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Ted Scambos, Fiamma Straneo & Marco Tedesco

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## How fast is the Greenland ice sheet melting?

**THE ISSUE.** The Greenland Ice Sheet and the glacier-covered areas of Alaska and other Arctic lands are losing ice at an accelerating rate, contributing billions of tons of water to sea level rise.

**WHY IT MATTERS.** Ice loss from the ice sheets contributes directly to sea level rise. These losses are likely to increase rapidly as warming in the Arctic continues. Surface melt and runoff is now increasing more quickly than all other factors driving Greenland's ice loss, although faster glacier outflow remains important. Increased ice loss from Alaska's glaciers is also due mainly to surface melting. Given these trends, and the rapid warming in the Arctic (twice the global rate of warming), the Arctic is poised to lose ice even more rapidly and raise sea level.

**STATE OF KNOWLEDGE.** Since 2000, the net loss of ice from the Greenland Ice Sheet has increased five-fold, from 50 billion to about 250 billion tons per year<sup>1,2</sup> (362 billion tons is equal to 1 mm in sea level rise). Ice losses in the Gulf of Alaska region have risen from about 40 to 70 billion tons per year<sup>3</sup>. These trends are confirmed by three independent satellite methods, using gravitational changes, elevation changes, and changes in the mass budget (the net difference between snowfall and the combination of glacier outflow and runoff)<sup>1</sup>. In total, the Arctic currently contributes approximately 350 billion tons (~1 mm) to sea level each year, primarily from Greenland, Alaska, and Arctic Canada. Recent measurements of the rate of sea level rise are 3.0 mm per year, with the additional rise coming from other glaciers and Antarctica (~0.4 mm) and expansion of the oceans due to warming (~1.7 mm)<sup>4</sup>. Slightly cooler summer seasons for Greenland in 2013 and 2014, and again in 2017 and 2018, temporarily reduced the rate of ice loss. Ocean temperatures cooled in some places along the western Greenland coast, slowing glacier outflow there<sup>5</sup>. However, strong melting in 2015, 2016 and 2019 again contributed large amounts of runoff to the ocean<sup>2</sup>. Because surface melt is closely tied to seasonal weather conditions, it is more variable than ice loss due to increased glacier outflow. Despite this variability, the overall

warming trend of Arctic air and ocean has driven greatly increased melting and ice loss in Greenland and Alaska in the past two decades. As spring and summer temperatures have increased, net runoff of meltwater has grown dramatically (Figure 1). Ice loss due to faster glacier flow has remained stable overall and is unlikely to accelerate as rapidly as melting. Current increases in surface melt runoff rate are about twice that of ice loss due to increased ice flow speed<sup>1</sup>. As intense summer melt seasons like 2012, 2016, and 2019 become more common, further increases in melt runoff are inevitable.

**WHERE THE RESEARCH IS HEADED.** The major factor driving changes in surface melting of Arctic land ice, besides increasing temperatures, is a decrease in the reflectivity of surface snow, which in turn is caused by the darkening of snow under warm conditions and the concentration of impurities at the surface. Subtle variations in the reflectivity of snow have a very large impact on the energy absorbed by the surface. Clean dry snow has a reflectance of 90 percent or more, and a 10 percent decrease in reflectivity doubles the amount of energy absorbed. Satellite monitoring of reflectivity in Greenland shows that the surface in summer is now several percent darker than at the beginning of this century. This is thought to be due to concentration of



Figure 1. Greenland ice sheet, July 2020. Photo by Jason Gulley.

the impurities such as soot and dust on the surface by melting, and by higher temperatures directly. A warmer summer and longer surface melt season darkens the Greenland ice sheet by coarsening the snow, concentrating dust and other impurities at the surface as the snow melts or evaporates, and exposing old snow and bare ice. All these surface types are much darker than fresh powder snow. In general, the concentrations of contaminants in Alaskan snow are small, and the main cause of ice loss is warmer temperatures<sup>1</sup>.

For glacier flow, the main driver is the effect of increased delivery of 'warm' ocean water (a few degrees above freezing) to the deep keels of thick glaciers that reach the ocean. Understanding interactions between a glacier ice front and the ocean is a major focus for predicting changes in flow rates for Greenland's glaciers. Ocean water temperatures at depths of a few hundred feet below the surface are rising, although with variation<sup>6</sup>. Pulses of this mid-level water reaching the glacier front, or the cavity beneath a floating glacier, have caused rapid glacier retreats and flow speed increases that have lasted a decade or more. This environment is hard to observe, because the presence of large jostling blocks of ice is extremely destructive for instrumentation. Researchers are developing technologies to explore this environment and establish a monitoring program for the major glacier outlets.

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## Supplementary material

Supplemental references for this article can be accessed at <https://doi.org/10.1080/15230430.2021.1946241>

## Contact Authors for More Information:

Ted Scambos

*CIRES, University of Colorado, USA*

✉ [tascambos@colorado.edu](mailto:tascambos@colorado.edu)

Fiamma Straneo

*Woods Hole Oceanographic Institution, USA*

✉ [fstraneo@ucsd.edu](mailto:fstraneo@ucsd.edu)

Marco Tedesco

*Columbia University, USA*

✉ [mtesesco@ldeo.columbia.edu](mailto:mtesesco@ldeo.columbia.edu)

