

***Ice Cover in the Earth System***

***Rapidly Responding to  
Climate Change***

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***NASA Goddard Space Flight Center***

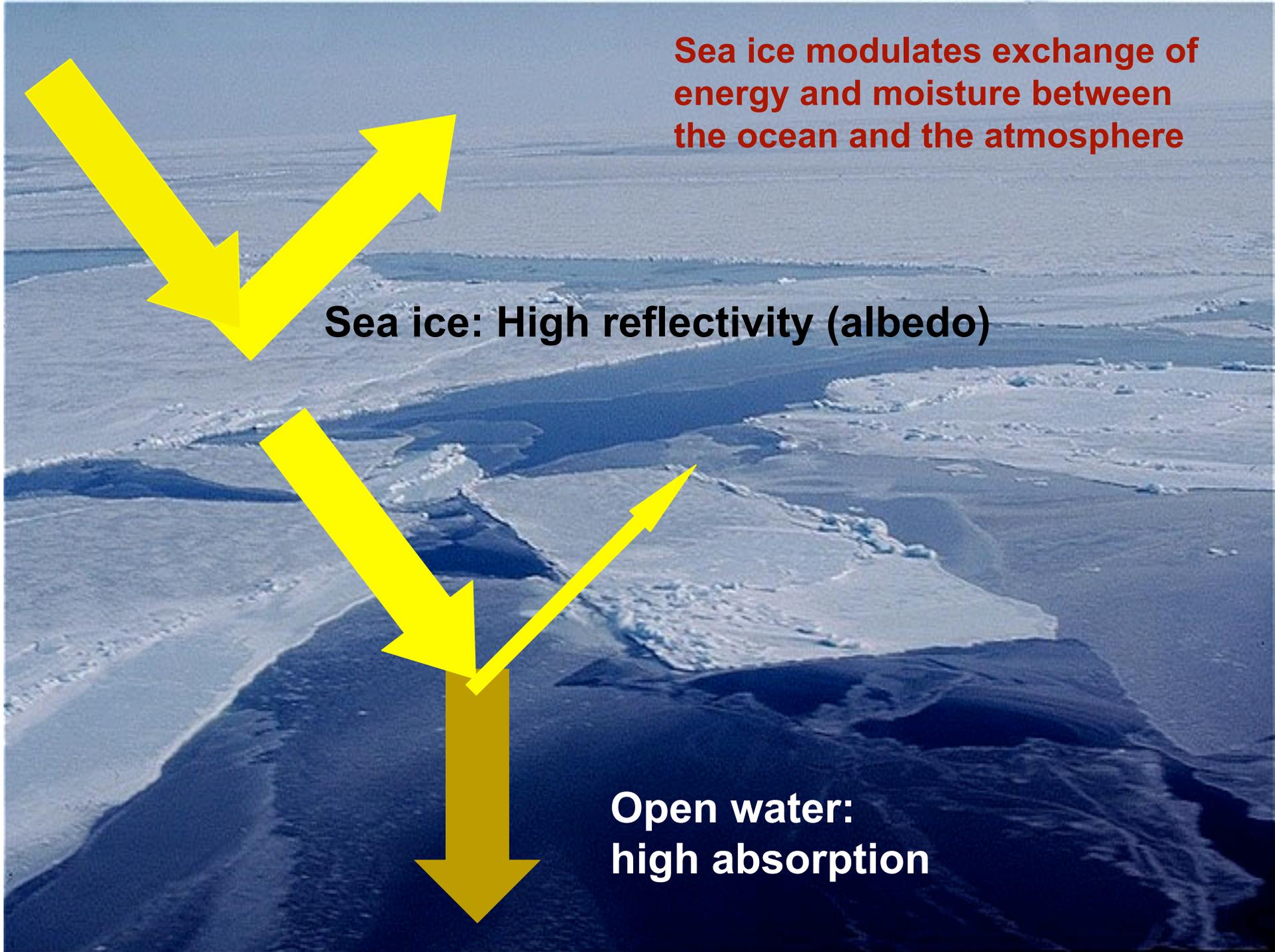
# The Cryosphere and Climate

- **Cryosphere: the frozen elements of the Earth System**
  - **Sea ice**: Frozen ocean surface water
  - **Ice sheets**: enormous ice masses of Greenland and Antarctica
  - **Glaciers and Ice Caps**
  - Lake and river ice
  - Permafrost
  - Snow

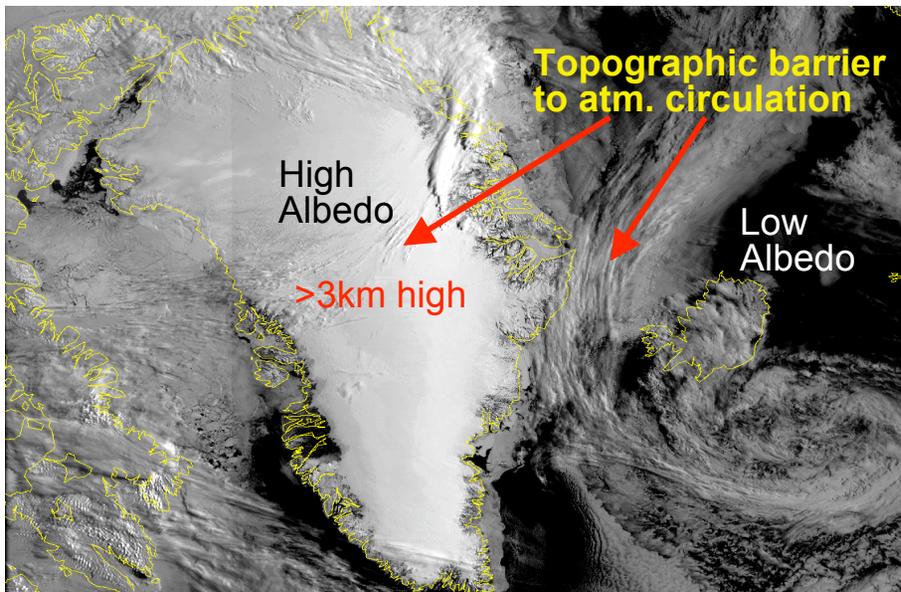
**Sea ice modulates exchange of energy and moisture between the ocean and the atmosphere**

**Sea ice: High reflectivity (albedo)**

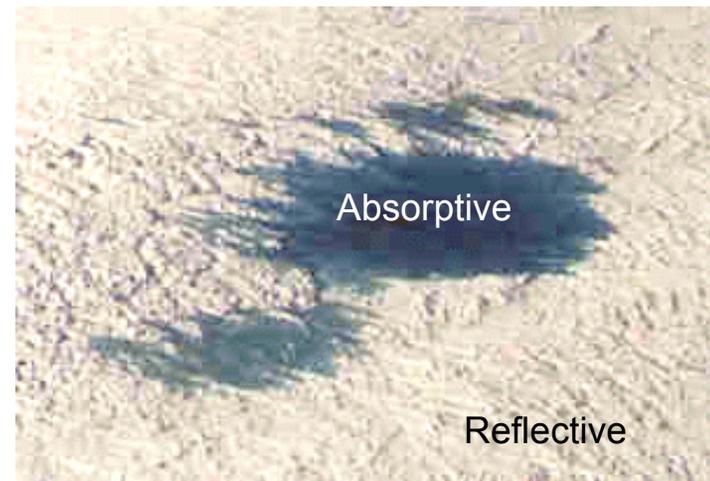
**Open water:  
high absorption**



# The Same is True for Ice on Land



Tendency of melt is to enhance melting



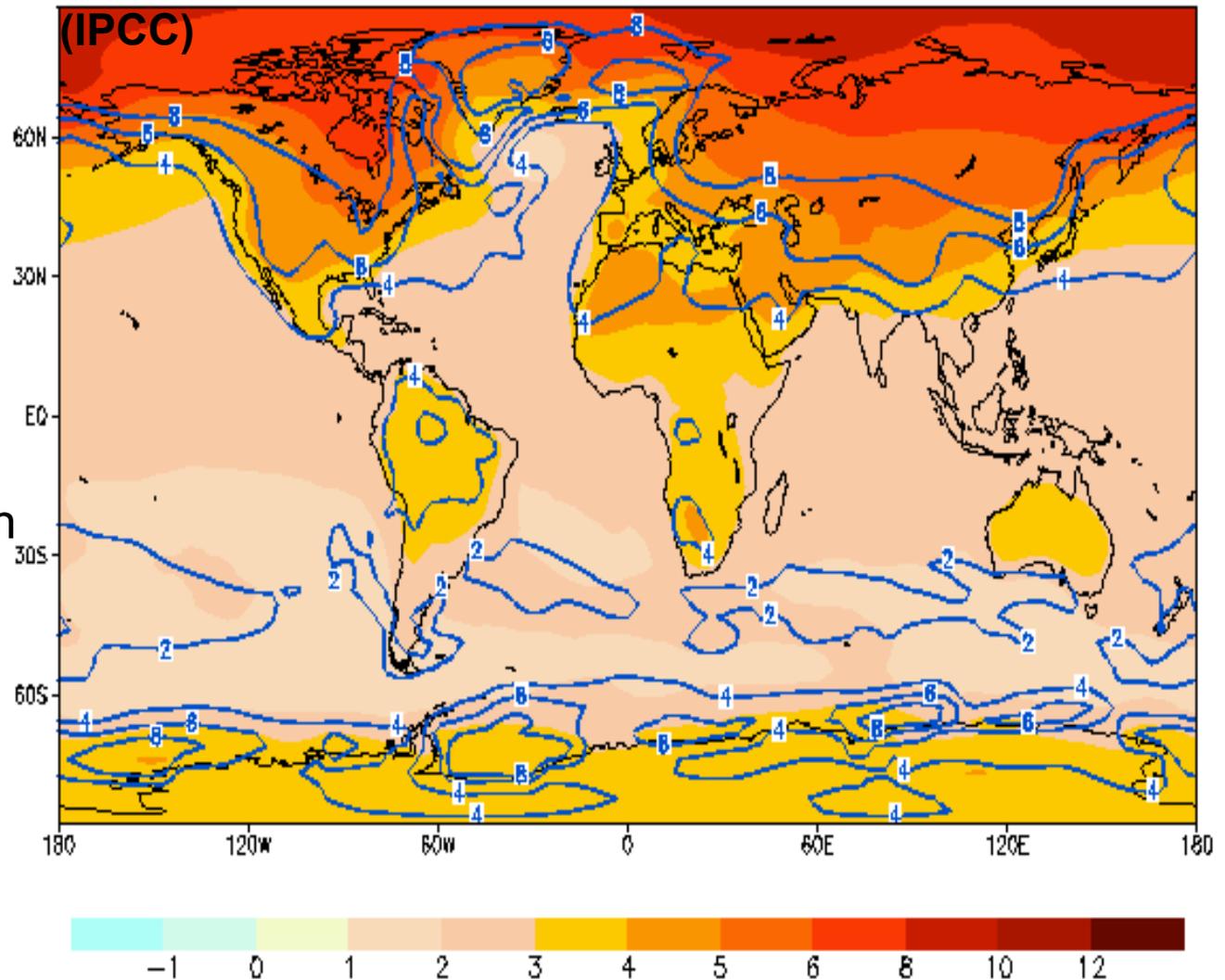
- Ice sheet/glacier and snow melting also provides a positive feedback
  - Decreased albedo
  - Increased evaporation
    - Less latent heat
    - Water vapor is a greenhouse gas

# Climate Projections

Predicted 100-year surface temperature change

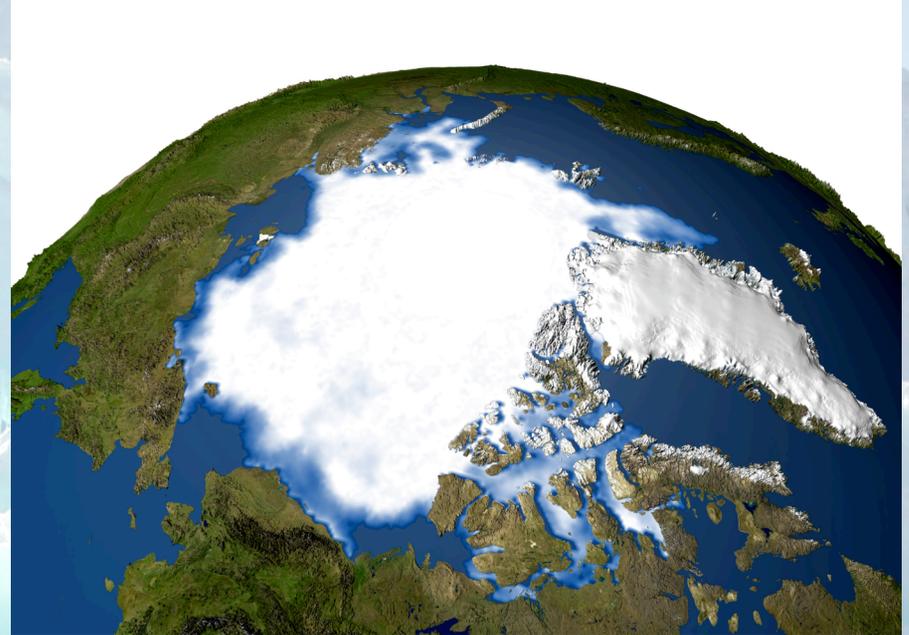
**Polar regions are particularly sensitive to climate change**

- positive albedo feedback
- sea ice insulation of polar waters



# Importance of the Cryosphere

- Polar-global climate links
- Ice-Free Arctic Ocean
  - New Climate patterns
  - New sea routes
  - New security concerns
- Sea level change
  - 1/3 of world's population lives in coastal areas
  - Currently estimated to be rising at nearly 2 mm/yr
  - Evidence that it was 30x greater in the past
  - 1 meter rise in sea level will cost US ~\$400 billion (EPA, 1997)
  - Sea level will rise faster than IPCC-3 states
- Snow as a water resource
  - Up to 80% of water in western US is snowmelt



# Why NASA?

Harsh Environment

*This is true of many places on Earth but ...*

Difficult and Costly Access

Difficult to Appropriately Sample

*... it is especially true for polar regions*



# ***Perspective, Access, Safety and Cost***



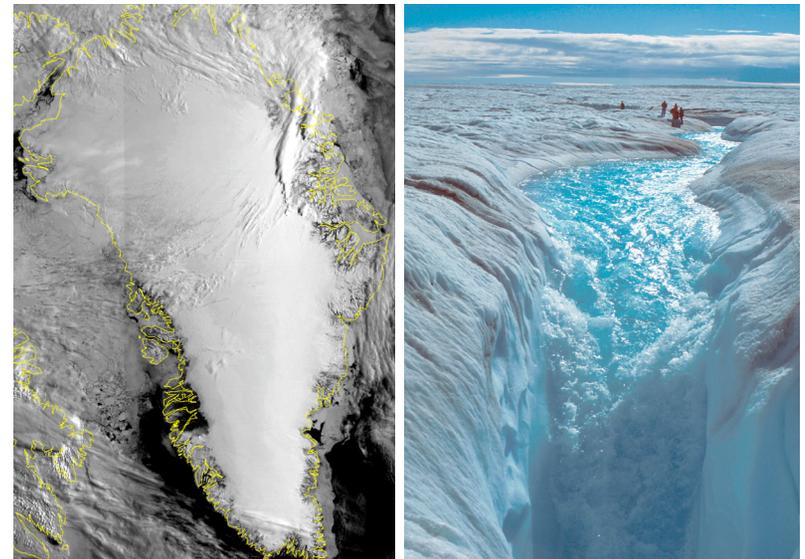
# Two Ice Sheets With Great Potential

## Antarctica



- 70 m sea level equivalent (SLE)
- West Antarctic ice sheet (7 m SLE) grounded below sea level on marine sediment experiencing high geothermal heat flow
- **Inherently unstable?**

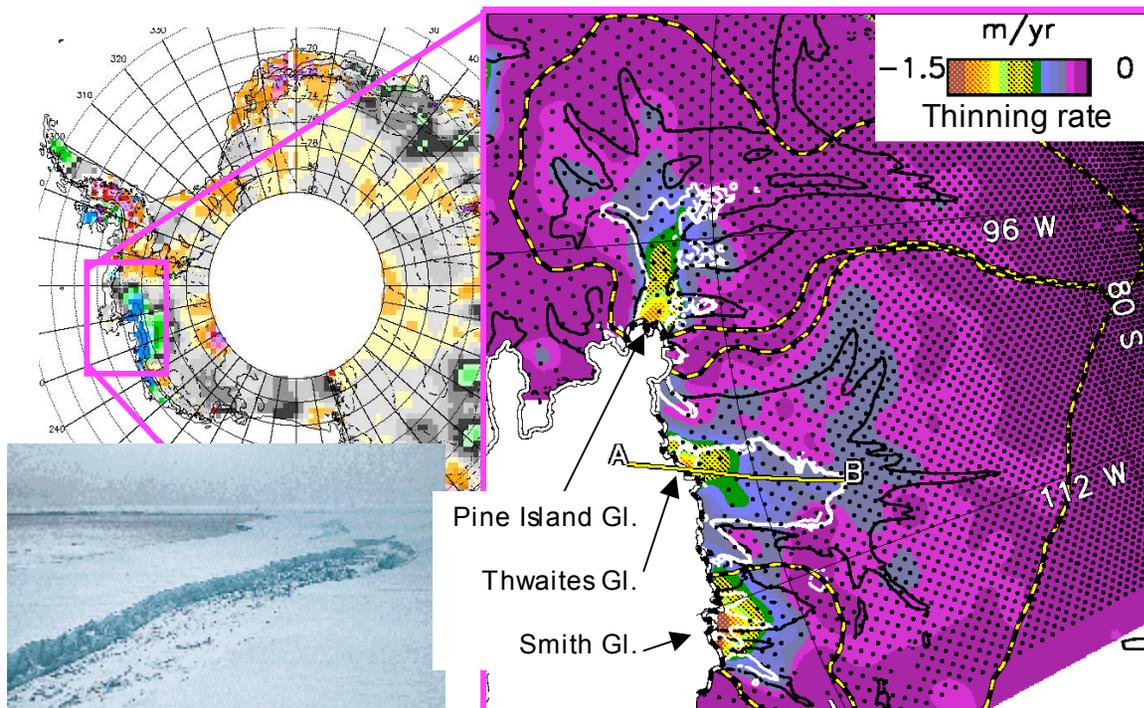
## Greenland



- 7 m sea level equivalent
- Experiences substantial melt that lubricates ice/bedrock interface
- **Slippery when wet!**

# Regional Collapse in Antarctica

Major portion of West Antarctic ice sheet exhibits expected signs of collapsing

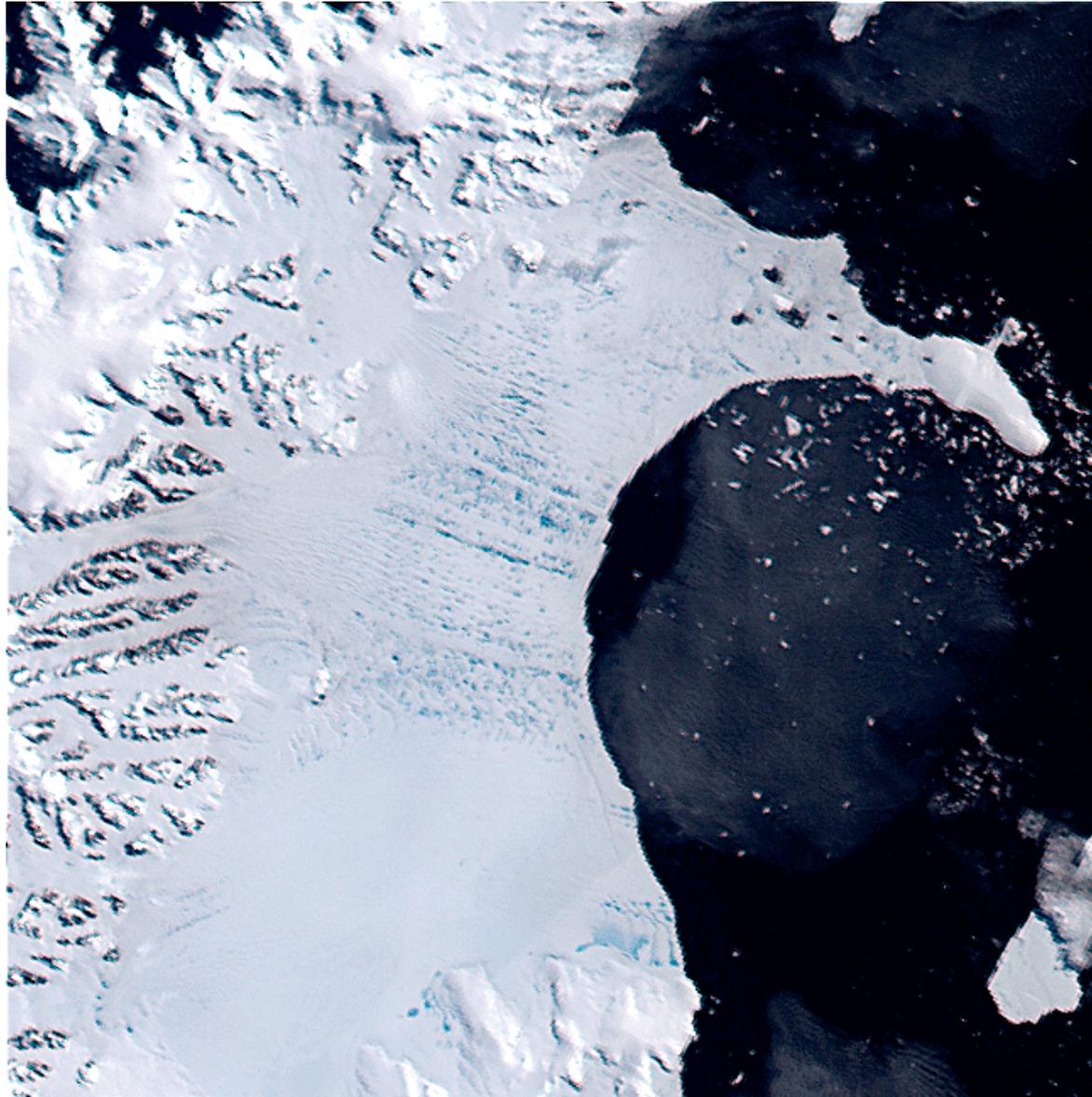


- Thinning increasing towards coast (satellite and aircraft altimetry)
- Flow acceleration (InSAR)
- Retreat of grounding line (Landsat and InSAR)
- Calving of large icebergs (MODIS)

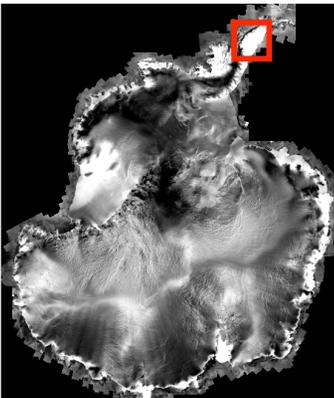
**All** observations by satellite sensors. Most of this area has **never** been visited by humans.

Thinning rate is accelerating. Recent changes contributing 10% of present sea level rise (Thomas et al., 2004)

# Larsen B Break-up 2002

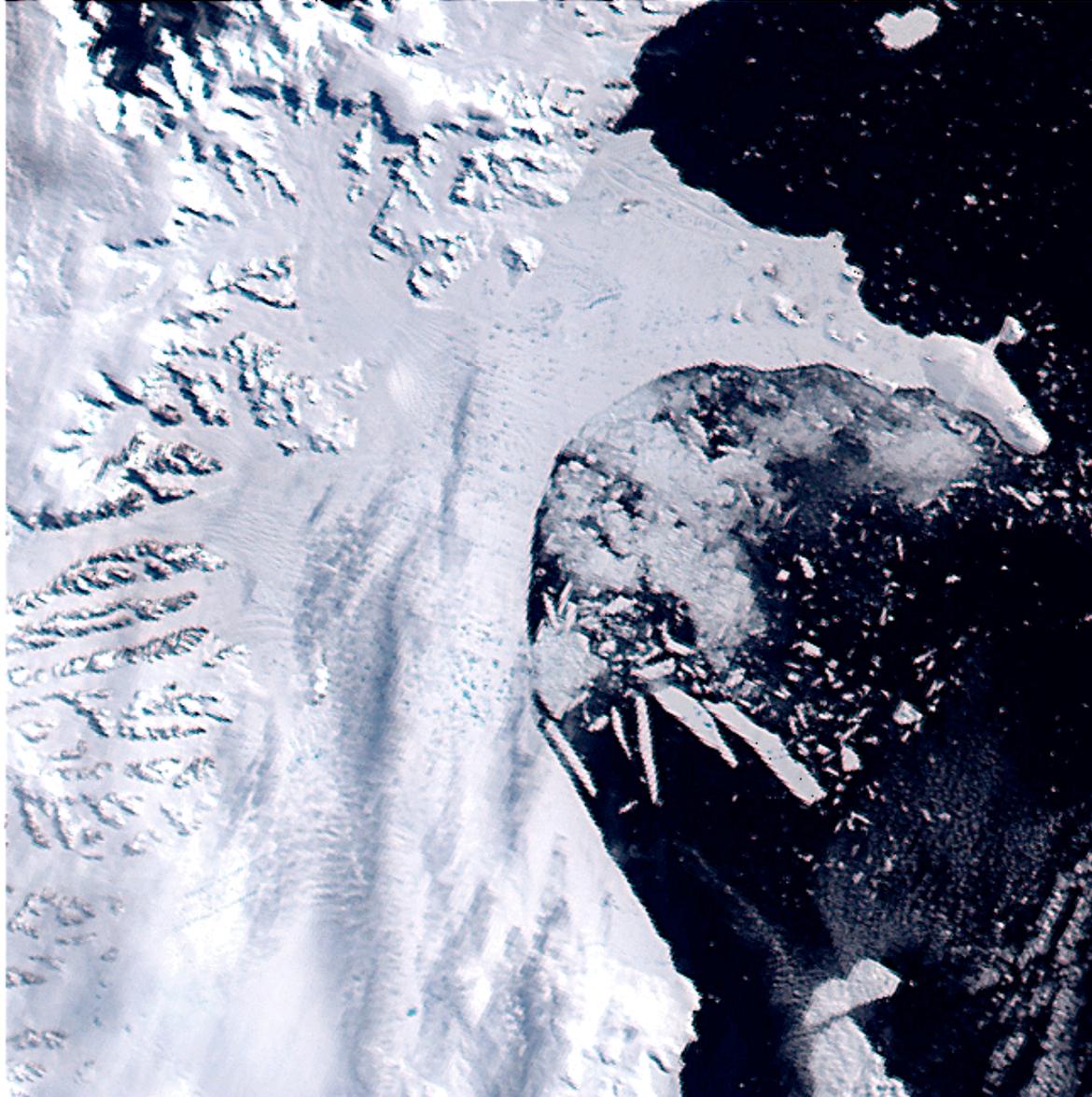


January 31

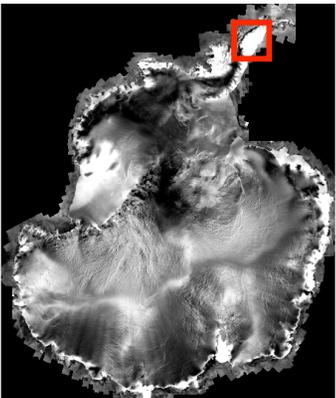


Ted Scambos, NSIDC

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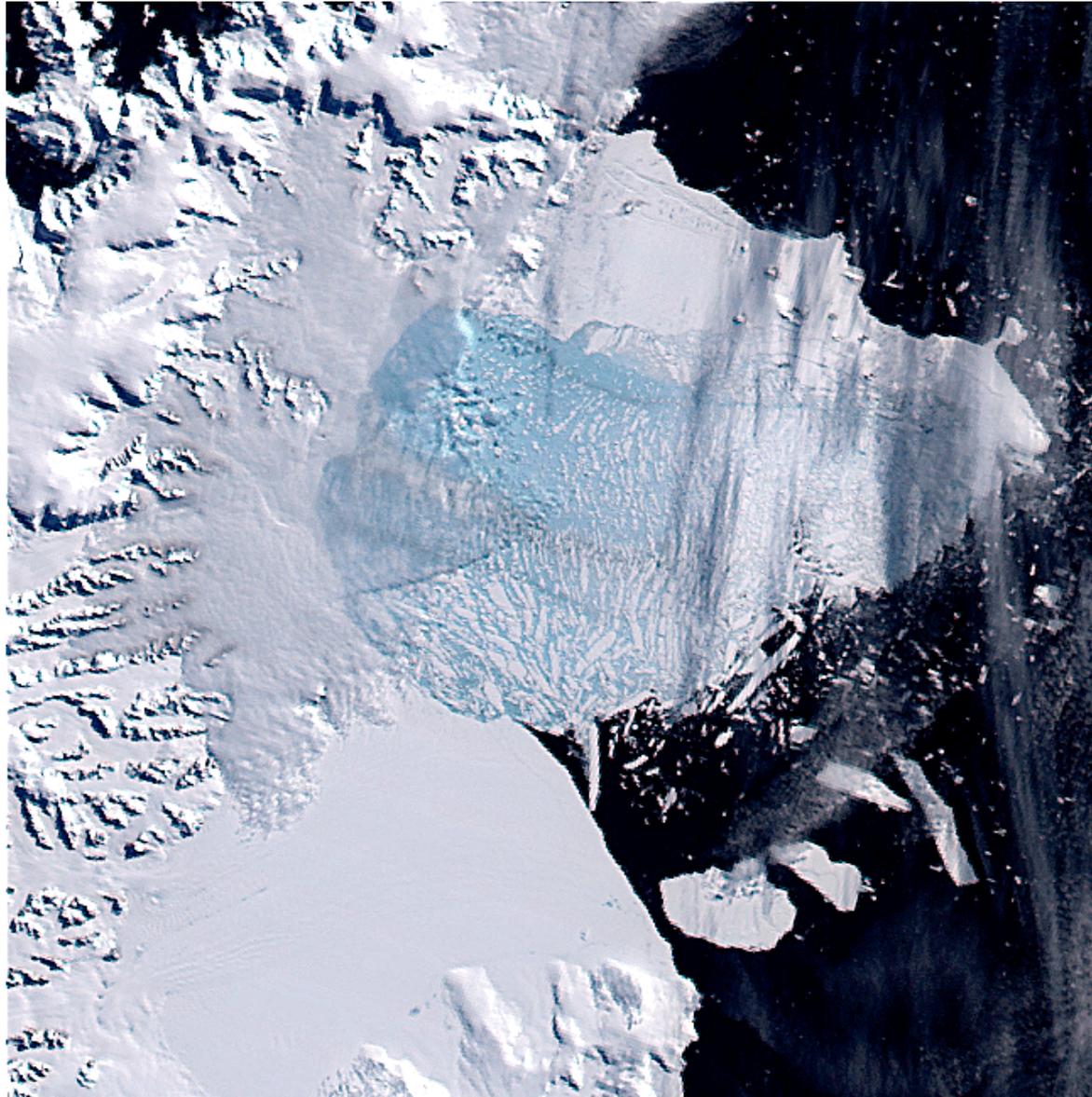


February 3

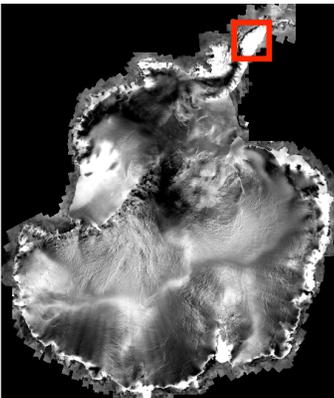


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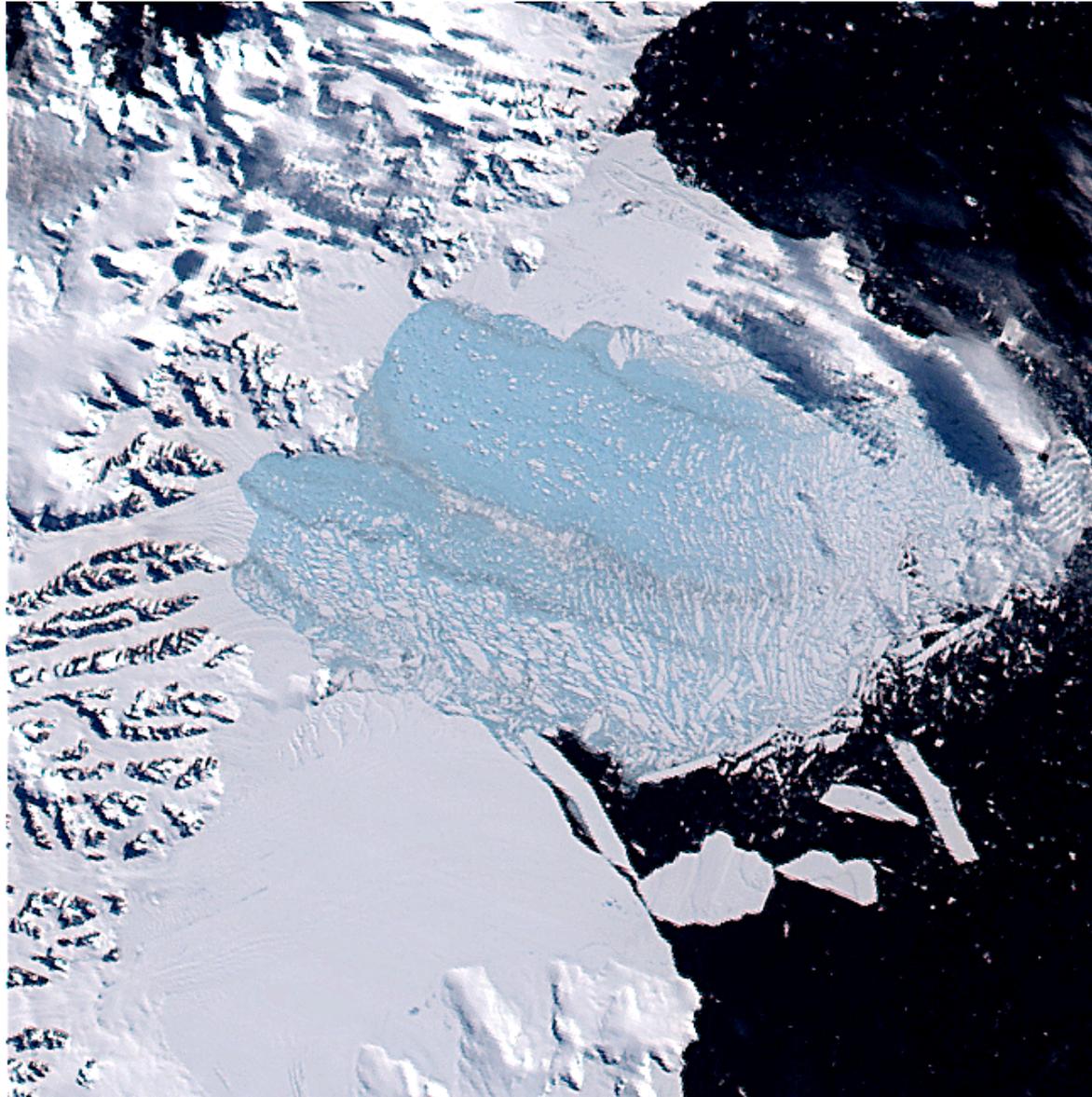


March 5

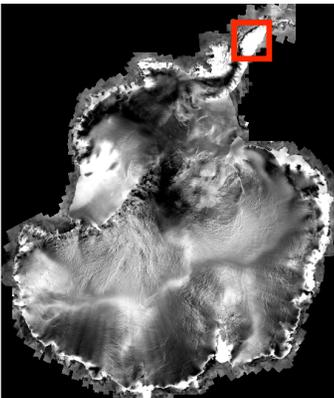


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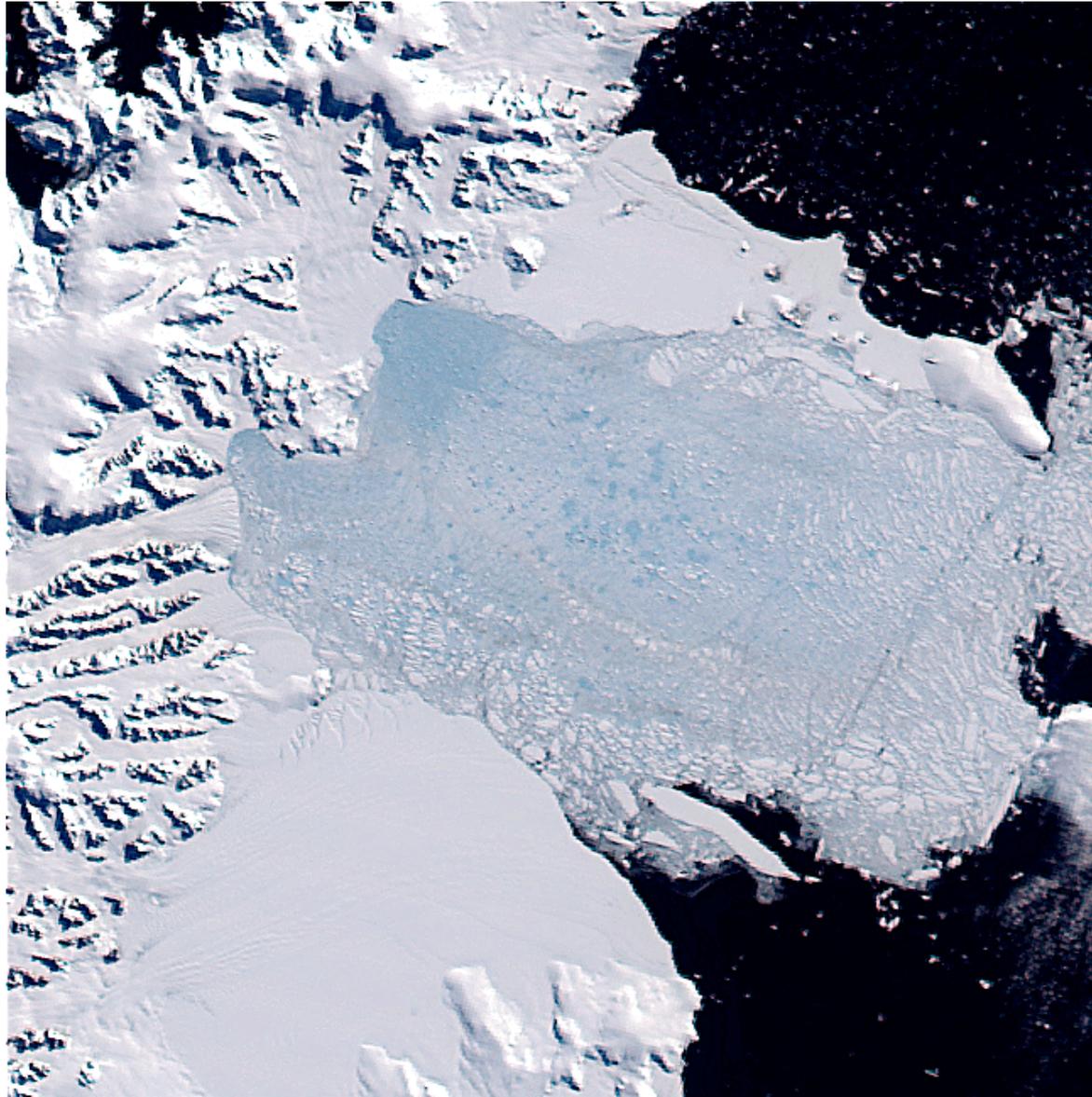


March 7

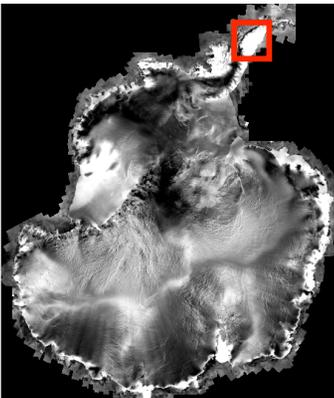


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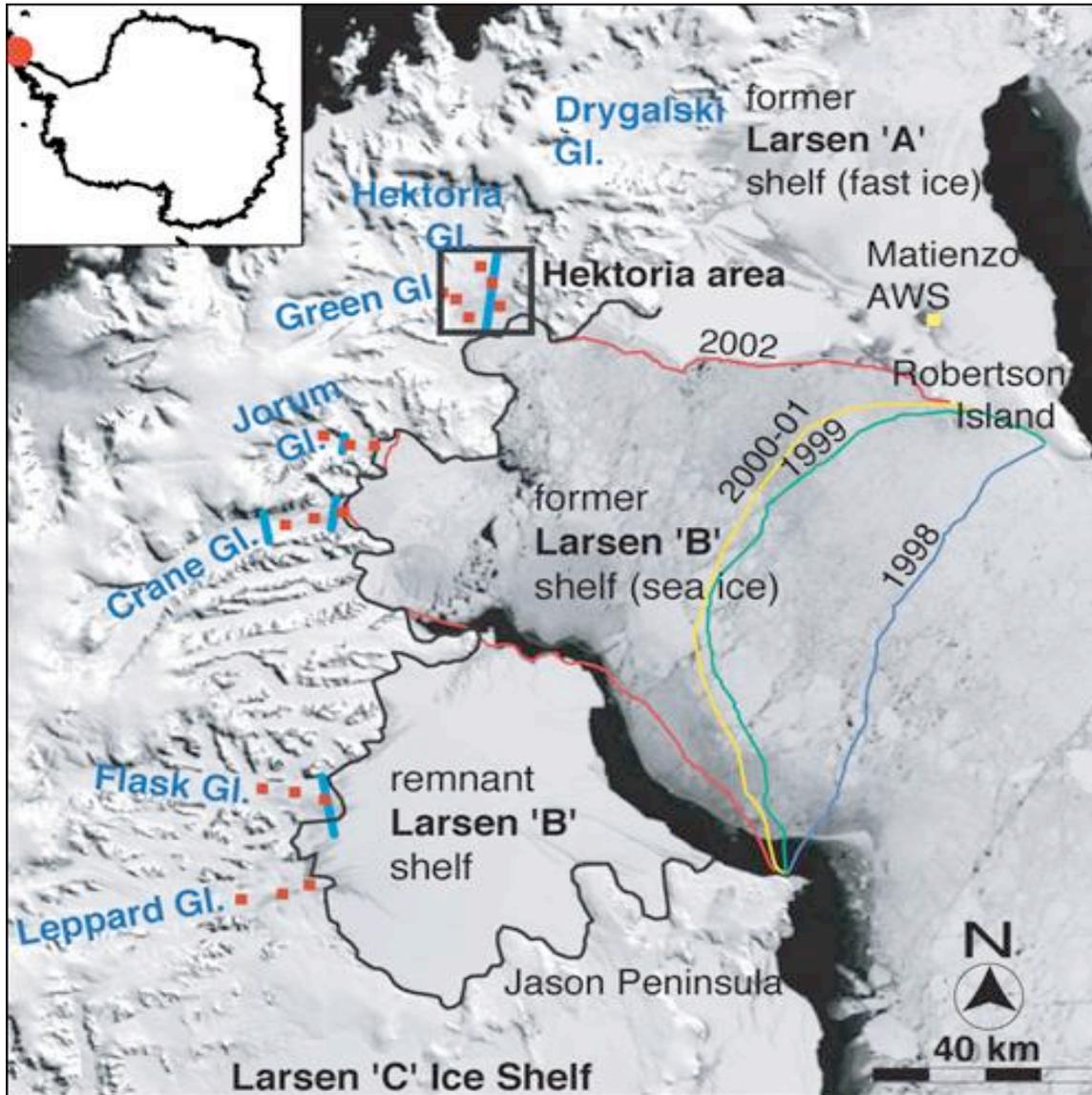


March 17



Ted Scambos, NSIDC

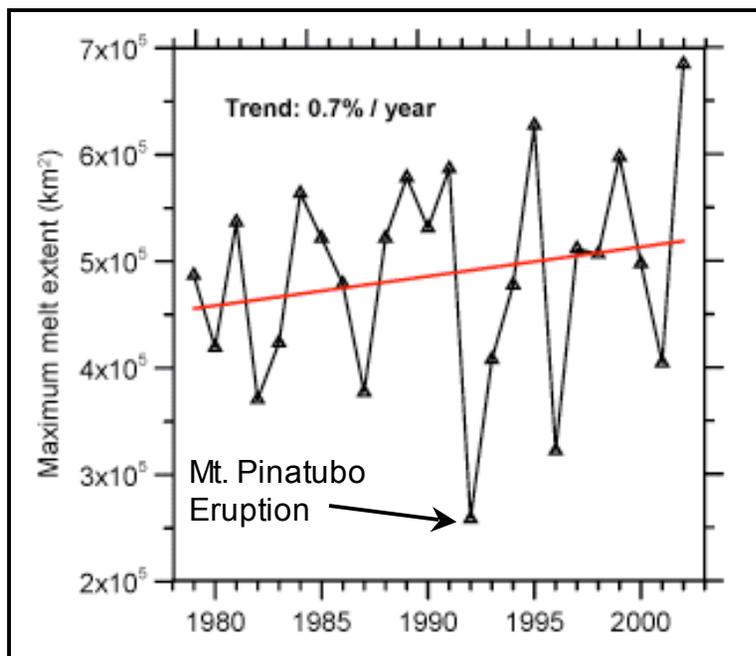
# Collapse of Larsen Ice Shelf



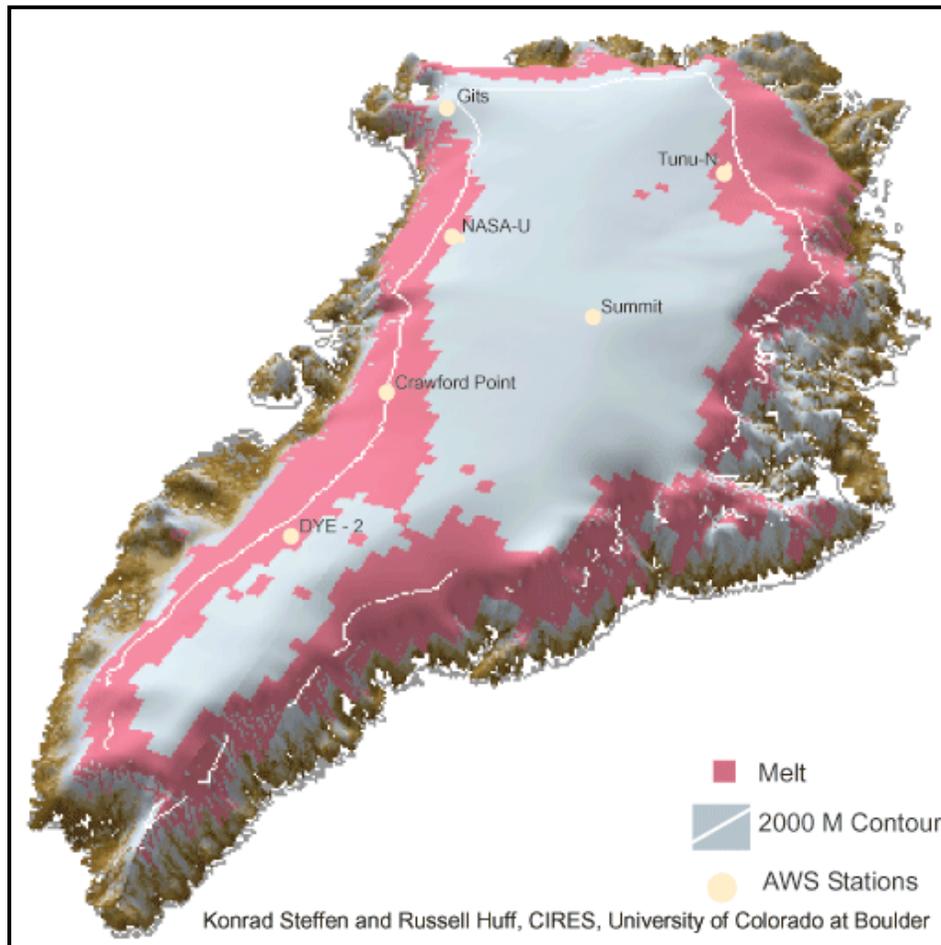
10,000 years of ice gone in one month

- Following break-up glaciers accelerated 8x
- ICESat shows thinning by 38 m (blue lines)

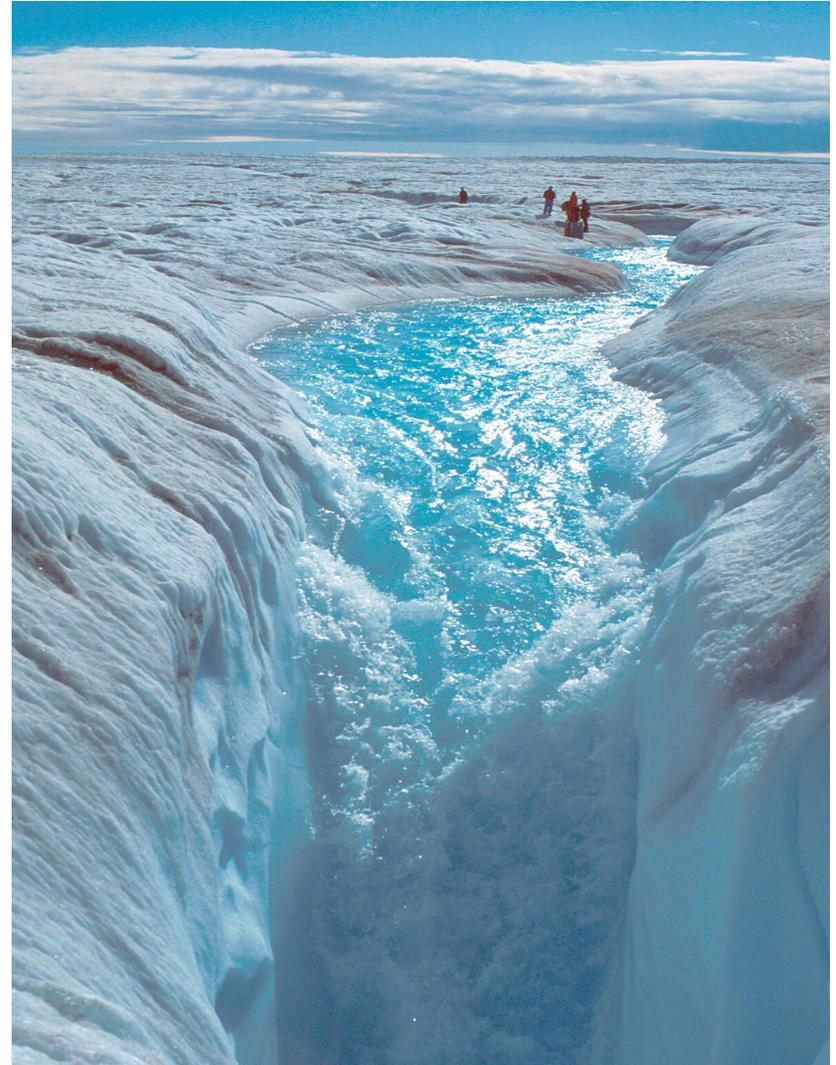
# Increasing Melting of Greenland



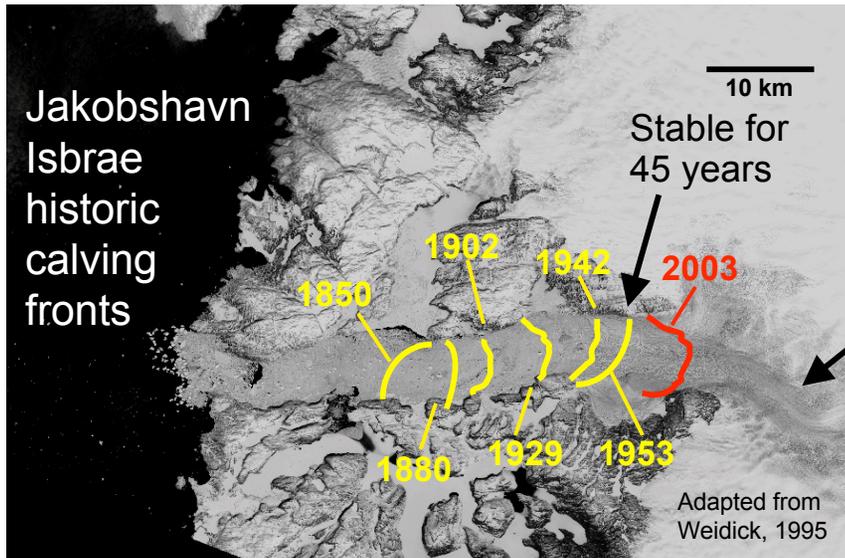
- 2002: 24-year record melt area  
- 50-100 year temp record suggests longer
- 16% increase from 1979 to 2002
- Meltwater accelerates ice flow



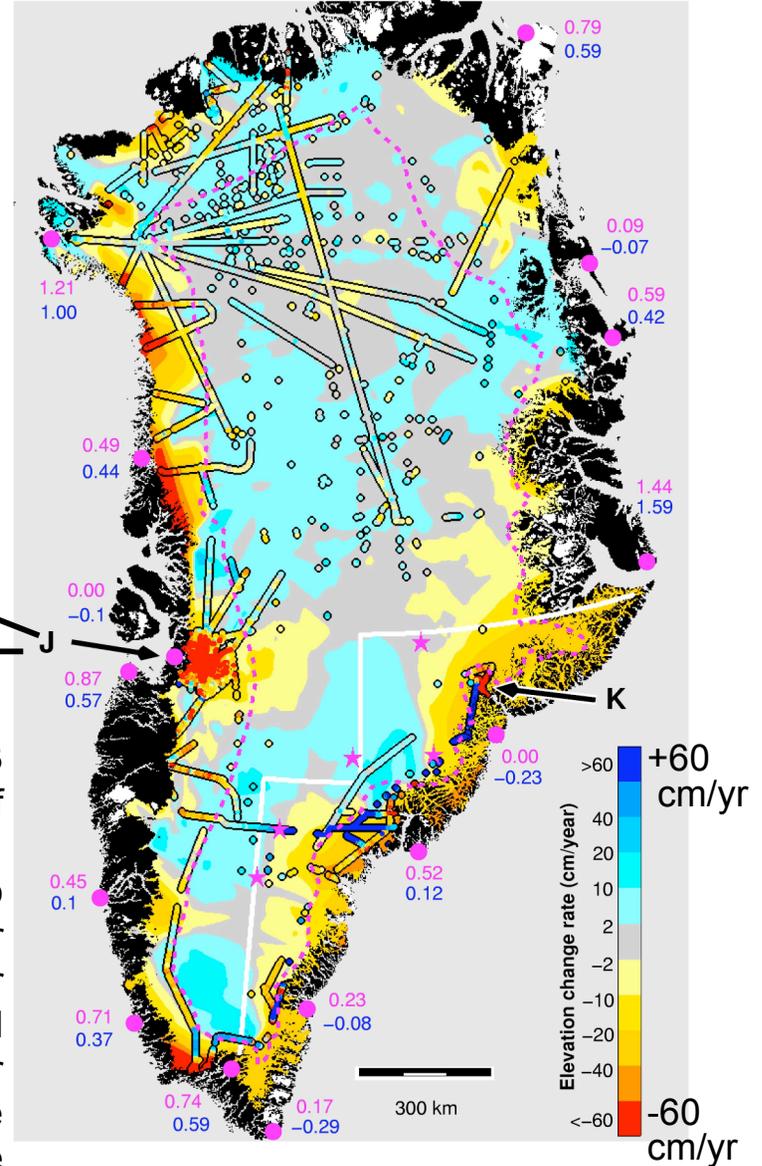
# Meltwater Accelerates Glacier Flow



# Greenland Margins: Where the Action Is

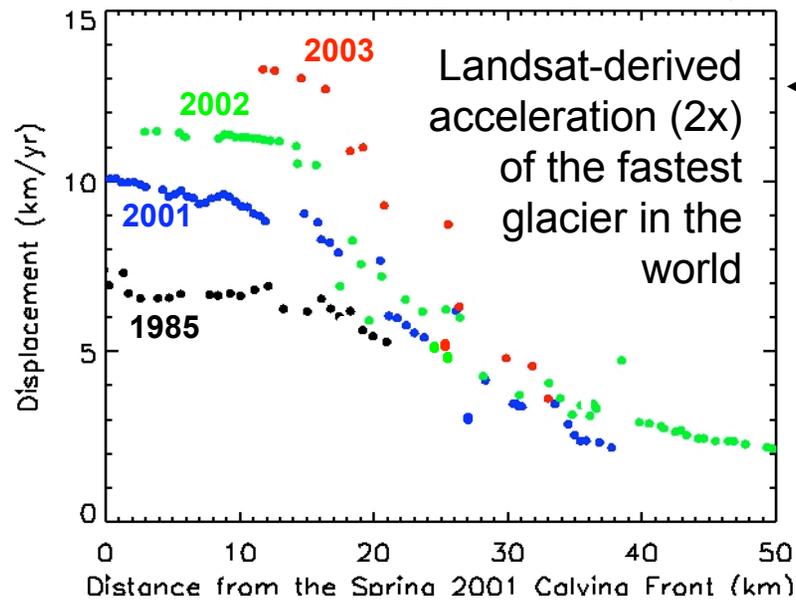


Airborne Laser Altimetry: 1993-2003

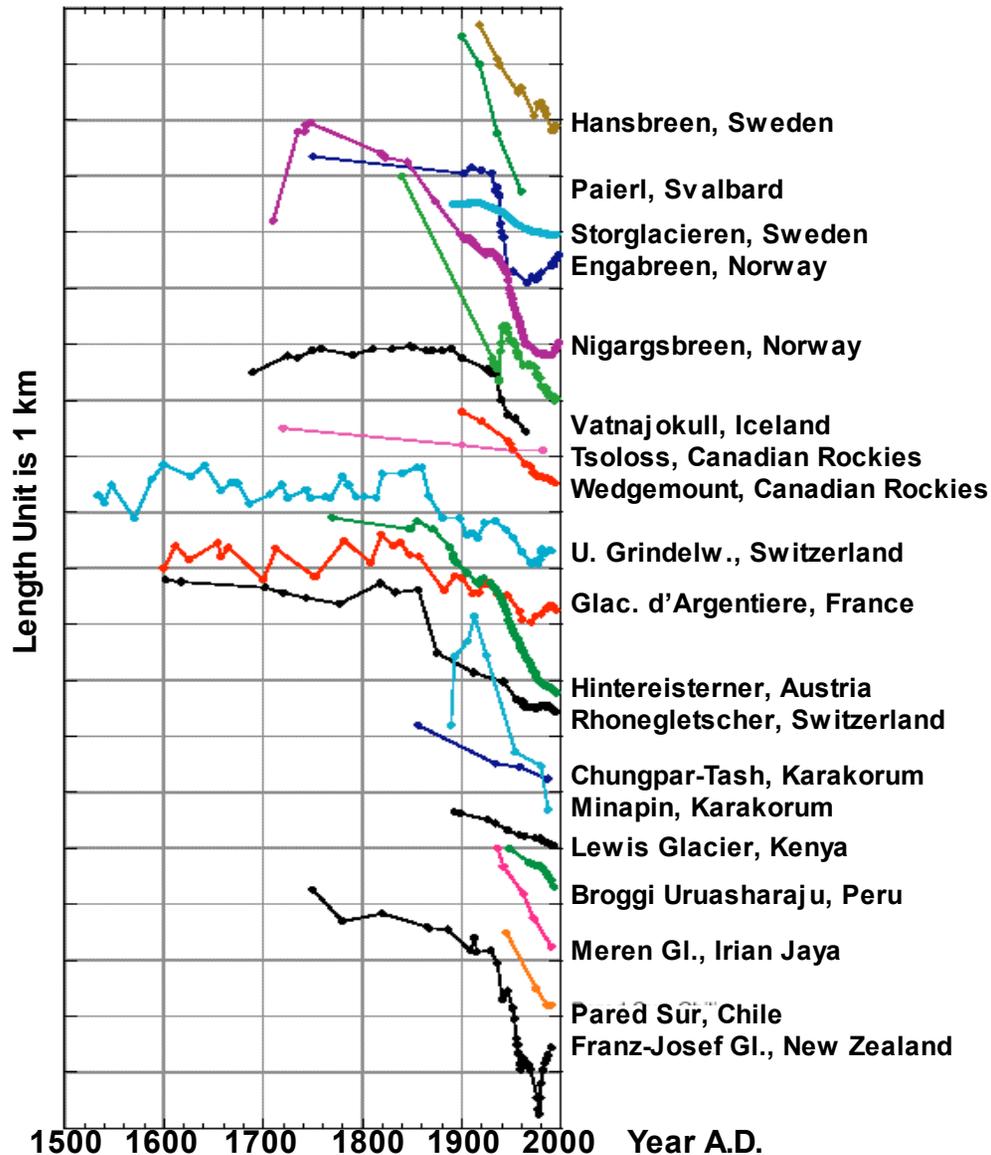


90 m thinning between 1997-2003

1997-2003 doubling of neg. balance to 100 km<sup>3</sup>/yr (.26 mm/yr sea level rise) over mid/late 1990s rate



# Worldwide Glacier Retreat



- **Satellite data increase the quality and quantity of retreat records**
- **Glaciers in all regions now retreating**

**Retreat is accelerating**

# Current Ice Sheet/Glacier Contributions to Sea Level Rise

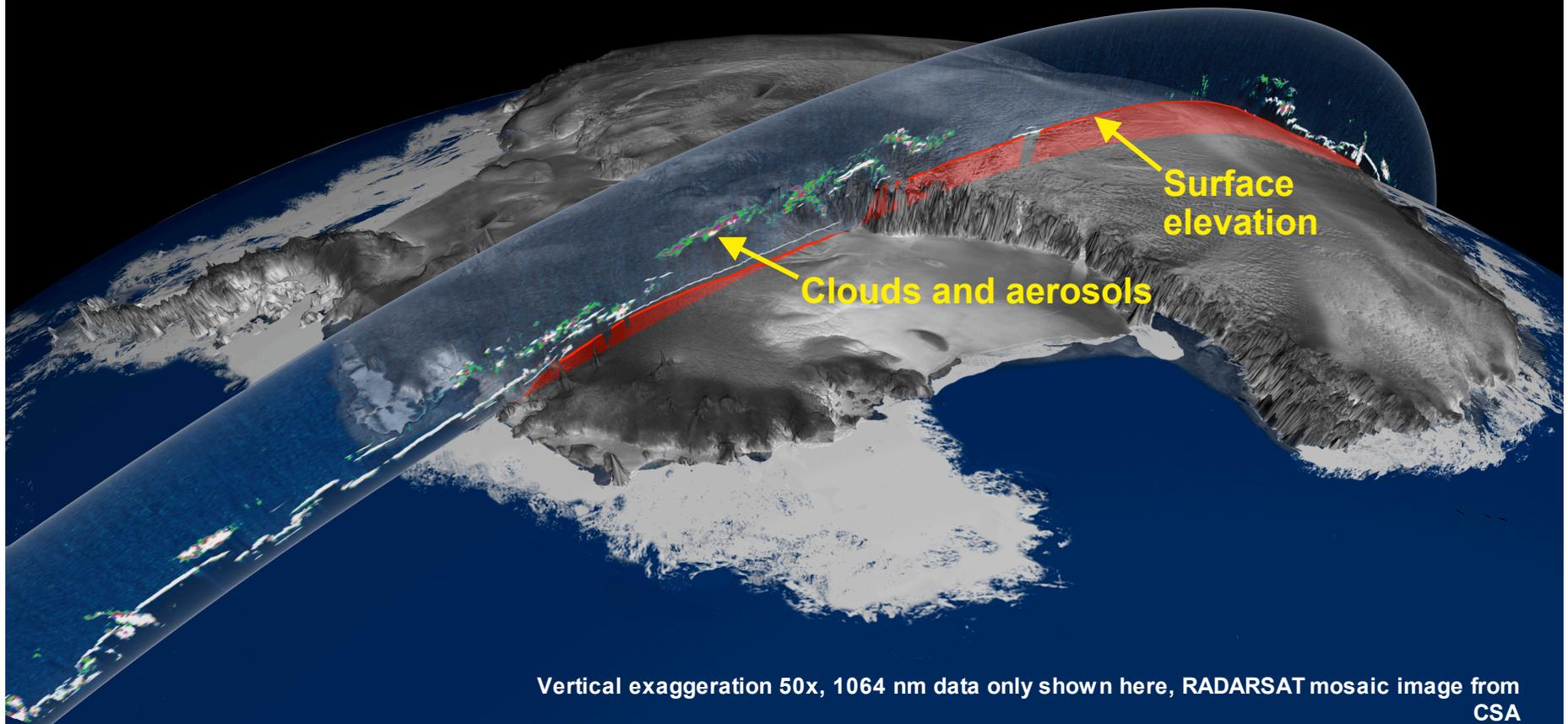
Ice-Covered Region	Sea Level Input (mm/yr)	
Canadian Ice Caps		+0.065 (1995-2000)
Patagonian Ice Fields	+0.042 (1968/75 - 2000)	+0.105 (1995-2000)
Alaskan Glaciers	+0.14 (mid 50s - mid 90s)	+0.27 (1995-2000)
Greenland	+0.13 (1993/4 -1998/9)	+0.20 (1997-2003)
Pine Island	+0.01 (1992-1999)	+0.24 (2002-2003)
Antarctica	???	

- All inputs are positive (Ice is shrinking)
- All available data indicate recent acceleration
- IPCC estimate ice is 0.2 - 0.4 mm/yr (1 - 2 mm/yr total SLR)
  - These ice masses alone add up to 0.88 mm/yr
  - Derived from remote sensing observations
- Glaciers and ice sheets respond rapidly to present climate change

# Ice Cloud and land Elevation Satellite (ICESat)

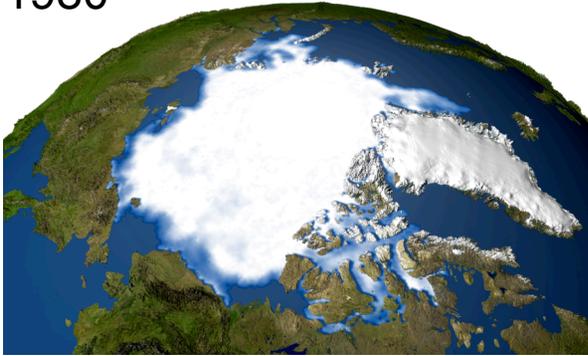
ICESat uses laser altimetry to measure precise ice sheet elevations and volume changes

- Enables estimates of mass changes (sea level contributions)
- Ice sheet processes manifest in topography and its changes



# Decline of Perennial Arctic Pack Ice

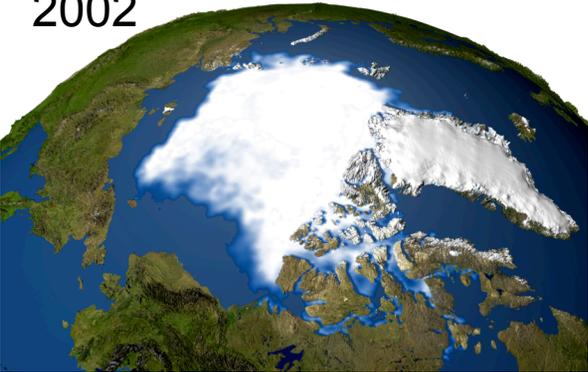
1980



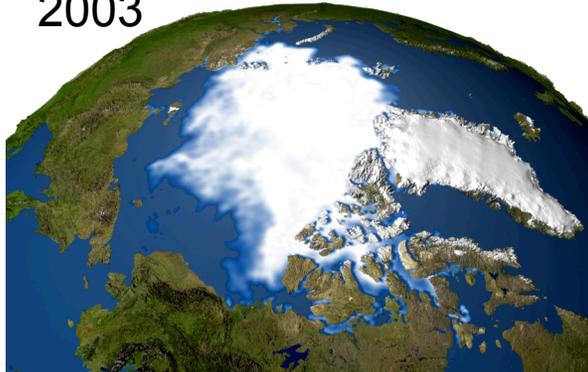
2002 and then 2003 set new records for minimal summer ice extent during the satellite era (i.e., past 30 years)

2004 reinforces the trend

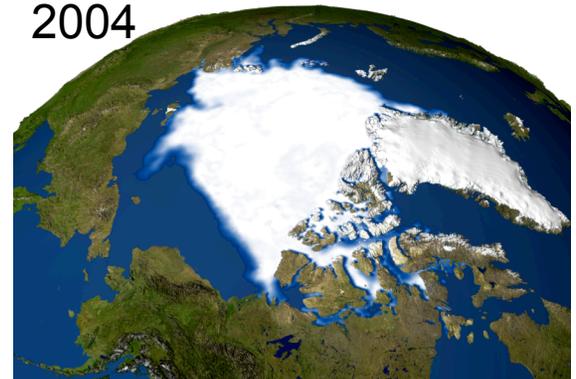
2002



2003



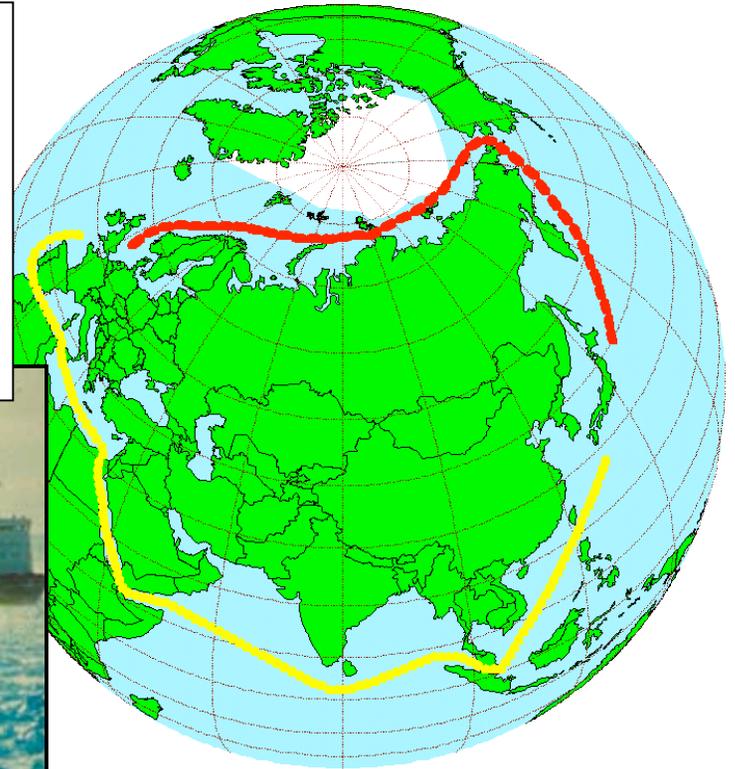
2004



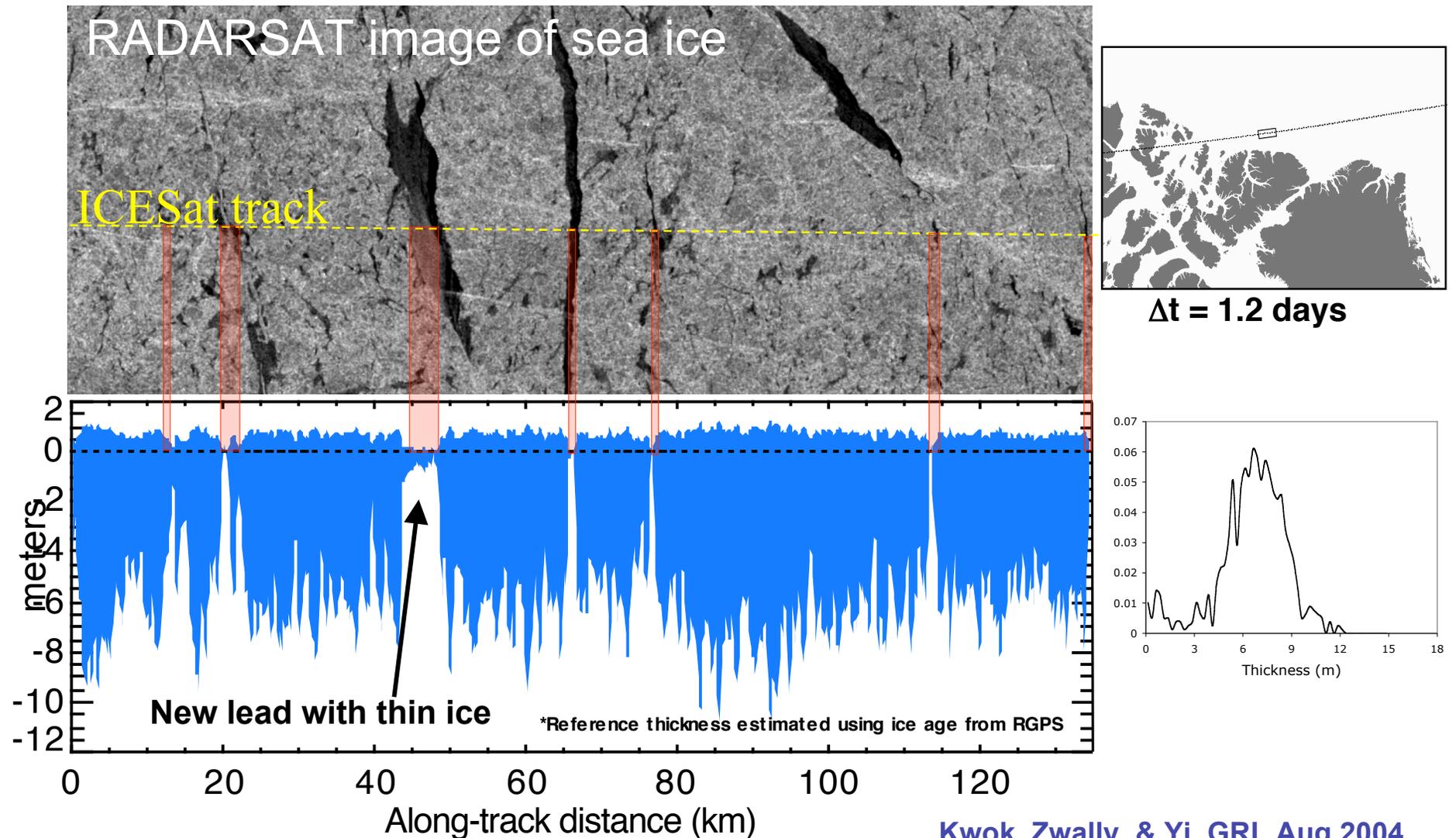
Summer minimum decreasing at 9.2% per decade

# Impact of Ice-Free Arctic Ocean

- Trans-pole shipping becomes possible via Northern Sea Route
- Improved access to resources
- New security issues

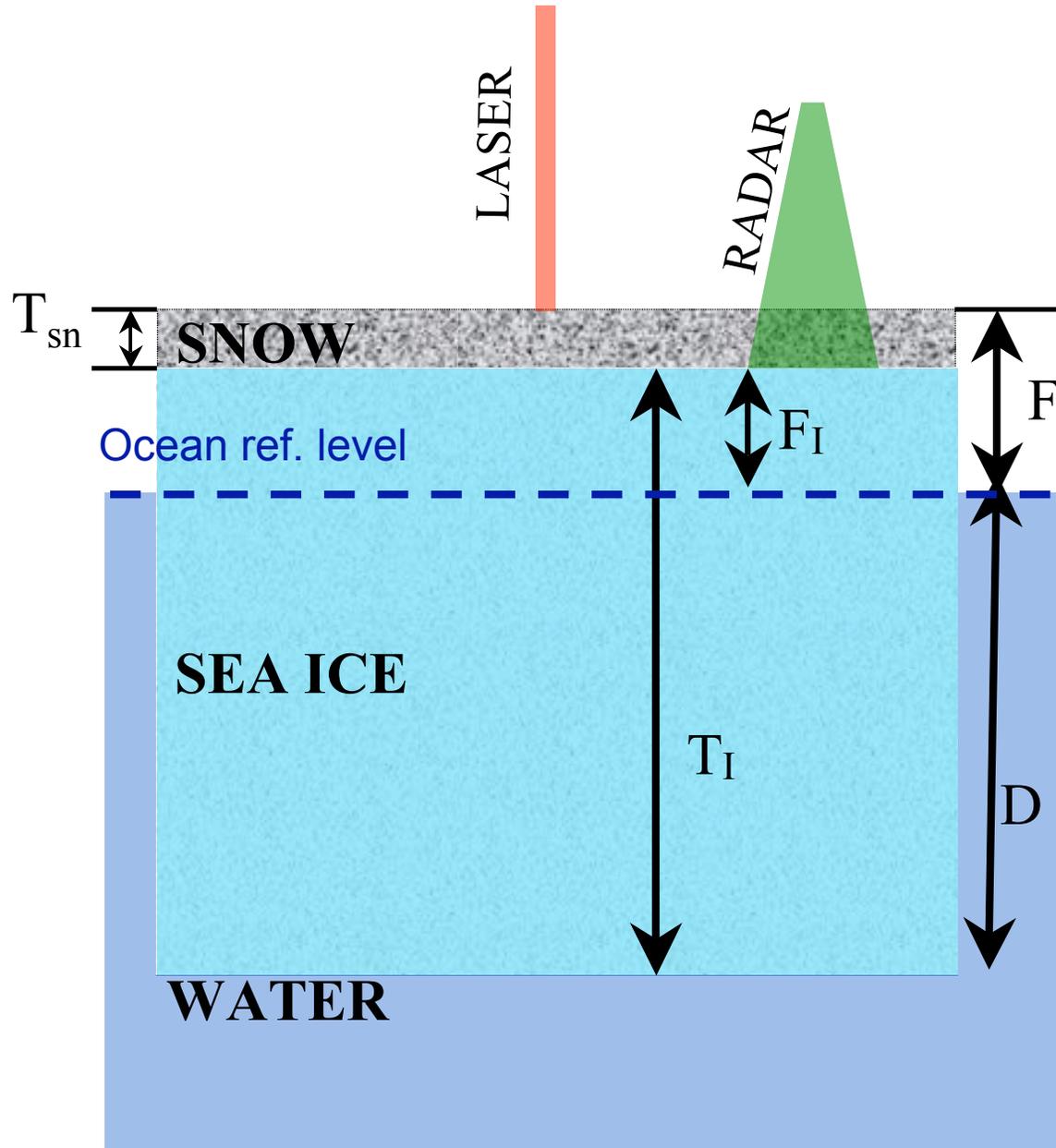


# Near-coincident ICESat and RADARSAT Data Over Arctic Sea Ice



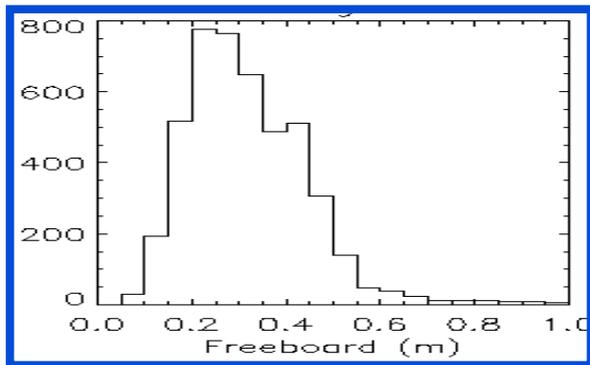
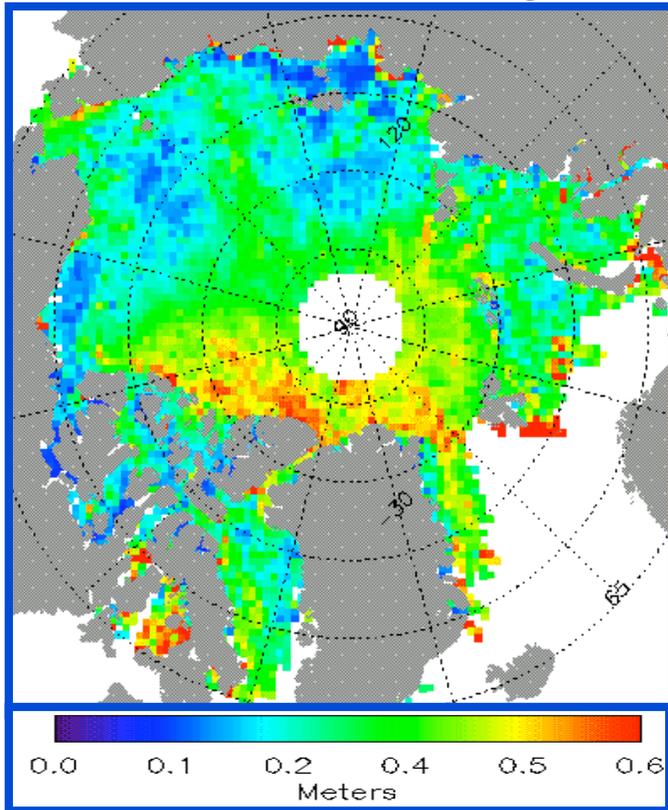
Kwok, Zwally, & Yi, GRL Aug 2004

# Sea Ice Freeboard and Thickness

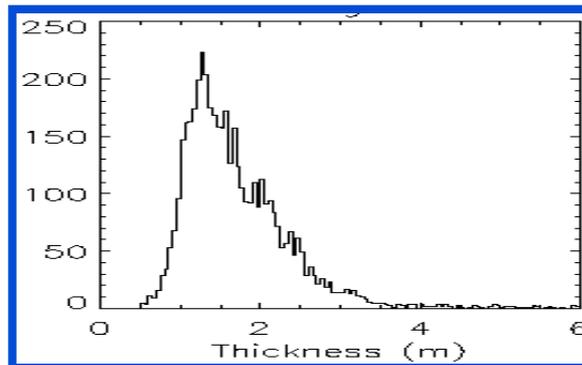
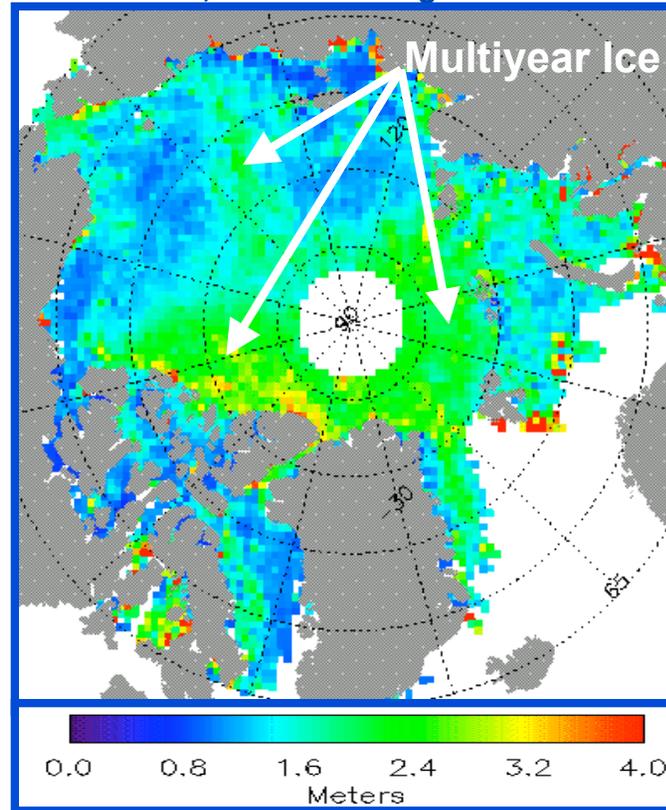


# ICESat-derived Sea Ice Thickness

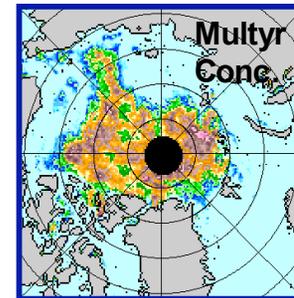
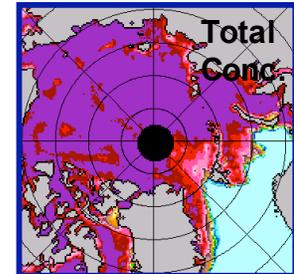
Sea Ice Freeboard from ICESat  
March 12-28, 2003 50 km grid



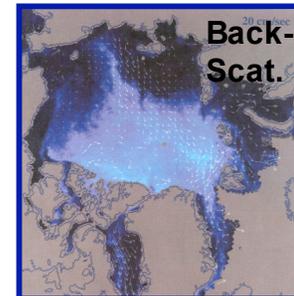
Sea Ice Thickness from ICESat  
March 12-28, 2003 50 km grid



Passive  
Microwave



QuikScat

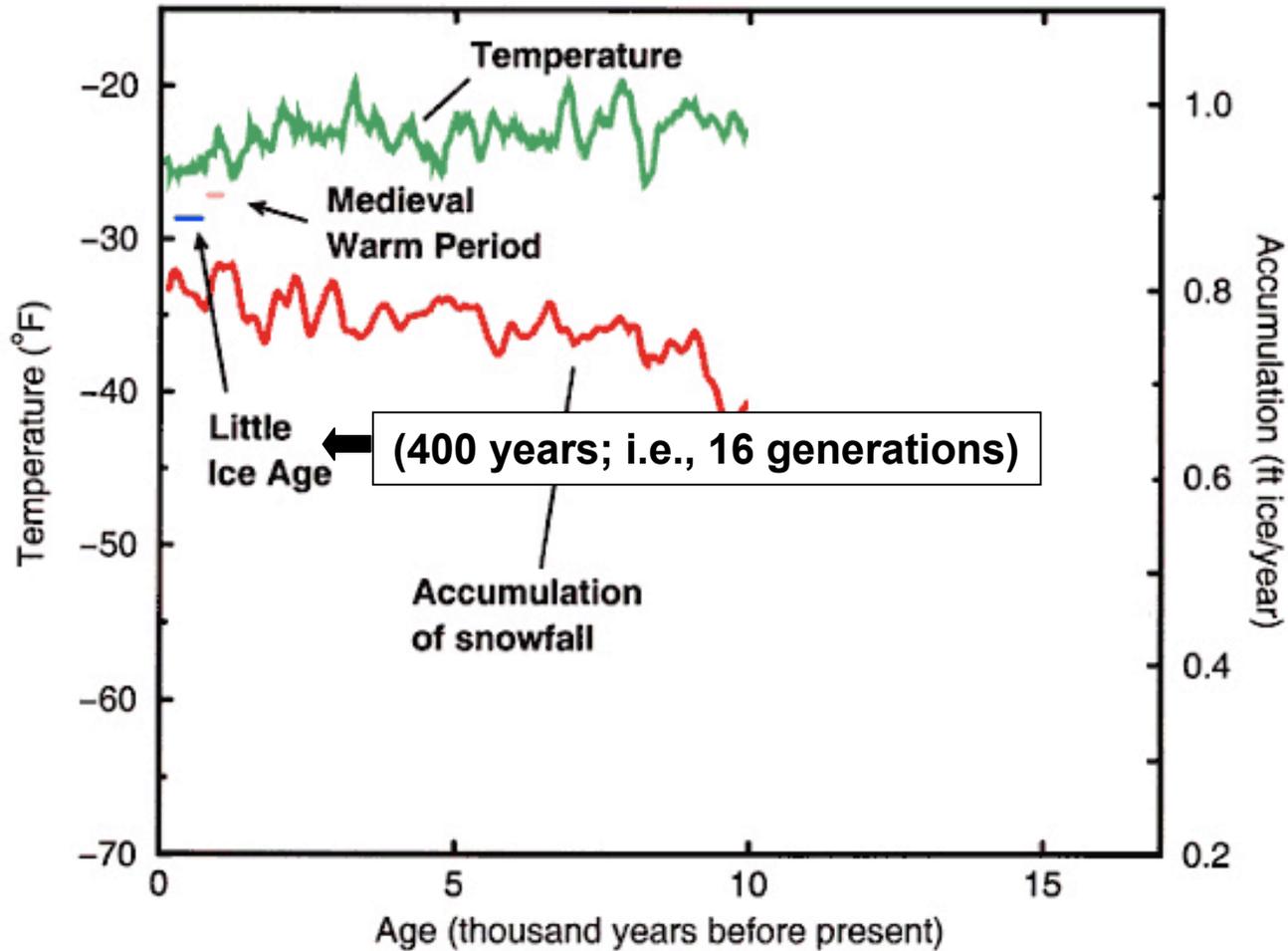


March 20, 2003

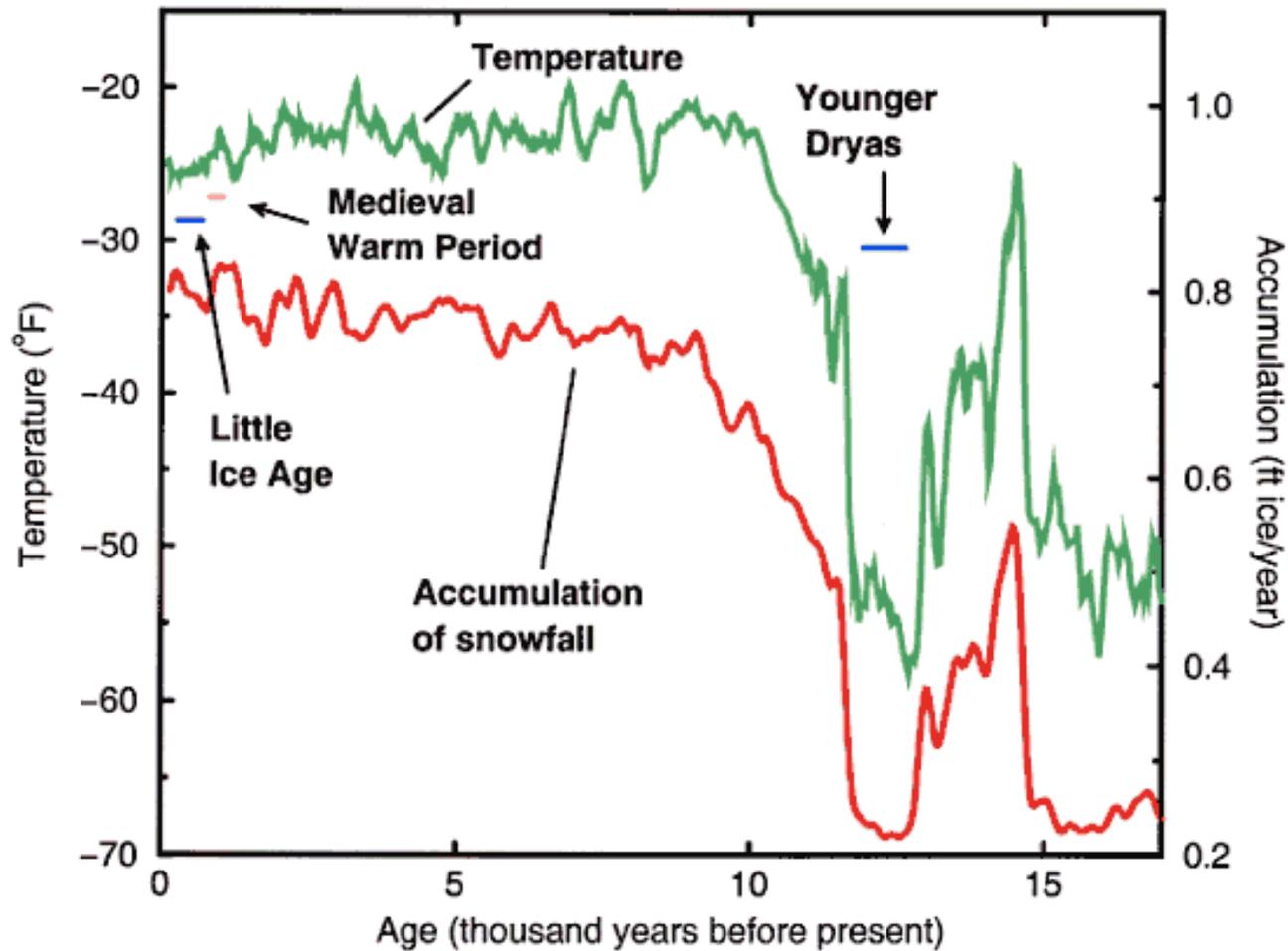
# Other Recent Changes

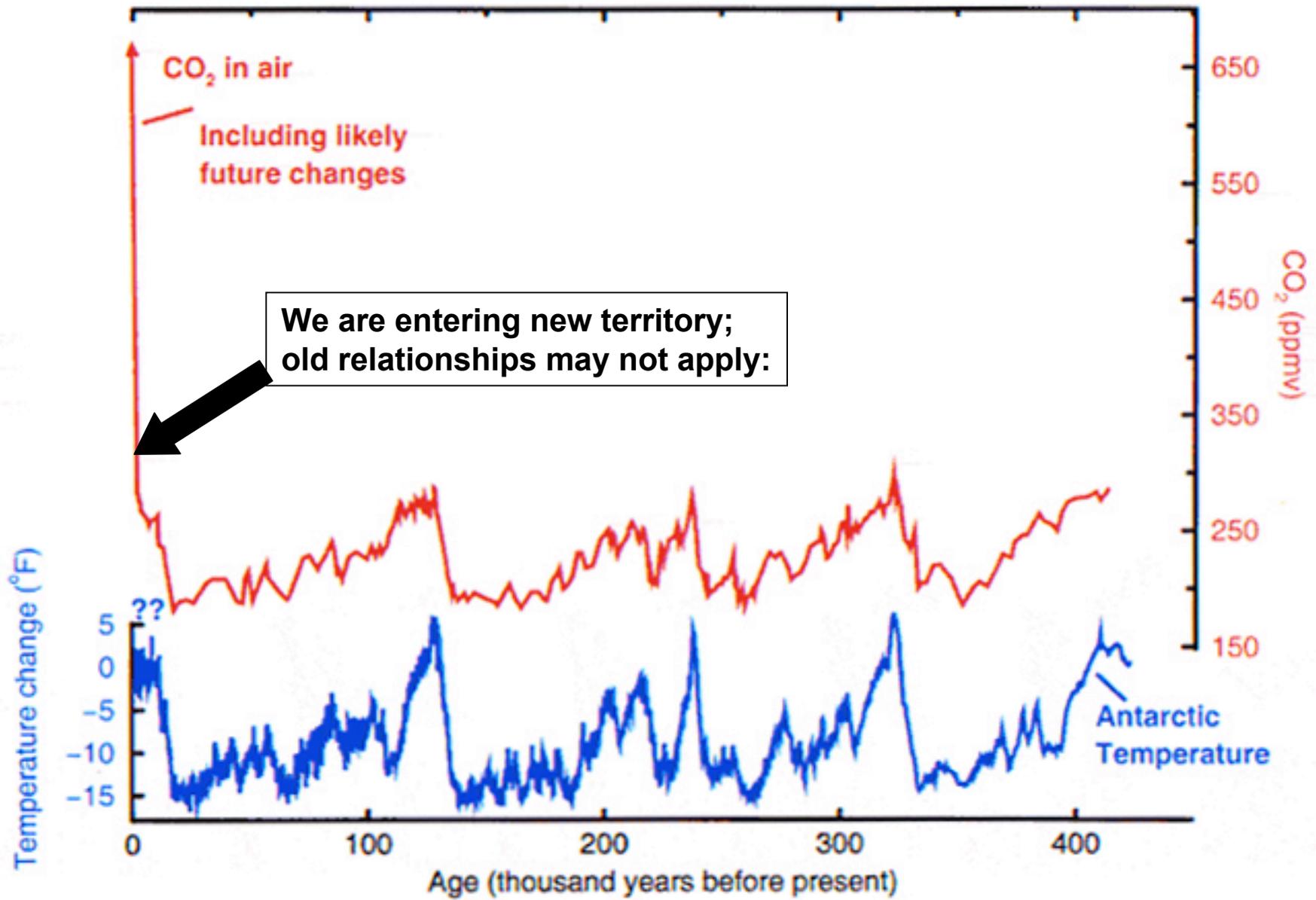
- **Warming high-latitude surface temperatures**
  - More than any other place on Earth
- **Melting permafrost**
  - Alaska: \$35M/yr infrastructure repair costs
- **Earlier melt onset of sea ice**
- **Earlier lake- and river-ice break-up**
- **Earlier snow melt**
- **Ocean and atmospheric circulation**

# Climate Record Stored in Ice

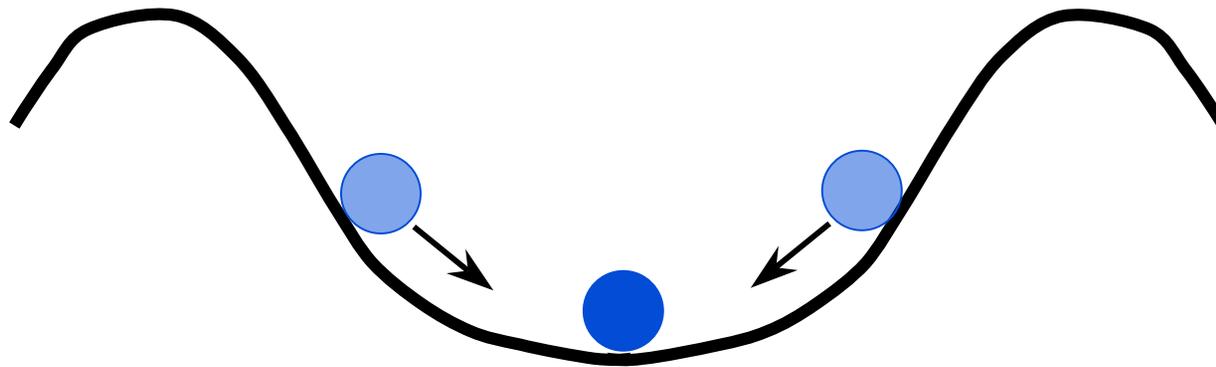


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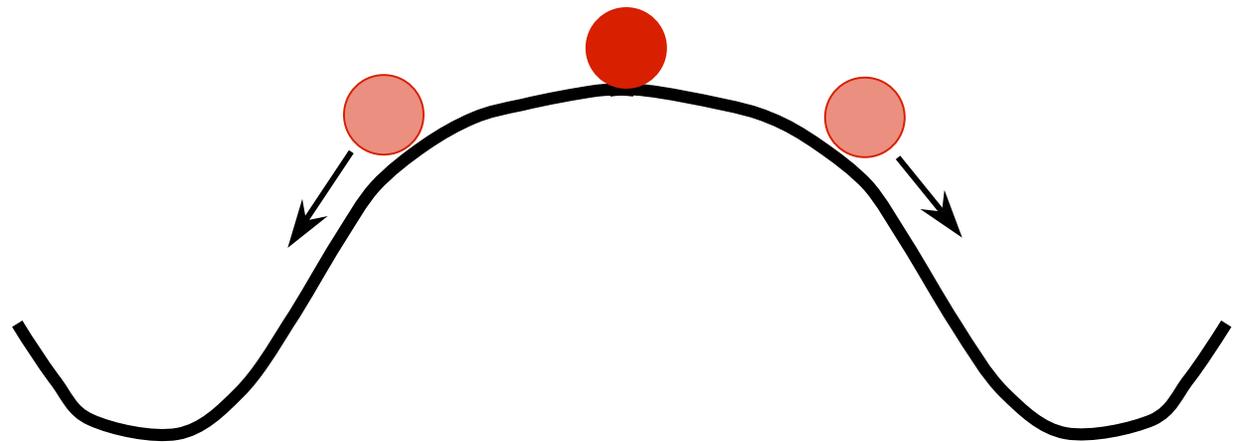




# System Stability

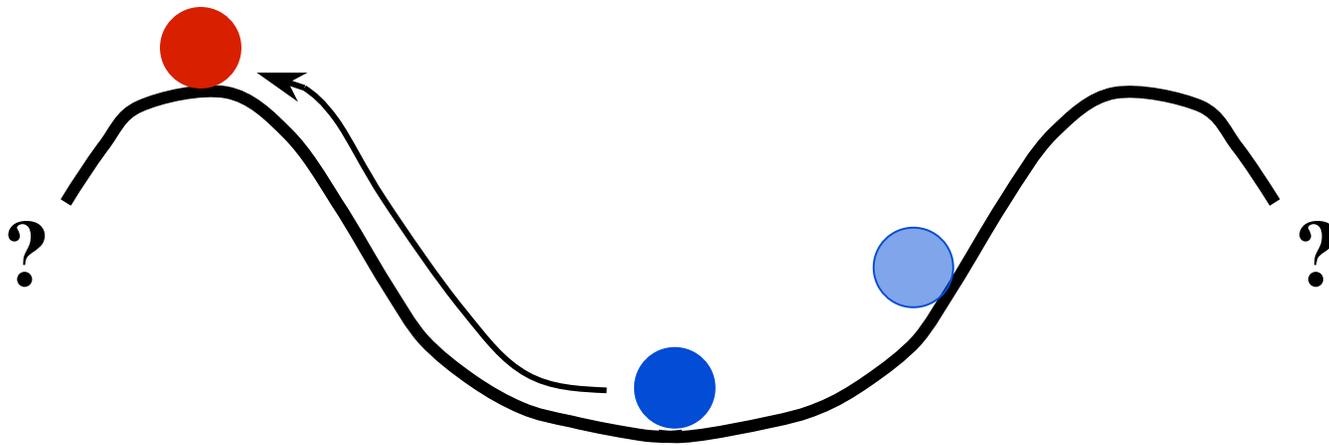


**Unstable System**  
Positive Feedbacks:  
Small disturbance  
corrects itself.

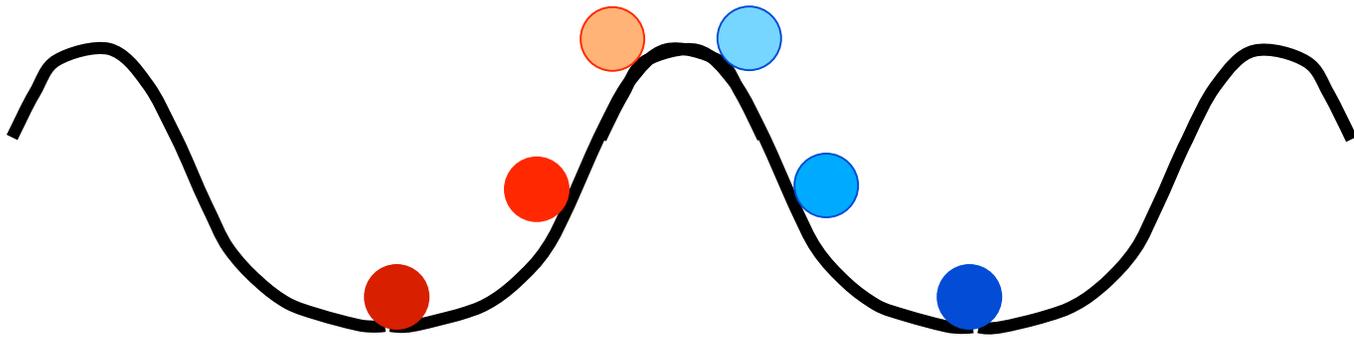


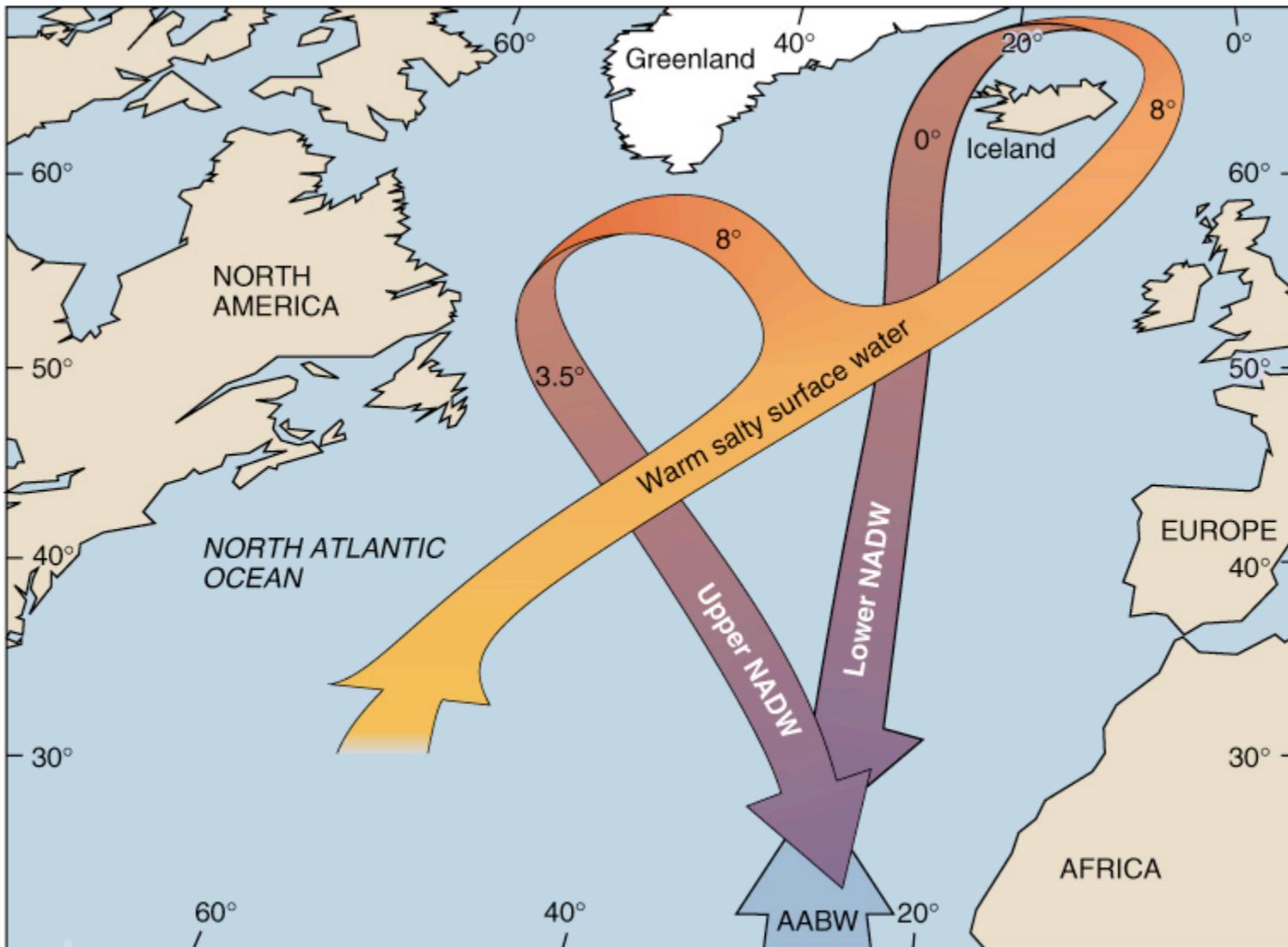
**Stable System**  
Negative Feedbacks:  
Small disturbance is  
amplified itself

Do Climate Systems Behave the same way?

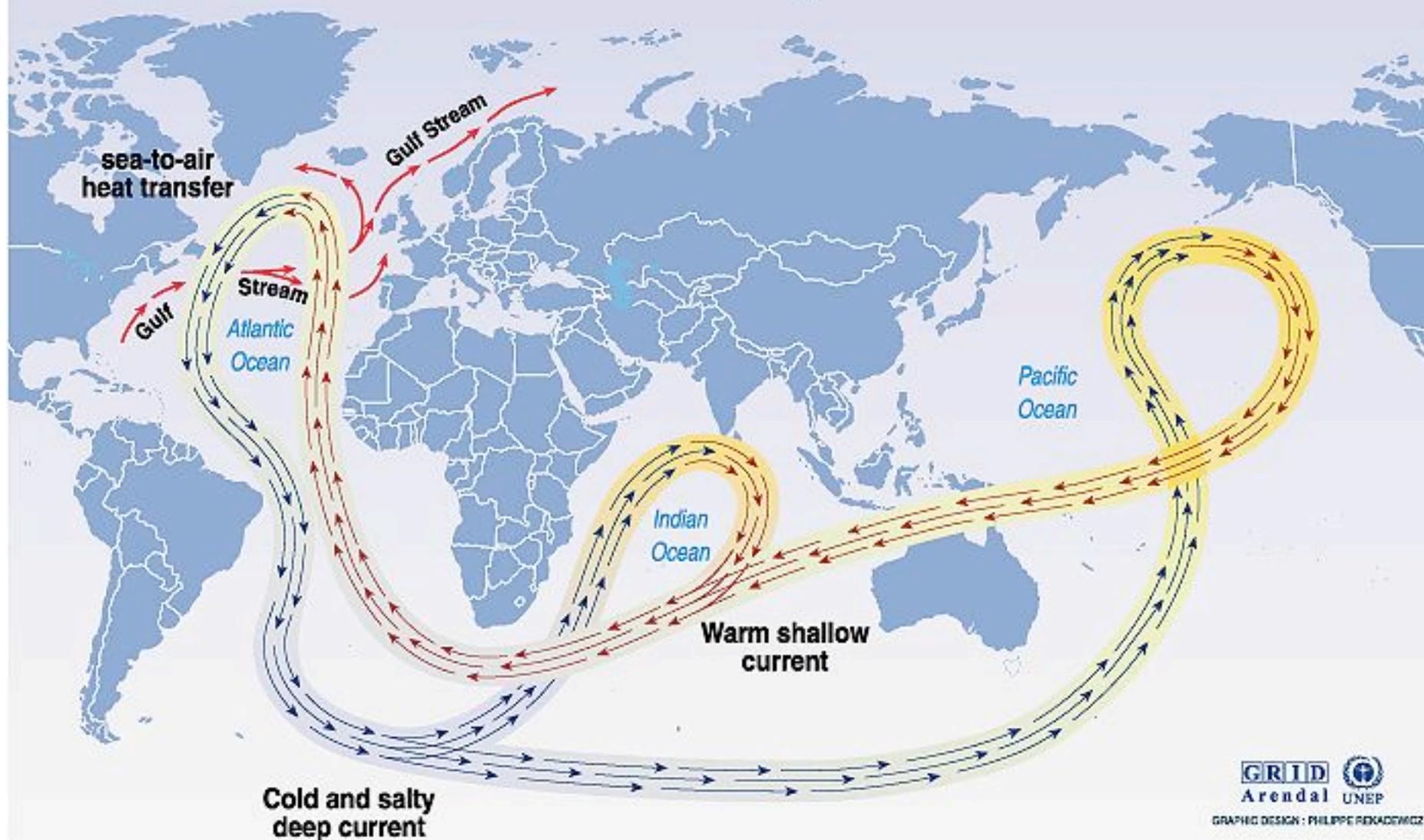


Are there different “stable”  
climates?





## Great ocean conveyor belt



Source: Broecker, 1991, in *Climate change 1995, impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change*, UNEP and WMO, Cambridge press university, 1996.

# Summary and Conclusions

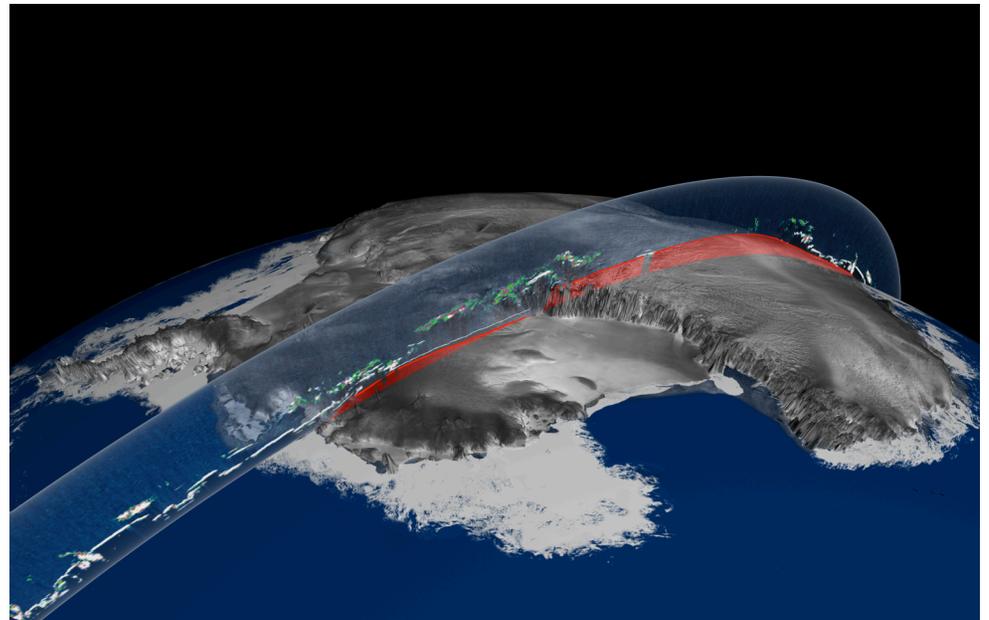
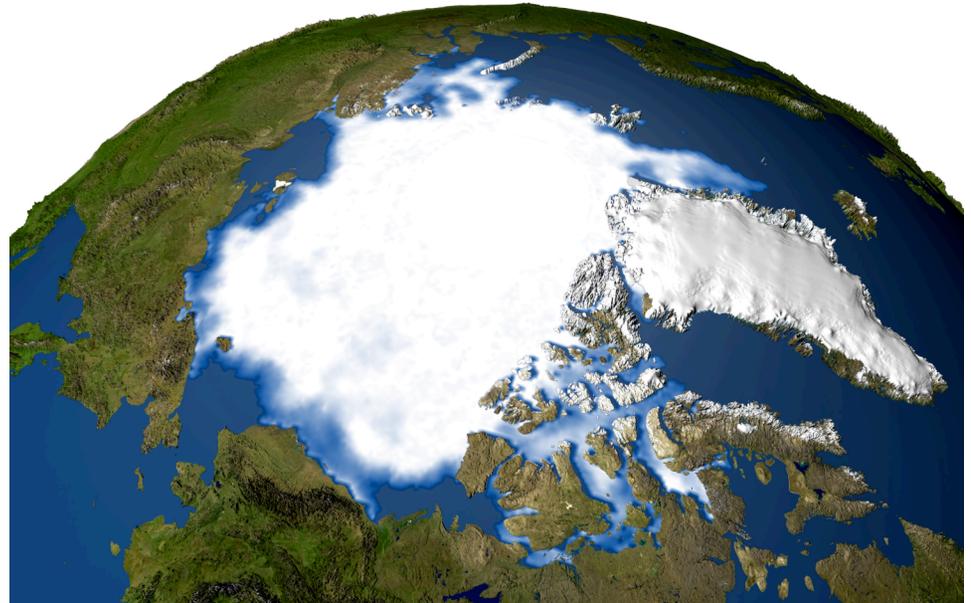
- **Glaciers and ice sheets are contributing substantially to sea level rise**
- **Contributions are accelerating**
- **The response time of glaciers and ice sheets is short**
- **Sea ice is declining in the Arctic, but not changing significantly in the Antarctic**
- **NASA has led the way in 2-d observation of the Cryosphere**
- **ICESat and its successor(s) will lead the way in exploring the third dimension**
  - **Changes in ice sheets, ice shelves, grounding lines, sea ice thickness, snow height, etc.**



***Climatologically we are in uncharted territory, and the world's ice cover is responding dramatically***

***The key to success under changing conditions lies in understanding and predicting these changes***

**By looking  
at the Earth  
as a whole  
and its  
farthest  
reaches,  
NASA is  
leading the  
way**





**Thank You!!!**