GLACIER CHANGE

Dynamic projections

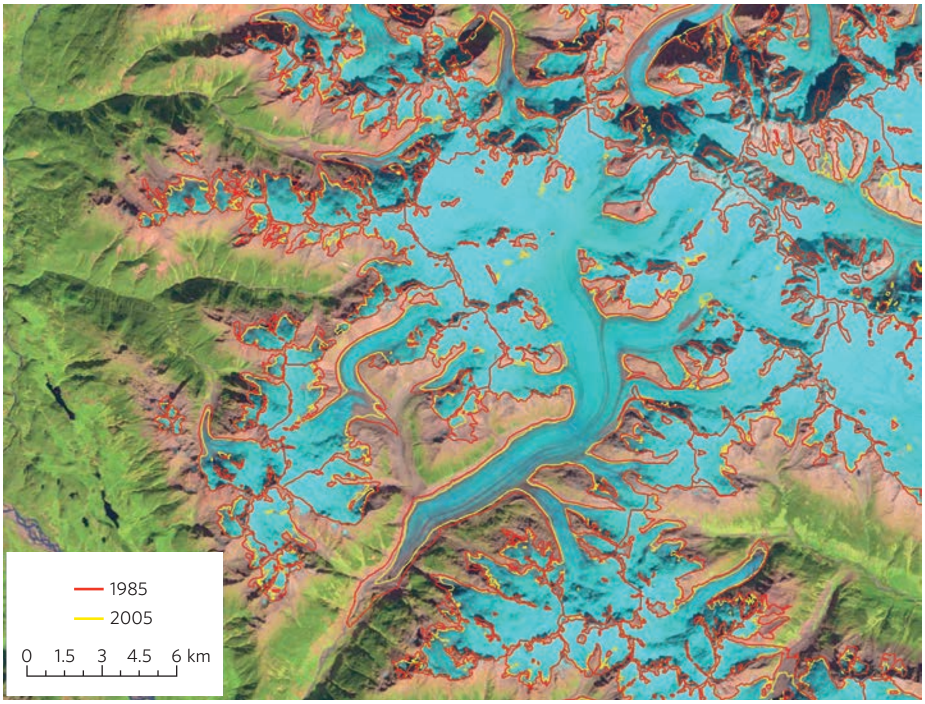
Mountain glaciers around the world are in decay. According to a modelling study that — unusually — includes full ice flow physics, those in Western Canada will largely be restricted to the coastal region by the year 2100.

Andreas Vieli

Glaciers are abundant in the world's high mountain regions, and they are sensitive to changing climatic conditions. They can influence river discharge and water resources, particularly in arid regions such the Tien Shan in Central Asia[1]. In past decades, many mountain glaciers have been observed to progressively shrink in mass and extent in response to atmospheric warming[2]. Mass loss of mountain glaciers currently contributes about 0.7 mm of sea-level rise per year[2], similar to the combined addition from the ice sheets of Greenland and Antarctica. However, predictions on regional to global scales are uncertain: they rely heavily on upscaling from a small, well-studied subsample of the world's 170,000 glaciers[3]. Writing in *Nature Geoscience*, Clarke *et al.*[4] present a comprehensive modelling framework that simulates the large-scale evolution of glaciers in Western Canada at high resolution, and fully account for glacier flow.

Changes in glacier extent and volume result from variations in the surface mass balance, that is, the balance between accumulation of snow in the colder high-elevation areas of a glacier and ice melt in low-elevation ablation areas. Surface mass balance is therefore directly steered by local meteorological factors such as air temperature and snow fall. Ice flow, caused by gravity, then transfers ice from the accumulation to the ablation area. Glaciers respond to changing climatic conditions by adjusting their shape, a process that involves ice flow. However, these dynamic adjustments take time and result in a delayed and smoothed response of glacier geometry to the climatic signal.

Regional to global scale projections of glacier change that are relevant for sea-level estimates and hydrology face the challenge of dealing with very large numbers of glaciers, each with a different geometry. Observations from glaciers are limited, therefore projections largely rely on models of surface mass balance derived from a few tens of glaciers that have been measured in detail. These are then scaled-up to whole glacier populations based on simple attributes such as terminus elevation and scaling relationship between glacier volume and area[5–7]. These approaches mostly ignore or highly simplify the role of ice flow on mass redistribution and they cannot consider delays in the response to a change in climate, or local effects of complex topography.



USGS-GLOVS/LC80500242014263LGN00

Figure 1 | Glacier area by satellite. The general recession in the glacierized region of Mount Waddington in coastal southwest Canada, as well as the diversity in size and shape of its glaciers are apparent in the glacier outlines from 1985 and 2005, mapped onto a satellite image (Landsat OLI Scene of September 2014). Clarke and colleagues[4] explicitly simulate ice flow at high resolution to obtain more realistic projections of future ice mass change. Figure courtesy of T. Bolch. University of Zurich; data from ref. 8.

Clarke and colleagues[4] address these deficiencies head on. In their modelling framework for predicting the evolution of glacierized mountain regions of Western Canada, they explicitly simulate the physics of ice flow. This modelling approach allows a fully three-dimensional representation of glacier geometry at a high resolution of 200 m, and it also accounts for time-lags in response to climatic forcing and related dynamic feedbacks.

They find that for four future climate scenarios that span the range considered by the Intergovernmental Panel on Climate Change, the glaciers in Western Canada will recede rapidly. The projections suggest that these glaciers will shrink to less than 10% of the present area by the year 2100 for the interior regions, and to about 30% for the coastal regions with a more maritime climate. The peak in additional discharge from deglaciation in response to atmospheric warming is expected within the next 20 years. Discharge later decreases again, because the glacier area where ice is available to melt declines. As discussed by Clarke and colleagues, this rapid rate of glacier recession has implications for regional hydrology, water resources and the future landscape. It is, however, broadly in line with earlier projections and global trends[3].

Perhaps the most important added value of the study lies in its methodological aspects. For example, Clarke and colleagues show that the inclusion of flow physics leads to a loss of 60% of glacier mass, compared to 47% in the less sophisticated simulations that are solely based on surface mass balance modelling. It is therefore possible to assess the uncertainties that result from feedbacks related to ice flow.

Moreover, Clarke and colleagues' approach provides a complete chain of modelling elements that start with the derivation of subglacial topography and include downscaling procedures from global circulation model data, corrections for orographic precipitation and a transient approach for model initialization. Importantly, this modelling framework is highly generic and solely based on input data sets that are readily available — such as digital elevation models or climate model outputs. The methodology can therefore potentially be applied to a wide range of glacierized regions, or to reconstructions of past glaciations. Importantly, the model system can be constrained with detailed glacier outlines[8,9] that are readily available from satellite imagery (Fig. 1). Given the dearth of ground-based data on glaciers, it is essential to use all the available information to reduce model uncertainty for projections of the future.

Nevertheless, a number of important challenges remain. Projections are ultimately affected by uncertainties in the available climate change scenarios for the future, and our limited understanding of processes, such as the role of albedo and debris cover. Model initialization remains difficult; and the proposed modelling framework does not consider glaciers that terminate in the sea on an inland sloping bed, that have the potential for unstable retreat and are also influenced by ocean temperatures. Such calving glaciers are, however, widespread and make up 38% of all glaciers outside the large ice sheets[2].

The study by Clarke and colleagues[3] provides an important step forward in our ability to include ice flow physics in simulations of larger-scale glacier mass loss, and to assess its impact on loss rates. In addition to model development, the next steps include a rigorous intercomparison between the various models — including intermediate approaches with a highly reduced treatment of ice flow[9]. This work has recently been initiated by the Glacier Model Intercomparison Project (http://go.nature.com/edmSbO). ❐

Andreas Vieli is in the Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland.
e-mail: andreas.vieli@geo.uzh.ch

References

1. Sorg, A., Bolch, T., Stoffel, M., Solomina, O. & Beniston, M. *Nature Clim. Change* **2,** 725–731 (2012).
2. Vaughan, D. G. *et al.* in *Climate Change 2013: The Physical Basis* (eds Stocker, T. F. *et al.*) Ch. 4 (IPCC, Cambridge Univ. Press, 2013).
3. Church, J. A. *et al.* in *Climate Change 2013: The Physical Basis* (eds Stocker, T. F. *et al.*) Ch. 13 (IPCC, Cambridge Univ. Press, 2013).
4. Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radić, V. & Menounos, B. *Nature Geosci.* http://dx.doi.org/10.1038/ngeo2407 (2015).
5. Radić, V. *et al. Clim. Dynam.* **42,** 37–58 (2014).
6. Marzeion, B., Jarosch, A. H. & Hofer, M. *Cryosphere* **6,** 1295–1322 (2012).
7. Giesen, R. H. & Oerlemans, J. *Clim. Dynam.* **41,** 3283–3300 (2013).
8. Bolch, T., Menounos, B. & Wheate, R. *Remote Sens. Environ.* **114,** 127–137 (2010).
9. Pfeffer W. T. *et al. J. Glaciol.* **60,** 537–552 (2014).
10. Huss, M., Jouvet, G., Farinotti, D. & Bauder, A. *Hydrol. Earth Syst. Sci.* **14,** 815–829 (2010).

Published online: 6 April 2015