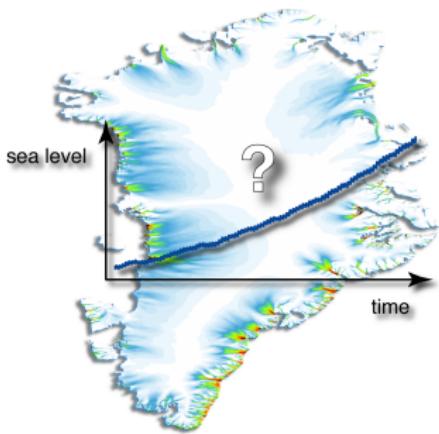
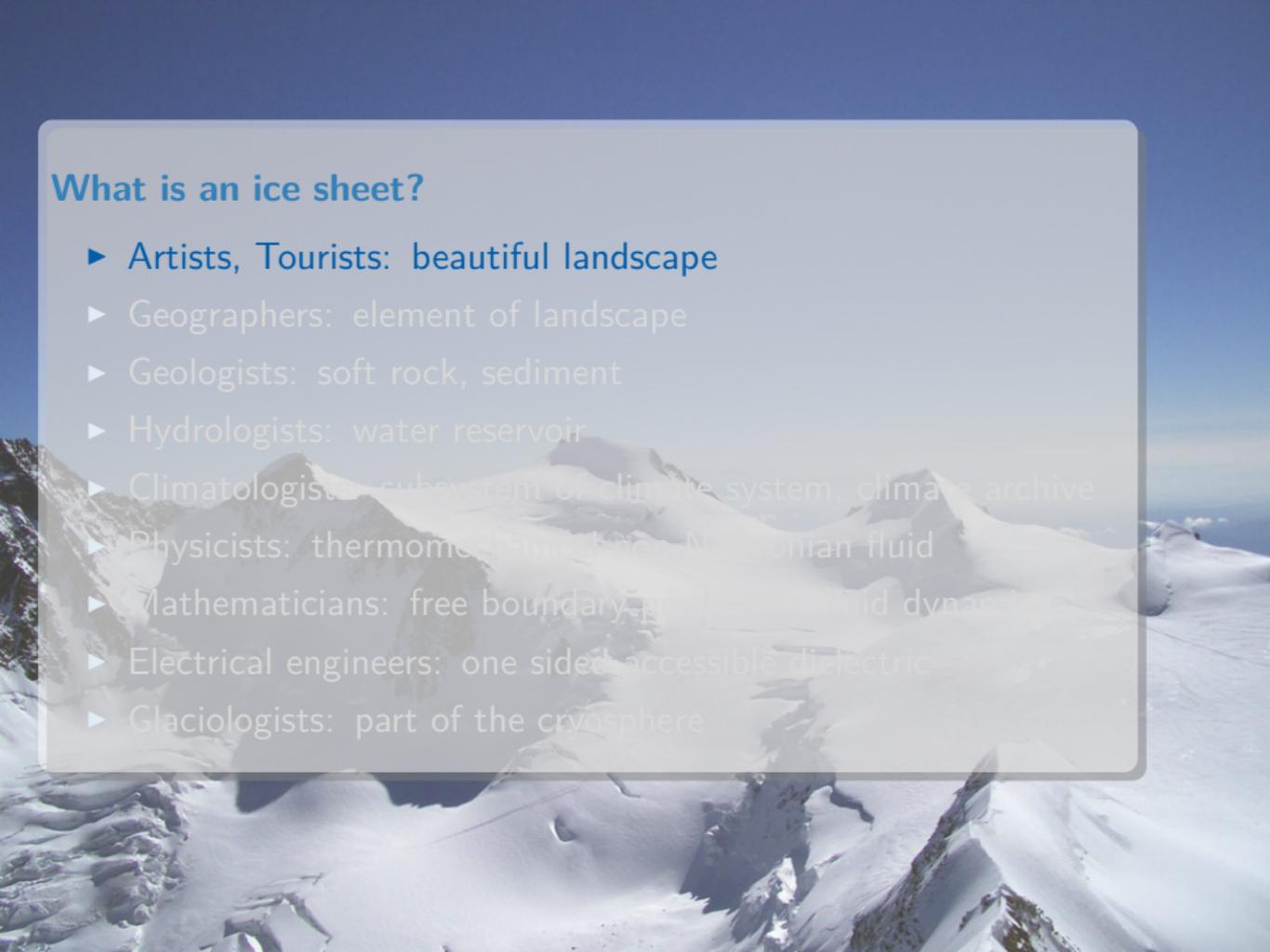


# Understanding ice sheets through observations and models

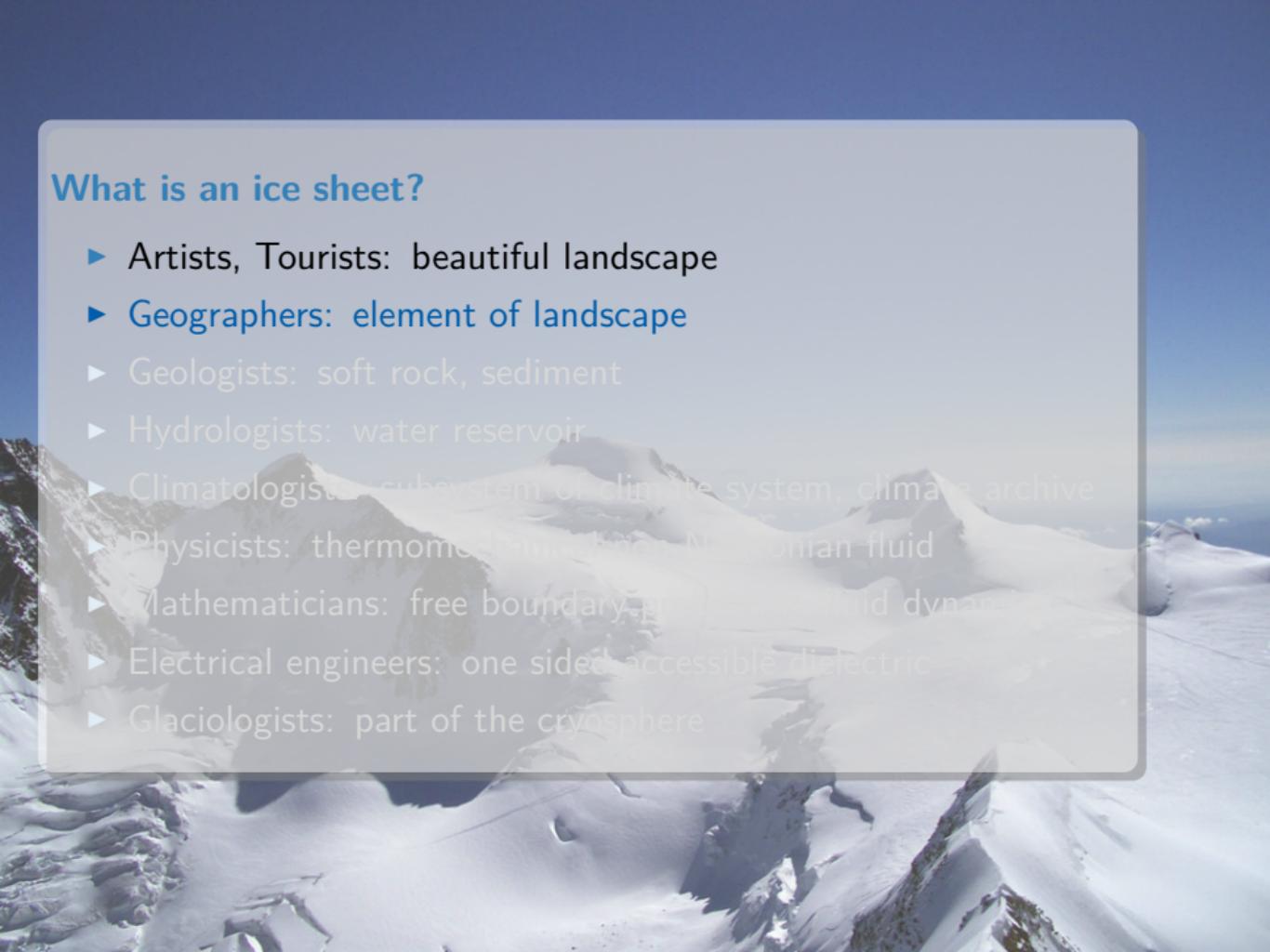
Andy Aschwanden





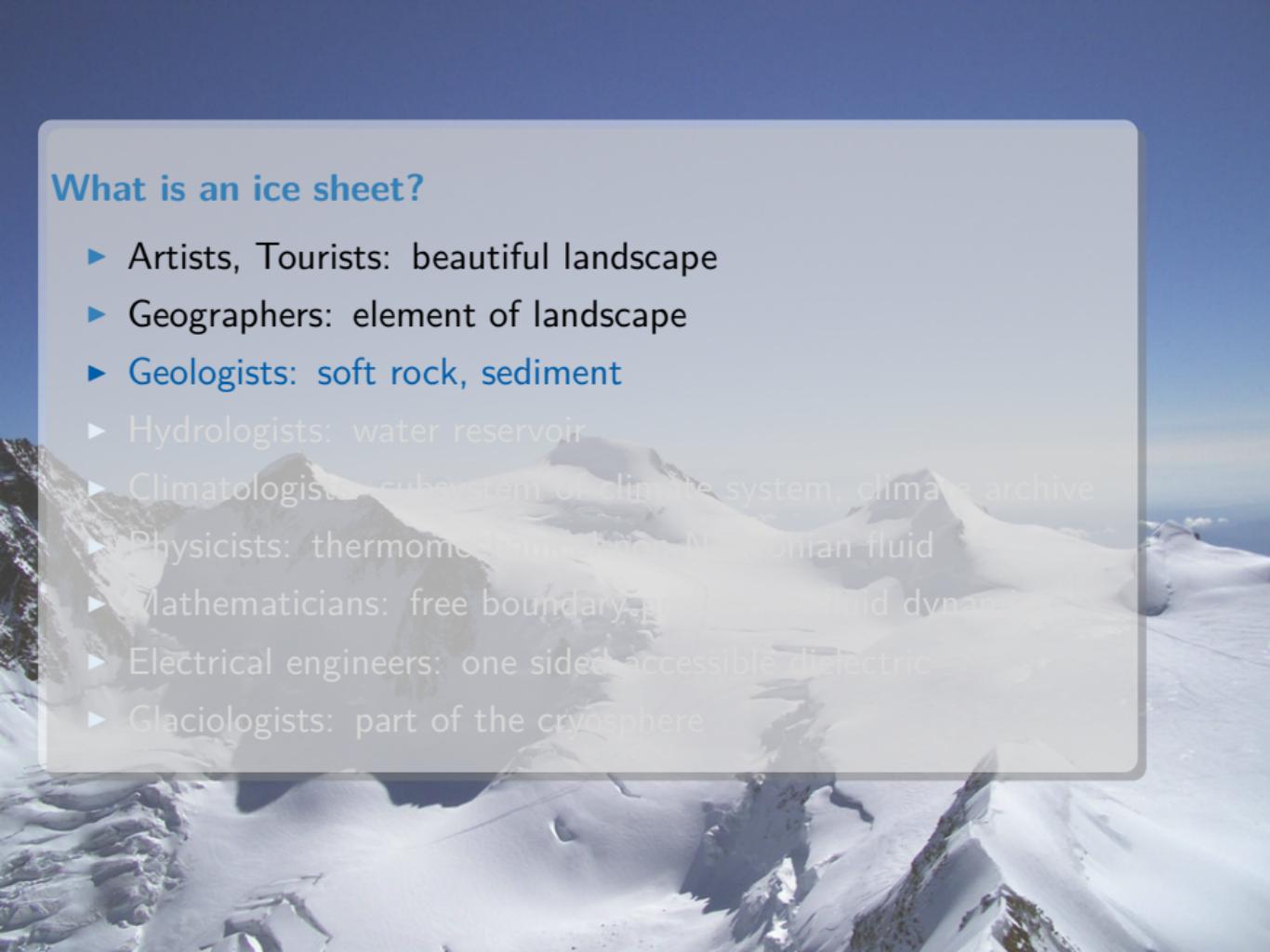
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- ▶ Climatologists: subsystem of climate system, climate archive
- ▶ Physicists: thermodynamics of a non-Newtonian fluid
- ▶ Mathematicians: free boundary problem, fluid dynamics
- ▶ Electrical engineers: one sided accessible dielectric
- ▶ Glaciologists: part of the cryosphere



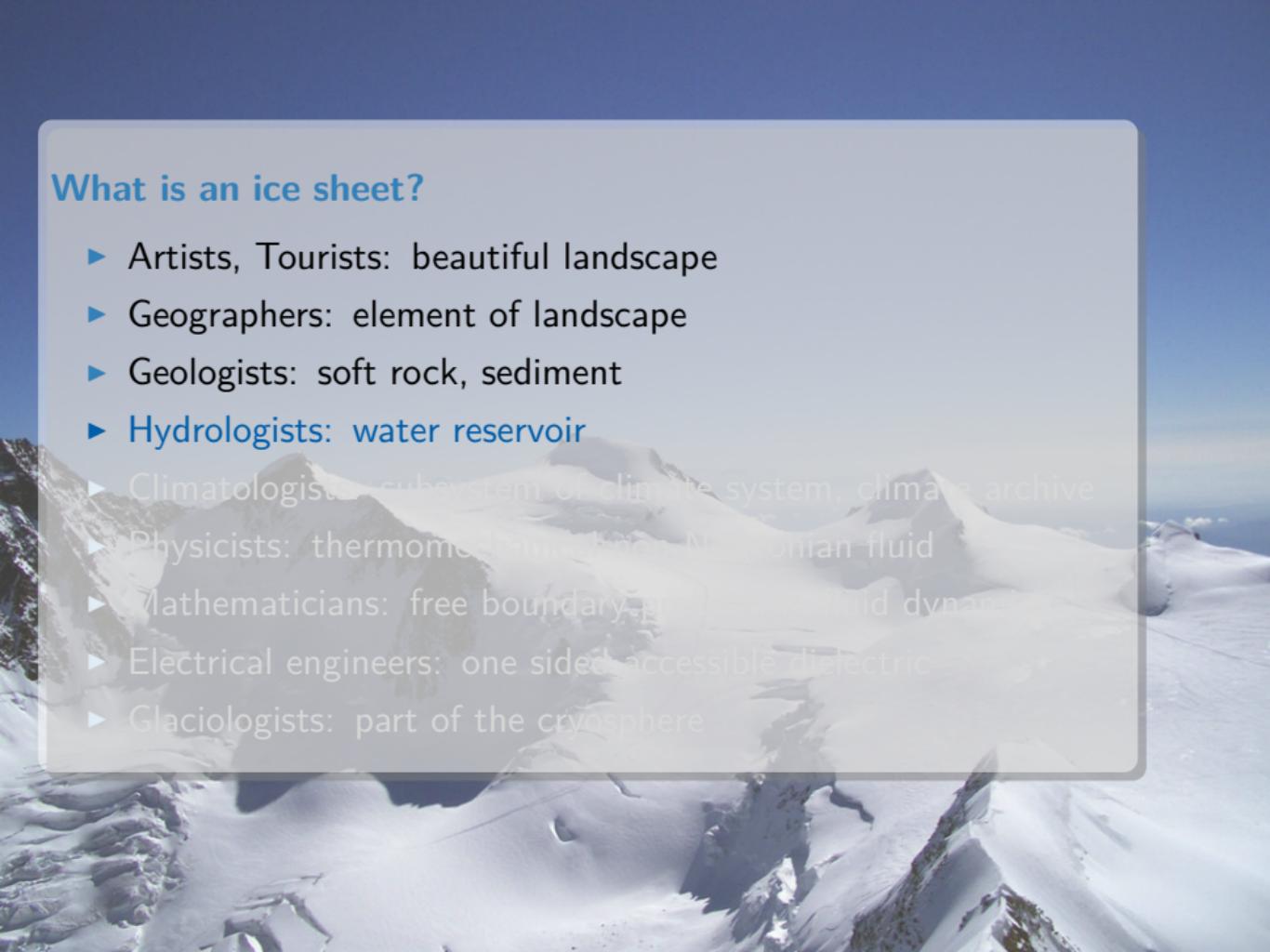
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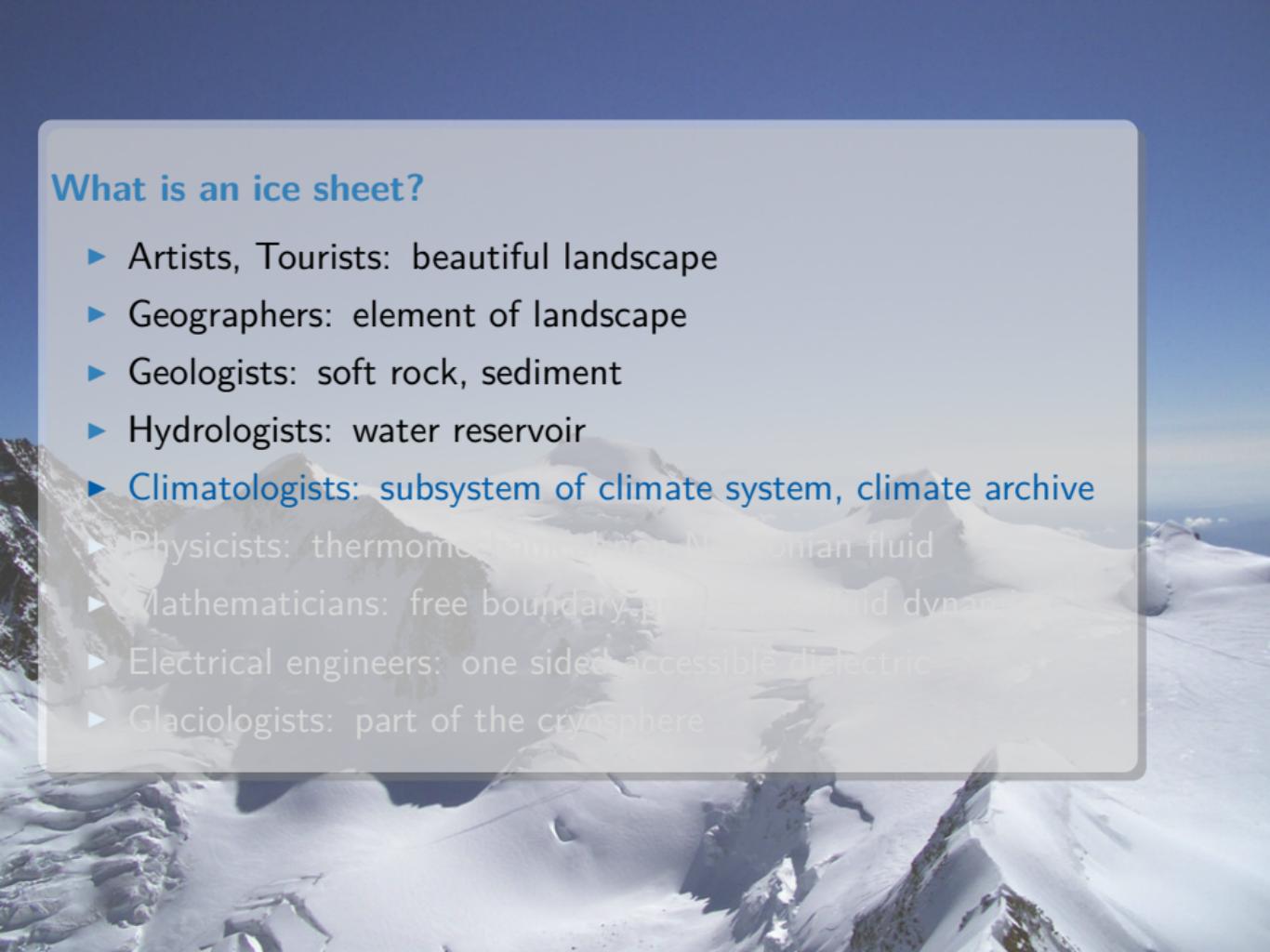
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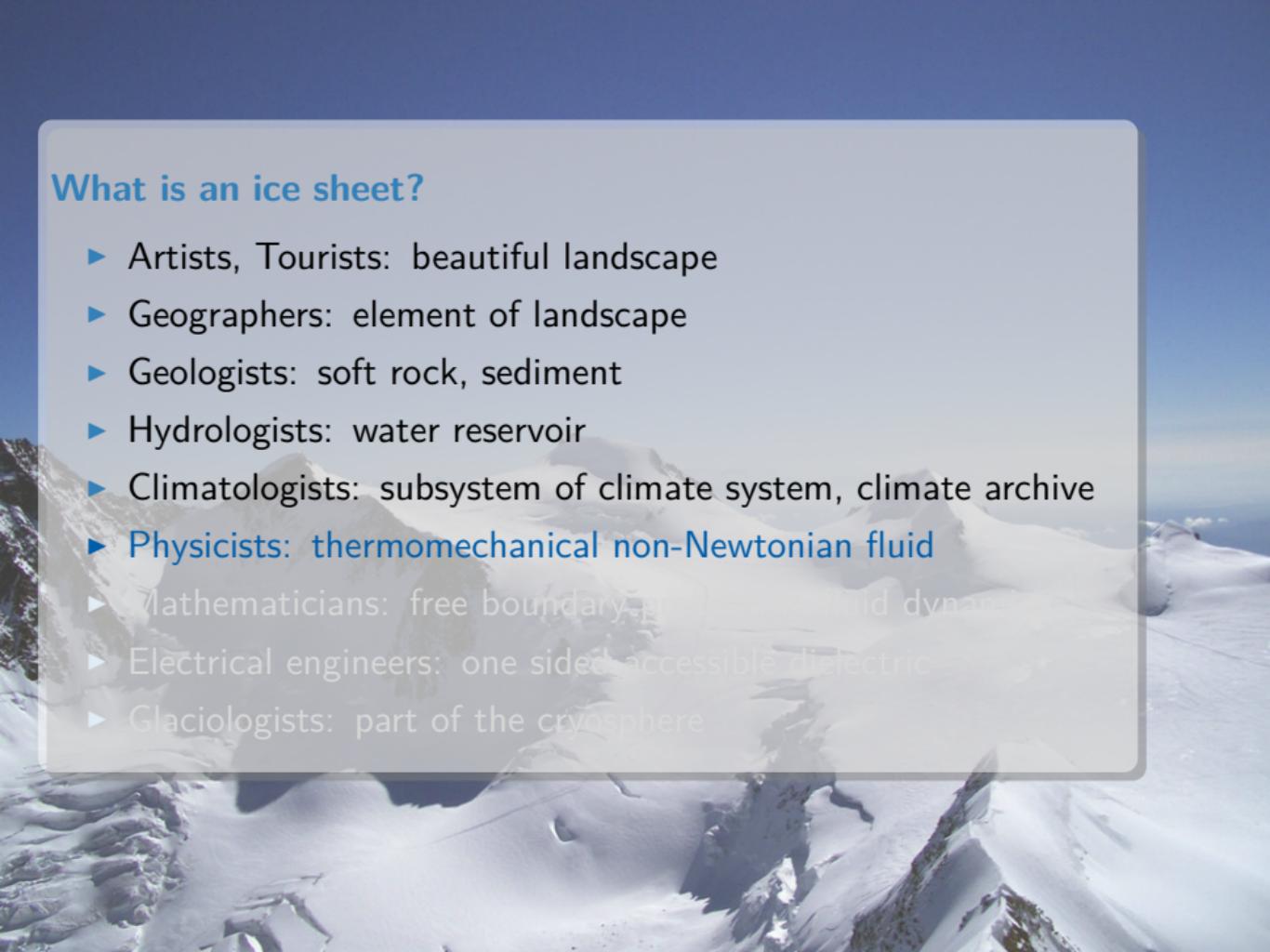
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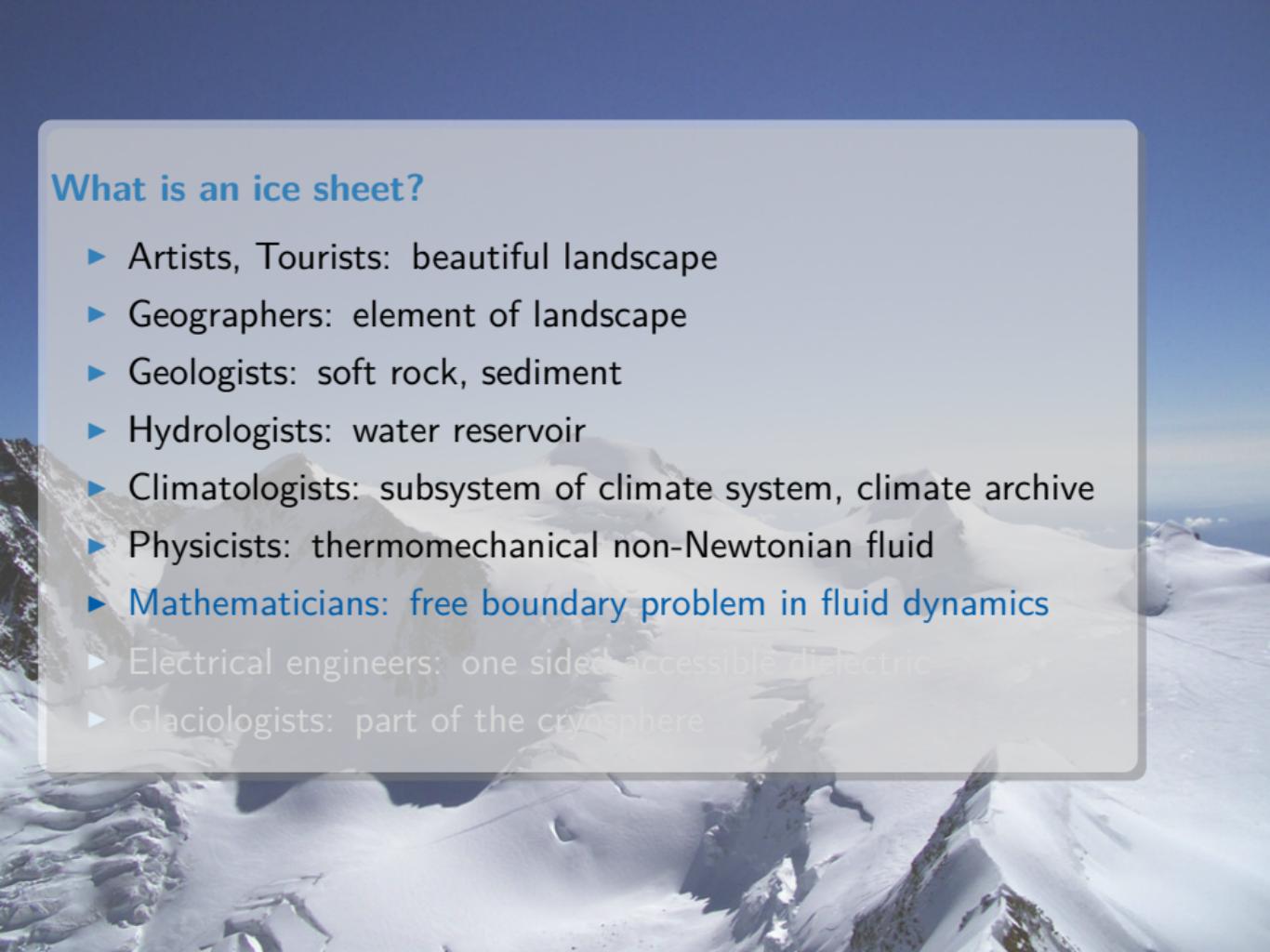
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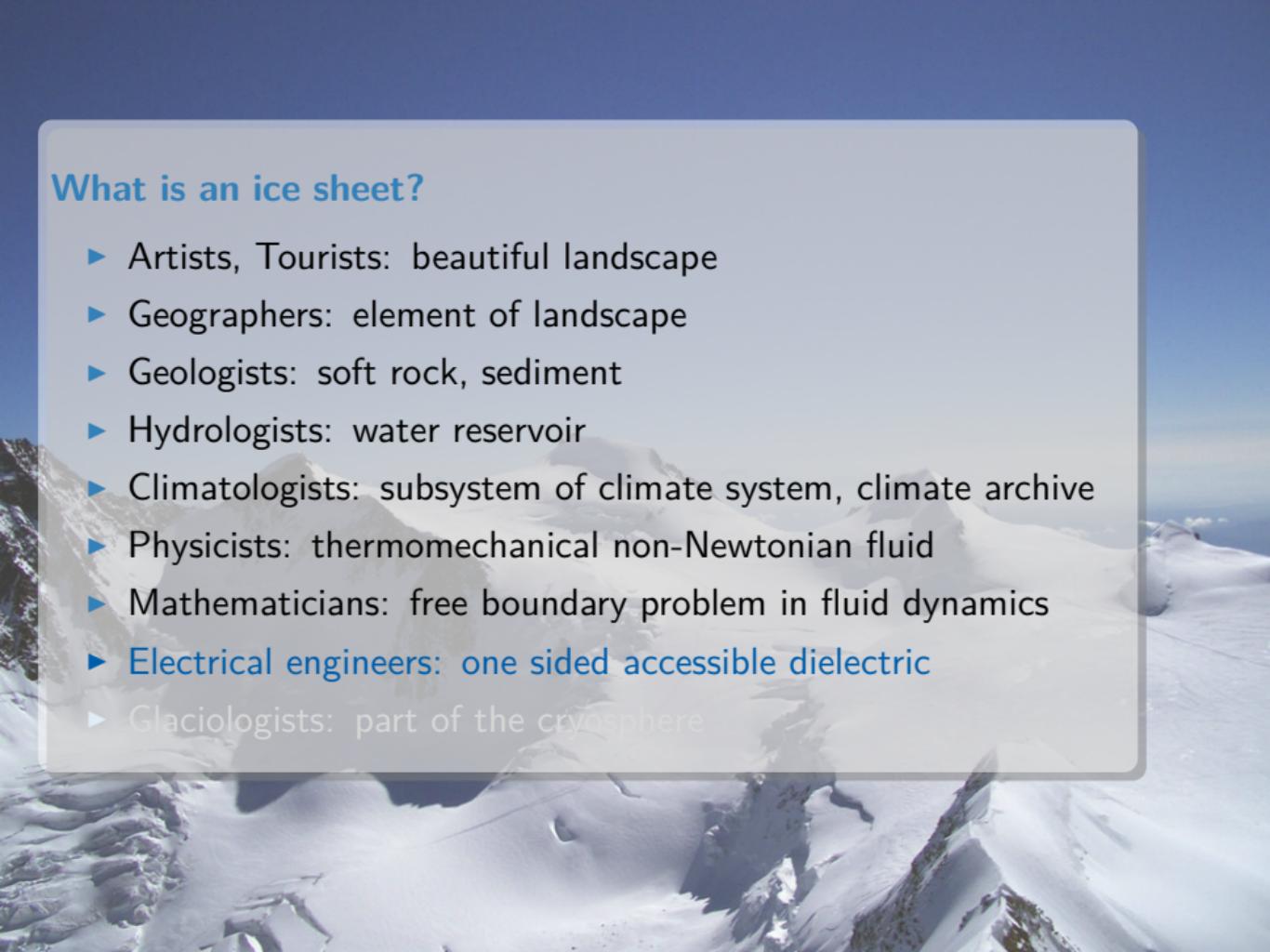
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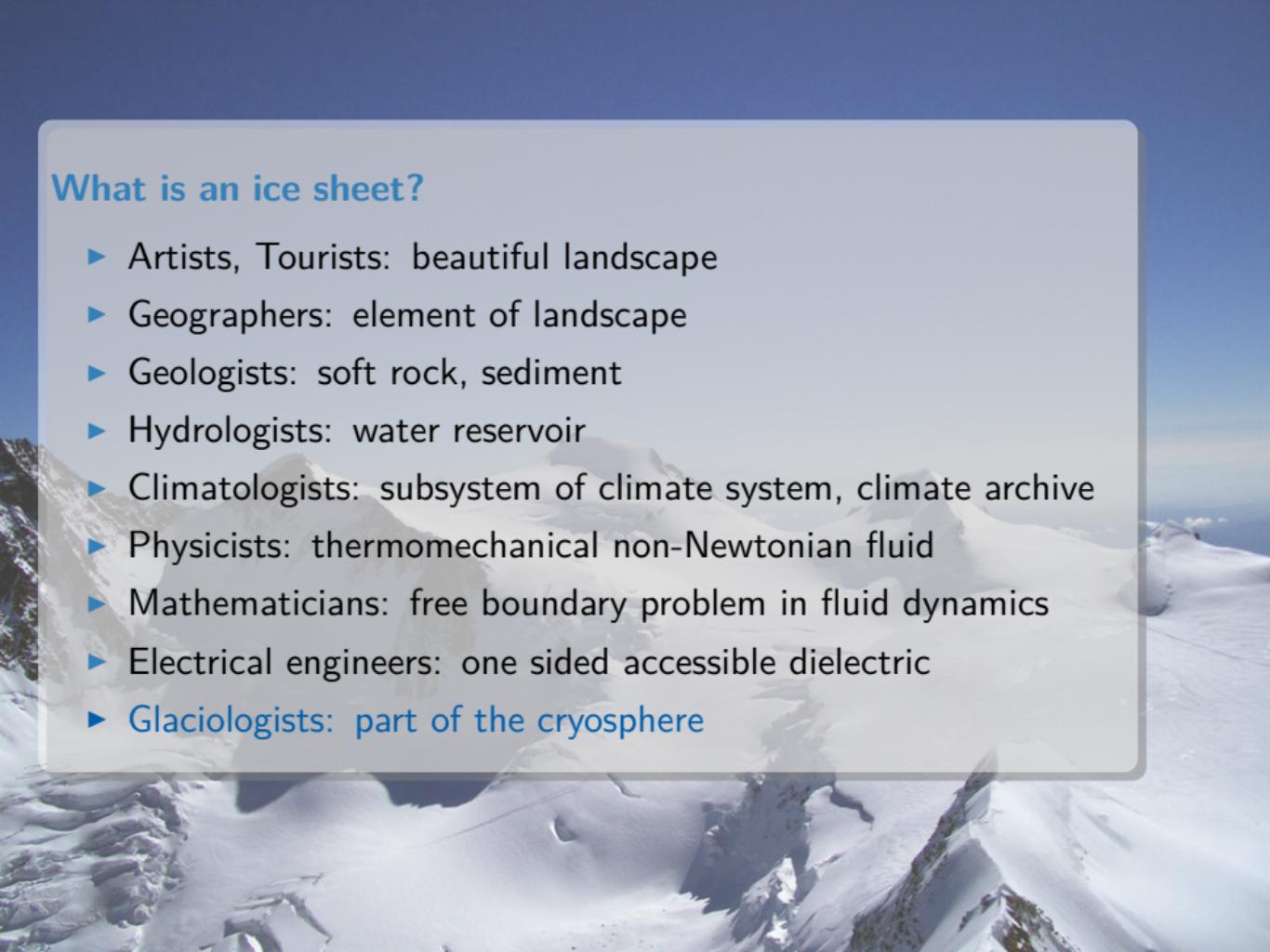
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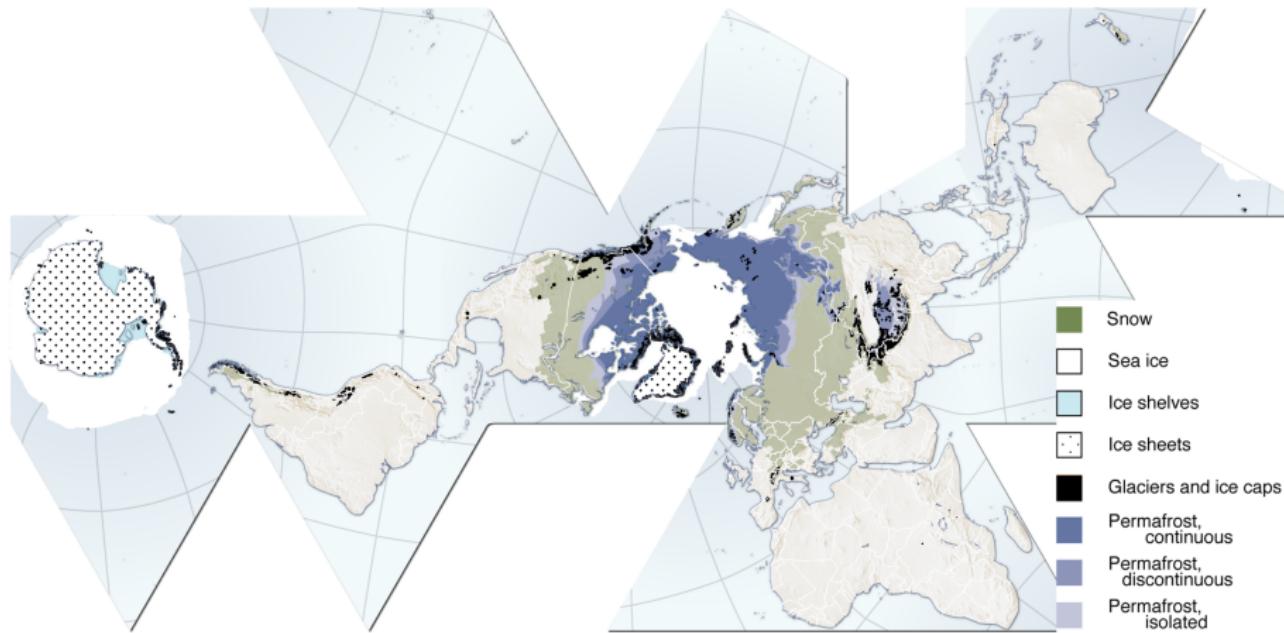
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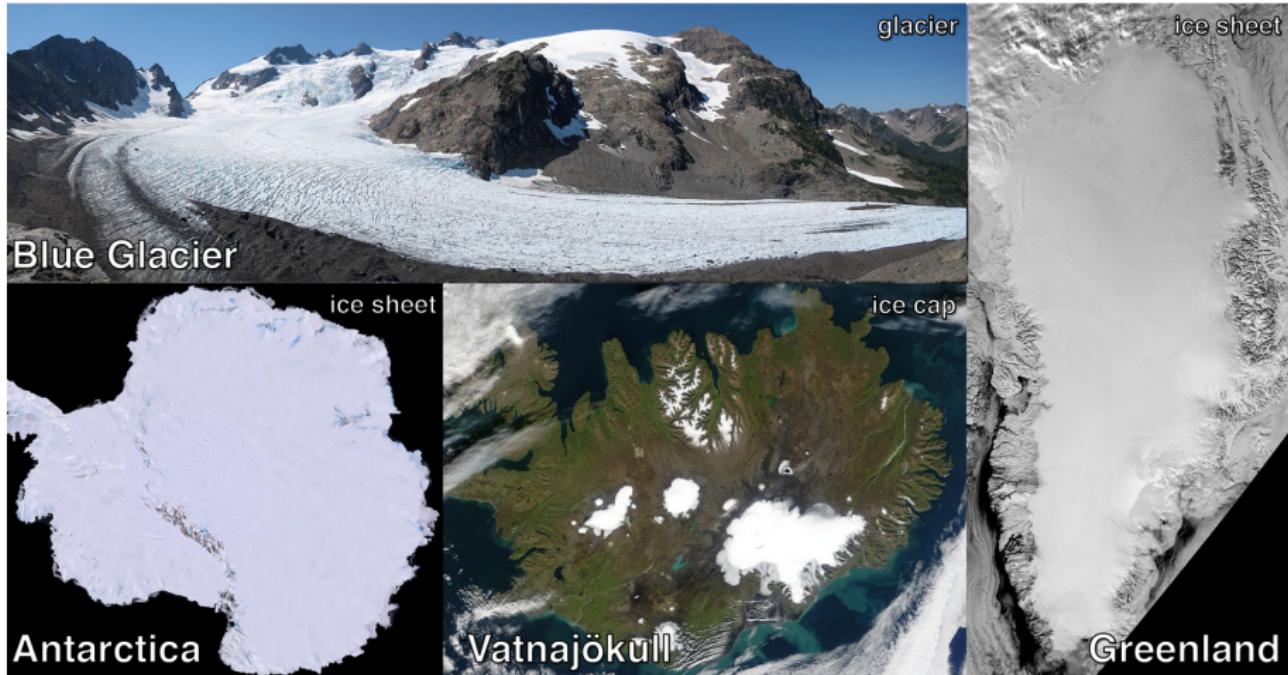
# The Cryosphere



source: UNEP Outlook for Ice Sheets

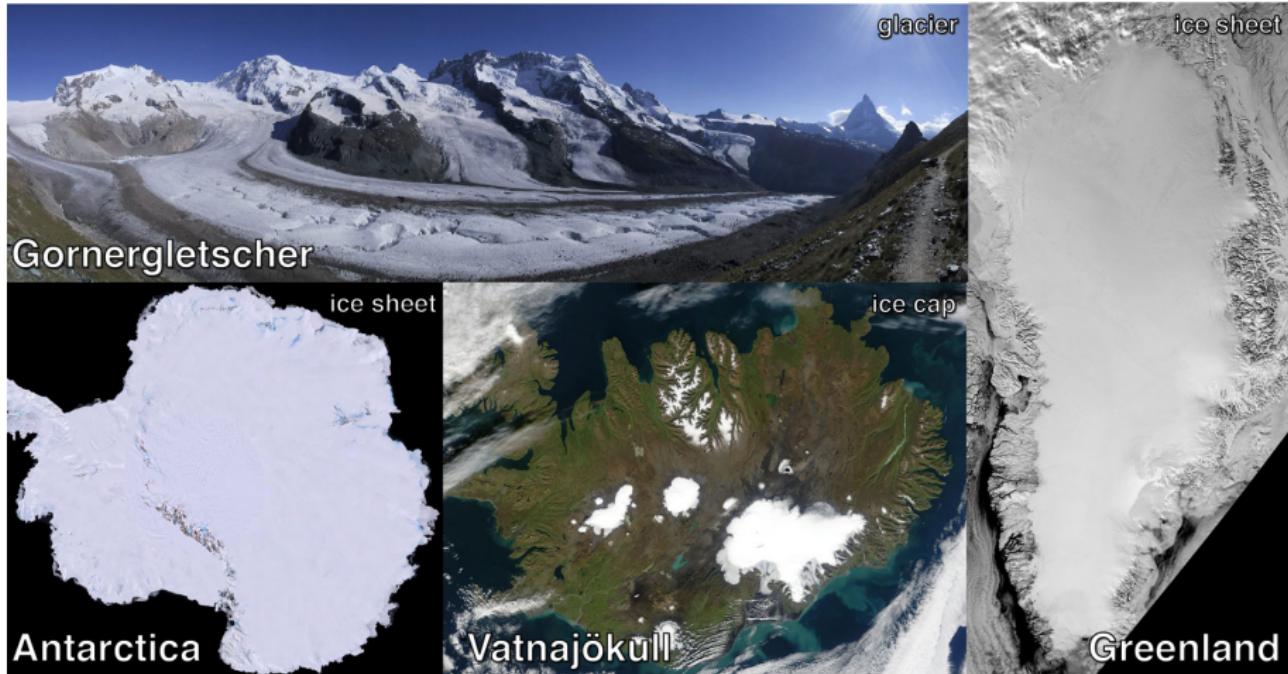
land ice = { ice sheets, ice caps, glaciers}

# Land ice



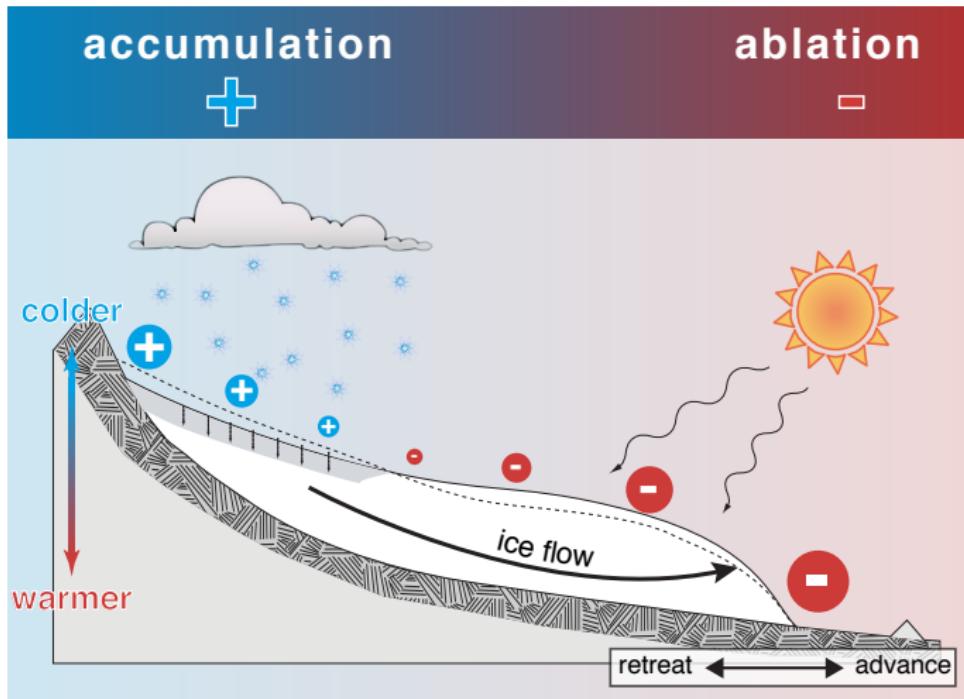
not to scale

# Land ice



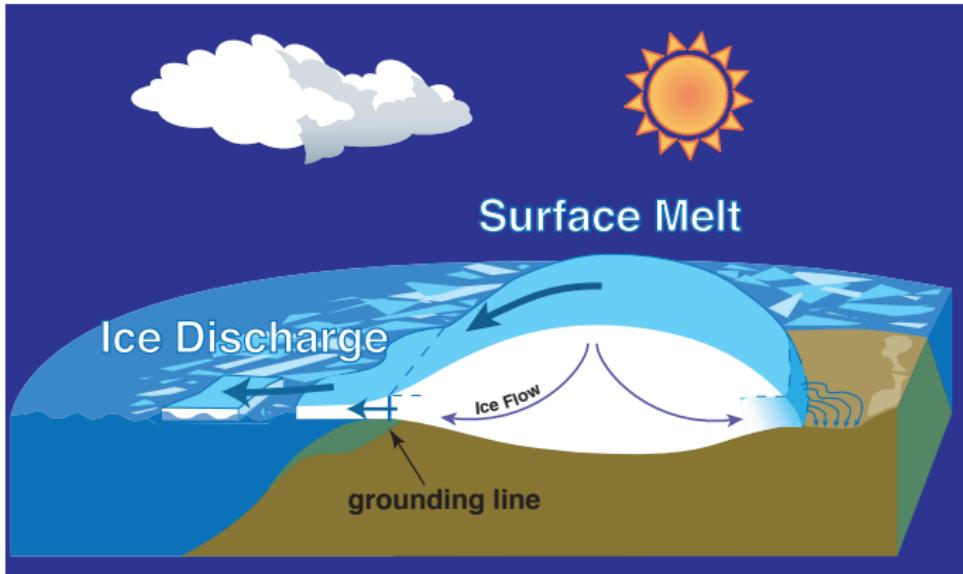
not to scale

# Glacier response to climate



- ▶ glaciers can adjust to changes in climate ⇒ stable

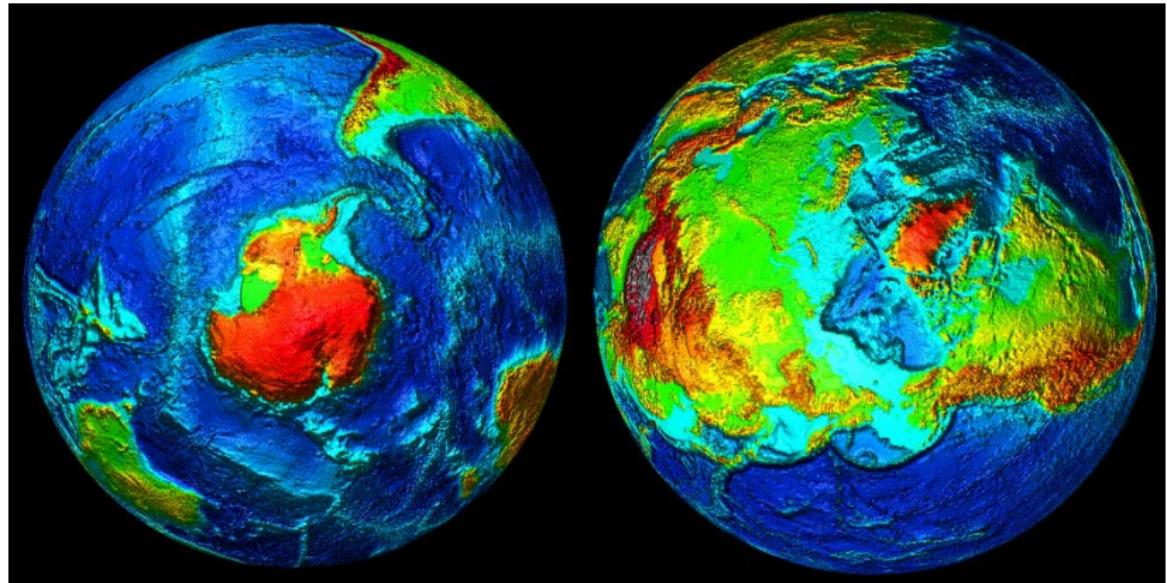
# Ice sheet response to climate



modified from ICESat brochure

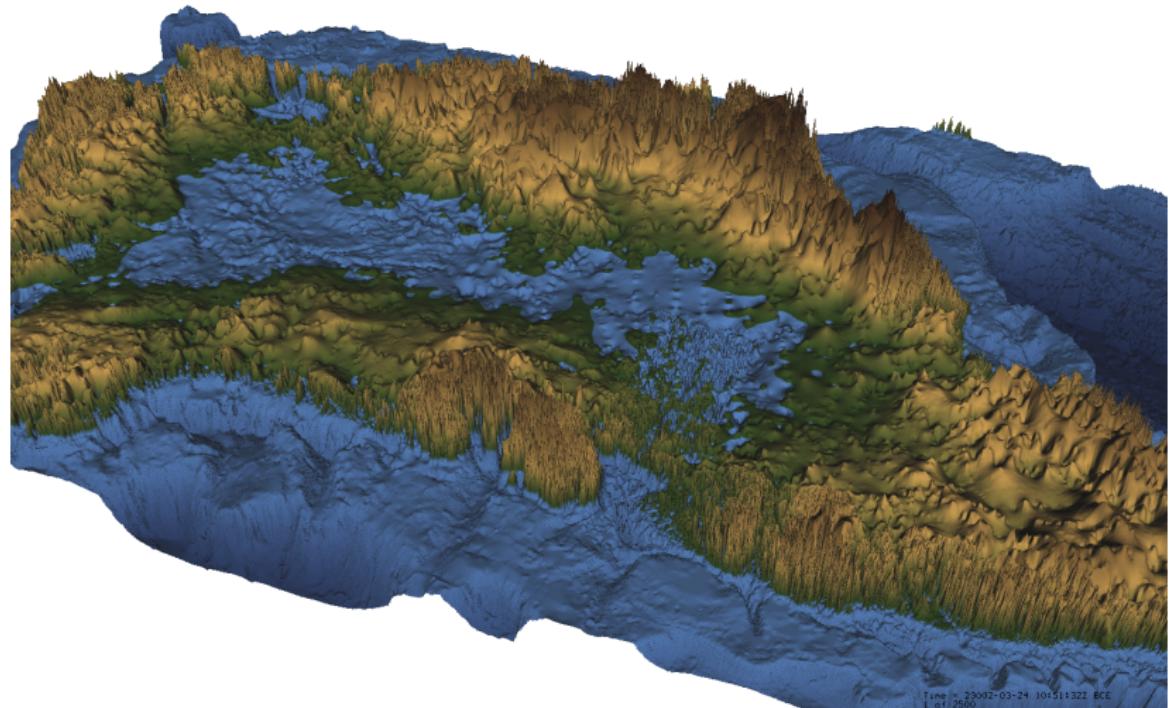
- ▶ **ice discharge:** vertically-averaged horizontal flow velocity  $\times$  ice thickness
- ▶ 50/50 split for Greenland
- ▶ mostly ice discharge for Antarctica

## Ice sheets really stick out

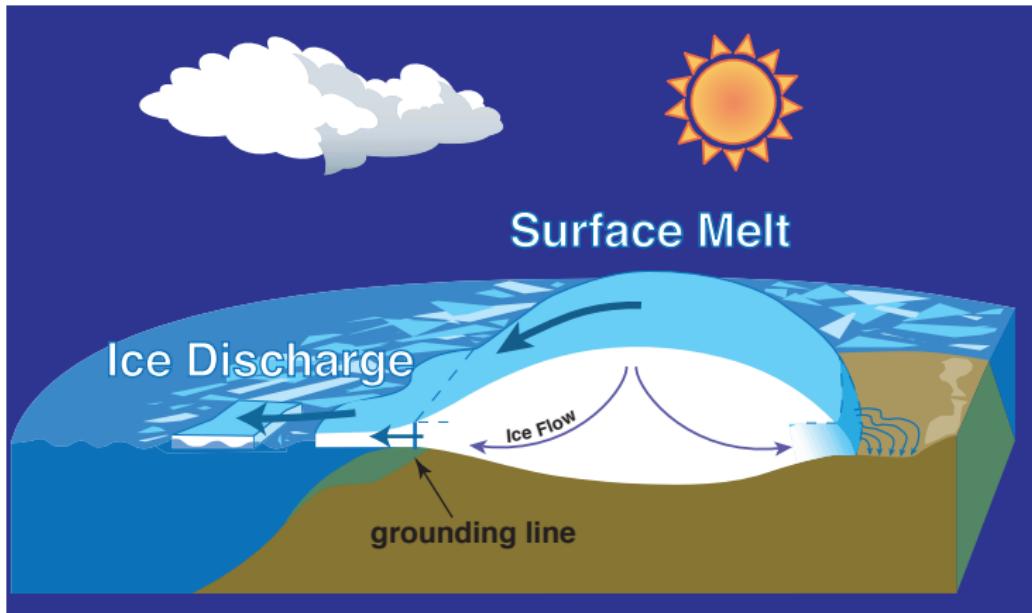


- ▶ ice sheets rise high enough to create their own weather

# Build your own ice sheet



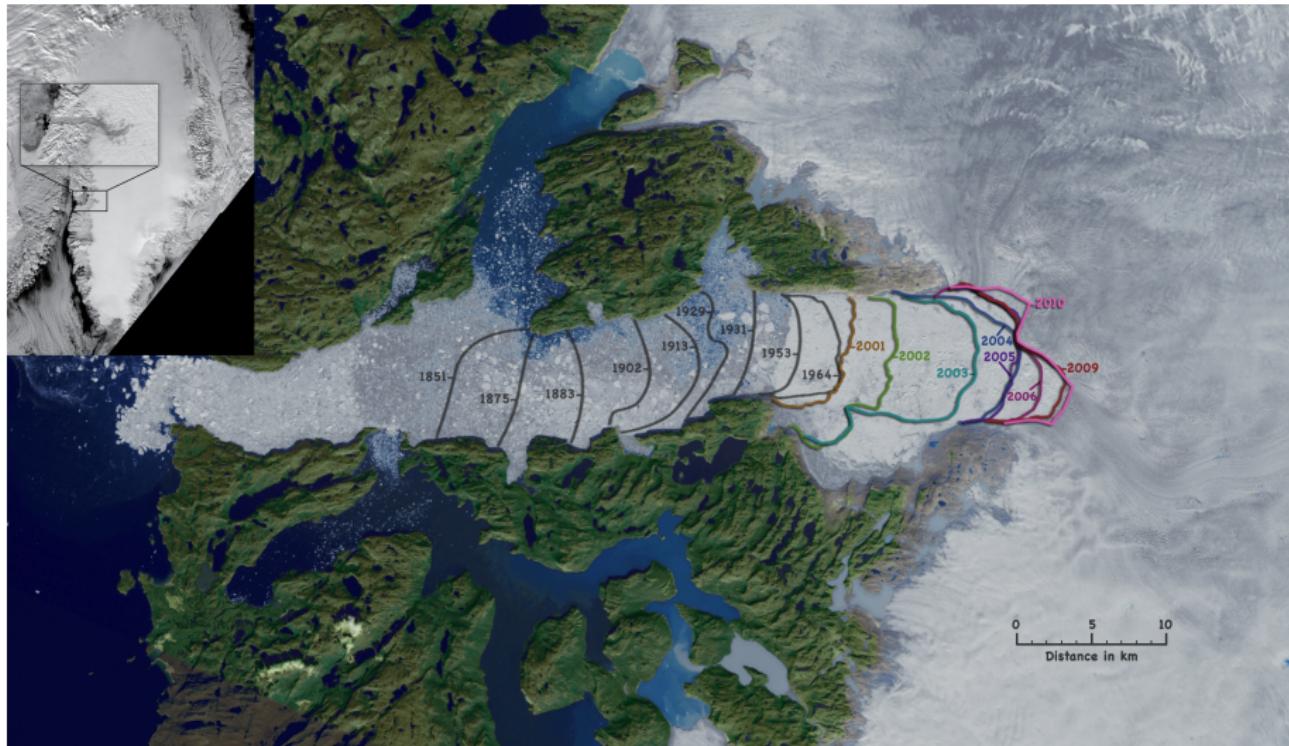
# Ice sheet response to climate



modified from ICESat brochure

- ▶ surface processes are reasonably well understood
- ▶ ice discharge is the wildcard

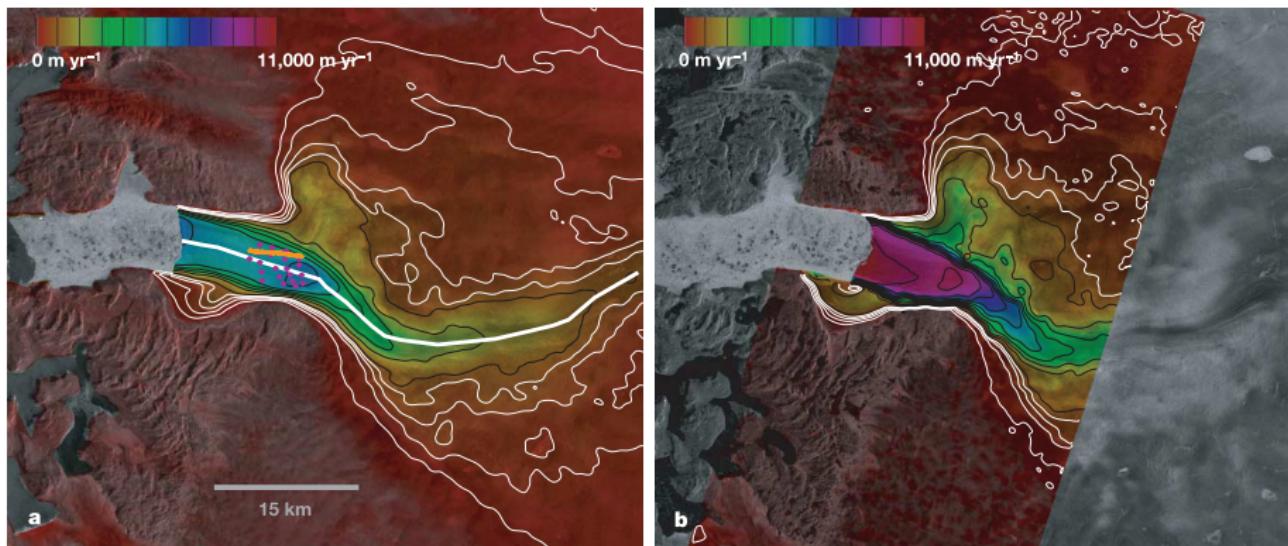
# Jakobshavn Isbræ, west Greenland



credit: NASA SVS and M. Fahnestock

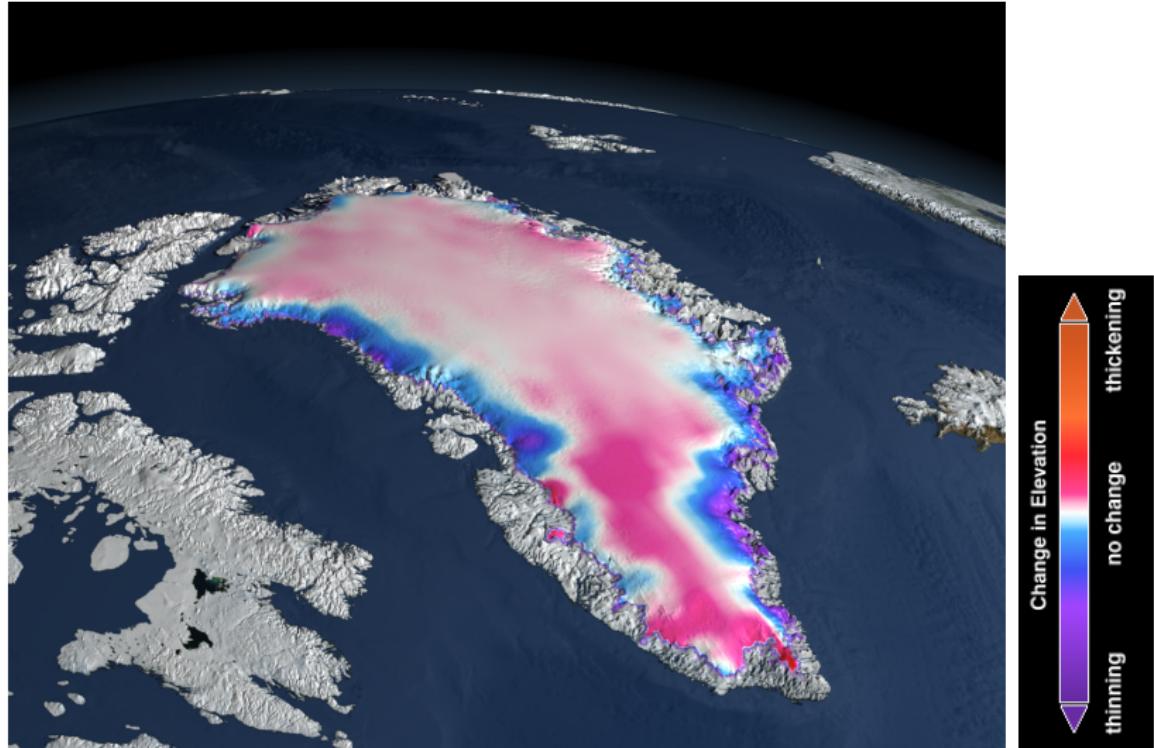
# Speed-up of Jakobshavn Isbræ mid 80's–2008

- more than doubled its flow speed between the mid-80's and 2008



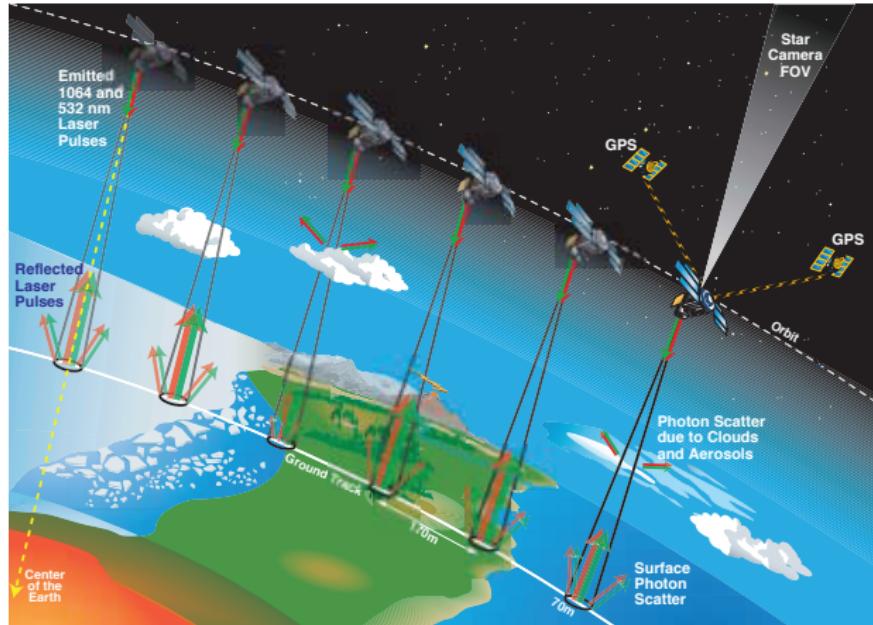
Joughin et al. (2004)

# Elevation change between 2003 and 2006



NASA/Goddard Space Flight Center Scientific Visualization Studio

# Ice Cloud Land Elevation Satellite (ICESat)

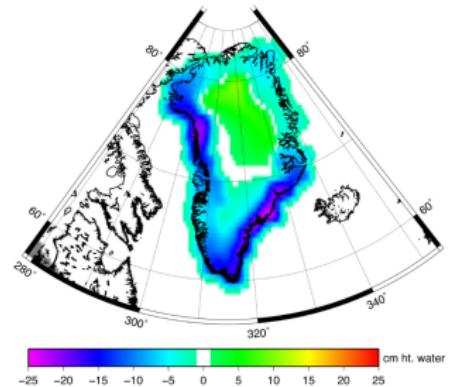
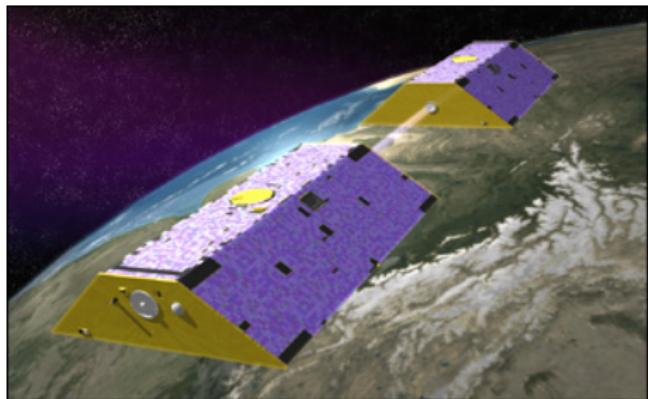


2003–2009



credit: NASA Goddard Space Flight Center

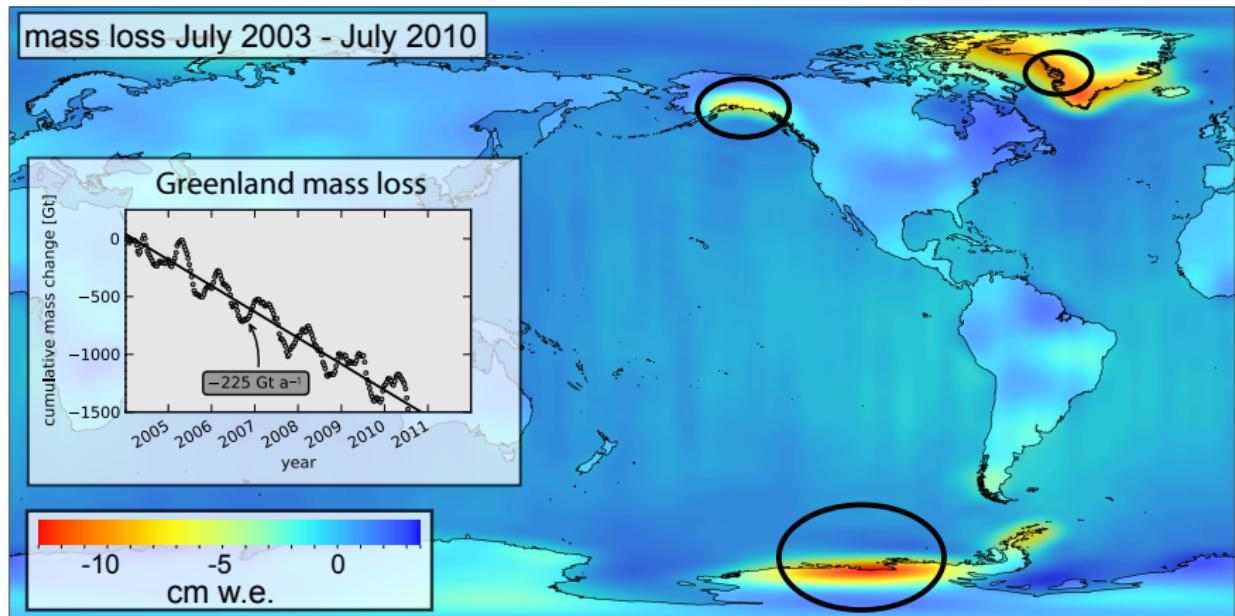
# Gravity Recovery and Climate Experiment (GRACE)



courtesy of A. Arendt

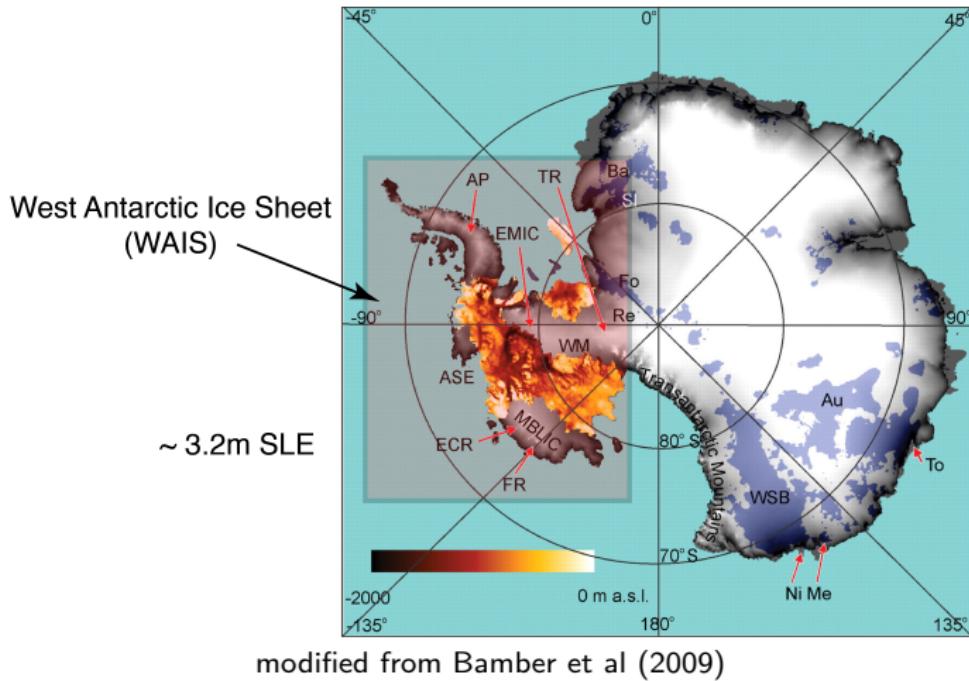
- ▶ precise measurements of orbital variations of tandem satellites are used to construct time variable gravity field

# Global mass changes observed by GRACE



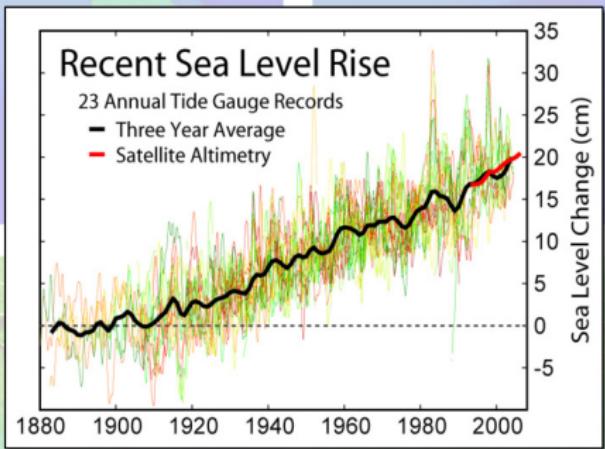
credit: A. Arendt, S. Luthcke, modified

# Antarctica

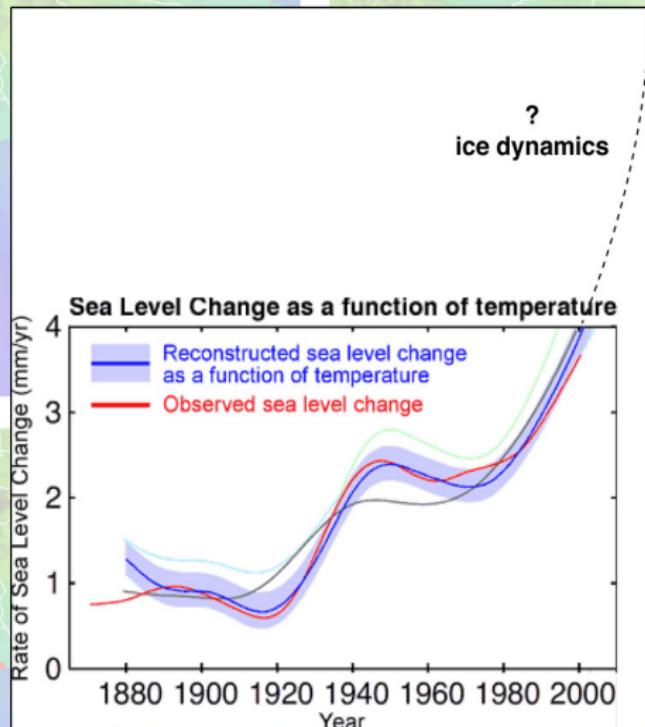


- ▶ WAIS is potentially unstable
- ▶ could raise global mean sea level by ~3 m

# Why we care



# Why we care



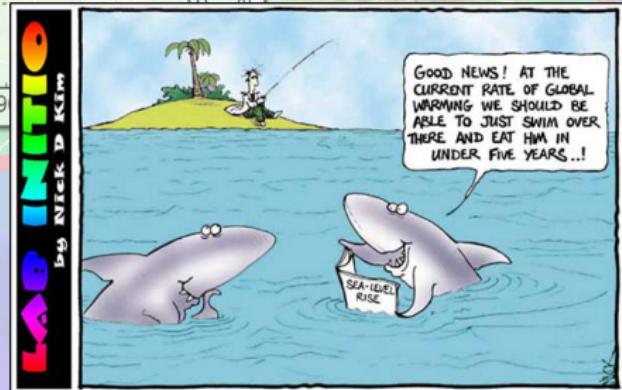
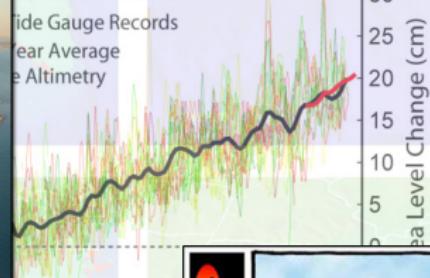
# Why we care



## Sea Level Rise

Tide Gauge Records  
Satellite Altimetry

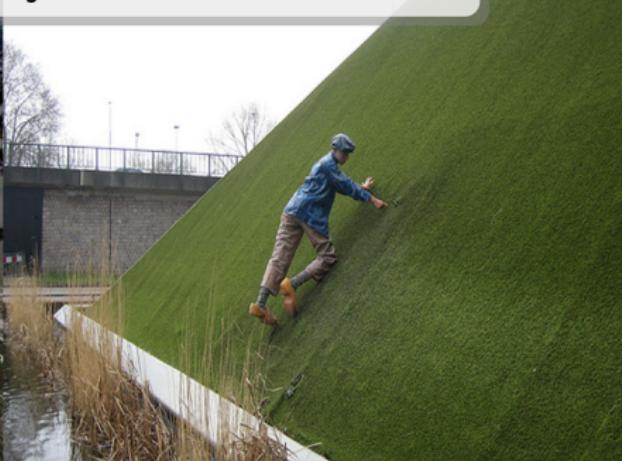
1880 1900 1920 1940 1960



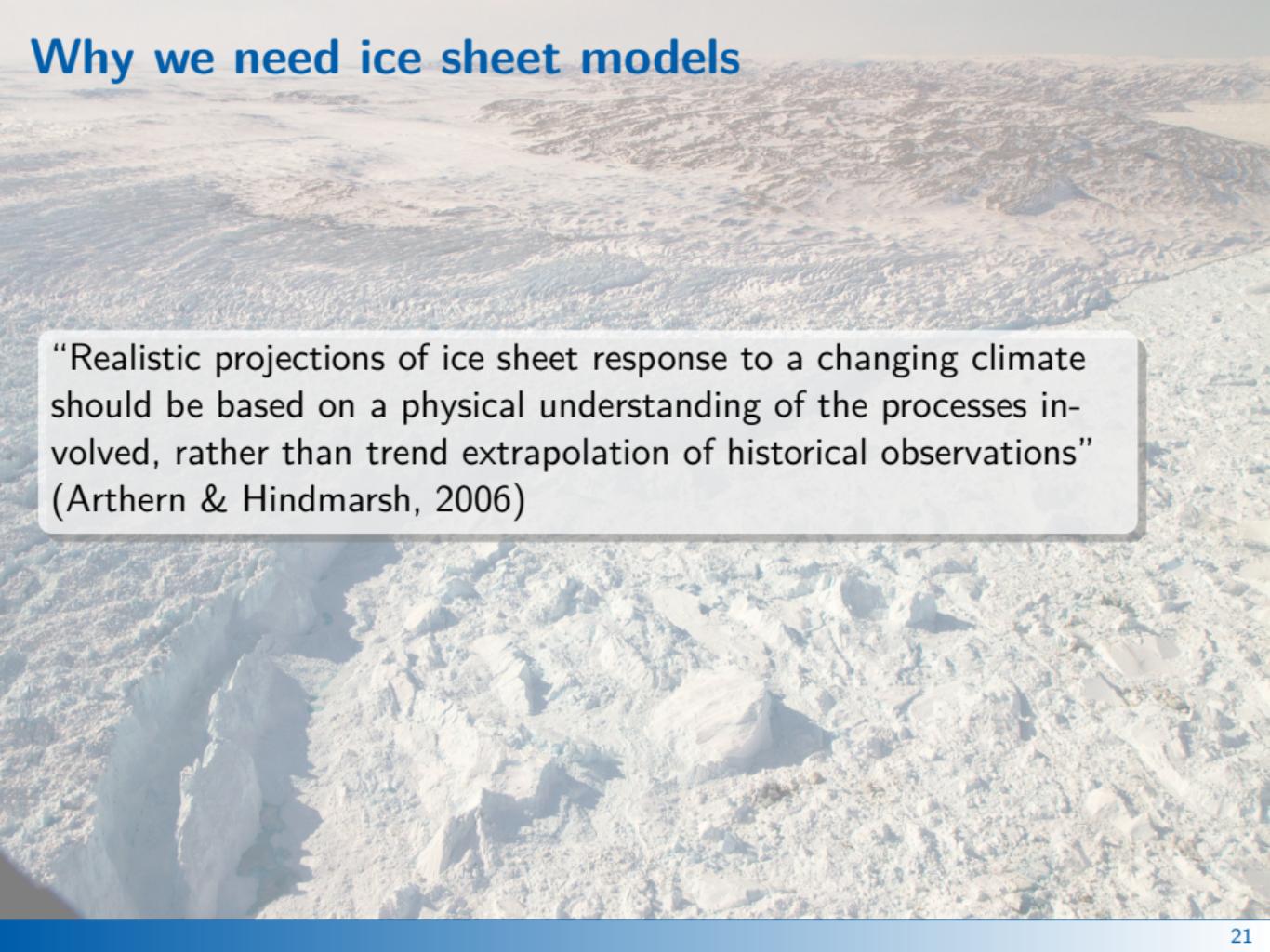
## Why we care



- ▶ mitigation and adaptation efforts require long-term planning
- ▶ appropriate measures depends on projected sea-level rise

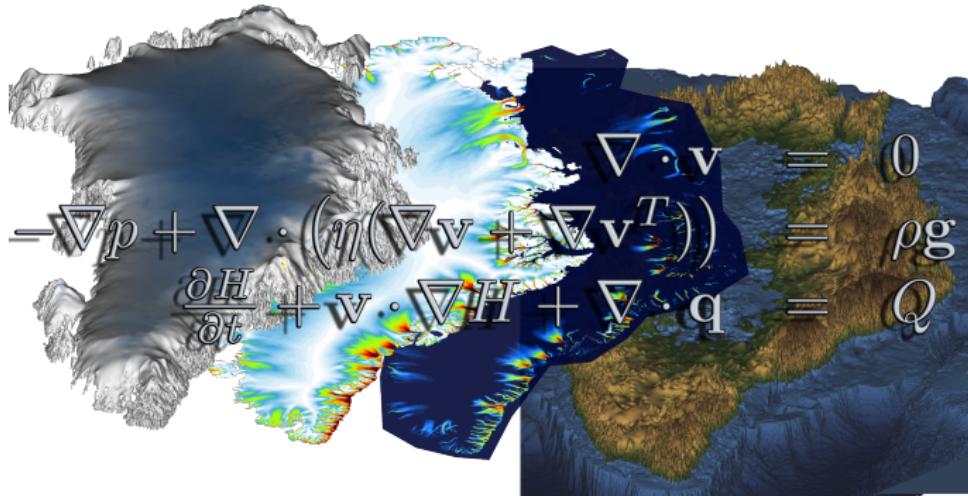


## Why we need ice sheet models

The background image shows a wide expanse of a glacier or ice sheet from an aerial perspective. The surface is covered in intricate, light-colored patterns of crevasses, ridges, and meltwater channels, indicating complex geological and hydrological processes. The terrain appears rugged and dynamic.

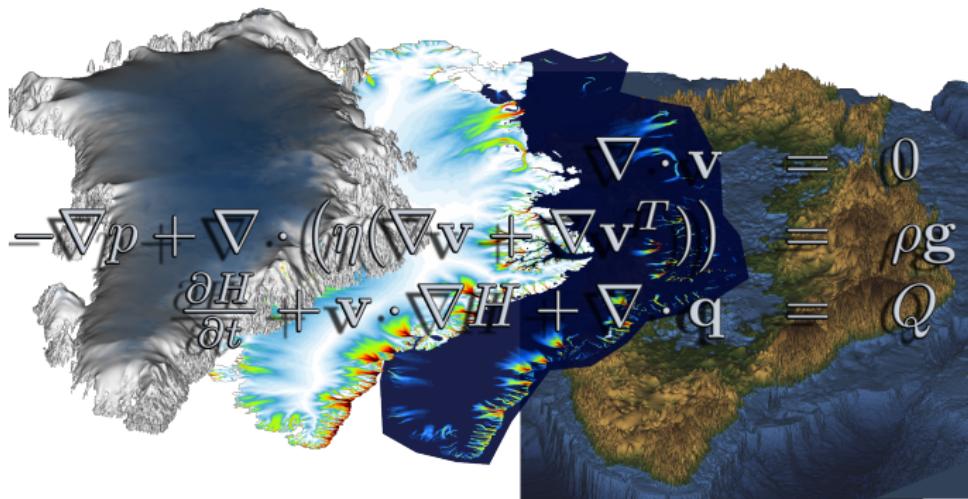
“Realistic projections of ice sheet response to a changing climate should be based on a physical understanding of the processes involved, rather than trend extrapolation of historical observations”  
(Arthern & Hindmarsh, 2006)

# What is an ice sheet model?



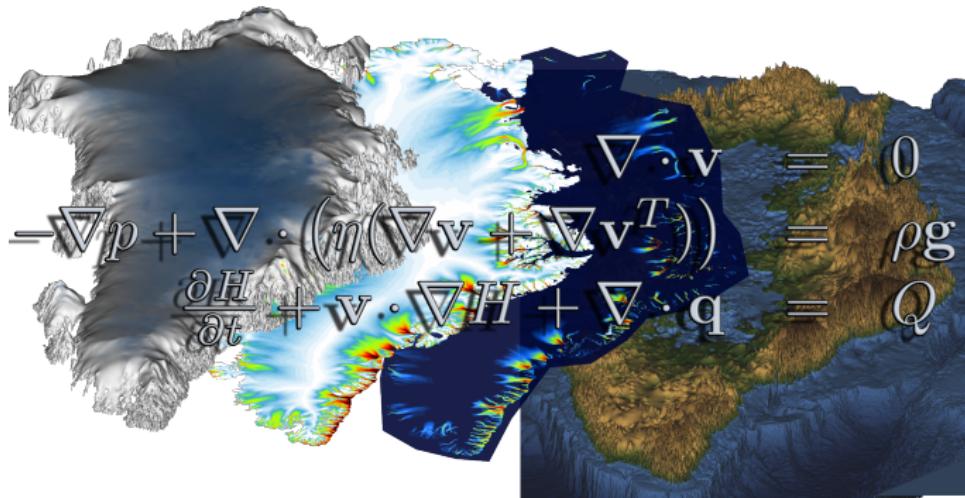
- ▶ ice dynamics
- ▶ boundary conditions
- ▶ thermodynamics
- ▶ hydrology
- ▶ surface processes
- ▶ ice-ocean interaction (e.g. calving)

# Why ice sheet modeling is easy



- ▶ composed of a single, largely homogenous material
- ▶ flow governed by the Stokes equations known since the mid-19th century
- ▶ flows slowly: we can ignore turbulence, Coriolis and other inertial effects

# Why ice sheet modeling is so hard

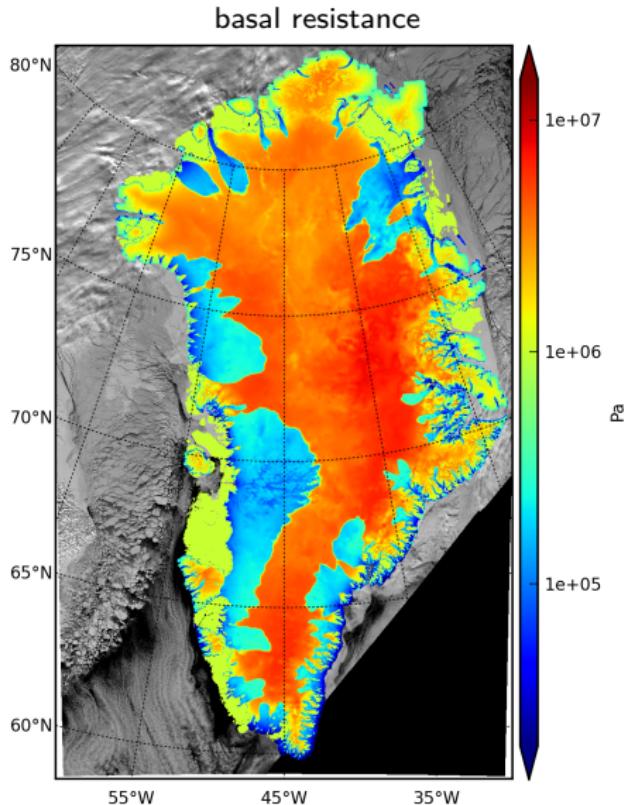


Specifying the stress boundary condition at the

- ▶ seaward margin
- ▶ base

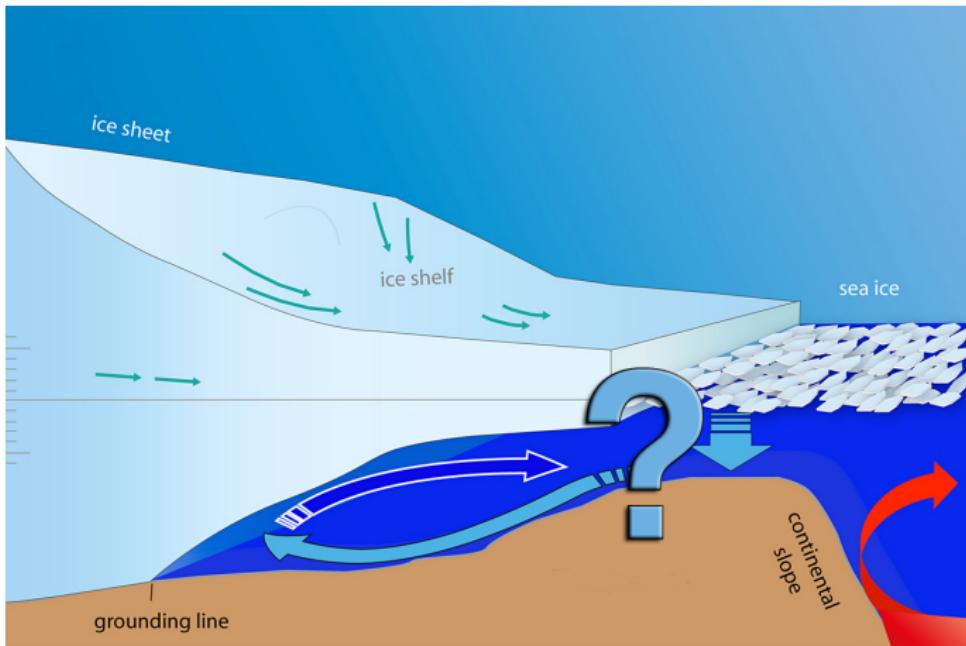
is challenging.

# Challenge: ice base



- ▶ stresses vary by orders of magnitude
- ▶ transience and complexity of basal water flow
- ▶ despite more than 5 decades of research, we only have crude parametrizations

# Challenge: seaward margin



- ▶ ocean circulation  $\Rightarrow$  basal melt rates
- ▶ calving mechanism

# IPCC and ice sheet models

## IPCC (2007), Box 4.1: Ice Sheet Dynamics and Stability

“...but recent changes in ice sheet margins and ice streams cannot be simulated accurately with these models, . . .”

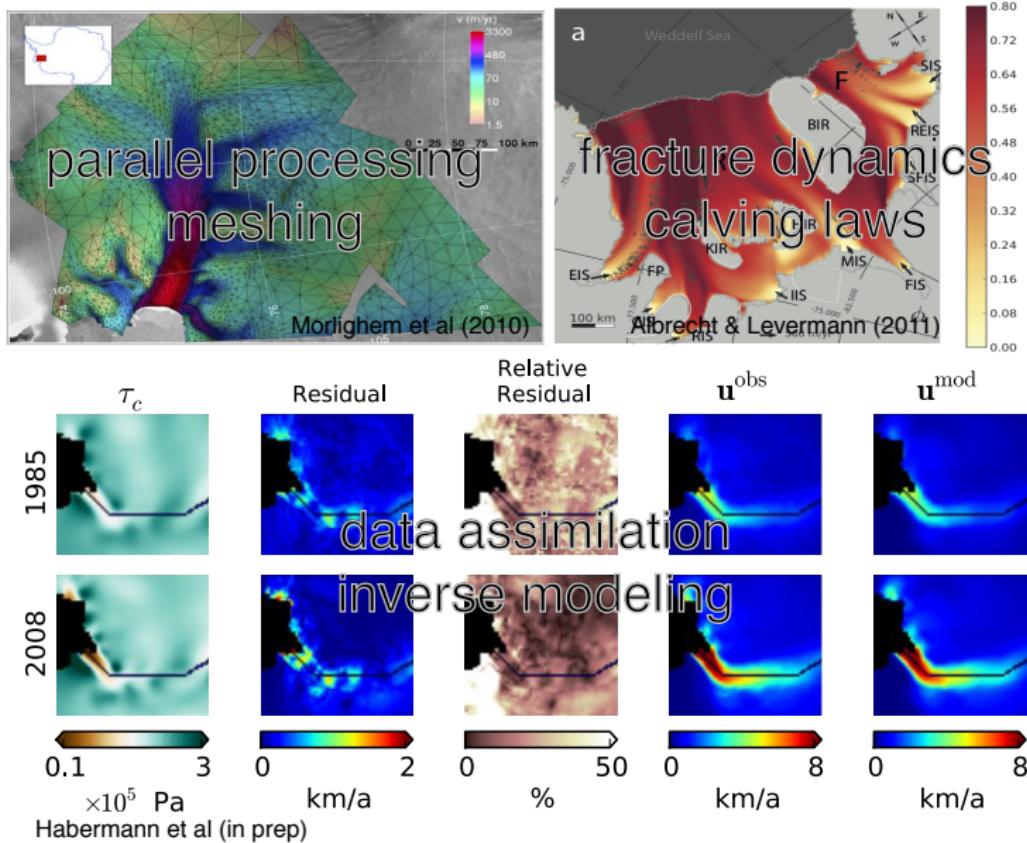
- ▶ the above statement received lots of attention
- ▶ triggered projects such as SeaRISE (Sea Level Response to Ice Sheet Evolution) and ice2sea

# Ice Sheet Models, 2007–

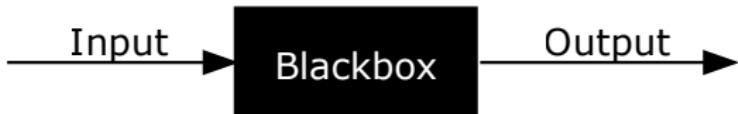
The screenshot shows the homepage of the **Ice Sheet Model** (ISSM) from 2007. At the top, the NASA logo and "Jet Propulsion Laboratory California Institute of Technology" are visible. The header includes links to "JPL HOME", "EARTH", "SOLAR SYSTEM", "STARS & GALAXIES", "SCIENCE & TECHNOLOGY", and "BRING THE UNIVERSE TO YOU: JPL Email News | RSS | Podcast | Video". Below the header is a large banner featuring the ISSM logo, a globe, and a color-coded map of ice sheet models. The banner also displays the Elmer/Ice logo and a search bar. A navigation menu at the bottom of the banner includes "NEWS", "PUBLICATIONS", "CAPABILITIES", "USERS", "COMMUNITY", and "COURSES/TUTORIALS". On the left side, there is a vertical sidebar with links to "Home", "About ISSM", "News", and "ISSM Workshop". The main content area features a large image of a glacier with a color scale indicating relative change ( $\Delta B/B (\%)$ ) ranging from -2 to 15. To the right, there is a detailed map of a glacier with a color scale from 4.1 to 10000. The PISM logo and text are also present.

The screenshot shows the homepage of the **Parallel Ice Sheet Model** (PISM). The header includes a "PISM" logo and the text "Parallel Ice Sheet Model". Below the header is a navigation menu with links to "Home", "Getting PISM", "PISM Docs", "PISM Publications", and "Projects". The main content area features a large image of a glacier with a color scale indicating stress or energy levels. A sidebar on the left shows a vertical stack of three images of ice sheet models. The sidebar also includes a "Latest News" section. The right side of the page contains text about the model's capabilities and a detailed map of a glacier with a color scale from 10000 down to 100. A legend on the right indicates a scale of 200 km.

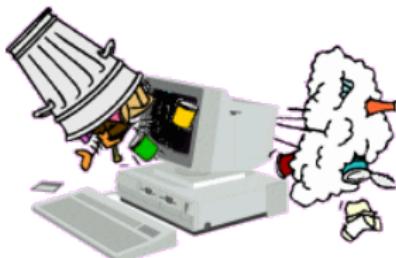
# Ice Sheet Models, 2007–today



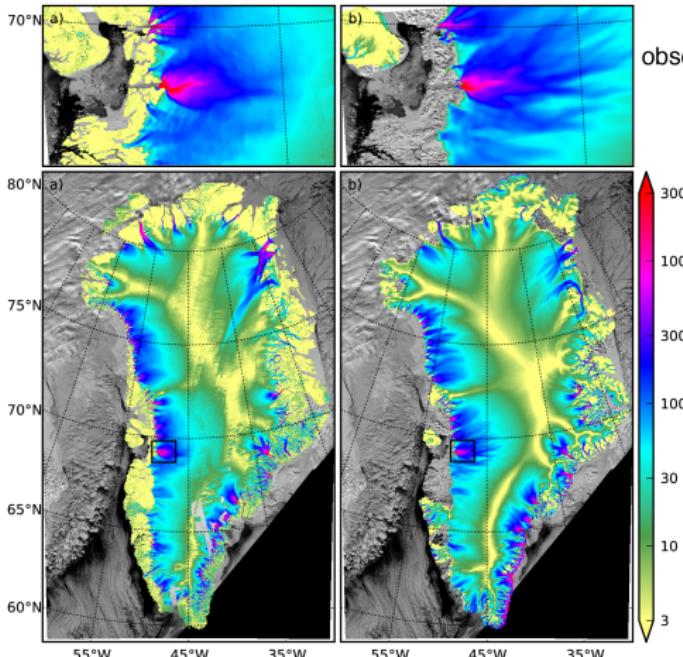
## A word of caution



- ▶ ice sheet models should not be used as a “black-box”
- ▶ require serious modeling choices (physics, physical and numerical parameters, etc) based on glaciological knowledge
- ▶ “garbage in  $\Rightarrow$  garbage out”, sometimes “garbage in  $\Rightarrow$  gospel out”
- ▶ a model is only as good as the input data (at best)

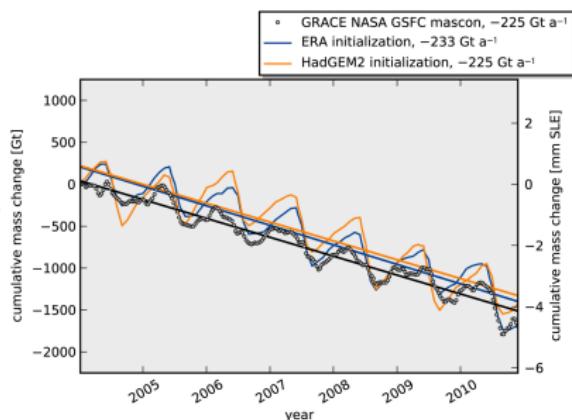


# Ice Sheet Models, 2007–today

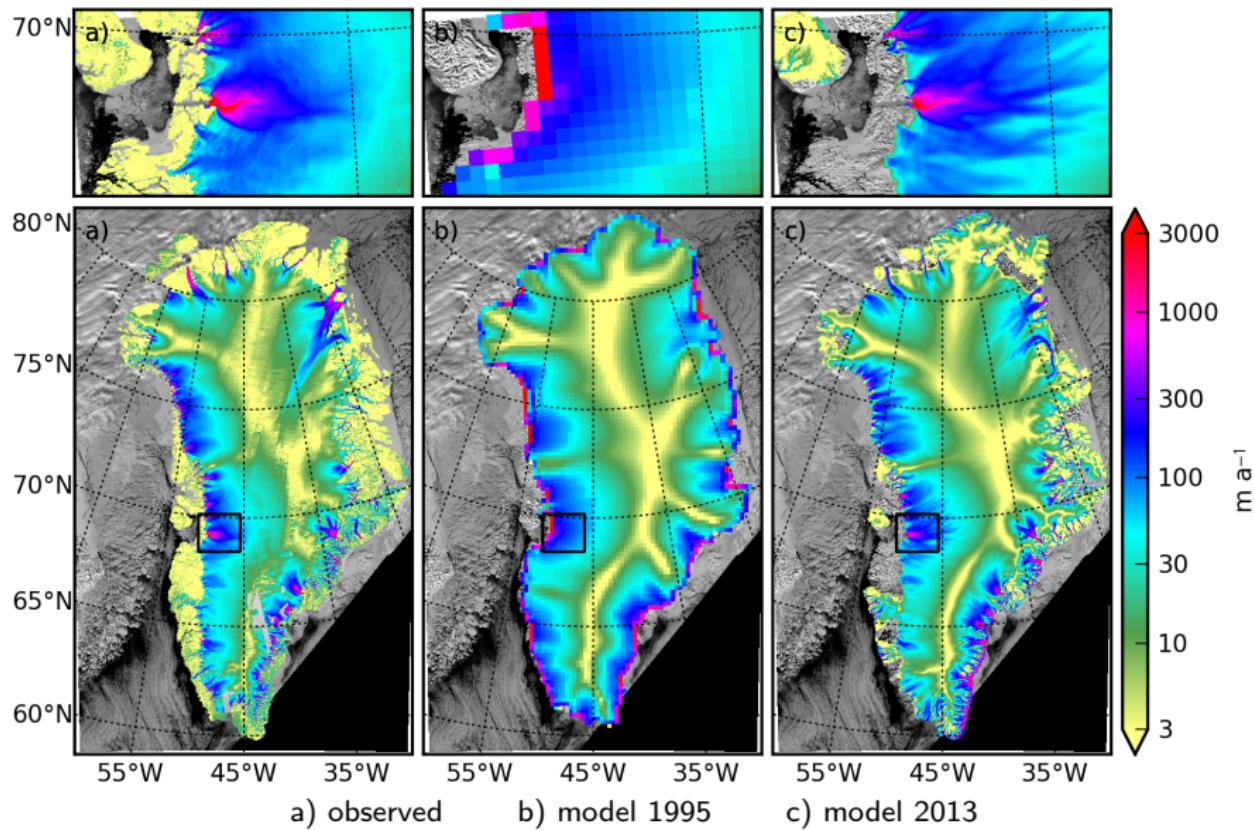


surface speeds  
observed and simulated

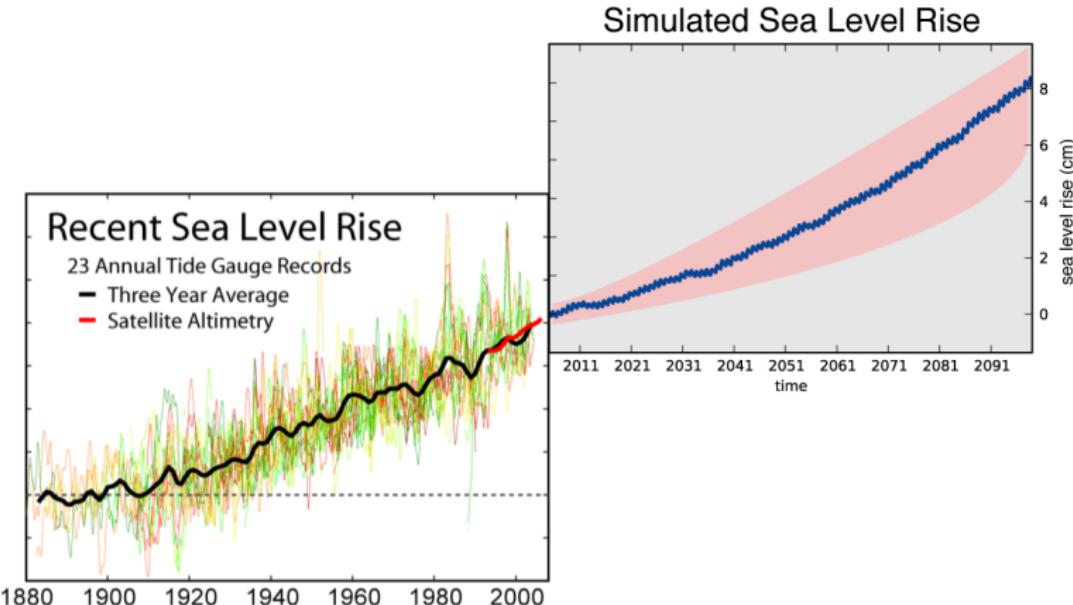
Greenland total mass loss  
observed and simulated



# Modeling in 1995 and today



# Ready for the future?



- ▶ we now have decent numerical ice flow models
- ▶ but we need uncertainty quantification