Through-Ice-Shelf Drainage of Surface Meltwater Lakes and its Implications for Antarctic Ice Shelf Stability

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Abstract

Many of Antarctica's ice shelves experience significant surface melting each season, yet it is generally assumed that nearly all the produced meltwater re-freezes rather than being lost as runoff. Individual events of direct surface meltwater loss to the ocean have been documented, but were thought to be rare. We here present evidence of widespread through-ice-shelf drainage of supraglacial lakes, observed across various Antarctic ice shelves. We demonstrate that meltwater can accumulate for many melt seasons, in lakes that are often covered by an ice lid. Such buried lakes can drain into the sub ice shelf ocean cavity nearly instantaneously, creating an ice doline. These doline formation events are observed year-round and likely occur via a through-cutting crevasse that propagated from the lake bed by hydrofracture. The removal of a large load from the top of the floating ice shelf results in flexural uplift in the region around the drained lake basin. These surface elevation changes can be monitored using high-resolution satellite remote sensing data, such as ICESat-2 laser altimetry and digital elevation models created from WorldView stereo satellite imagery pairs. We show that doline formation has the potential significantly change the surrounding ice shelf surface hydrology, leading to different processes with opposing effects on ice shelf stability. If the surface depression formed by the former lake bed acts to capture meltwater and channels it straight down to the ocean via the newly-created drainage pathway, this process could halt supraglacial meltwater system growth and thus prevent meltwater from reaching areas more vulnerable to hydrofracture. However, if flexural uplift diverts meltwater flow around the doline and delivers it to adjacent areas on the ice shelf surface, this can lead to repeated hydrofracture in multiple locations and thus act to destabilize the ice shelf. Which of these mechanisms dominates over time on each ice shelf may ultimately be crucial for its long-term resilience in a warming climate.

Through-Ice-Shelf Drainage of Surface Meltwater Lakes and its Implications for Antarctic Ice Shelf Stability

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BACKGROUND: **Meltwater on ice shelves** can lead to their **collapse by hydrofracture.** When ice shelves collapse, more grounded ice flows into the ocean, leading to **sea-level rise**. When a melt **lake drains** through an ice shelf, the **floating ice shelf flexes upward** in response to the removal of the load. This process alters the ice shelf's surface topography and **hydrology.** Observational data of such lake drainage ("ice doline" formation) events across Antarctica's ice shelves **have not been systematically studied** before.

METHODS: We complied an **inventory of through-ice-shelf drainage events** around Antarctica by looking at changes in satellite imagery. We used high resolution **satellite data** of **surface elevation change** (ICESat-2 repeat-track laser altimetry and lagrangian differencing of Worldview3 stereophotogrammetric digital elevation models) to generate **observational data of ice shelf flexure** in response to lake drainage. We tracked resulting **changes in ice shelf surface hydrology** to find out whether this process is more likely to stabilize or de-stabilize ice shelves.

RESULTS:

- Through-ice shelf drainage of lakes is **more widespread than previously thought.**
- **High-resolution satellite data** of surface elevation change can **improve** our **understanding of ice shelf mechanics.**
- Doline formation can significantly **change ice shelf surface hydrology** nearly instantaneously, thus affecting **ice shelf stability.**
  - **Meltwater capture stabilizes:** it removes water from the surface and **prevents future hydrofracture.**
  - **Meltwater diversion de-stabilizes**: it can **re-route water** to downstream areas that are more **vulnerable to collapse by hydrofracture.**

TAKEHOME MESSAGE: Through-ice-shelf lake drainage is an ice shelf process that is more widespread across Antarctica than we thought. It can have large impacts, so **we should care about it.**

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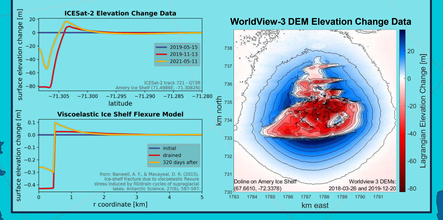
We found many examples of melt **lakes draining through ice shelves** around Antarctica.

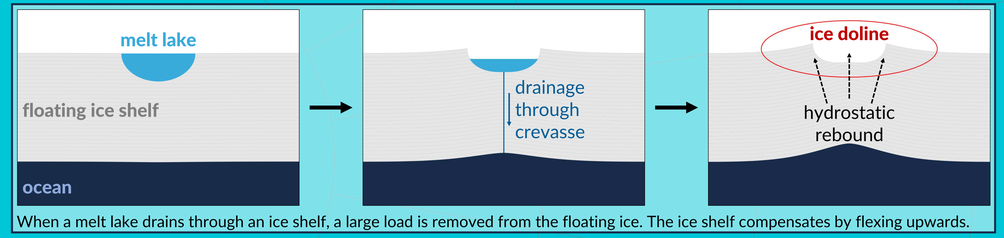
Satellite data of lake drainages can help us **better understand** ice shelf **flexure,** and how meltwater impacts **ice shelf stability**.

Observational Data of Ice Shelf Flexure

High-resolution satellite data of surface **elevation change** provide **observational data** of ice shelf **flexure** in response to lake drainage. This can help us better understand the **mechanical properties** of ice shelves, to validate or **improve models.**



The Mechanism: **"Ice Doline Formation"**



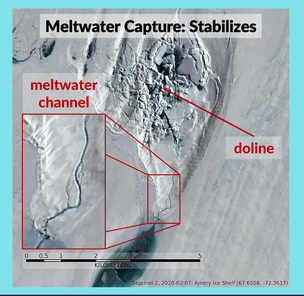
When a melt lake drains through an ice shelf, a large load is removed from the floating ice. The ice shelf compensates by flexing upwards.

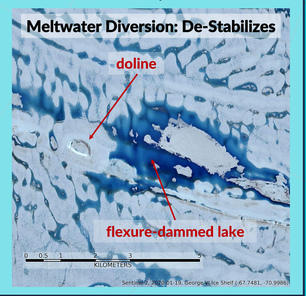
Implications for **Ice Shelf Stability**

Doline Formation has **two** possible, **opposing mechanisms** on stability:

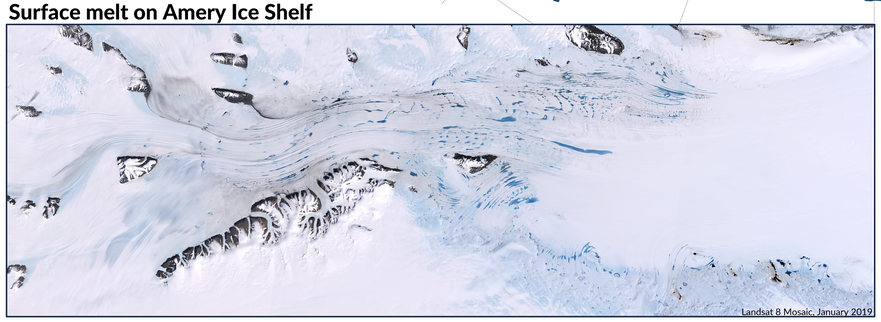
1) Meltwater **capture stabilizes** the ice shelf: the **drainage crevasse** provides a **pathway to remove water** from the surface, **preventing** future **hydrofracture**.

2) Meltwater **diversion de-stabilizes** the ice shelf: the **flexural uplift** can prevent future meltwater from entering the collapse basin and instead **re-route** it to regions **further downstream** that are more **vulnerable to hydrofracture.**





Surface melt on Amery Ice Shelf



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