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Climate science

Future ice loss captured by historical snapshots

Twila A. Moon

Archival images of glacial ice on a Norwegian archipelago, together with the islands' climatic diversity, enable application of an innovative method for making long-term projections of ice loss using short-term observations. **See p.374**

Melting glaciers, ice caps and ice sheets are wreaking havoc at shorelines around the world, and there is widespread recognition of the need to understand where, when and how much ice will be lost in the future as a result of climate change. Much of what we know about Earth's existing land ice is gleaned from rich remote-sensing records, yet relatively few of these records span more than a couple of decades – time periods that are short enough to be biased by sporadic glacier behaviour. On page 374, Geyman *et al.*[1] use observations of glaciers on the Norwegian islands that make up Svalbard to improve projections of the ice mass that is expected to be lost in this area during the twenty-first century.

The team borrowed a method, known as space-for-time substitution, that is commonly used in other long-timescale research fields[2]. It takes advantage of the fact that Svalbard's relatively small land mass contains more than 1,500 glaciers across a range of climate zones. Ideally, scientists would study a single glacier – Glacier X – over hundreds of years to unravel how it responds to climate changes. Instead, Geyman *et al.* studied hundreds of glaciers over shorter timespans, with the requirement that these glaciers exist over a wide range of climate zones – from the colder climate that Glacier X experienced in the past to the warmer climate that the glacier will face in the future. In this way, the authors used climate variation in space as a substitute for climate variation over time.

The space-for-time substitution method can run into road blocks if the observational timescale is too short to avoid sporadic variability. Some glaciers can undergo brief, rapid surges of ice motion, and a few of these surging glaciers could derail a ten-year record, falsely suggesting rapid mass loss for a particular climate zone. Geyman *et al.* overcame this challenge with the help of more than 5,500 aerial photographs that had been taken from a scout aeroplane in 1936 and 1938, and that were gathering archival dust. Even readers who gloss over the study details will be astounded by the image comparisons that accompany the research.

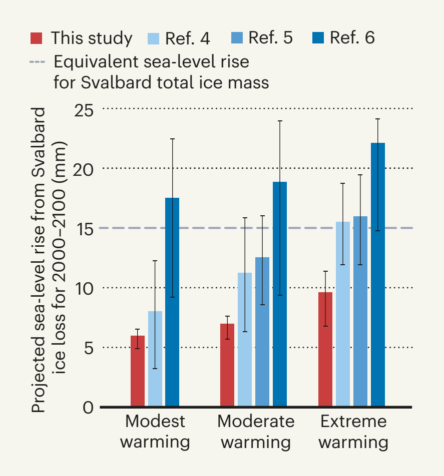

Figure 1 | Projections for twenty-first-century ice loss on Svalbard. Geyman *et al.*[1] estimated, on the basis of three scenarios used by the Intergovernmental Panel on Climate Change[3], that future ice loss on the Norwegian archipelago of Svalbard will be more moderate than projections reported in previous studies. Ice mass loss is measured by the equivalent rise in sea level (in millimetres), and values from the present study are compared with previously reported values (refs 4–6). The dashed line indicates the equivalent sea-level rise that Geyman and colleagues estimated for loss of all Svalbard glaciers, which represents an upper limit on possible ice loss. The projected loss will still have serious global consequences requiring mitigation, and the result does not change other global ice-loss projections. (Adapted from Fig. S7 of ref. 1.)

These aerial images allowed Geyman *et al.* to painstakingly recreate a digital elevation model for Svalbard in the 1930s. The authors then compared this reconstructed ice surface with modern elevation models to extract a record of Svalbard-glacier mass change spanning more than seven decades – long enough to suppress most short-term variability caused by glacier dynamics.

Using their record of the ice lost since the 1930s, Geyman and colleagues found a strong linear relationship between mean summer temperature and change in glacier surface elevation across the whole of Svalbard. They then used the space-for-time method to predict future changes in glacier surface elevation, and converted these estimates into mass changes. By testing three warming scenarios used by the Intergovernmental Panel on Climate Change[3], ranging from modest to extreme warming, the authors project twenty-first-century glacier thinning rates that are at least double the 1936–2010 rates.

Applying a linear relationship between mean summer temperature and glacier thinning does not take into account any future lengthening of the summer melt season – a development that seems likely. By introducing an alternative method that accounts for a lengthening melt season, Geyman *et al.* found that their projections change substantially (with increased ice loss) for only the most extreme warming scenario. Fortunately, current global climate pledges, if realized, are expected to limit warming to below this level, for which the linear relationship suffices (see go.nature.com/3cn3ppk).

Geyman and colleagues are also not able to fully explore the potential implications of changes in amplified near-surface air temperature at the poles, relative to the rest of the planet. This Arctic amplification is especially strong in winter, so that Arctic winters are warming more rapidly than Arctic summers. As a result, observational records thus far show a wider temperature variation between seasons than is expected in the future[4], and projected decreases in this inter-seasonal variation might have unconsidered consequences for mass loss.

The work by Geyman *et al.* paints a different picture of future ice loss from that of previous studies[5–7], almost all of which projected that more ice would be lost during the twenty-first century than Geyman *et al.* estimate, and which included values that now seem to be unrealistic (Fig. 1). These unrealistic values are highlighted by the authors' estimation of the total volume of ice on Svalbard using an ice-free surface-topography data set published previously[8]. The volume they calculated would be equivalent to a mean sea-level rise of 15 millimetres if all of the ice mass were lost. Thus, the previous estimates of sea-level rise exceeding this amount would be unfeasible.

The smaller future ice loss projected by Geyman and colleagues is welcome news for an area experiencing some of the fastest warming rates on the planet. However, the ice lost will still have consequences for coastal environments around the world, and the result does not change projections for other areas that have land ice. Glaciologists must now address the reasons for the shift in study outcomes — a question that Geyman *et al.* leave unaddressed.

For those who might consider using a space-for-time substitution for glaciological projections elsewhere, the 70-year time period in Geyman and colleagues' study might make the method seem impractical. The authors' tests, however, suggest that shorter records might still provide robust results. Researchers will have to assess the confidence with which they can link similar or different climate metrics to glacier mass change over small time periods for other locations. Geyman *et al.* found little evidence in Svalbard for threshold behaviours — tipping points that might make a glacier respond differently to temperature change above or below some value. Whether this holds true for other glaciated regions remains to be determined.

Geyman and colleagues' robust Svalbard-wide results are laudable but have limitations. Individual glaciers and smaller subregions might display different relationships between mean summer temperature (or other metrics) and glacier thinning. Those seeking to understand the local future of Svalbard's ice loss — to project changes in local habitat or plan for regional conservation — might require further detail. But the authors' rich historical data set and observation-based projection framework can provide a foundation for such work. They will also inspire other glaciologists looking to make new use of short-term observations to improve projections for the roughly 200,000 glaciers across the rest of the world.

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Archaeology

A radiocarbon revolution sheds light on the Vikings

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Advances in the precision of radiocarbon dating can offer year-specific data. Analyses of archaeological sites in Denmark and Canada provide insights into the chronology of the global networks of the Viking Age. **See p.388 & p.392**

During the twentieth century, our knowledge of the past was revolutionized by the introduction of radiocarbon dating, by the calibration of radiocarbon data to calendar dates using wood controls of known age and by advances in dating increasingly small samples. Now, another radiocarbon revolution is under way. There is a growing trend in harnessing calibration data that can be pinpointed to an individual year — measured using single rings of individual trees. For the years for which such calibration data exist, the most-recent international radiocarbon calibration curve, called IntCal20, represents a principal advance over the previously used approach (which often combined several tree rings for calibration analysis)[1]. Philippsen *et al.*[2] (page 392) and Kuitems *et al.*[3] (page 388) report how this method was used to clarify the timelines of two key Viking sites.

The potential of this new calibration curve is being tapped by research projects that also harness the opportunities presented by solar particle events (SPEs). SPEs are marked by spikes in atmospheric carbon in the form of carbon-14 that occur during years of extreme solar flares. These spikes are detectable in sequences of radiocarbon dates crossing chronologies that include an SPE. Radiocarbon dating becomes exceptionally precise in these, admittedly rare, circumstances — in the best cases, the exact year of an SPE can be identified in the archaeological record.

Two such SPEs occur near key chronological thresholds of the Viking Age. One is in AD 775, shortly before the conventionally accepted beginning of the Viking Age (approximately AD 793, as defined by the appearance of characteristic artefacts in Scandinavia, and the onset of Scandinavian raiding in Britain and Ireland). Another is in AD 993, near the time of the westernmost Scandinavian expansion of the Viking Age — to Greenland and northeastern North America. In Newfoundland in Canada, a short-lived settlement existed at L'Anse aux Meadows (Fig. 1), which is the only definite Viking site known in North America.

The opportunity therefore now exists to gain further insights into the chronology and character of the Viking Age. Philippsen and colleagues have established the chronology of the introduction of Middle Eastern glass trade beads (in AD 785–810) to the important medieval trading town of Ribe in Denmark. Crucially, the authors show that this introduction occurred after the emergence of long-range regional trade in Scandinavia (as revealed by imported Norwegian products such as reindeer antlers) and with continental western Europe (based on finds such as pottery from the Rhineland, Germany). Therefore, on the basis of chronological analyses, world-system linkages with the Middle East were probably not the main causal factor in the emergence of expanding networks during the Viking Age, although they were essential to its later development.

This discovery is notable because the arrival in Scandinavia of Middle Eastern silver coins called dirhams, which circulated alongside the beads, has sometimes been viewed as a crucial Viking Age catalyst of Scandinavian trade, urbanism and piracy. Instead, it seems that a more-prolonged and more-local process was responsible. Valued, but not always precious, resources (such as pottery or reindeer antlers) were incrementally obtained from ever-larger surrounding areas, fuelling the growth of urban centres such as Ribe. These items were traded before silver and beads from the Middle East entered the markets. A single explanation of the Viking phenomenon, albeit simplified for brevity, is thus ruled out.

Turning to the culmination of expansion during the Viking Age, Kuitems *et al.* determined the precise date of L'Anse aux Meadows, a medieval Scandinavian outpost. The previously available dating information for this UNESCO World Heritage Site was surprisingly limited. More than 150 dates for L'Anse aux Meadows have previously been obtained using the ^{14}C method, 55 of which relate to the time of the Scandinavian occupation. However, many dates are for materials of varying