The Melting of Greenland

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LANL Climate Study Group, 6 March 2007

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Outline

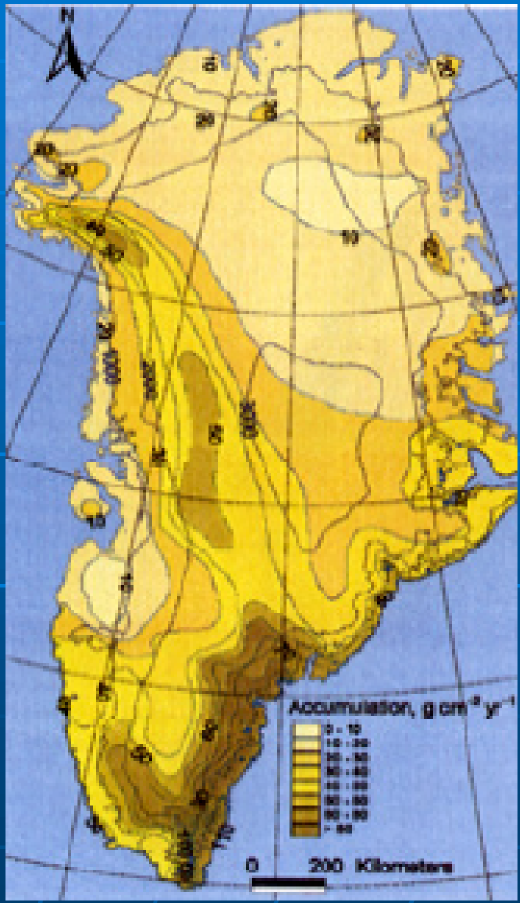
- Introduction to ice sheets
- Ice sheets and sea level rise
- Recent observations of Greenland
- Ice sheet models
- LANL's role in Greenland research

Definitions

- A **glacier** is a mass of ice, formed from compacted snow, flowing over land under the influence of gravity.
- An **ice sheet** is a mass of glacier ice greater than 50,000 km^2 (Antarctica, Greenland).
- An **ice cap** is a mass of glacier ice smaller than 50,000 km^2 (e.g., Iceland, Svalbard).
- An **ice shelf** is a large sheet of floating ice attached to land or a grounded ice sheet.
- An **ice stream** is a region of relatively fast-flowing ice at the ice sheet margin, bounded on the sides by slower moving ice.
- An **outlet glacier** is a region of fast-flowing ice at the ice sheet margin, bounded on the sides by rock walls.

Greenland ice sheet

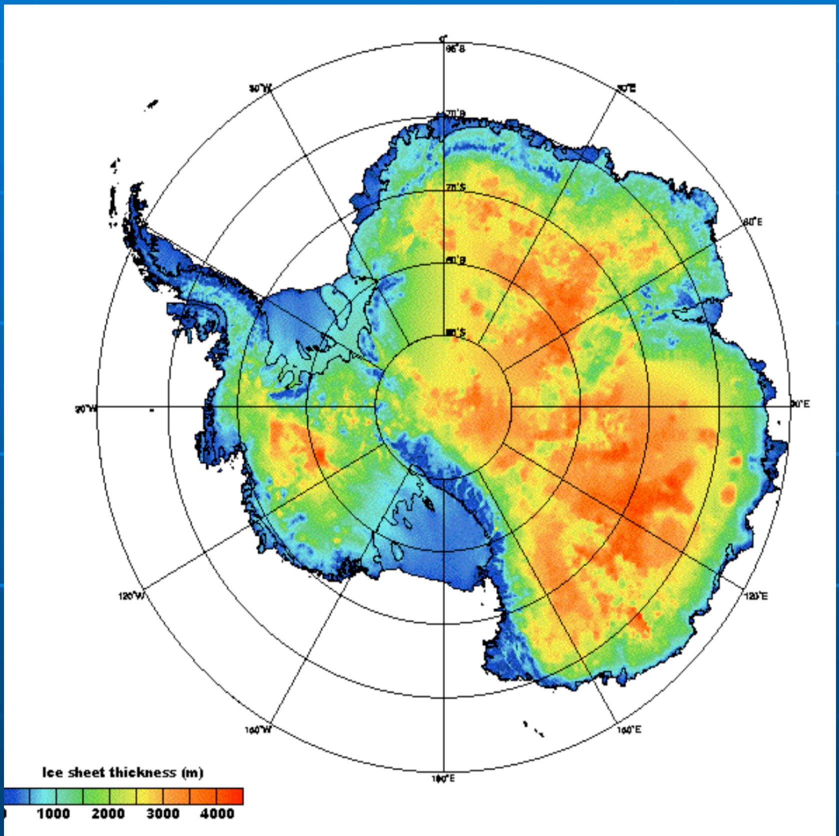
- Volume ~ 2.8 million km^3
  (~7 m sea level equivalent)
- Area ~ 1.7 million km^2
- Mean thickness ~ 1.6 km
- Accumulation ~ 500 km^3/yr
- Surface runoff ~ 300 km^3/yr
- Iceberg calving ~ 200 km^3/yr



Annual accumulation
(Bales et al., 2001)

Antarctic ice sheet

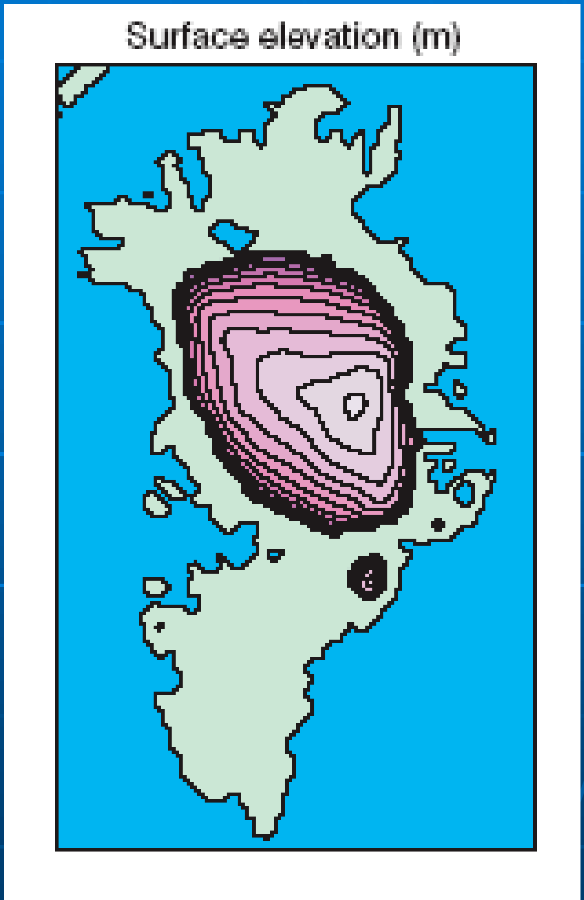
- Volume ~ 26 million km^3 (~61 m sea level equivalent)
- Area ~ 13 million km^2
- Mean thickness ~ 2 km
- Accumulation ~ 2000 km^3/yr, balanced mostly by iceberg calving
- Surface melting is negligible



Antarctic ice thickness
(British Antarctic Survey BEDMAP project)

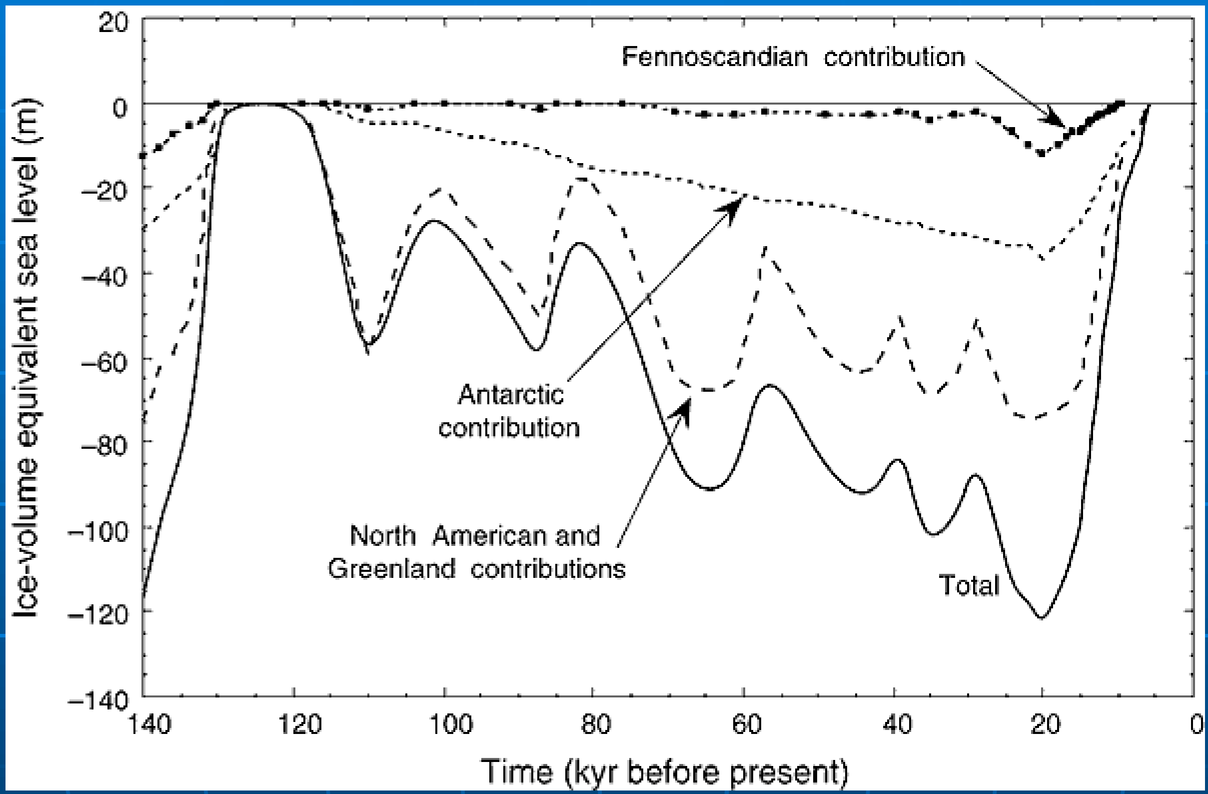
Eemian interglacial (~130 kyr ago)

- Global mean temperature was 1-2^{o} higher than today
- Global sea level was 4-6 m higher
- Much of the Greenland ice sheet may have melted



Greenland minimum extent
(Cuffey and Marshall, 2000)

Sea level change since Eemian



IPCC TAR (2001), from Lambeck (1999)

- Sea level rose by ~15-20 cm in 20th century
- Past rates were up to 10 times greater

IPCC: Sea level observations

- Global sea level increased at a rate of ~18 cm/century, 1961-2003 (based on tide gauges, satellite altimetry).
- The rate was faster, ~31 cm/century, during 1993-2003.
- Ice sheets very likely contributed to the observed sea level rise during 1993–2003.

Source	Rate of sea level rise, 1961-2003	Rate of sea level rise, 1993-2003
Thermal expansion	4 cm/century	16 cm/century
Glaciers and ice caps	5 cm/century	8 cm/century
Ice sheets	2 cm/century	4 cm/century

IPCC: Sea level predictions

- Sea level will rise by ~20-50 cm in the 21st century, excluding "rapid dynamical changes in ice flow."
- Understanding of ice sheet dynamic effects "is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise."

Emissions scenario	Temperature change	Sea level rise
B1	1.1 – 2.9 °C	18 - 38 cm
A1B	1.7 – 4.4 °C	21 - 48 cm
A1F1	2.4 – 6.4 °C	26 - 59 cm

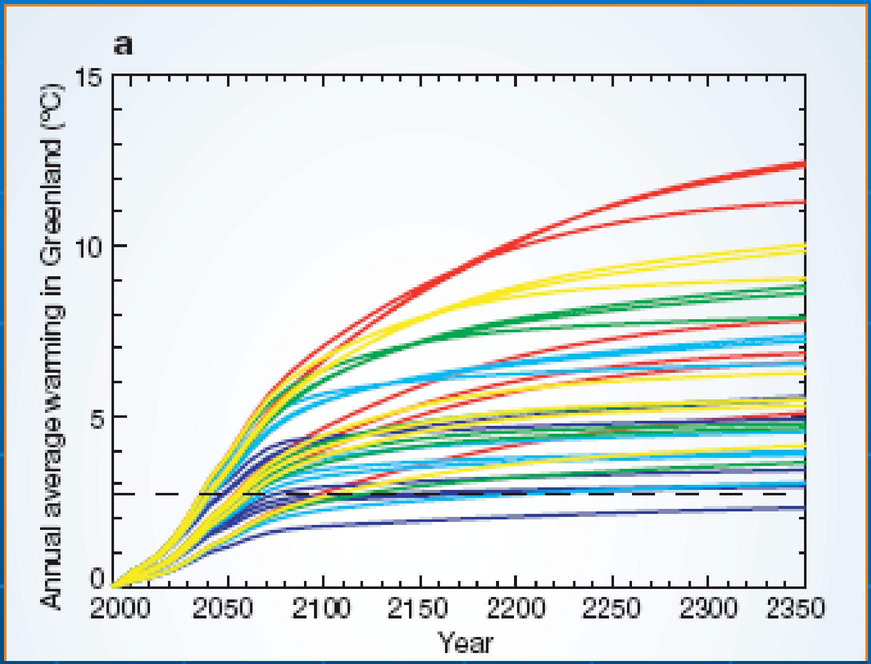
Stability of Greenland

- IPCC: The surface mass balance of Greenland will become negative at a global average warming in excess of 1.9 – 4.6 °C (roughly the range of the A1B "business-as-usual" scenario). This level of warming, if sustained for many centuries, would melt virtually all of the ice sheet.

- Standalone ice sheet models (e.g., Huybrechts & De Wolde, 1999; Greve, 2000) suggest that *local* warming of ~3 °C, if sustained, would melt the ice sheet. Positive feedbacks (elevation, albedo) speed melting.

- Models also suggest that if Greenland were removed *in present climate conditions*, it would not regrow (Toniazzo et al., 2004). There may be a point of no return

IPCC scenarios and Greenland



Greenland warming under IPCC forcing scenarios (Gregory et al., 2004)

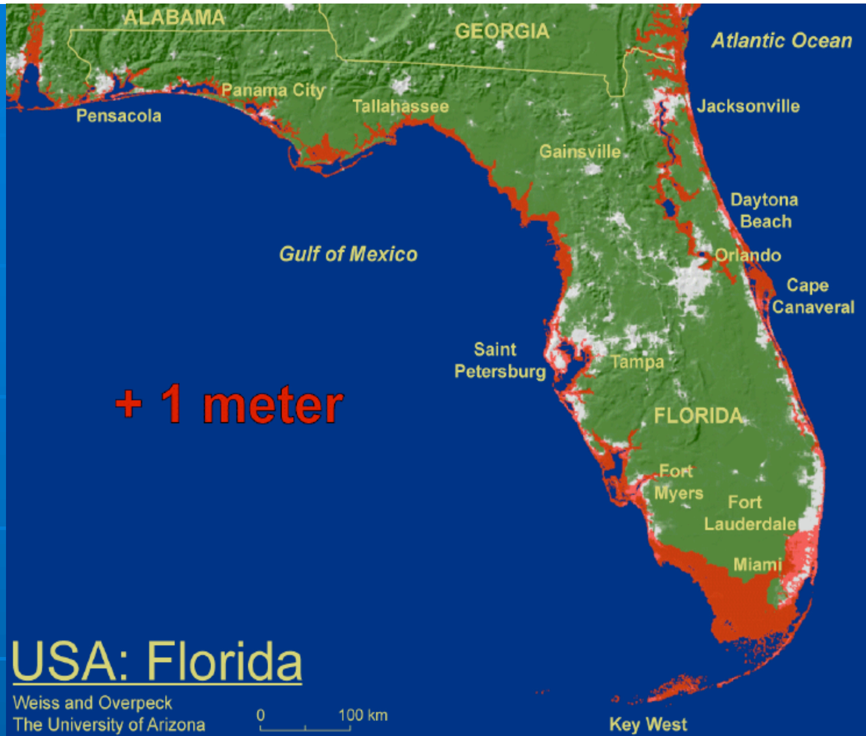
- GCMs predict that under most scenarios (CO_2 stabilizing at 450-1000 ppm), greenhouse gas concentrations by 2100 will be sufficient to raise Greenland temperatures above the melting threshold.

Slippery slope?

- Recent observations show that ice sheets can respond more rapidly to climate change than previously believed.
- Sea level rise of ~1 m during this century cannot be ruled out.
- We need to better understand the time scales and mechanisms of deglaciation.

Photo by R. J. Braithwaite.

From Science, vol. 297, July 12, 2002.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Atlantic Ocean
Panama City
Tallahassee
Pensacola
Jacksonville
Gainsville
Daytona Beach
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Orlando
Cape Canaveral
Saint Petersburg
Tampa
+ 1 meter
FLORIDA
Fort Myers
Fort Lauderdale
Miami
USA: Florida
Weiss and Overpeck
The University of Arizona
0 100 km
Key West


ALABAMA
GEORGIA
Atlantic Ocean
Panama City
Tallahassee
Pensacola
Jacksonville
Gainsville
Daytona Beach
Gulf of Mexico
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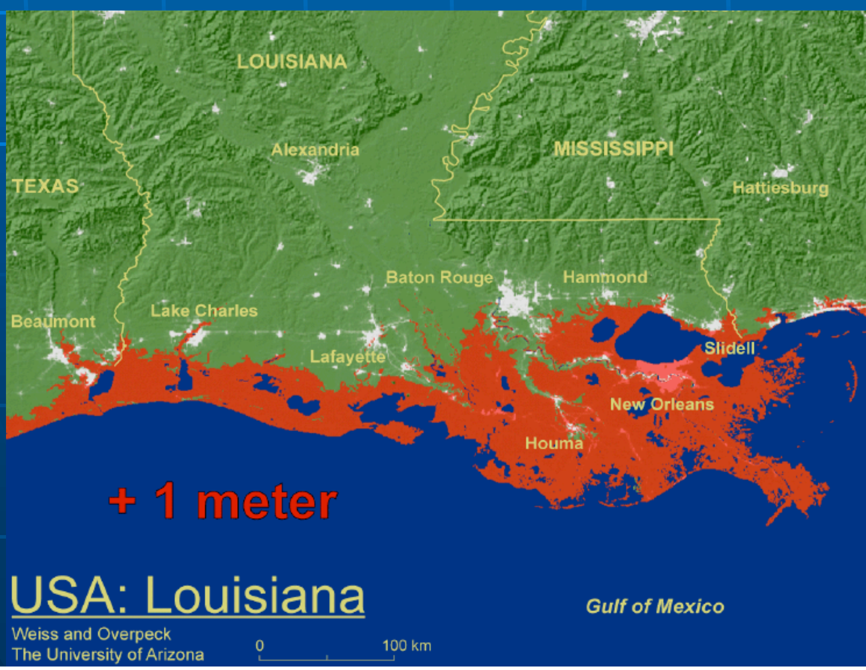
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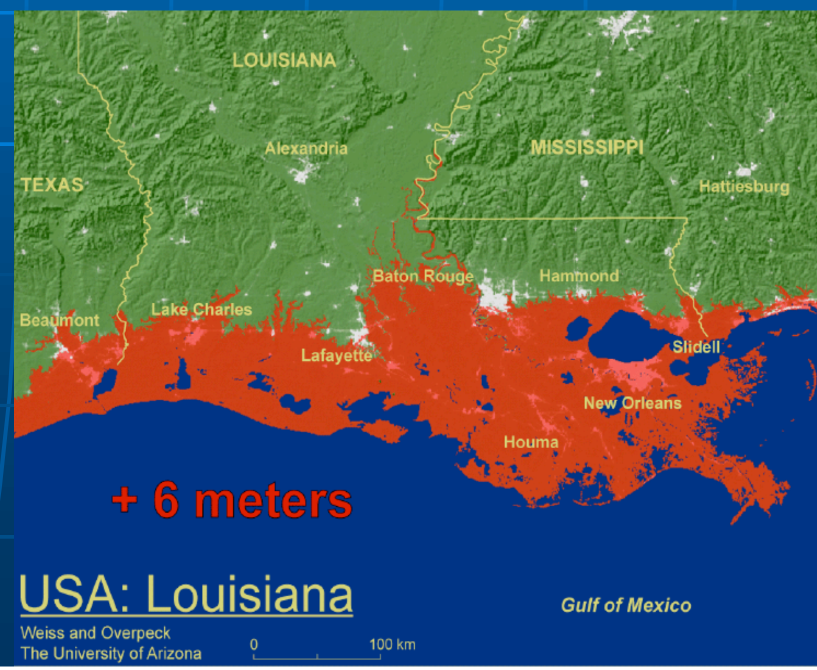
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USA: Louisiana
Gulf of Mexico
Weiss and Overpeck
The University of Arizona
0 100 km

Greenland mass balance

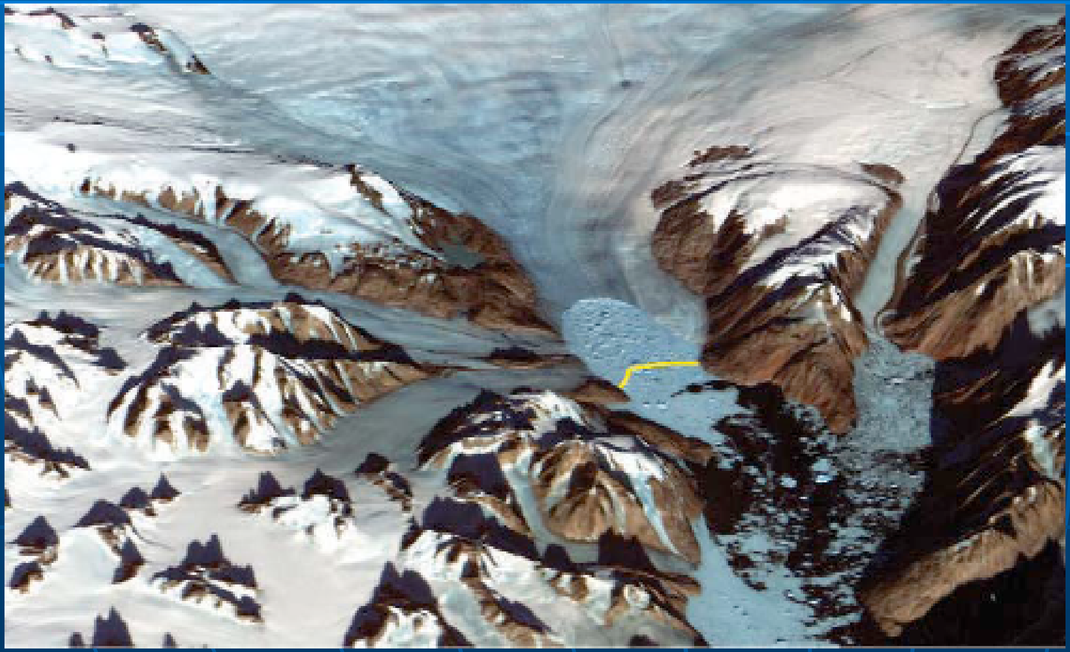
Three techniques:

- Mass balance is computed as the difference between accumulation and melting/outflow. (Accumulation and melting from field measurements and models; outflow velocities from SAR interferometry)
- Surface elevation changes are measured directly by airplane laser or satellite radar altimetry.
- Mass changes are computed from changes in the local gravity field (GRACE satellites).

Uncertainties are large, but all three techniques suggest that the Greenland ice sheet has been losing mass since the 1990s.

Method 1: Mass balance

- Rignot and Kanagaratnam (2006)
  - Greenland glaciers south of 66°N accelerated rapidly between 1996 and 2005.
  - The net rate of mass loss increased from ~90 to 220 km^3/yr* (uncertainty ~30-40 km^3/yr)
  - About 1/3 of the loss can be attributed to surface melting



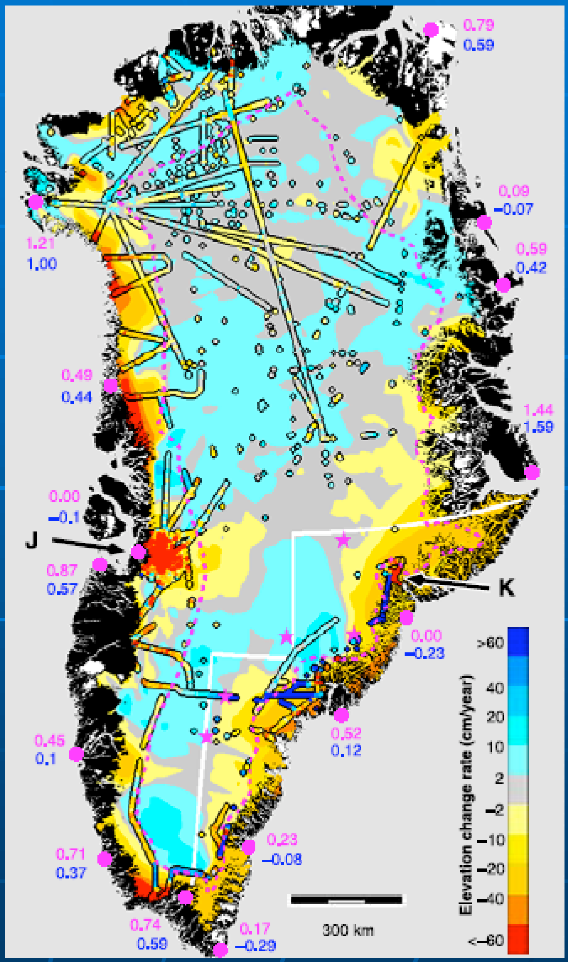
Kangerdlugssuaq glacier,
2000 v. 2005

*40 km^3/yr ~
36 Gt/yr ~
1 cm SLE/century

Method 2: Altimetry

- Aircraft laser altimetry (Krabill et al., 2004): Mass loss of 80 km^3/yr, 1997-2003, mainly near the coast. (Half from surface melting, half from glacier acceleration)

- Satellite radar altimetry (Zwally et al., 2005): Ice sheet was in near balance (+11 km^3/yr), 1992-2002.



Ice elevation change (Krabill et al., 2004)

Method 3: Gravity

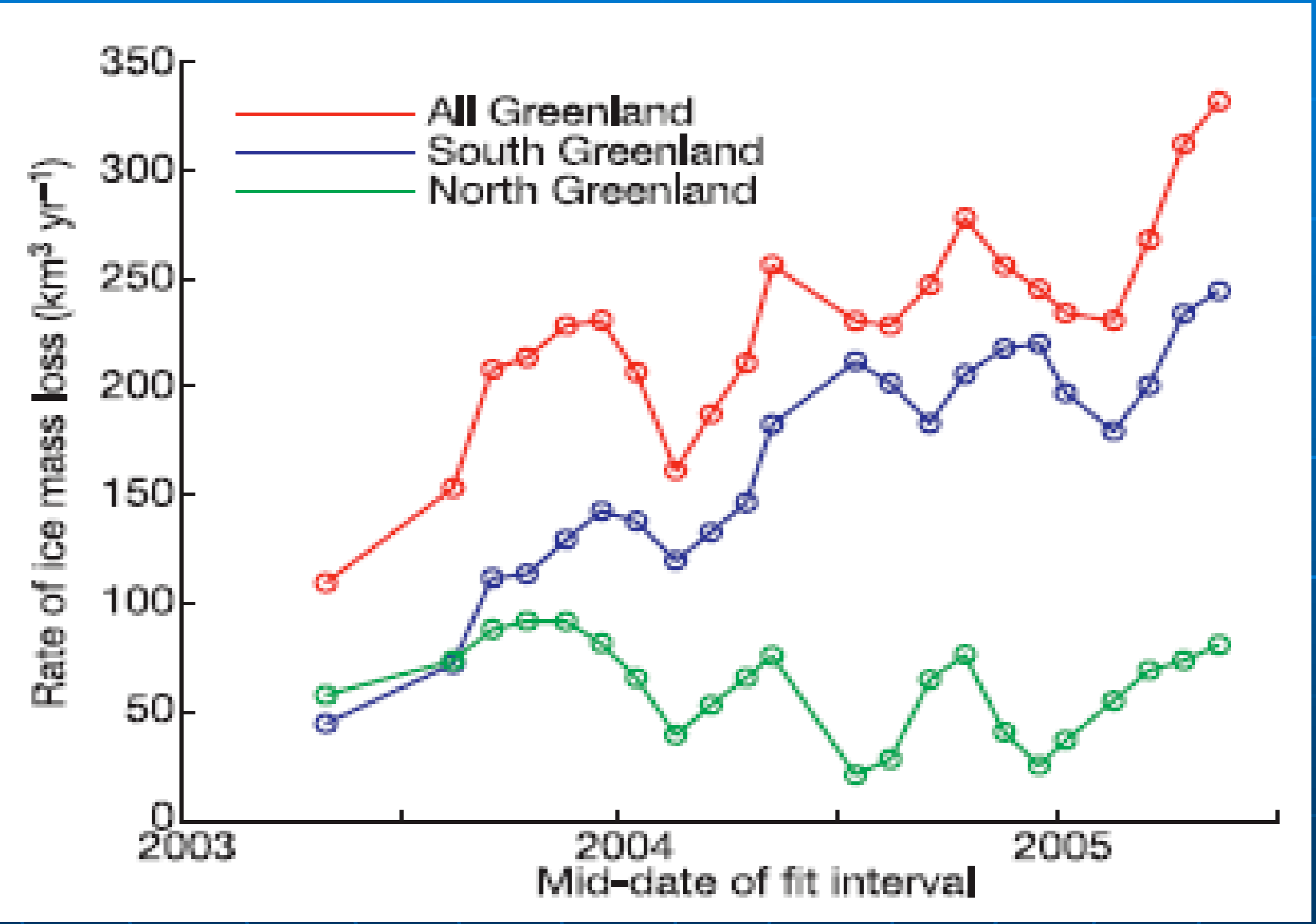
- Gravity Recovery and Climate Experiment (GRACE): Deduce Earth's gravity field by measuring changes in the distance between two satellites (220 km apart).

- Measures mass, not volume

- Velicogna and Wahr (2006): Loss of 212-284 km^3/yr, 2002-2006, with most of the melting in 2004-2006

- Luthcke et al. (2006): Loss of 87-118 km^3/yr, 2003-2005

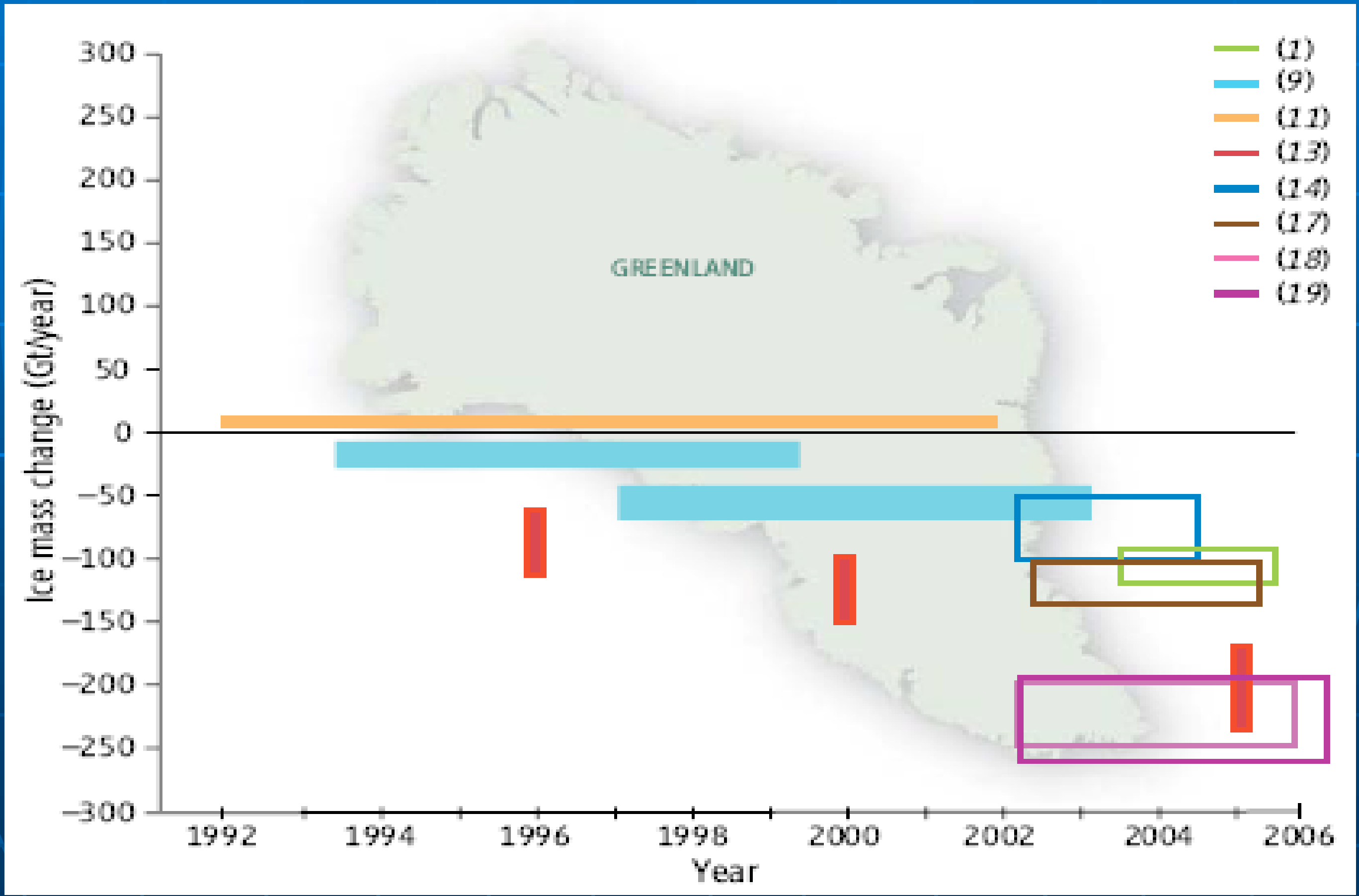
GRACE mass loss



Velicogna and Wahr (2006)

Greenland: Overall picture

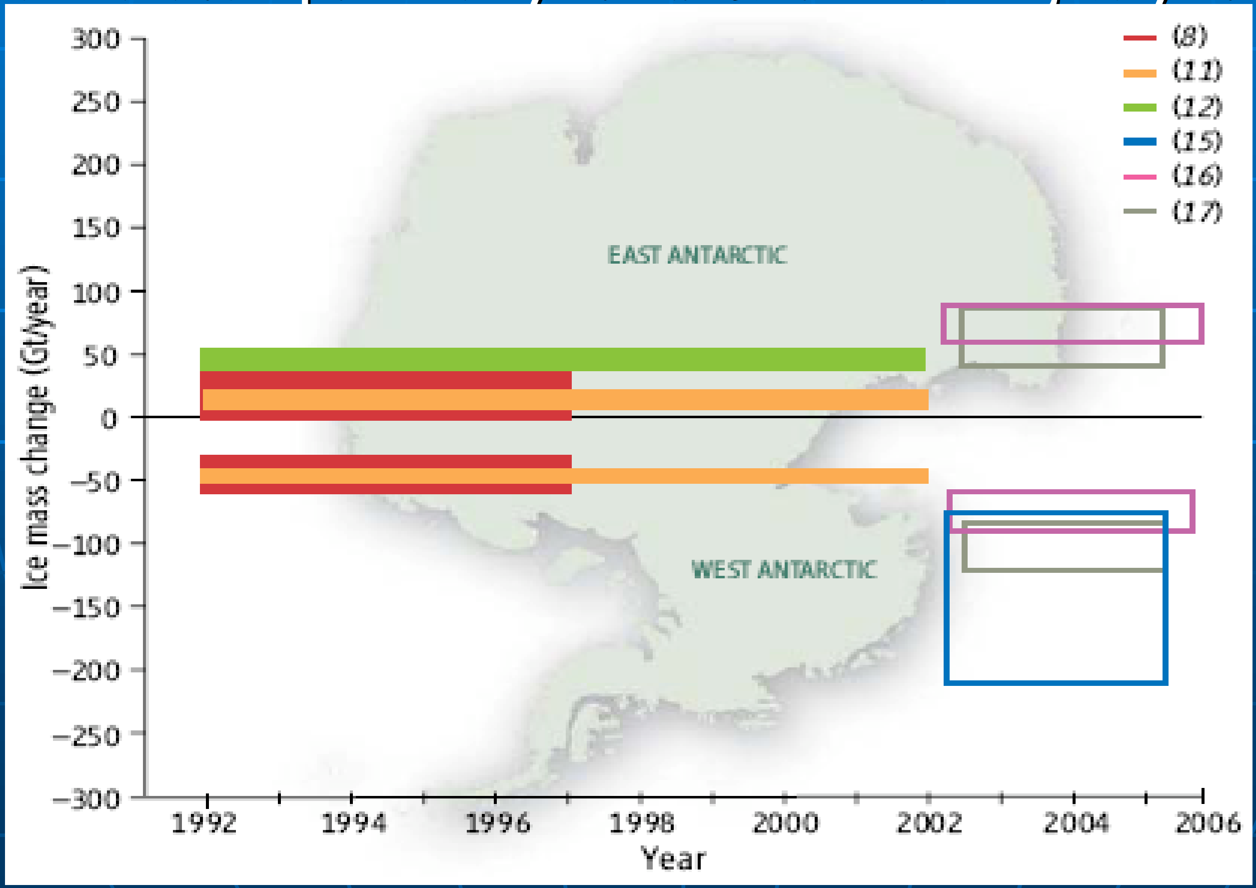
- Significant mass loss (~100-200 km^3/yr) since late 1990s, mainly in coastal regions of south Greenland
- Slight mass gain in high central regions



Cazenave, 2006

Antarctica: Overall picture

- Mass loss (~50-100 km^3/yr) in West Antarctica
- Small mass gain (~0-50 km^3/yr) in East Antarctica
- Net balance probably near zero or slightly negative



Cazenave, 2006

Causes of ice sheet retreat

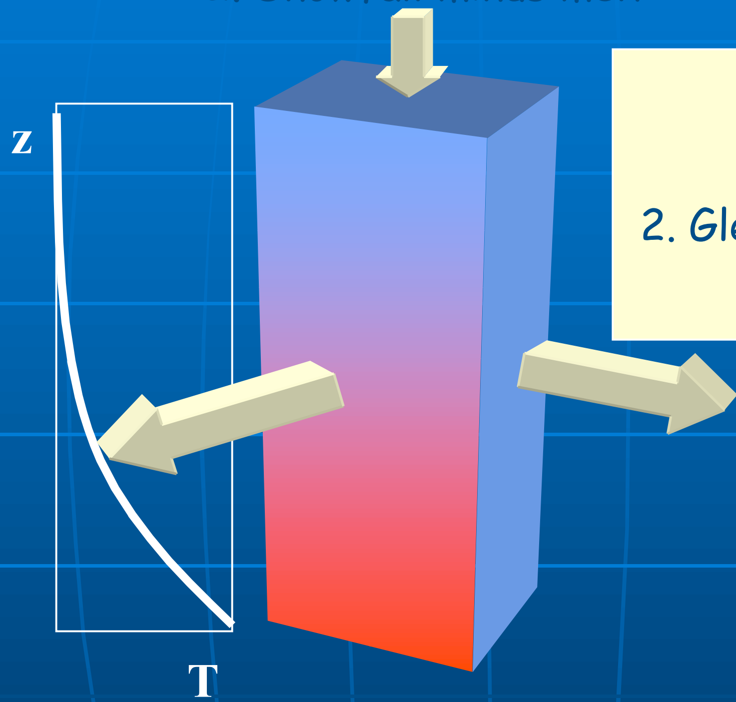
- Increased surface melting due to warmer air temperatures
- Dynamic changes
  - Loss of buttressing ice shelves and ice tongues
  - Increased basal sliding due to subsurface water (possibly associated with surface melting: Zwally et al., 2002)

Current ice sheet models are too crude to simulate these dynamic changes.

Thermomechanical ice sheet models

Upper boundary

1. Air temperature
2. Snowfall minus melt



Temperature evolution

1. Diffusion
2. Advection
3. Dissipation

Ice flow

1. Gravity balanced locally
2. Glen's flow law for horizontal velocity
3. Vertical velocity from flow

Thickness evolution

1. Horizontal flow divergence
2. Accumulation

Lower boundary

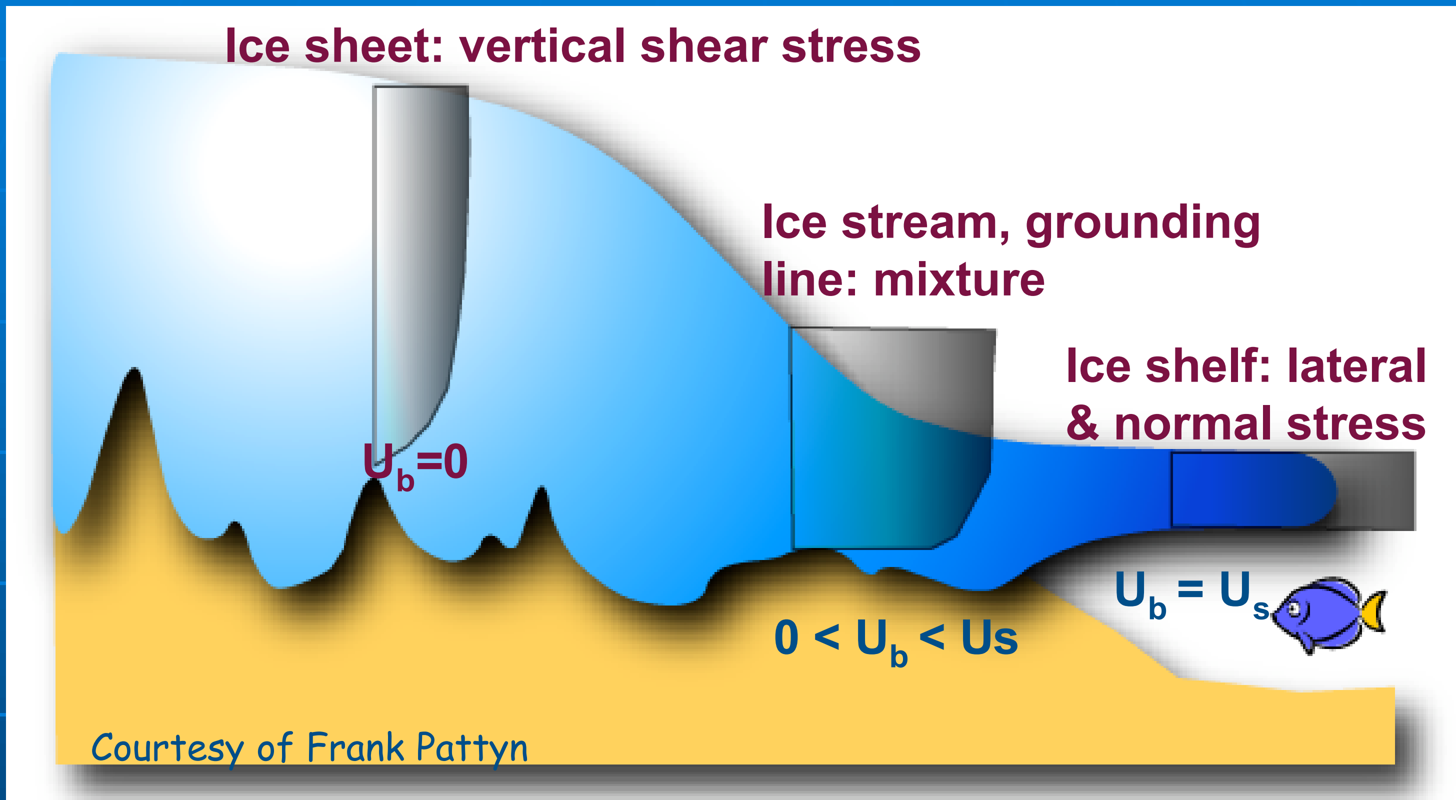
1. Slip velocity
2. Basal friction
3. Geothermal heat flux

Isostasy

1. Flexure in response to ice load
2. Mantle flow

Courtesy of Tony Payne

Ice sheet dynamics



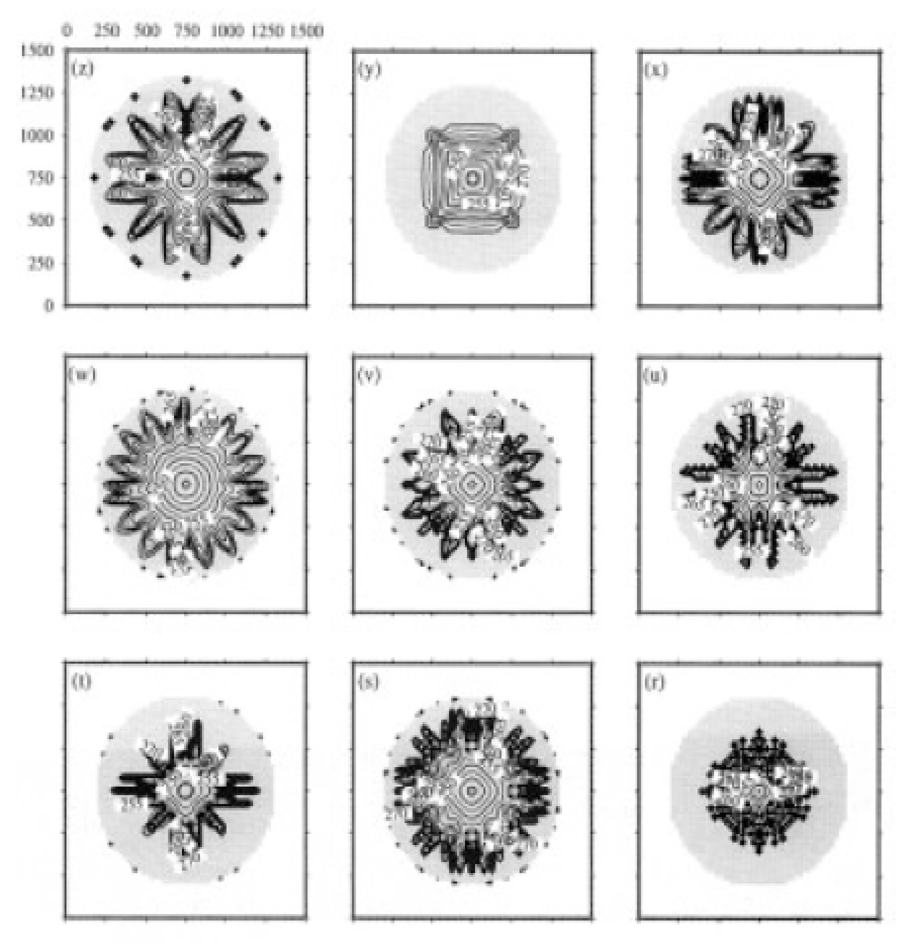
- Ice sheet interior: Vertical shear stresses dominate
- Ice shelves: No basal drag; lateral/normal stresses dominate
- Transition regions: Need to solve complex 3D elliptic equations – still a research problem (e.g., Pattyn, 2003)

Numerical issues

Thermoviscous instability:

Fast flow => warm ice => low viscosity => fast flow

- Fingering instability observed in simple experiments
- Unclear to what extent the instability is numerical v. physical



Payne et al., 2000

Ice sheet mass balance

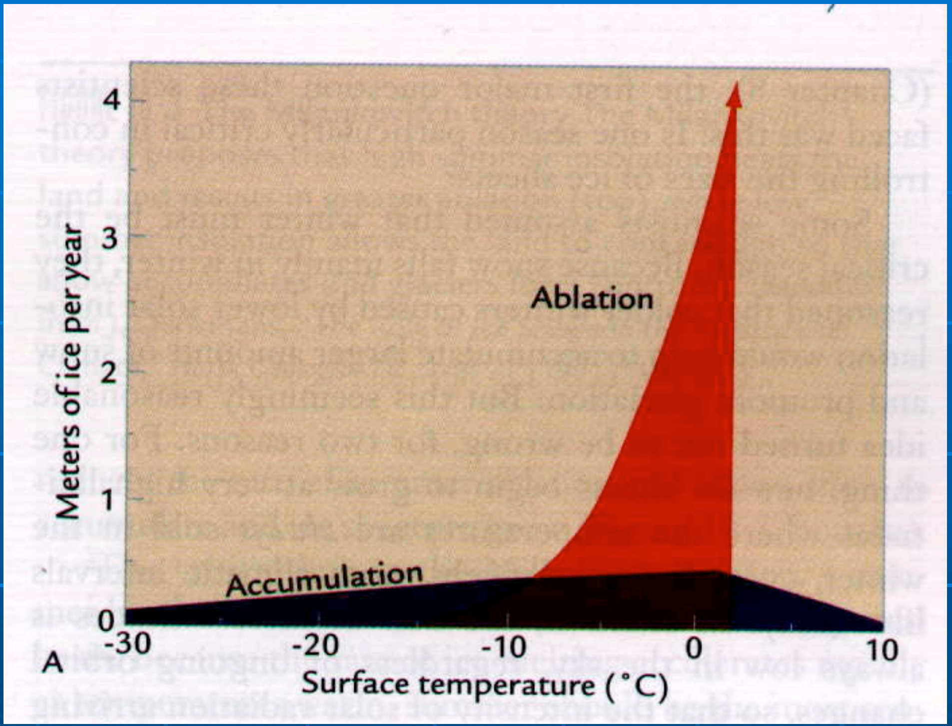
$b = c + a$

c = accumulation

a = ablation

Two ways to compute ablation:

- Positive degree-day
- Surface energy balance (balance of radiative and turbulent fluxes)



Accumulation and ablation as function of mean surface temperature

Highly nonlinear!

Next-generation ice sheet models

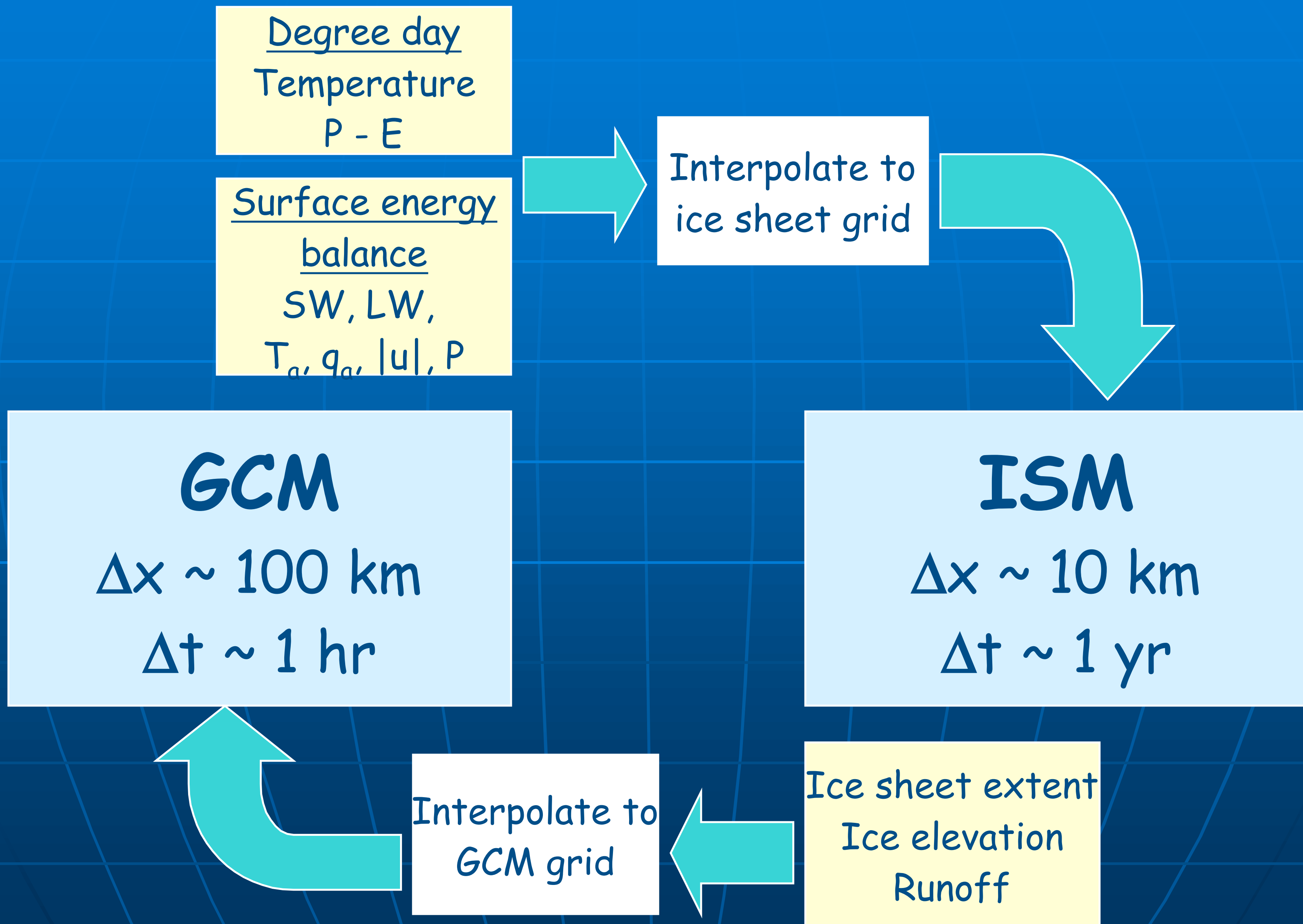
- Small-scale (~10 km) surface energy balance
- Unified treatment of all stresses (vertical, lateral, and longitudinal) with accurate, robust numerics
- Higher resolution (~1-5 km) to resolve grounding lines, ice streams, and outlet glaciers
  - Parallel codes
  - Nested/unstructured grids
- Basal sliding (surface and subglacial hydrology)
- Iceberg calving (fracture mechanics)
- Interaction of ice shelves with ocean

Coupling ice sheet models and GCMs

Until recently, ice sheet models have been run offline with GCM output. Most climate models have static ice sheets. Coupling is now under way:

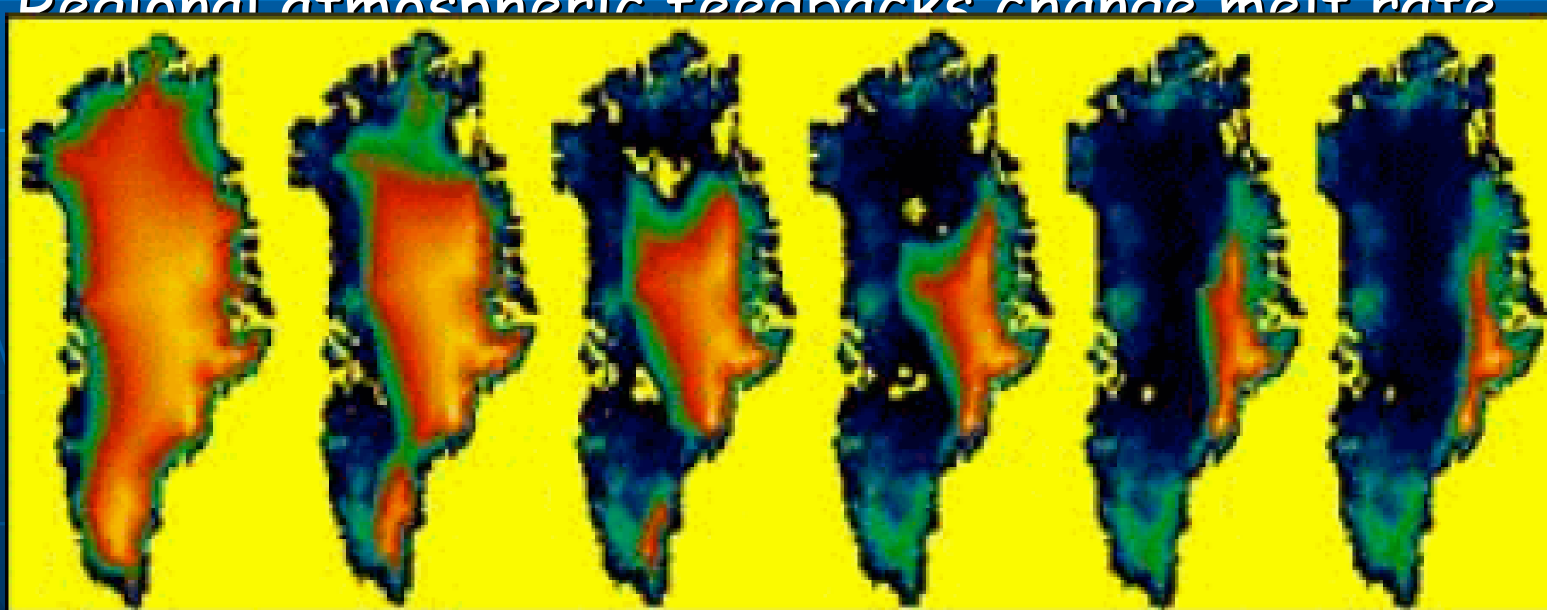
- As an ice sheet retreats, the local climate changes, modifying the rate of retreat.
- Ice sheet changes could alter other parts of the climate system, such as the thermohaline circulation.
- Interactive ice sheets are needed to model glacial-interglacial transitions.

Coupling ice sheet models and GCMs



Coupled climate-ice sheet modeling

- Ridley et al. (2005) coupled HadCM3 to a Greenland ice sheet model and ran for 3000 ISM years (~735 GCM years) with 4 x CO_2.
- After 3000 years, most of the Greenland ice sheet has melted. Sea level rise ~7 m, with max rate ~50 cm/century early in simulation.
- Regional atmospheric feedbacks change melt rate



LANL mission relevance

- "Understanding the consequences of our energy choices is a key component of the energy security mission of the laboratory."
- "Climate change is likely to cause dramatic environmental change, resulting in population migration and conflicts as nations adapt and compete for resources."
- "Climate change provides a science problem of national and global importance that can draw new talent to the lab with the computational modeling and instrument development skills that can be easily transferred to other lab missions."

(From the Complex Systems white paper)

LANL role: Modeling

- The DOE SciDAC program is funding ice sheet model development as part of a 5-year earth systems modeling effort.

Goals:

- Improved numerical methods and computational efficiency
  - Full stresses
  - High-resolution parallel modeling
  - Adaptive grids
- Coupled climate predictions with dynamic ice sheets
  - Coupling to Community Climate System Model

LANL role: Remote sensing

- Current observations of surface melt area are very coarse (~25 km resolution).
- MODIS data can be used to create high-resolution (< 1 km) maps of surface melting.

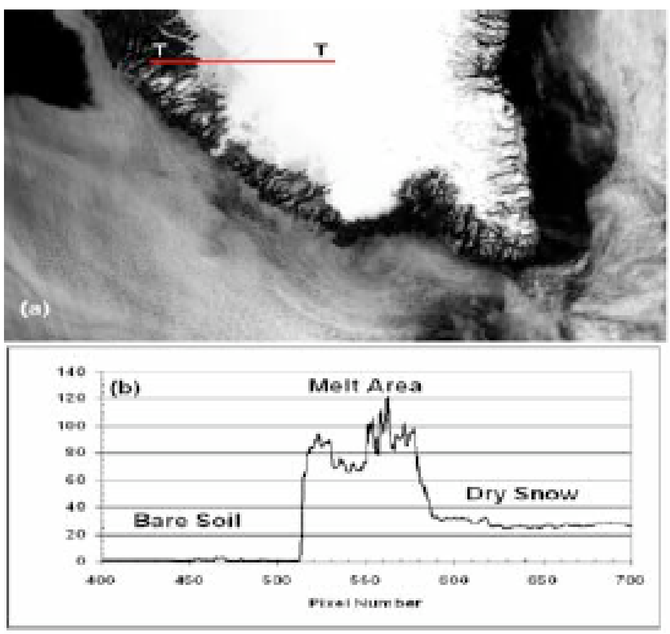


Fig. 1: Melt area detection

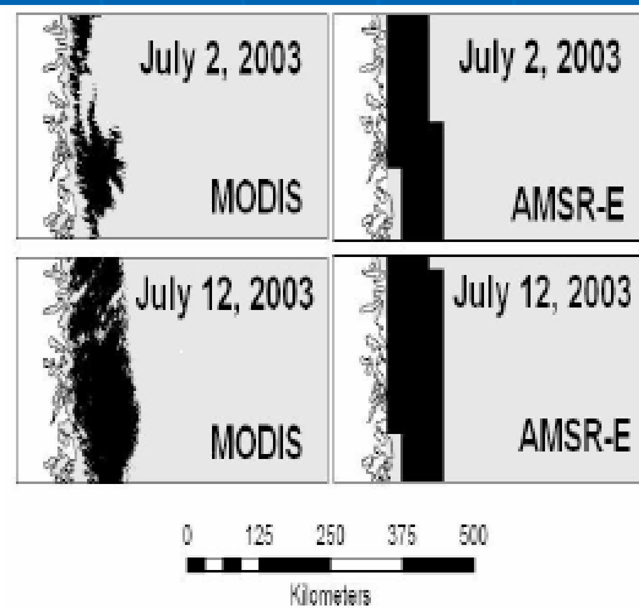


Fig.2 : Comparison of new (left) and microwave method of melt detection

Courtesy of Petr Chylek

LANL role: In situ sensing

- Rowe et al. LDRD proposal:
  - Develop automated sensor networks for inexpensive, small-scale observations in extreme polar conditions (e.g., fast-moving Greenland outlet glaciers).
  - Transmit data in near real-time without sensor retrieval.
  - Use combined velocity and seismic measurements to validate models of ice sheet dynamics.

Summary

- Since the late 1990s the Greenland ice sheet has been losing mass at a rate of ~100-200 km^3/yr.
- The West Antarctic ice sheet is also losing mass, but this loss is at least partly balanced by thickening in East Antarctica.
- In a business-as-usual emissions scenario, temperatures will likely be high enough by the end of this century to melt most or all of the Greenland ice sheet (if sustained over centuries).
- Ice sheet melting rates will very likely increase in the next few decades, possibly raising sea level by several tens of cm during this century.
- Reliable predictions of sea level rise are not possible without significantly improved ice sheet models and better

Preview of coming attractions:

Seasonal Acceleration of Inland Ice via Longitudinal Coupling to Marginal Ice

Steve Price

University of Bristol

Thursday March 29

CNLS Conference Room


The End