free of any restriction, or disposed of in Greenland by the Government of the United States of America *after consultation with the Danish authorities*…" (emphasis added). Given the multinational origin and multigenerational legacy of Camp Century, there appears to be substantial ambiguity surrounding the political and legal liability associated with mitigating the potential remobilization of its pollutants. Interests likely differ across NATO members, particularly Denmark, the U.S. and Canada, partly because of their distinct levels of historical participation and their future potential for pollutant exposure.

Our study highlights that Camp Century now possesses unanticipated political significance in light of anthropogenic climate change. The potential remobilization of wastes that were previously regarded as properly sequestered, or preserved for eternity [*Clark et al.*, 1962], is an instance, possibly the first, of a potentially new pathway to political dispute associated with climate change. Several such pathways have already been identified, including disputes over emissions reductions [*Victor*, 2011], changing agricultural patterns [*Raleigh et al.*, 2014], forced migration [*Barnett and Adger*, 2007], and newly accessible Arctic resources [*Borgerson*, 2008]. While we have focused on cryospheric change in the Arctic, the effects of climate change are multifaceted and far-reaching. Sea level rise, for example, is now poised to remobilize hazardous wastes at low-lying decommissioned sites, civilian and military alike [*Flynn et al.*, 1984; *Gerrard*, 2015]. Climate change is thus likely to amplify political disputes associated with abandoned wastes in a variety of settings. In this context, the shifting fate of abandoned ice sheet military bases under climate change may provide a microcosm through which to examine the multinational and multigenerational challenges presented by climate change.

Acknowledgments
W.C. conceived of the study. H.M. contributed to all sections of the study. M.M., D.V., and J.M. contributed to sections 2 and 3. J.C. contributed to sections 1 and 4. We thank the Libraries of University of Colorado Boulder for making several rare hardcopy USACE documents available for this work, through their diligent maintenance of a Federal Depository Library and their skilled navigation of the Inter-Library Loan system. The political implications described here do not constitute institutional endorsement of these views by either the Geological Survey of Denmark and Greenland or NASA. The MARv3.5 climate projections used in this study are available at ftp://ftp.climato.be/fettweis/MARv3.5/Greenland. The NASA airborne radar data used in this study are available at http://nsidc.org/data/icebridge. The MEaSUREs surface ice velocity data used in this study are available at http://nsidc.org/data/nsidc-0478. The Greenland Ice Mapping Project digital elevation model used in this study is available at http://nsidc.org/data/nsidc-0645.

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