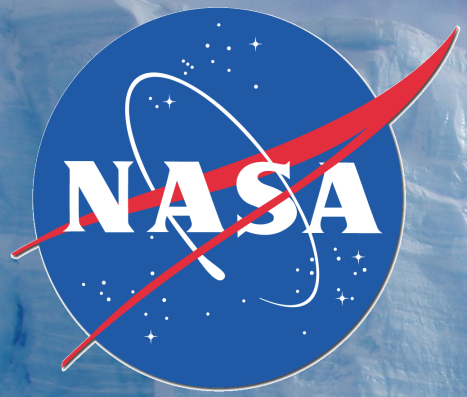




# Oceans Melting Greenland

## How we intend to investigate the impacts of a warm/warming ocean on the Greenland Ice Sheet

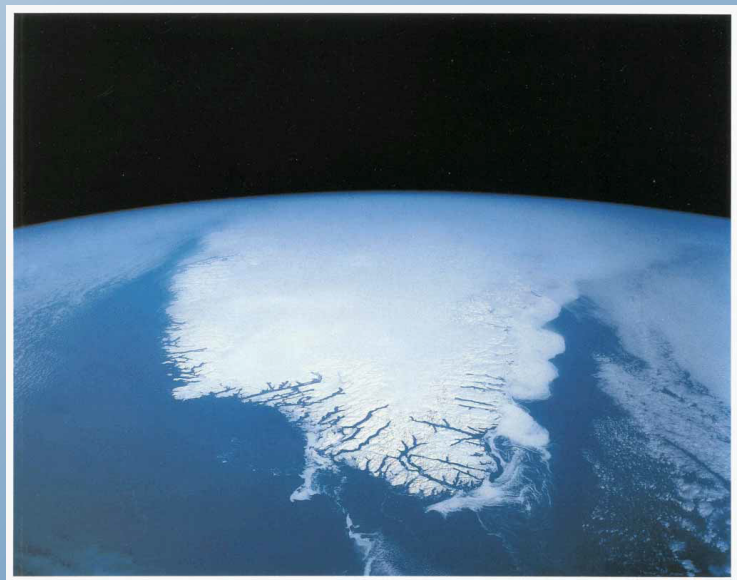
Michael Schodlok

J. Willis (PI), S. Dinardo, I Fenty, R. Fosberg, I. Fukumori, D. Holland, M. Jakobsson, A. Khazendar, W. Mateer, D. Moller, J. Morrison, E. Rignot, A. Thompson, K. Tinto

# Greenland

…. covered with ice up to 2500 m thick

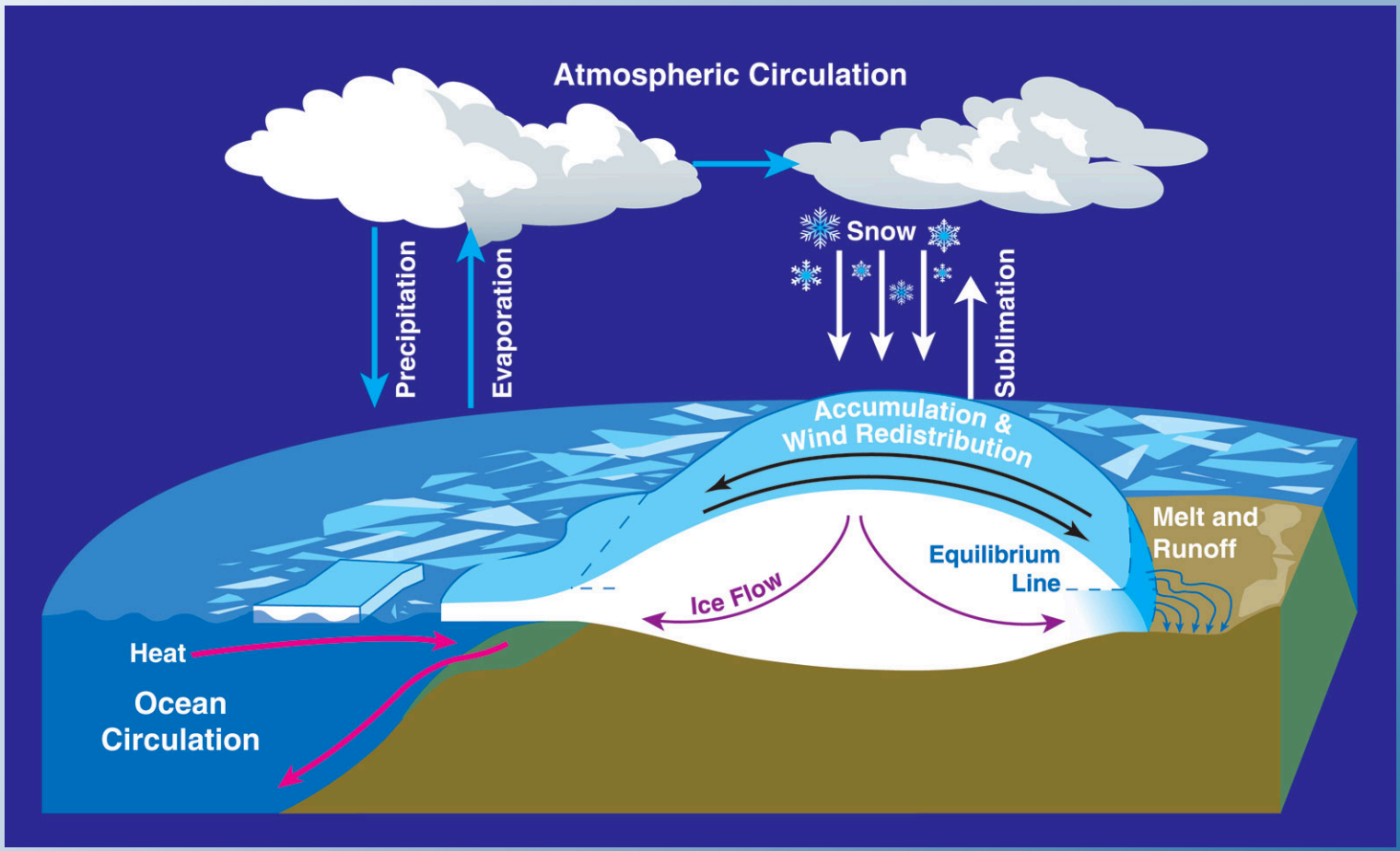
…. the largest remnant of the last **Ice Age** in the Northern Hemisphere



Space shuttle photograph 29 March 1992

| | |
|---|---|
| Total ice volume | 2,800,000 $km^3$ |
| Average ice thickness | 2.5 km (1.5 miles) |
| Annual net surface accumulation | 250 $km^3$ |
| Sea level equivalent | 7 m (22ft) |

# The Greenland Ice Sheet in the climate system




The water cycle with respect to polar ice and sea level

Figure credit: NASA

# The Greenland ice sheet is thinning, especially along its coastal margins in the SE and NW and net annual mass loss is increasing through the GRACE period

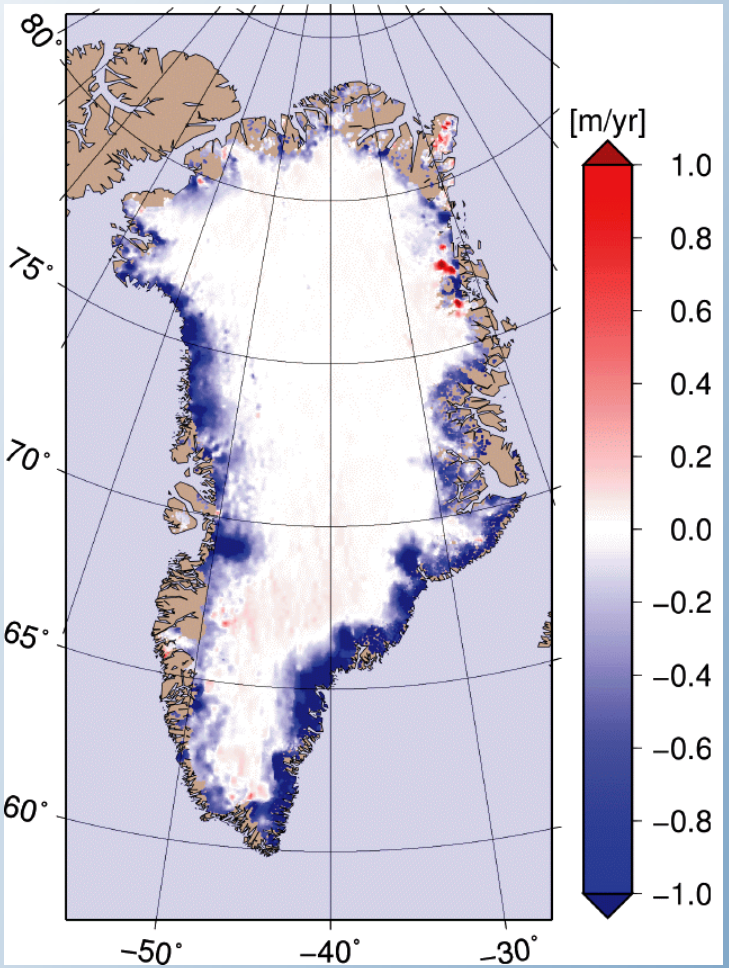



Figure: ICESat elevation changes 2003-2009 (L. Sørensen, DTU-Space).

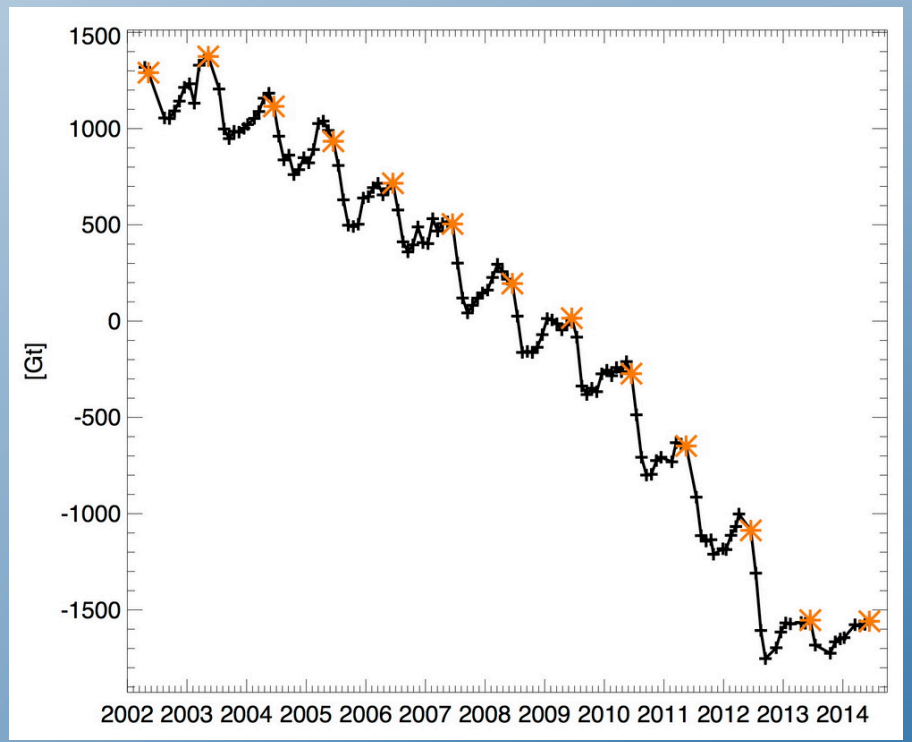


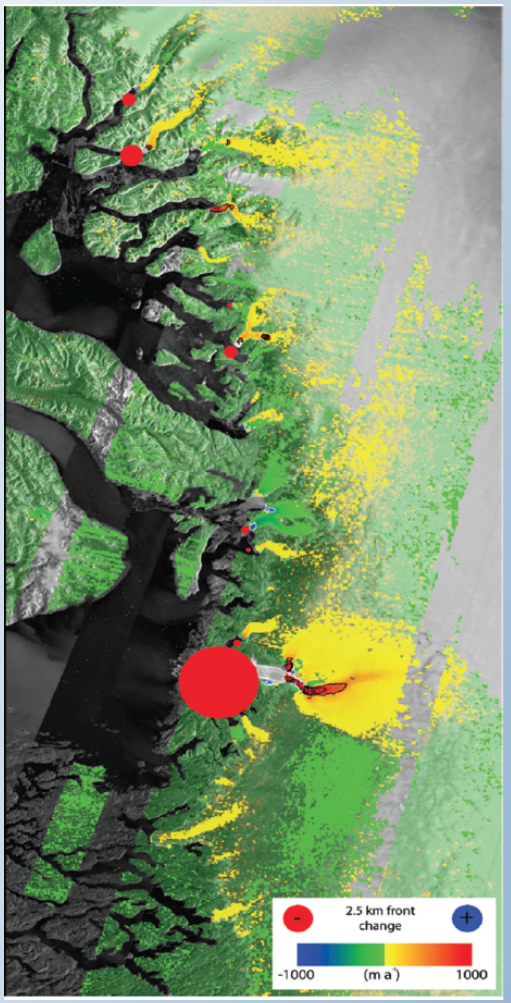

Fig. 3.3. Monthly mass anomalies (in Gigatonnes, Gt) for the Greenland ice sheet since April 2002 estimated from GRACE measurements. The anomalies are expressed as departures from the 2002-2014 mean value for each month. For reference, orange asterisks denote June values (or May for those years when June is missing). (Tedesco et al 2015)

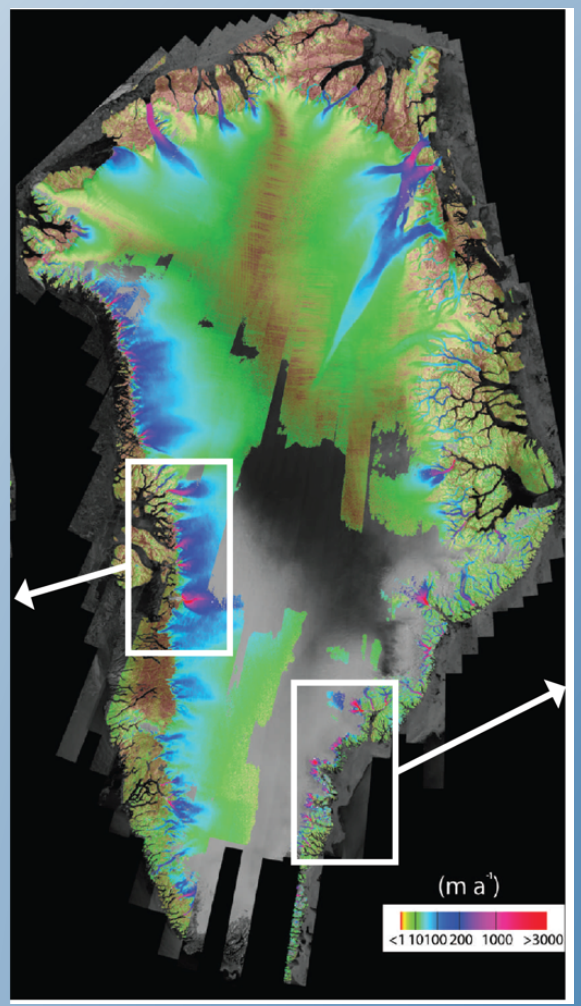
# Outlet glaciers are **accelerating** and r**etreating.**

*Glacier*

- retreat (Circles)
- acceleration (Color)

Flow speed (color) for the winter 2005/06



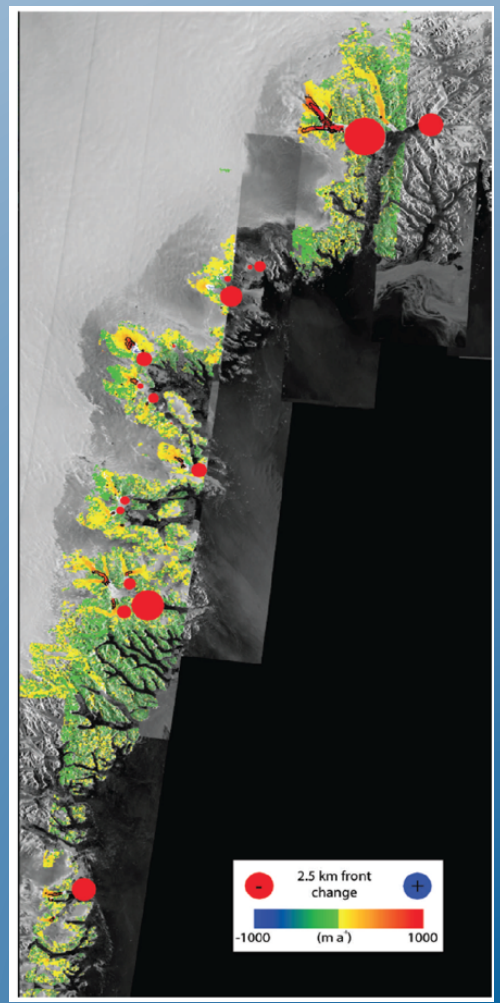



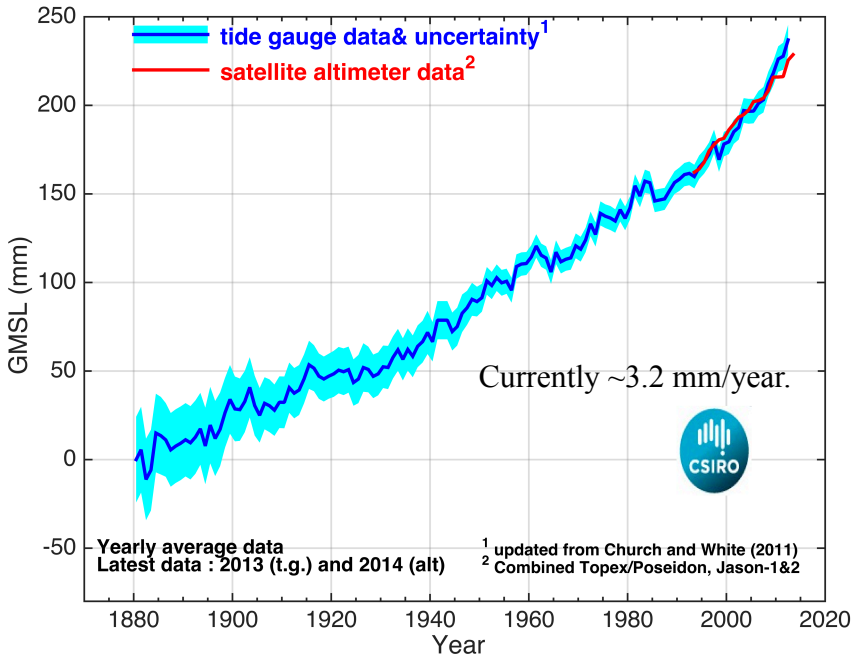

Figure adapted from Joughin et al. (2010) *Journal of Glaciology.* doi:10.3189/002214310792447734

# Greenland and Antarctica Ice sheet melting is responsible for about half of current sea level rise

Surface meltwater disappears down a moulin.

Photo credit: Konrad Steffen/CIRES, University of Colorado

Global Mean Sea Level (GMSL) - 1880 - 2014




Much of the acceleration of sea level rise has been linked to the increase of melting in Greenland and Antarctica.

Figure Credit: CSIRO Sea Level Project
http://www.cmar.csiro.au/sealevel/sl_hist_few_hundred.html

1. The **ice sheet is thinning, especially along its coastal margins.**

2. Its glaciers are **accelerating** and **retreating.**

3. The water from the melted ice is flowing into the ocean **contributing to sea level rise**

**How and Why is Greenland's ice melting?**

Oceans Melting Greenland (OMG) is a new NASA sub-orbital mission that will pave the way for improved estimates of sea level rise during the 21st Century.

OMG will observe changes in ocean circulation and glacier retreat over a multi-year campaign using airborne and ship-based assets.

In conjunction with measurements of the shape and depth of the seafloor, these data will allow us to answer the over-arching science question:

**To what extent are the oceans melting Greenland's ice from below?**

Three primary questions:

a) **where and how much warm Atlantic Water intrudes onto the continental shelf?**

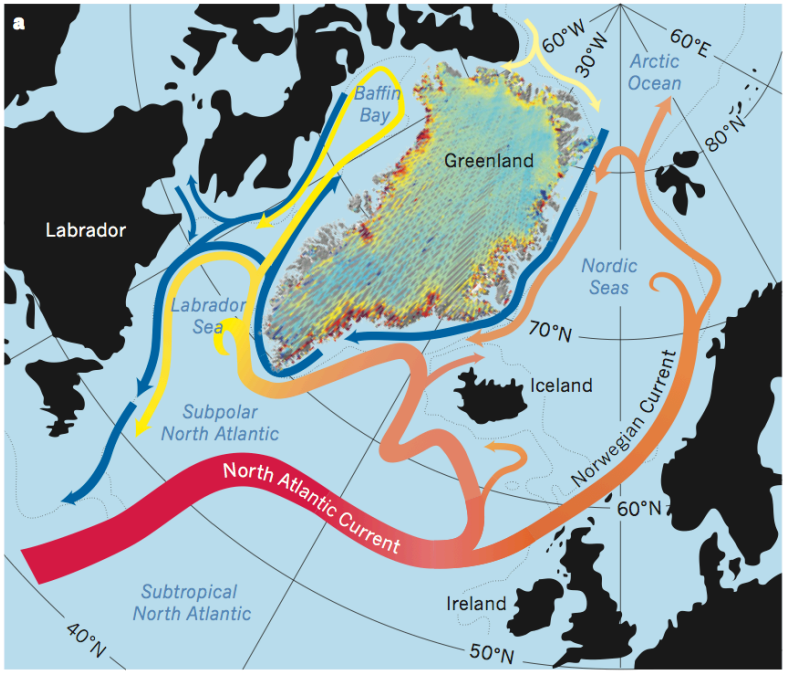
b) **how much warm water is transferred to the inner fjords towards the glacier faces?**

c) **what is the response of the glaciers to changing ocean water temperatures in the inner fjords, combined with other forcing (e.g., surface melt from atmospheric warming)?**

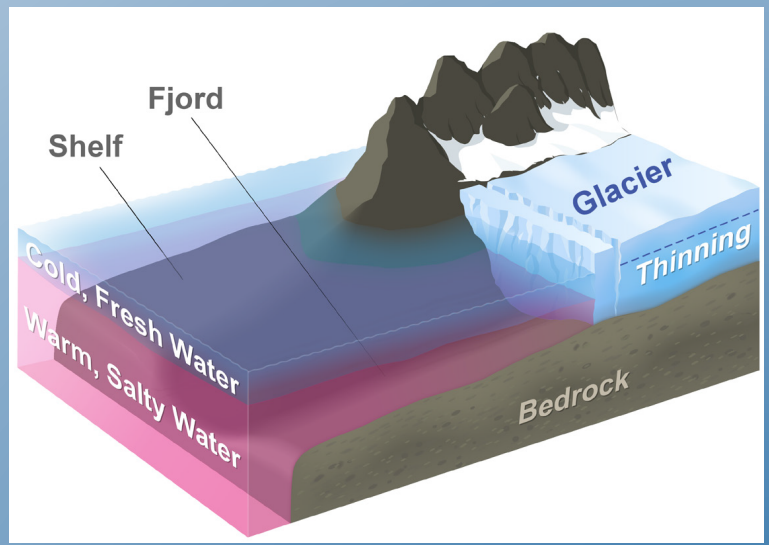
(a)

Warm waters advected towards Greenland are modified (mainly freshened and cooled) relative to their 'original' properties on the NAC.

**Upper ocean temperature and circulation schematic**




(Straneo and Heimbach 2013)

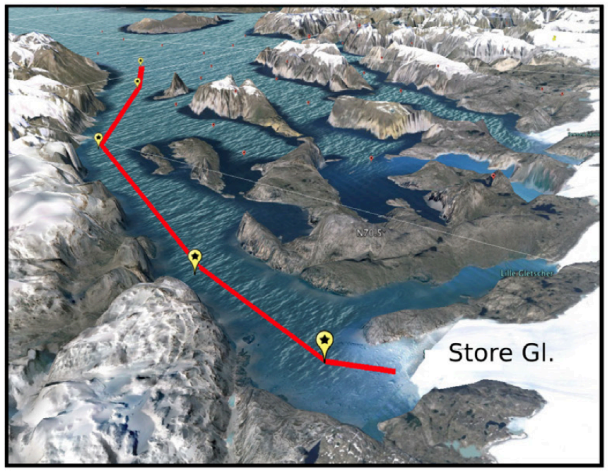



While flowing around Greenland, shelf break these warm waters may advance across the continental shelf towards the ice sheet within deep canyons (or troughs) carved out of the seafloor by advancing glaciers in earlier glacial periods. These canyons often become fjords at the coast.

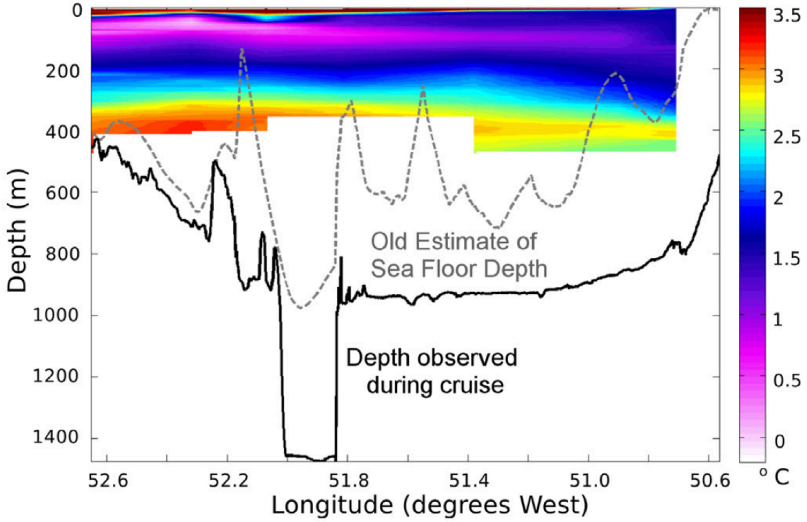
(b)

# The seafloor topography around Greenland probably determines to a large extent where warm ocean waters can reach glacial fjords.

Rendering of a Glacial Fjord and Ship Track



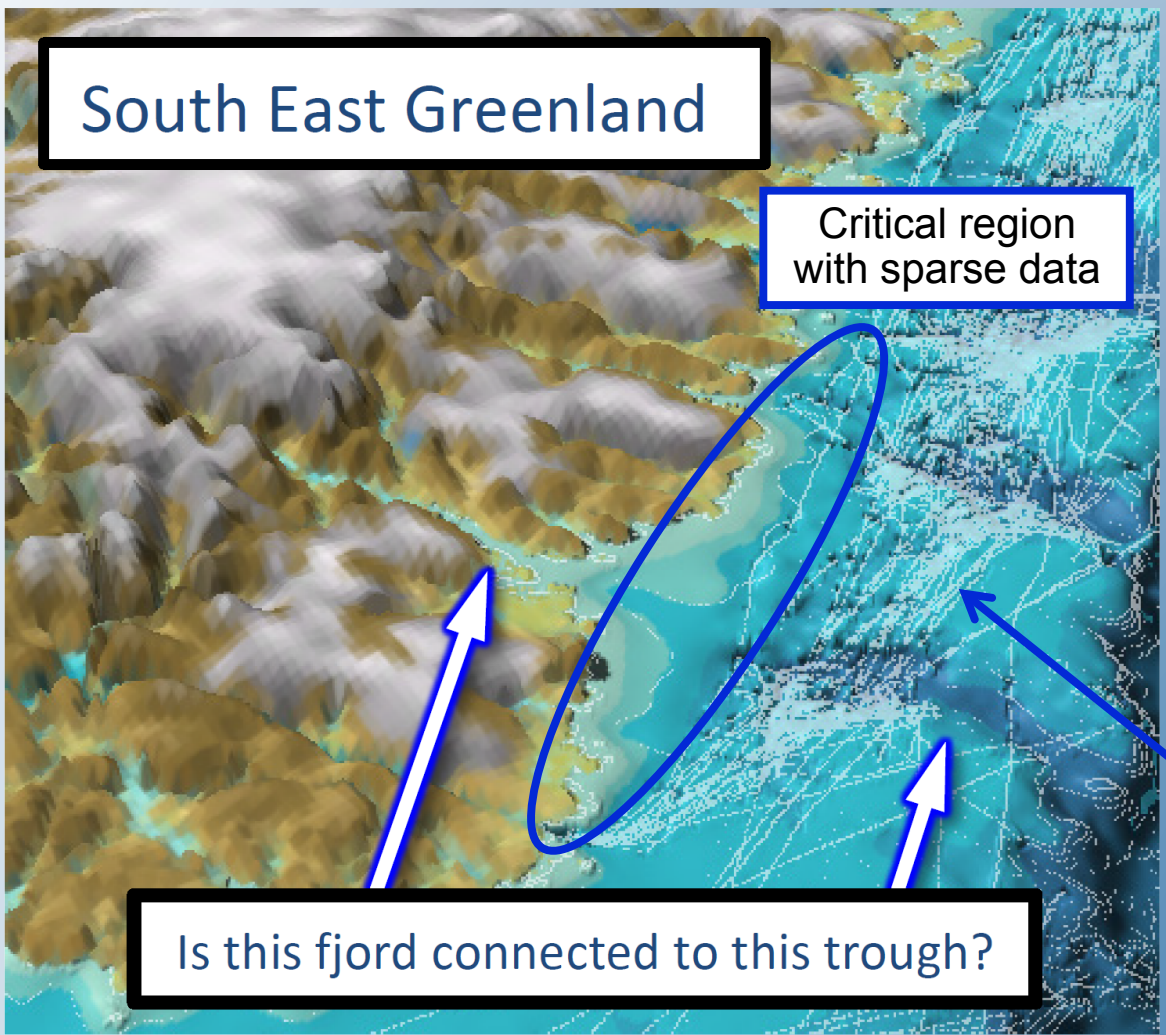

Temperature and Seafloor Depths along Track




- Temperature data from Uummannaq Fjord in Western Greenland. The water at 400 m is ~3°C warmer than the surface water. This warm, subsurface layer spread 150 km into the fjord.

*(Figure I. Fenty )*

# Caveat: The Unknown Shape of the Sea Floor




*(Bathymetry from Becker et al., 2009)*

The shape of the sea floor (bathymetry) determines whether warm water from the shelf can enter the fjord and increase ice loss at the glacier terminus

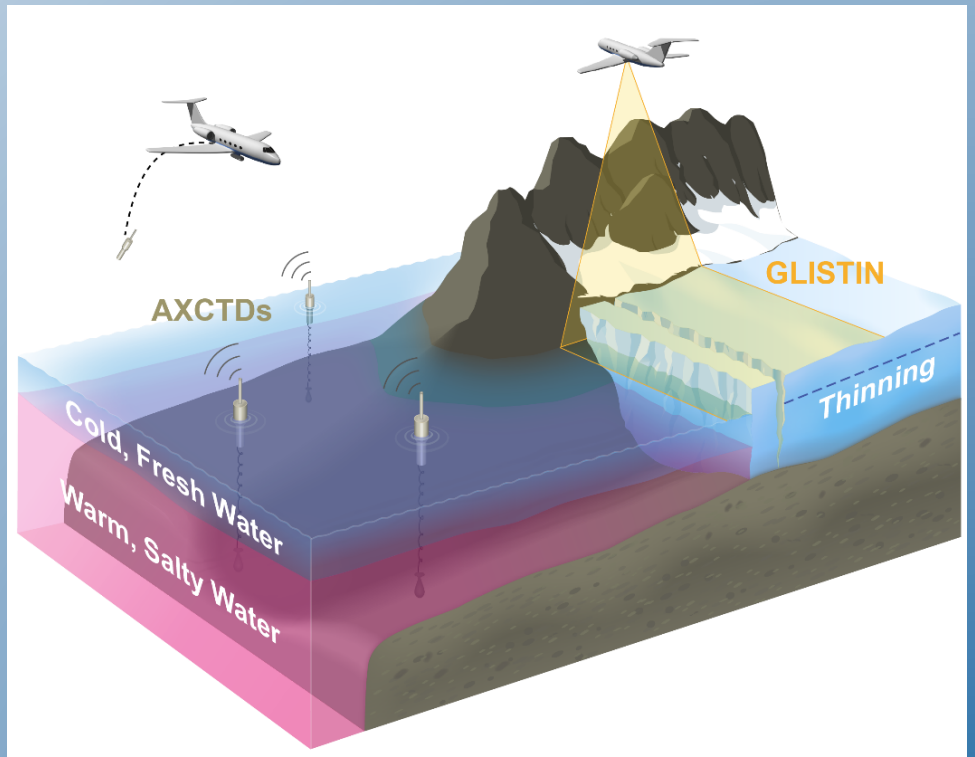
Small dots show locations of existing depth measurements

# OMG's observational components:

1) Three years of oceanographic observations above the continental shelf from airplane-deployed probes.

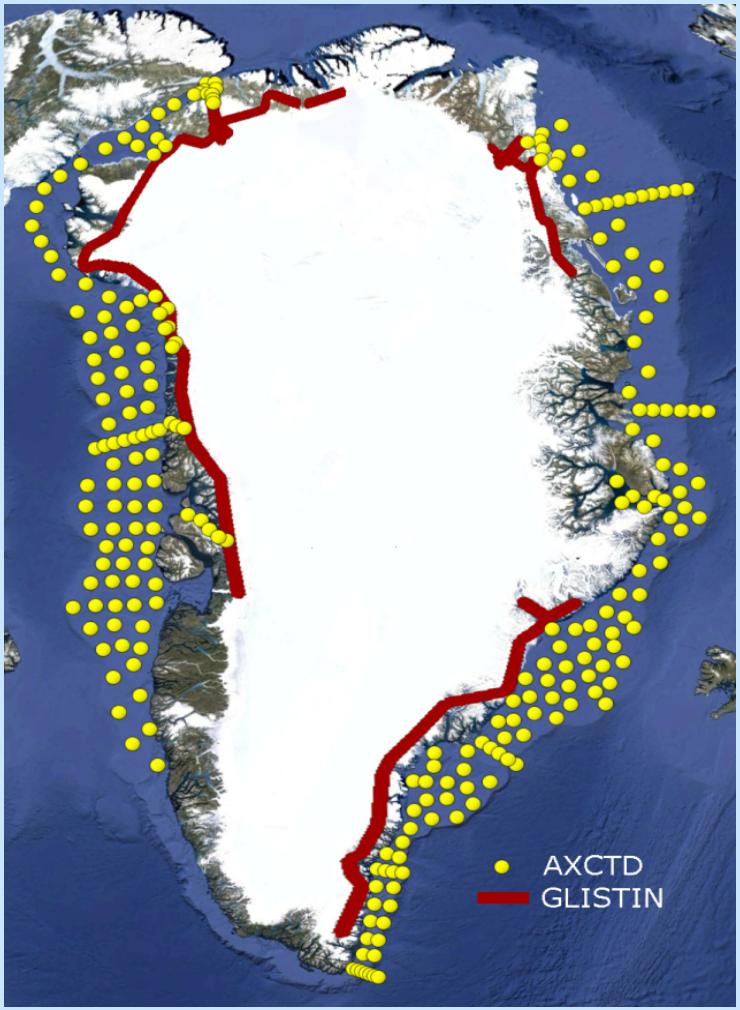
2) Three years of elevation changes of glaciers near their termini using airborne radar.

3) A one-time survey of seafloor geometry on the continental shelf using a airborne gravimetery and ship-based sonar.



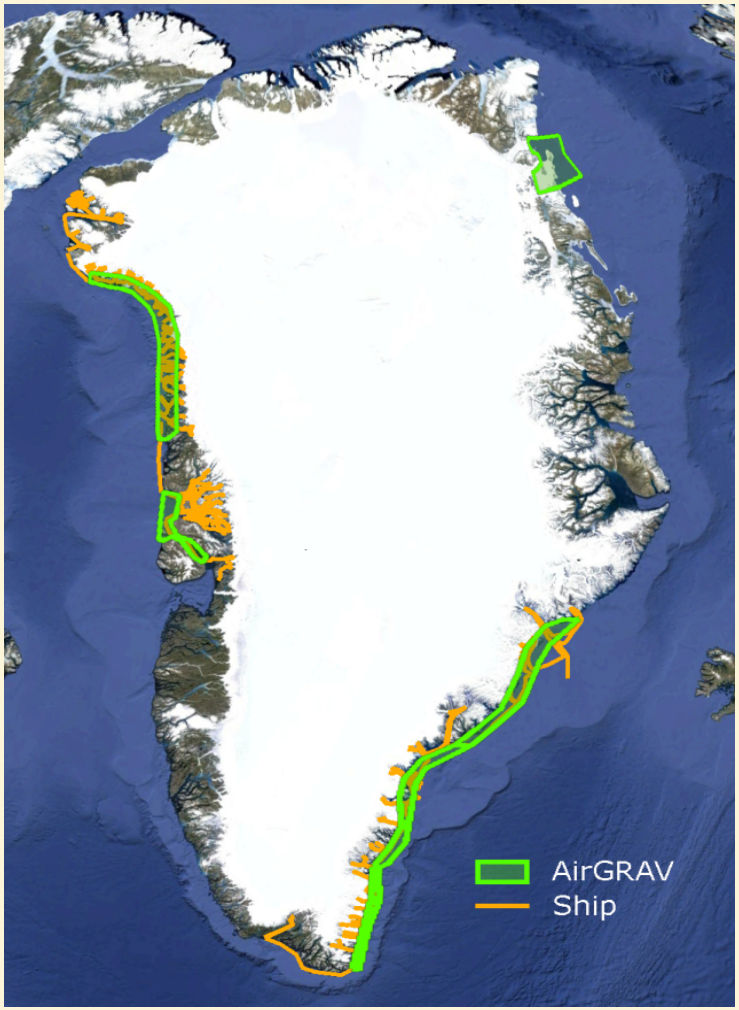
# OMG Observations

## Ocean & Ice




Once per year surveys

## Sea Floor

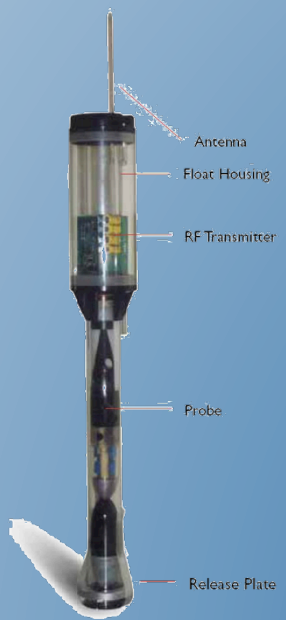


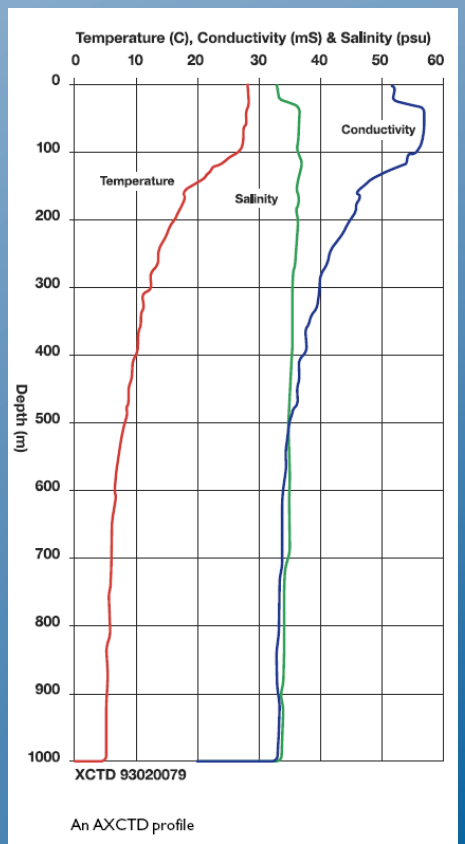

Contracted non-repeat surveys

# AXCTD Probes

- Aircraft eXpendable Conductivity Temperature Depth Probe (AXCTD)
  - Air-launched expendable probes
  - 1000 m depth range
  - FM radio transmission of data to aircraft
  - deployment of 250 probes in a selected grid patter

The placement of the probes is selected to provide a mapping of the volume and extent of Atlantic water around Greenland




An AXCTD profile

# GLacier and Ice Surface Topography INterferometer–Airborne


- airborne synthetic aperture radar altimeter
- high resolution, high-precision height maps of Greenland's coastal glaciers
- survey a 12km swath around the perimeter
- determine the annual changes in glacier topology
- <50 cm vertical precision at 25m horizontal resolution

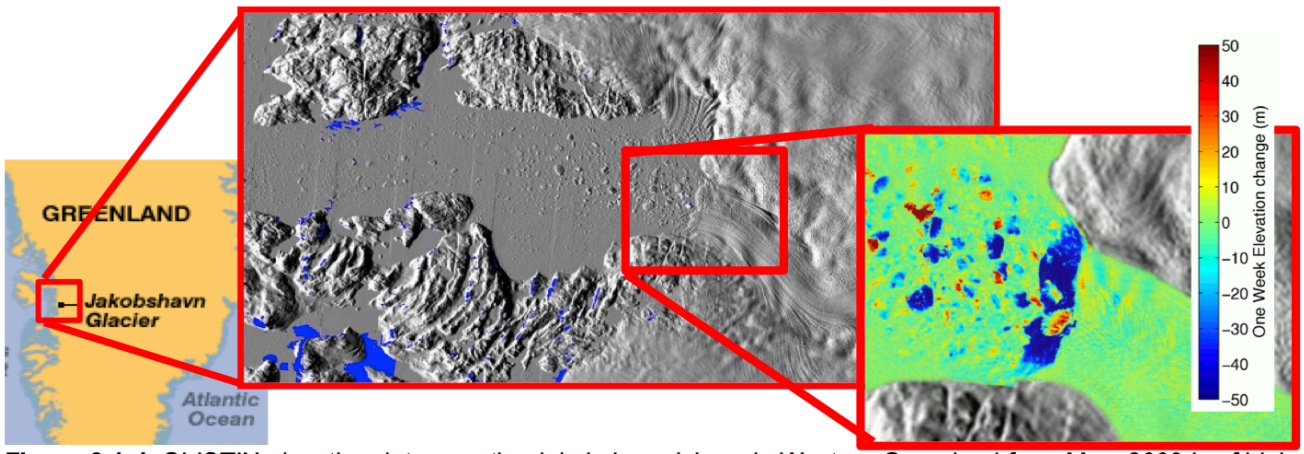



**Figure 2.1-4.** GLISTIN elevation data over the Jakobshavn Isbrae in Western Greenland from May, 2009 is of high quality and easily detects important signals. Colors in the inset show the change in elevation after one week. Between surveys a calving event sheared off the last kilometer of the glacier, resulting in the ~50 m drop in elevation illustrated by the large blue patch. The small red and blue patches are due to icebergs circulating in the fjord.

ship-based bathymetry survey area is characterized:

- Fjords with MTGs
- Shelf regions sparsely charted or uncharted
- NW and SE sectors

Multibeam echo sounder [MBES] maps a swath of the seafloor that is approx 3X water depth at sub-meter resolution.

Bathymetry map with horizontal resolution of 50 m and vertical precision of 1 m

Total approx survey length of 5000 nm

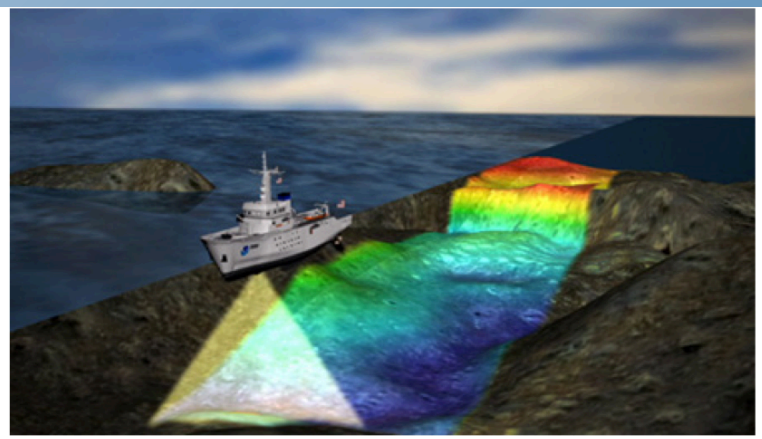


**Figure 3.1-6.** The MBES swath survey operating frequency, total angular swath, individual beam angle width and beam angle spacing will be tailored to meet the science goals of OMG. Image courtesy of NOAA

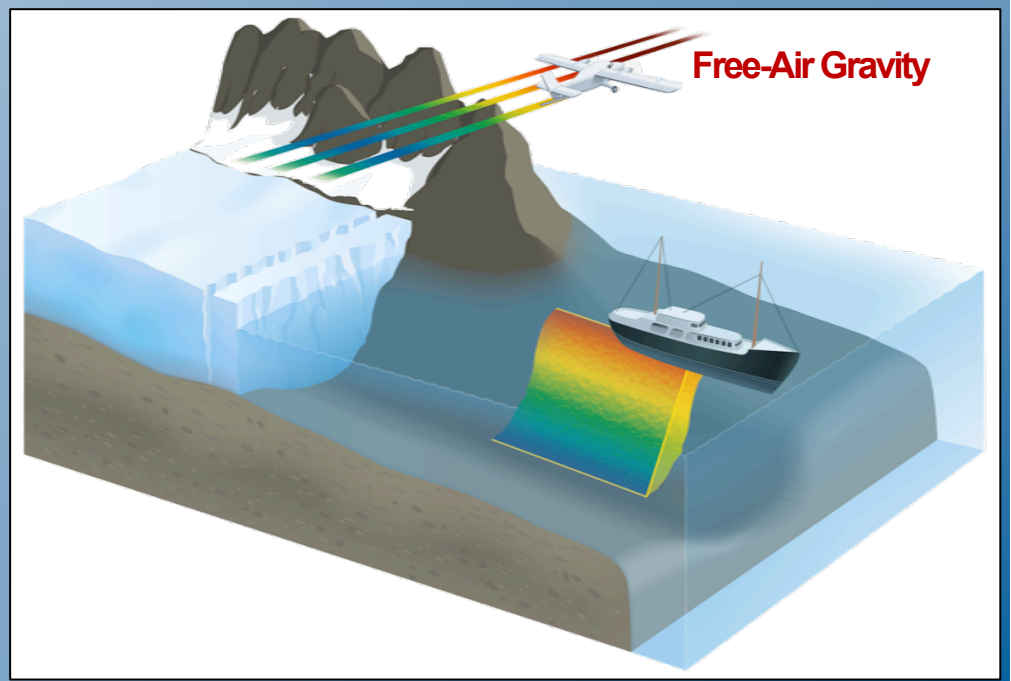
-survey seafloor depth over broader areas on the shelf with gravity survey of the coastline

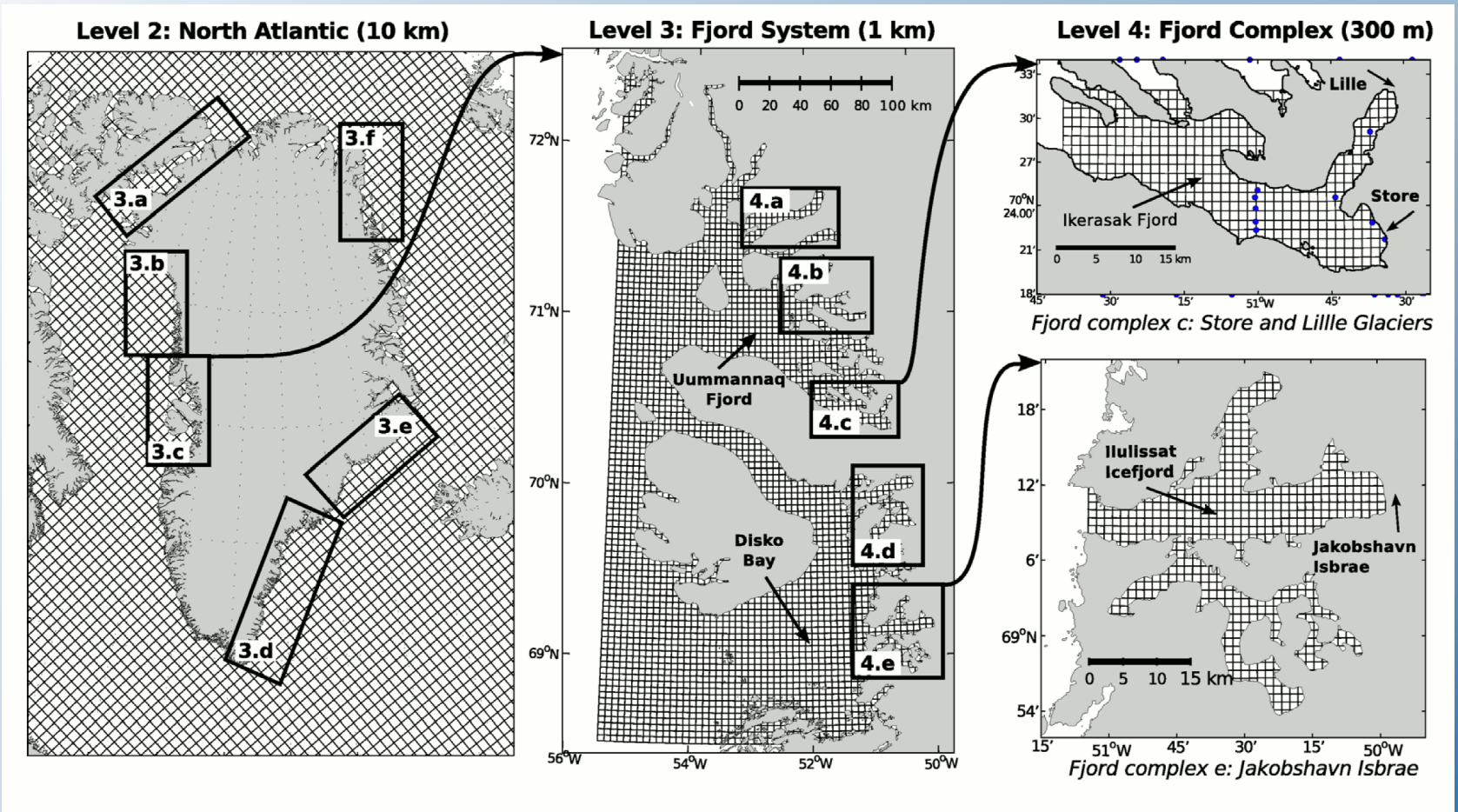
- Sander Geophysics Air-GRAV (used in NASA Operation IceBridge since 2009)

- Gravity precision, measured in milligal (mGal), and resolution depends on the aircraft speed, grid spacing, aircraft altitude, and instrument errors.

- bathymetry map with horizontal resolution of 1.5 km and a vertical precision of 100 m.

This is sufficient to identify major troughs extending from glacial fjords mapped with swath bathymetry and is also of sufficient precision and resolution for numerical ocean models.



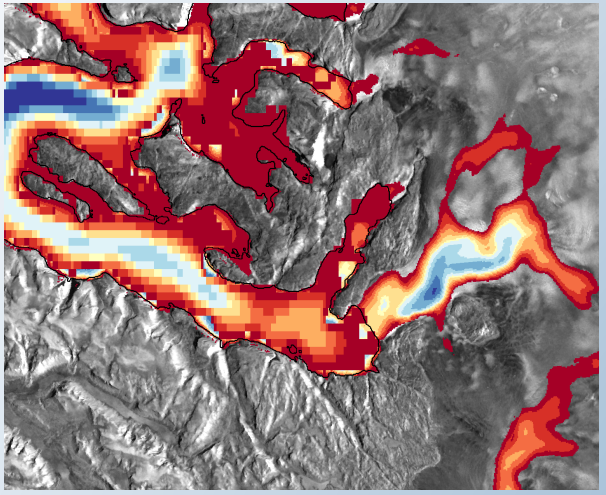



To understand how the oceans carry heat to the fjords, we need to run numerical simulations.

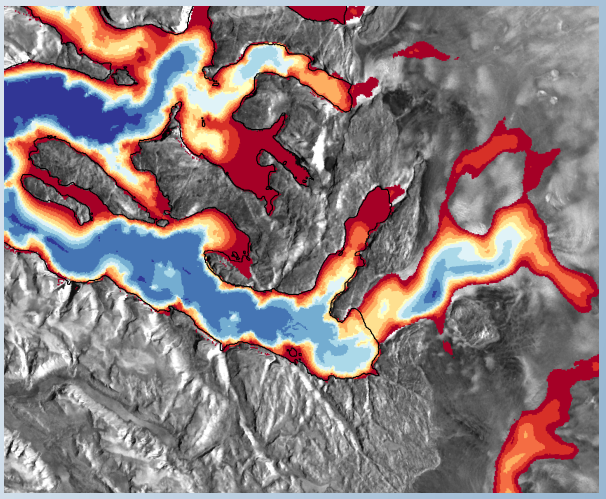
**OMG**: Downscale existing models to the reach the fjords

# OMG: First Season, First Results – multibeam and CTD survey (Jul 24 – Aug 19, 2015)

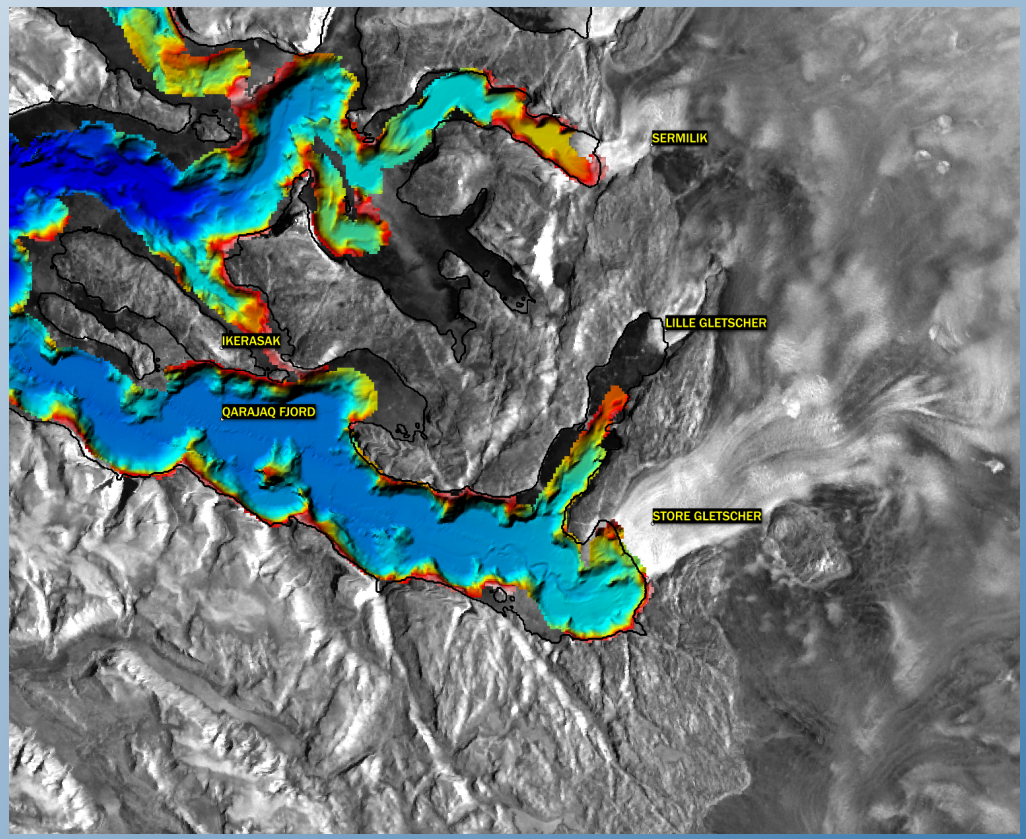
Existing bathymetry and bedrock



OMG bathymetry and bedrock

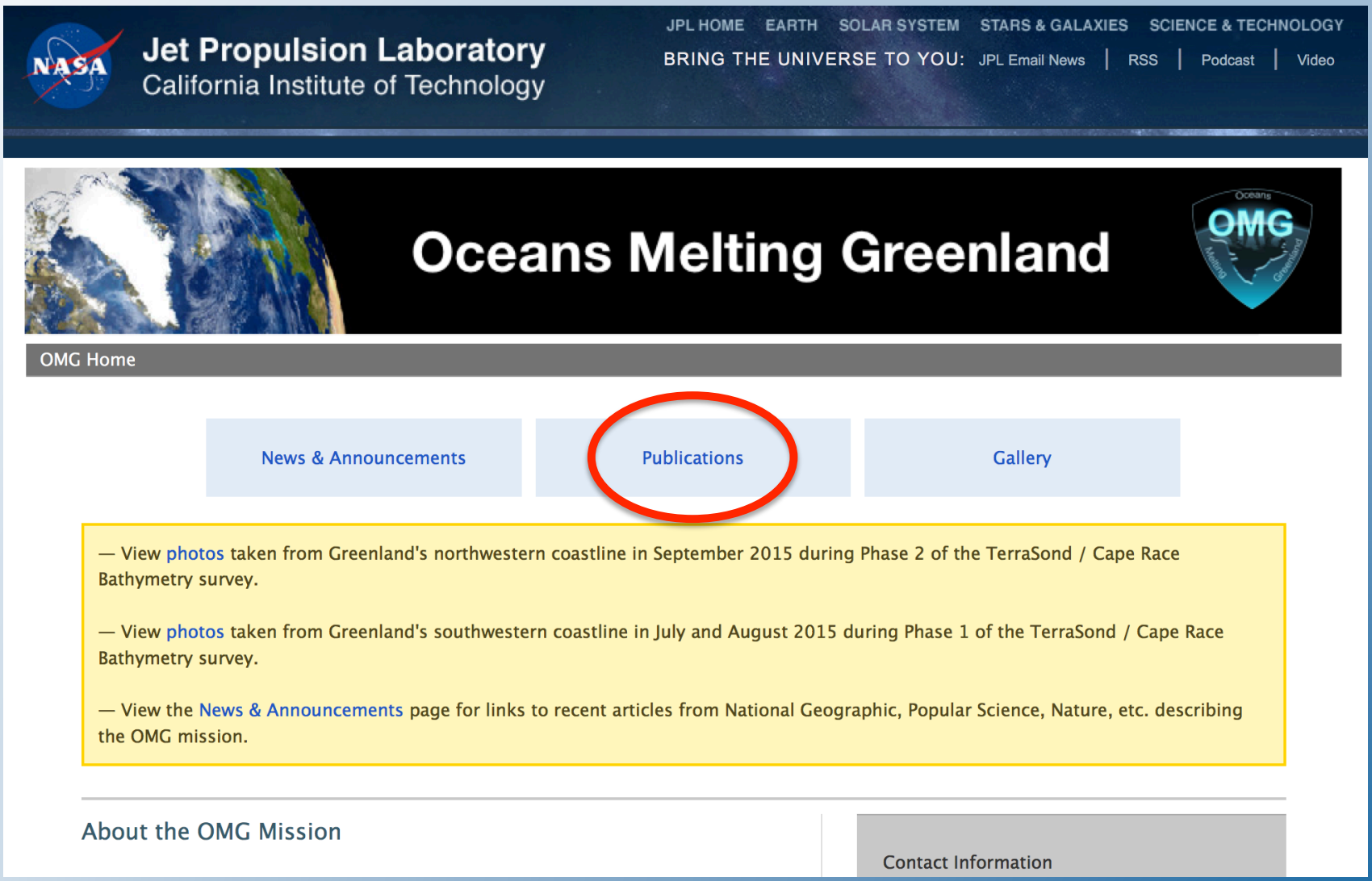


Store Glacier




Bathymetry data:

- OMG website
- Wait for new IBCAO data set

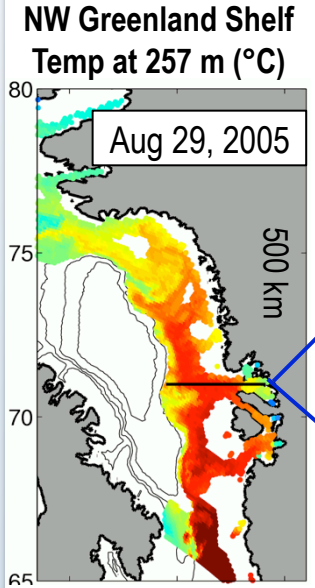


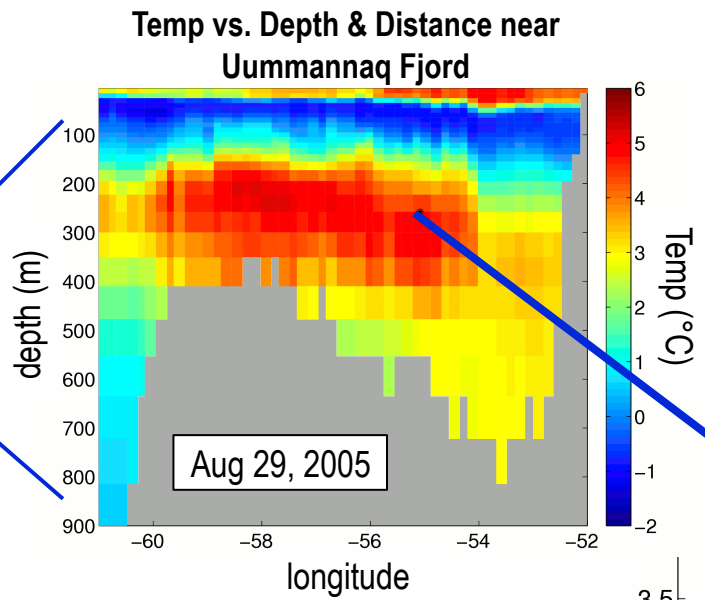

http://omg.jpl.nasa.gov


Thank You

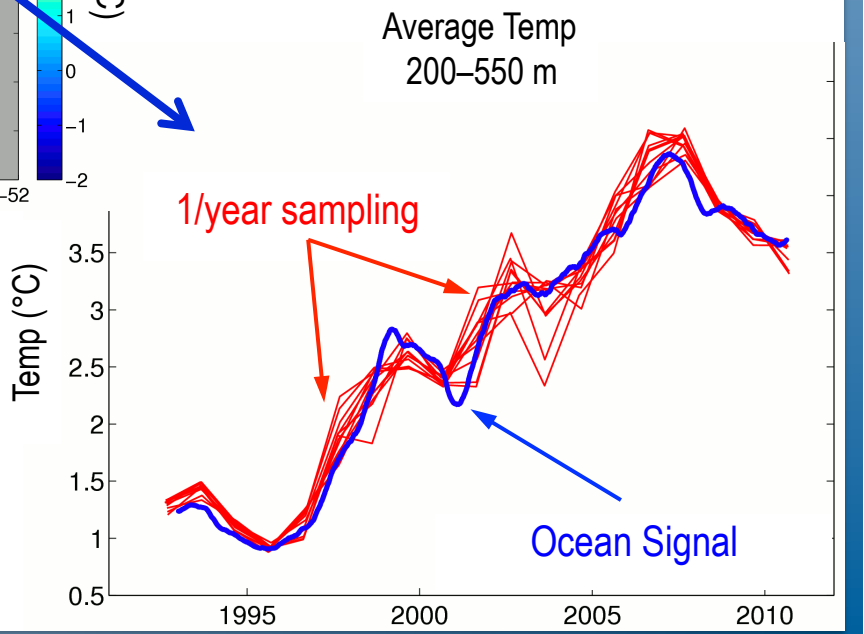
# Is Once Per Year Enough?

## ECCO-2 Ocean Model




- Ocean signal is clearly interannual on the shelf and in some fjords




***OMG: Survey shelf once per year with ~50 km spacing***