What needs to be known by 2050 about Arctic land ice and sea level rise

The Greenland Ice Sheet and glaciers and glaciated areas across Canada, Russia, the U.S., northern Europe, Iceland, and Svalbard make up the Arctic's "land ice". By 2050, land ice in the Arctic will likely be changing even more rapidly than it is today. Episodes of extreme surface melting are expected to be more frequent, exceeding the record levels of surface melt seen in Greenland during 2010 and 2012. There will likely be significant retreat of all glaciers. Particularly large retreats (many kilometers) are expected for most of the largest deep-keeled ocean-connected glaciers, which have the greatest potential for contributing to rapid sea level rise. For many large glaciers, ice flow speed will increase and related ice discharge (calving) will rise. Complicating matters, however, some glaciers will retreat into shallower water, slowing their speed and reducing their calving activity. Thus, the locations of iceberg production may shift in the future, potentially influencing wildlife, ocean conditions, and navigation hazards. Less clear is the future pace of ice sheet and outlet glacier change arising from ocean circulation shifts and warming within mid-ocean layers, as well as the impact of changes in snowfall and rainfall.

By 2050, policymakers, earth and life scientists, and the public will need to know the ongoing pace of ice sheet changes and the almost certainly increased rates of net ice loss. For planning and investment purposes, they will also need to know --- with more certainty than we do today --- what the future rates of sea level rise will be for the remainder of the century and beyond.

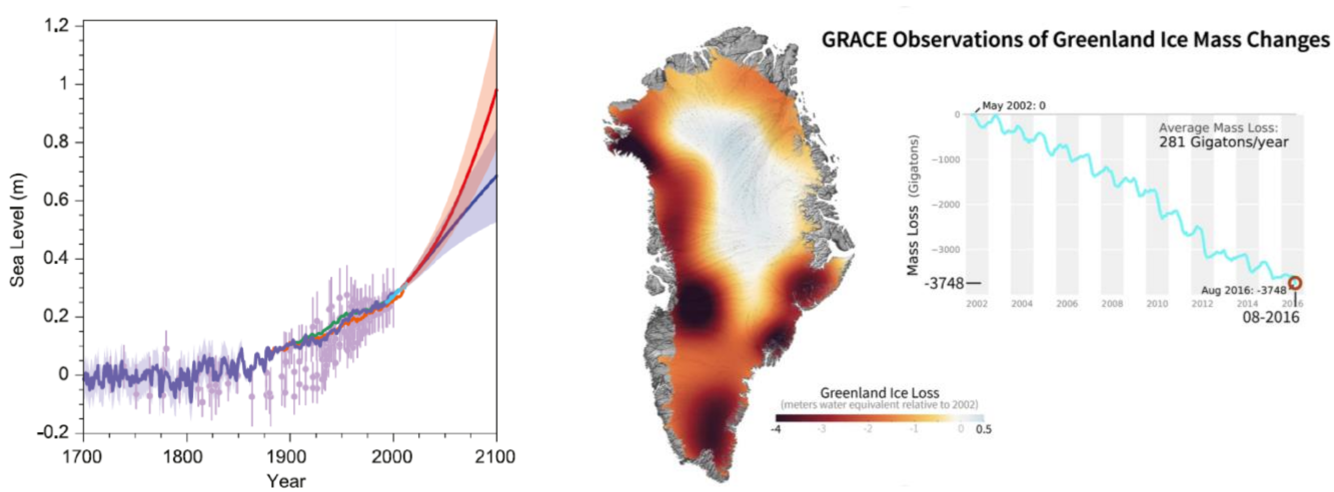
Scientists and society will need to be aware of the *processes* influencing and controlling land ice loss. These include trends in air temperature and circulation, changes in ocean properties, and multi-decade effects of ice-surface darkening (from aerosols, soot, dust, ice grain-size changes, and biological activity). Key data will come from ocean and ice sheet monitoring and observation systems. A comprehensive understanding of these processes is necessary to increase the accuracy of predictions of future sea level rise and assess the potential for more rapid sea level rise in the future. There is also a critical need to understand local changes in land uplift and gravitational pull as ice is lost. These processes influence how sea level rise varies from place to place, which in turn affects adaptation and planning measures.

To understand the processes, rates, and implications of sea level rise by 2050 and beyond, observations of phenomena that control or are an expression of these processes will be essential, along with models to analyze and predict land ice change. Satellite trends for elevation, ice flow speed, Arctic-wide snow accumulation, and other parameters such as albedo (the reflectiveness of ice), snow and firn conditions (e.g. temperature and density) will need to be available for easy scientific use and with well-established records extending back a few decades at minimum. Knowledge and informed advice on these parameters will allow fine-tuning of mitigation and adaptation strategies. For example, if dust or soot from particular locations has a substantial influence on ice loss, there may need to be a greater emphasis on fighting forest fires in some Arctic areas. Knowledge of the changing land ice system and the processes controlling it will also help determine the most important areas for monitoring or measurement or, potentially, what geo-engineering efforts are the most likely to achieve cost effective results. Ultimately, future sea level rise will depend on internationally-negotiated carbon emission and sequestration scenarios, as differences in emissions rates produce significant differences in the pace of land ice loss. Scientists' ability to predict future sea level rise will require knowledge of these scenarios.

Policymakers and planners will also need economic activity information and forecasts for the Arctic, for example, fishing and shipping expectations for regions near marine-connected ice. Because the fingerprint of sea level rise globally is not uniform and is affected by the location of ice loss, the coastlines near Greenland and southeast Alaska will experience sea-level *lowering* sufficient to potentially impact shallower marinas and harbors.

There will also be important impacts outside of sea level rise. Mining activity in regions near the (presumed) retreating ice edges will require forecasts of ice edge retreat for future planning regarding export and exploration. Retreat and ice loss will also change local hydrologic systems. These impacts may include changes in stream temperature, water volume, and timing of runoff. Hazards from glacier-dammed lakes may also increase in some areas. Iceberg calving and drift could also have a significant impact on tourism, fishing, and shipping in some Arctic ports.

Successfully characterizing, understanding, and predicting Arctic land ice contributions to sea level rise will inform (a) investments in coastal infrastructure, including roads, commercial property, private property, military installations, etc., (b) coastal flooding risk assessments, both directly from sea level rise or indirectly through storm surge, and (c) assessments of humanitarian and geopolitical risk resulting from displacement of populations in coastal areas. Decision makers also have to be aware of and planning for local and regional impacts of land ice loss, which include hydrological changes, glacial hazards, and ecosystem and navigation effects. From an economic, security, and humanitarian perspective, the implications of future sea level rise are tremendous, and without the necessary knowledge from scientists --- and effective use of that knowledge by policy makers --- the risks and vulnerabilities will only continue to rise.



Left: Observed and projected change in global mean sea level through 2100 under various scenarios of greenhouse emissions. Blue projection is for an optimistic scenario of future greenhouse gas emissions (RCP 2.6); orange projection is for a more likely scenario of future emissions (RCP 8.5; IPCC, AR5). Right: Ice mass loss from the Greenland Ice Sheet for the period 2002 – 2016 showing areas where ice loss is greatest (and areas of slight gain due to snowfall), and the trend and seasonal variation in ice sheet mass loss.