New programme for climate monitoring at Camp Century, Greenland

William Colgan, Signe B. Andersen, Dirk van As, Jason E. Box and Søren Gregersen

Camp Century was a military base constructed by the US Army Corps of Engineers (USACE) in 1959 in the near-surface layers of the Greenland ice sheet at 77.13°N and 61.03°W and 1910 metres above sea level (Clark 1965). The *c.* 55 ha base housed between 85 and 200 soldiers and was continuously occupied until 1964 (Fig.1). Camp Century primarily served as an experimental facility for the USACE to test ice-sheet construction concepts. Recent Danish scholarship has documented the political and military history of Camp Century in substantial detail (Petersen 2007; Nielsen & Nielsen 2016). To summarise, Project Iceworm, the US Army ambition to deploy offensive missiles within the ice sheet, was never realised. After three years of seasonal operation, Camp Century was finally abandoned with minimal decommissioning in 1967. The Government of Denmark has now established a GEUS-led programme for long-term climate monitoring, as well as one-time waste mapping, at Camp Century. Here, we briefly review the historical scientific activities at Camp Century and introduce the future goals of the Camp Century Climate Monitoring Programme. Finally, we discuss the challenges and outlook of climate monitoring and waste mapping at the former military site.

Scientific heritage

The USACE conducted extensive glaciological and climatological research during the operation of Camp Century (Fig. 2). Much of their glaciological research focused on characterising the strength and density of the relatively porous, near-surface ice-sheet layer known as firn. These projects included measuring the deformational closure rates of near-surface tunnels (Clark 1965), and excavating an inclined tunnel to 100 m depth to measure firn properties (Kovacs *et al.* 1969). Much of their climatological research focused on characterising spatial and temporal variability in snowfall. These projects include extensive surveys of regional snow-accumulation rates (Mock 1968), and maintaining a continuous weather station record from October 1960 to August 1964 that remains unpublished.

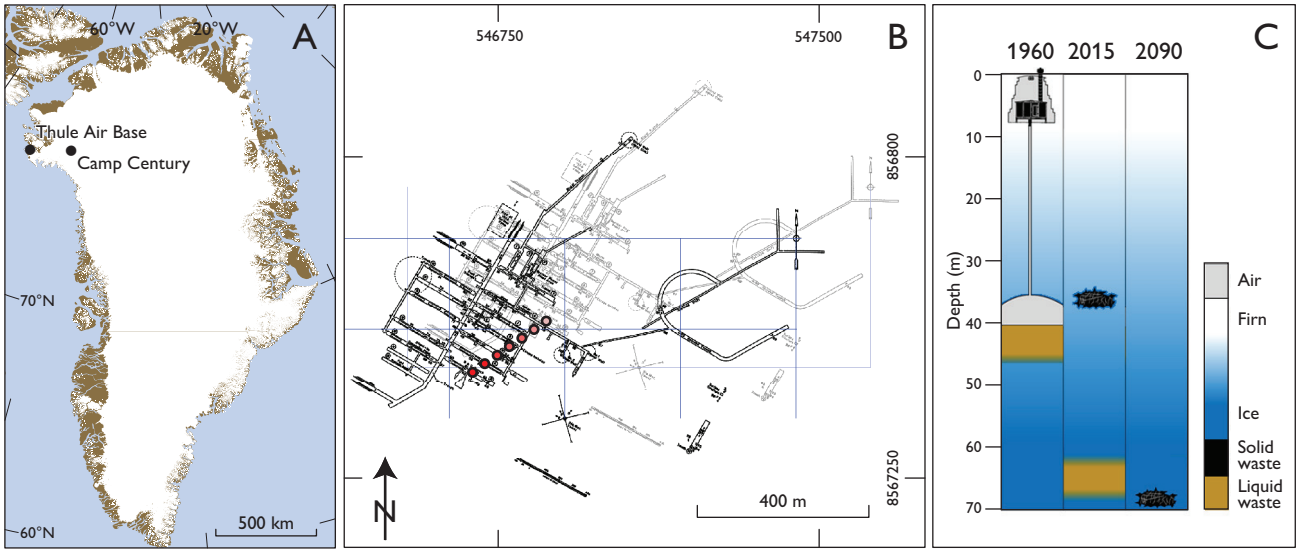

Fig. 1. **A**: Location of Thule Air Base and Camp Century in North-West Greenland. **B**: Camp Century as-built map with estimated georeferencing to 1960 (grey) and 2020 (black) locations in polar stereographic projection (EPSG 3413). Decadal borehole positions from 1960 to 2020 shown in red (Colgan *et al.* 2016). Blue lines denote a local coordinate system. **C**: Estimated depths of solid and refrozen liquid wastes in the firn and ice beneath Camp Century in 1960, 2015 and 2090 (Colgan *et al.* 2016).

Fig. 2. USACE-applied glaciology research at Camp Century. Left: Measuring the deformation of firn in 1961. Right: Measuring the compressive strength of firn in 1964. Photos: Søren Gregersen.

Today, the USACE-facilitated science at Camp Century is perhaps best known for producing the first systematic classification of ice-sheet snow facies (Benson 1962), and recovering the first ice core to the bed of the Greenland ice sheet (Dansgaard *et al.* 1969). Both the data and interpretations from these seminal studies continue to be highly cited today. After the closure of Camp Century, the US Air National Guard continued to use the Camp Century skiway, renaming it the Greenland Ice Sheet Training Site (GITS).

Aside from re-surveying the borehole position in 1977 and 1986 (Gundestrup *et al.* 1987), there appears to have been virtually no data collected at Camp Century between the abandonment of the base in 1967 and the start of NASA Program for Arctic Regional Climate Assessment (PARCA) activities at the site in 1993. PARCA activities included: deploying an automatic weather station in 1995 to record meteorology at the site (Steffen & Box 2001), drilling a 120 m deep ice core in 1996 to reconstruct snow accumulation rates (Mosley-Thompson *et al.* 2001), and measuring *in-situ* firn compaction rates in 1995–1996 (Hamilton & Whillans 2000). In 2010, a 35 m deep ice core was once again recovered at Camp Century, to further update snow accumulation and ice chemistry records since the termination of the USACE ice-core record (Buchardt *et al.* 2012). PARCA began regular airborne measurements of ice-surface elevation at Camp Century in 1993 (Krabill *et al.* 2000), with NASA Operation IceBridge regularly collecting ice-penetrating radar data over the site since 2010 (Leuschen *et al.* 2014). US National Science Foundation traverses from Thule Air Base (AB) to Summit Station, which have approximately followed the USACE trail to Camp Century since 2008, have been used as a science platform to measure accumulation rates (Hawley *et al.* 2014).

Mapping and monitoring

In 2016, GEUS participated in a multi-nation study that presented regional climate model simulations that suggested the ice-sheet surface mass balance at Camp Century may change from net snowfall to net melt by year 2100 under the UN Intergovernmental Panel on Climate Change (IPCC) RCP8.5 'business-as-usual' climate scenario (Colgan *et al.* 2016). However, under the emissions mitigation characterised by the RCP4.5 climate scenario, net snowfall would persist at Camp Century until 2100. While Colgan *et al.* (2016) also provided preliminary estimates of the non-trivial quantities of physical, chemical, biological and radiological wastes presently residing within the firn at Camp Century, at depths of between 35 and 65 m, perhaps the most socially significant outcome of this study was suggesting that the assumption that the abandoned base would be preserved for eternity by perpetually accumulating snowfall was no longer valid under the full range of IPCC climate pathways.

In response to concerns from the Government of Greenland over the potential remobilisation of contaminants from Camp Century within the next century, the Government of Denmark has now established a programme for long-term climate monitoring, as well as one-time waste mapping, at Camp Century. This Camp Century Climate Monitoring Programme will be led by GEUS and has four main goals:

1) To continuously monitor relevant climate variables, including the depth to which meltwater percolates, at the Camp Century site. This goal will be accomplished by installing an automated weather station that measures standard climatological variables controlling meltwater production (Citterio *et al.* 2015). Station measurements will be supplemented

by thermistor strings to monitor deep firn temperatures, as well as observations of firn density and compaction profiles.

2) To regularly update annual likelihoods of meltwater interacting with abandoned materials at the Camp Century site over the next century. This goal will be accomplished by using a physically-based numerical model that couples meltwater percolation and firn evolution (Charalampidis *et al*. 2016). This model will be forced by IPCC climate pathways and continuously improved using *in situ* observations, as well as novel parameterisations from community models.

3) To map the estimated spatial extent and vertical depth of abandoned wastes across the Camp Century site. This goal will be accomplished by using ice-penetrating radar and global positioning system measurements to map the Camp Century debris field during a one-time field campaign (Machguth *et al*. 2016). Delineating the present-day location of key infrastructure features will enable georeferencing of historical site maps.

4) To publicly report all findings from the Camp Century Climate Monitoring Programme in a timely manner. This goal will be accomplished by streaming the data collected by sensors deployed at Camp Century in near-real-time, maintaining an internet outreach presence of the programme, and regularly publishing GEUS reports and papers in open-access, peer-reviewed journals.

The Camp Century Climate Monitoring Programme will undertake initial fieldwork at Camp Century during the summer of 2017, to deploy automated climate and firn sensors and collect ice-penetrating radar and firn-core observations (Fig. 3). Subsequent fieldwork at Camp Century will be undertaken, as needed, to service deployed instrumentation. During subsequent site visits, additional ice-penetrating radar data may potentially be collected in more concentrated areas of the debris field. The analysis of climate measurements, including firn temperatures, as well as numerical modelling of future meltwater percolation depths, will begin during the autumn of 2017, with anticipated first public reporting in the summer of 2018. Near-real-time measurements from Camp Century, as well as programme outreach materials and publications, can be accessed at *www.campcenturyclimate.dk*.

Programme outlook

GEUS has a long tradition of applied glaciology research. Recent applied glaciology work includes operating the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) on behalf of the Government of Denmark (Ahlstrøm *et al*. 2008a), consulting for the Government of Greenland on the hydropower potentials associated with ice-sheet runoff (Ahlstrøm *et al*. 2008b), and a growing involvement in private sector proglacial mining projects (Citterio *et al*. 2009). With unique applied glaciology expertise gained through these and other operations, especially in-house development of robust automated ice-sheet instrumentation and previous dedicated ice-coring and radar-acquisition campaigns, GEUS is well-suited to lead the Camp Century Climate Monitoring Programme. Indeed, GEUS involvement with Camp Century stretches from its operational period, when GEUS emeriti Anker Weidick and Søren Gregersen participated in research at the site, to contributing to the preliminary waste inventory and climate projections of the Camp Century site published last year.

While the fundamental glaciology and climatology research performed by the USACE gives Camp Century an unparalleled scientific heritage amongst Greenland research

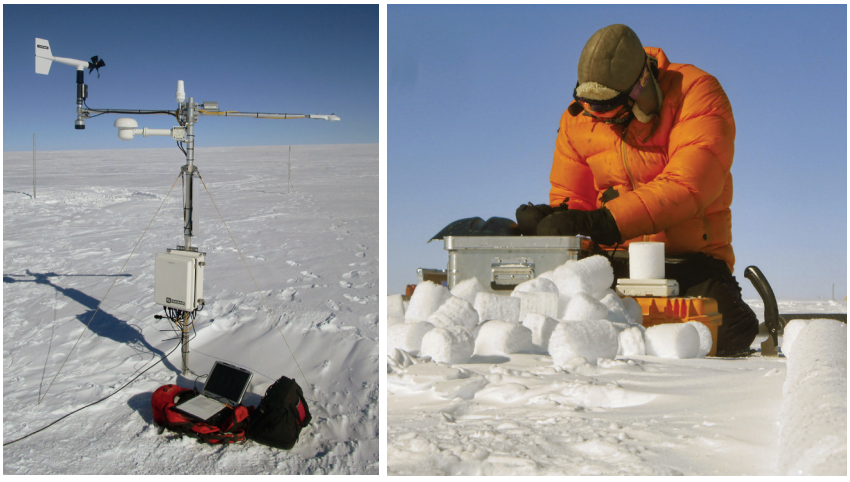

Fig. 3. Left: Servicing a PROMICE automated weather station in the ice-sheet accumulation area in 2016. Right: Measuring firn density from a shallow borehole into which thermistors were installed in 2016. Photos: Baptiste Vandecrux.

sites, the military history of Camp Century gives the site unanticipated social significance in light of climate change. Long-term climate monitoring, and one-time waste surveying, of Camp Century will provide Danish and Greenlandic stakeholders open access to relevant *in-situ* measurements and model projections. Refined knowledge of the spatial and depth distribution of different wastes, as well as the changes in firn structure and meltwater production anticipated under climate change, will facilitate a science-based discussion of the shifting fate of Camp Century. At the broadest level, a better understanding of the implications of climate change on Camp Century will perhaps provide a better understanding of the importance of mitigating greenhouse-gas emissions, and averting, rather than adapting to the consequences of business-as-usual climate change.

Acknowledgements

The Camp Century Climate Monitoring Programme is funded by the Danish Ministry for Energy, Utilities and Climate and by GEUS.

References

Ahlstrøm, A. & the PROMICE Team 2008a: A new programme for monitoring the mass loss of the Greenland ice sheet. Geological Survey of Denmark and Greenland Bulletin **15**, 61–64.

Ahlstrøm, A., Mottram, R., Nielsen, C., Reeh, N. & Andersen, S. 2008b: Evaluation of the future hydropower potential at Paakitsoq, Ilulissat, W. Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2008/37**, 50 pp.

Benson, C. 1962: Stratigraphic studies in the snow and firn of the Greenland ice sheet. Cold Regions Research and Engineering Laboratory. Research Report **70**.

Buchardt, S., Clausen, H., Vinther, B. & Dahl-Jensen, D. 2012: Investigating the past and recent delta18O-accumulation relationship seen in Greenland ice cores. Climate of the Past **8**, 2053–2059.

Charalampidis, C., Van As, D., Colgan, W.T., Fausto, R.S., Macferrin, M. & Machguth, H. 2016: Thermal tracing of retained meltwater in the lower accumulation area of the southwestern Greenland ice sheet. Annals of Glaciology **57**(72) 1–10.

Citterio, M., Mottram, R., Larsen, S. & Ahlstrøm, A. 2009: Glaciological investigations at the Malmbjerg mining prospect, central East Greenland. Geological Survey of Denmark and Greenland Bulletin **17**, 73–76.

Citterio, M., van As, D., Ahlstrøm, A.P., Andersen, M.L., Andersen, S.B., Box, J.E., Charalampidis, C., Colgan, W., Fausto, R.S., Nielsen, S. & Veicherts, M. 2015: Automatic weather stations for basic and applied glaciological research. Geological Survey of Denmark and Greenland Bulletin **33**, 69–72.

Clark, E.F. 1965: Camp Century evolution of concept and history of design, construction and performance. Cold Regions Research and Engineering Laboratory. Technical Report **174**, 69 pp.

Colgan, W., Machguth, H., MacFerrin, M., Colgan, J., van As, D. & MacGregor, J. 2016: The abandoned ice sheet base at Camp Century, Greenland, in a warming climate. Geophysical Research Letters **43**, 8091–8096.

Dansgaard, W., Johnsen, S.J., Møller, J. & Langway, C.C. 1969: One thousand centuries of climatic record from Camp Century on the Greenland ice sheet. Science **166**(3903), 377–380.

Gundestrup, N.S., Clausen, H.B., Hansen, B.L. & Rand, J. 1987: Camp century survey 1986. Cold Regions Science and Technology **14**(3), 281–288.

Hamilton, G. & Whillans, I. 2000: Point measurements of mass balance of the Greenland Ice Sheet using precision vertical Global Positioning System (GPS) surveys. Journal of Geophysical Research **105**, 16,295–16,301.

Hawley, R.L., Courville, Z.R., Kehrl, L.M., Lutz, E.R., Osterberg, E.C., Overly, T.B. and Wong, G.J. 2014: Recent accumulation variability in northwest Greenland from ground-penetrating radar and shallow cores along the Greenland Inland Traverse. Journal of Glaciology **60**(220), 375–382.

Kovacs, A., Weeks, W.F. & Michitti, F. 1969: Variation of some chanical properties of polar snow, Camp Century, Greenland. USA Cold Regions Research and Engineering Laboratory, Research Report **276**, 33 pp.

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W. & Yungel, J. 2000: Greenland Ice Sheet: High-Elevation Balance and Peripheral Thinning. Science **289**, *http://dx.doi.org/10.1126/science.289.5478.428*

Leuschen, C., Gogineni, P., Hale, R., Paden, J., Rodriguez, F., Panzer, B. & Gomez, D. 2014, updated 2016: IceBridge MCoRDS L1B Geolocated Radar Echo Strength Profiles, Version 2, [indicate subset used]. Boulder, Colorado USA: National Snow and Ice Data Center. *http://dx.doi.org/10.5067/90S1XZRBAX5N*

Machguth, H., MacFerrin, M., van As, D., Box, J., Charalampidis, C., Colgan, W., Fausto, R., Meijer, H., Mosley-Thompson, E. & van de Wal, R. 2016: Greenland meltwater storage in firn limited by near-surface ice formation. Nature Climate Change **6**, 390–393.

Mock, S. 1968: Snow accumulation studies on the Thule Peninsula, Greenland. Journal of Glaciology **7**, 59–76.

Mosley-Thompson, E., McConnell, J., Bales, R., Li, Z., Lin, P., Steffen, K., Thompson, L., Edwards, R. & Bathke, D. 2001: Local to regional-scale variability of annual net accumulation on the Greenland ice sheet from PARCA cores. Journal of Geophysical Research **106**, 33,839–33,851.

Nielsen, H. & Nielsen, K. 2016: Camp Century – Cold War City Under the Ice. In: Doel, R., Harper, K. & Heymann, M. (eds): Exploring Greenland: Cold War Science and Technology on Ice, 195–216. Palgrave Studies in the history of science and tehcnology, Palgrave Macmillan US.

Petersen, N. 2007: The iceman that never came. 'Project Iceworm', the search for a NATO deterrent, and Denmark, 1960–1962. Journal of Scandinavian History **33**, 75–98.

Steffen, K. & Box, J. 2001: Surface climatology of the Greenland ice sheet: Greenland Climate Network 1995–1999. Journal of Geophysical Research **106**, 33,951–33,964.

Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark; E-mail: *wic@geus.dk*