Ice Sheets and Climate Change

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What is an expert?

"An expert is somebody who is more than 50 miles from home, has no responsibility for implementing the advice he gives, and shows slides."

Edwin Meese III

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Outline

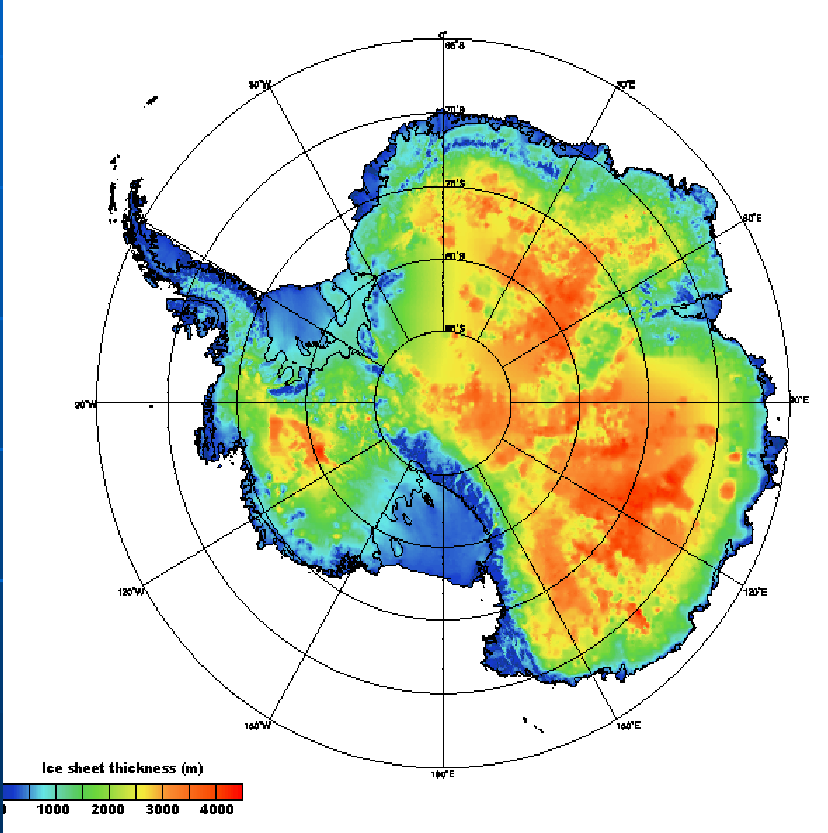
- Introduction to ice sheets
- IPCC Third Assessment Report
- Recent observations
- Ice sheet models
- Coupled climate-ice sheet modeling

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., 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 in a grounded ice sheet.

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

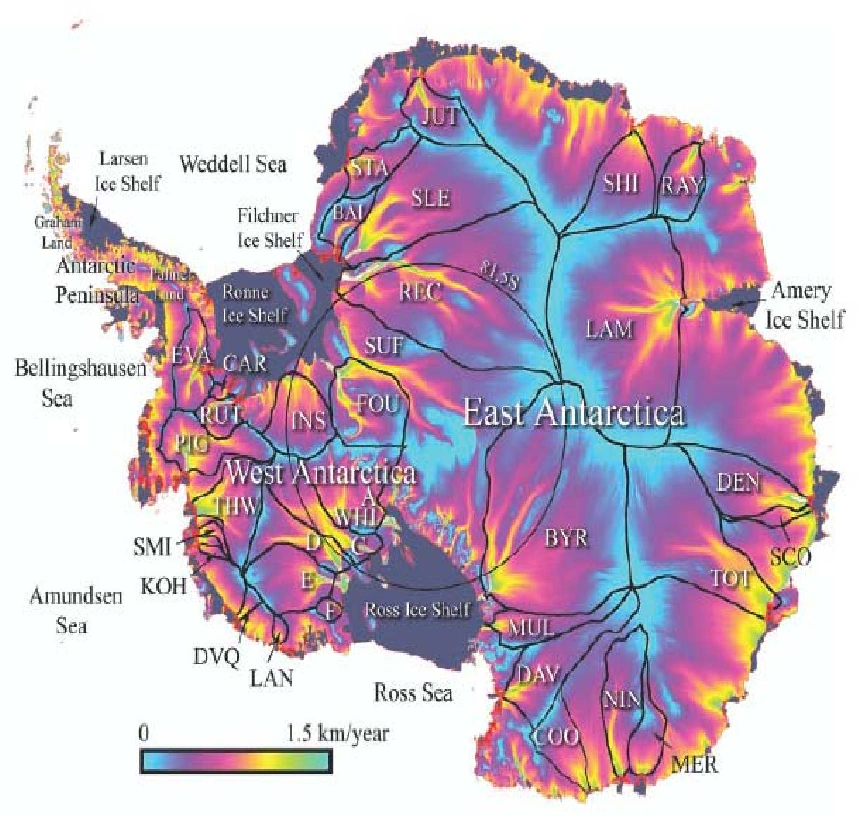


Antarctic ice thickness

(British Antarctic Survey BEDMAP project)

Antarctic regions

- East Antarctica (~55 m SLE)
  - Grounded above sea level; not vulnerable to warming
- West Antarctica (~5 m SLE)
  - Grounded largely below sea level; vulnerable to warming
- Antarctic peninsula (~0.3 m SLE)
  - Mountain glaciers; may be vulnerable to warming
- Ice shelves
  - Vulnerable to ocean warming; removal could speed up flow on ice sheet

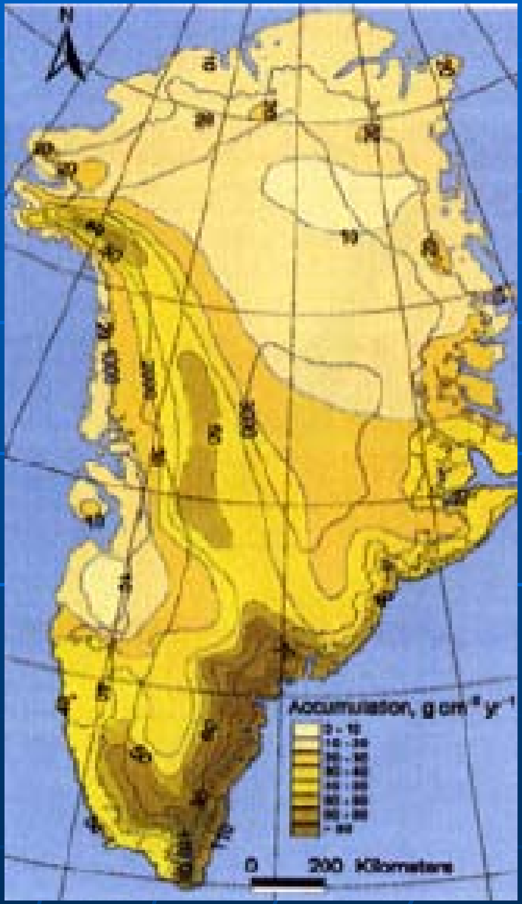


Ice flow speed

(Rignot and Thomas, 2002)

Greenland ice sheet

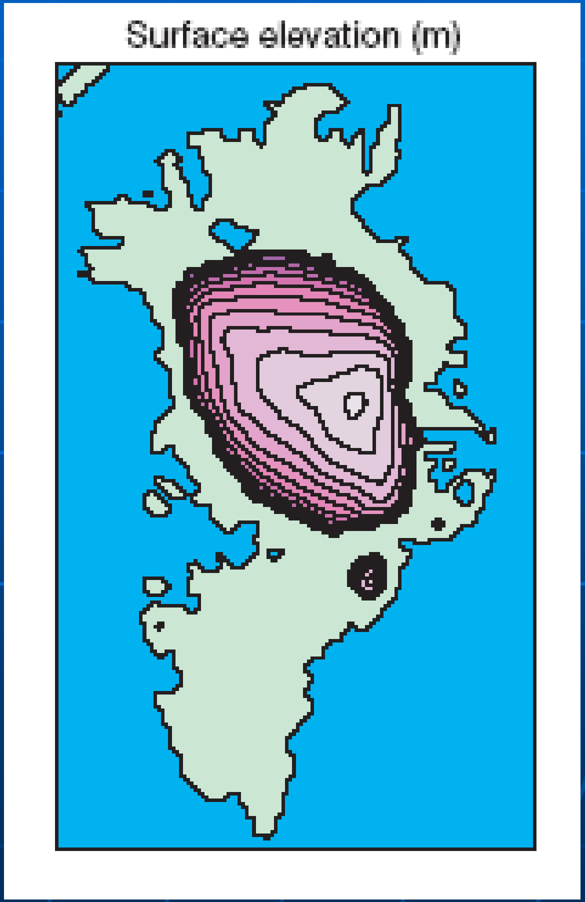
- Volume ~ 2.8 million km^3
  (~7 m sea level equivalent)
- Area ~ 1.7 million km^2
- Mean thickness ~ 1.6 km
- Accumulation ~ 500 km^3/yr
- Surface runoff ~ 300 km^3/yr
- Iceberg calving ~ 200 km^3/yr



Annual accumulation
(Bales et al., 2001)

Eemian interglacial (~130 kyr ago)

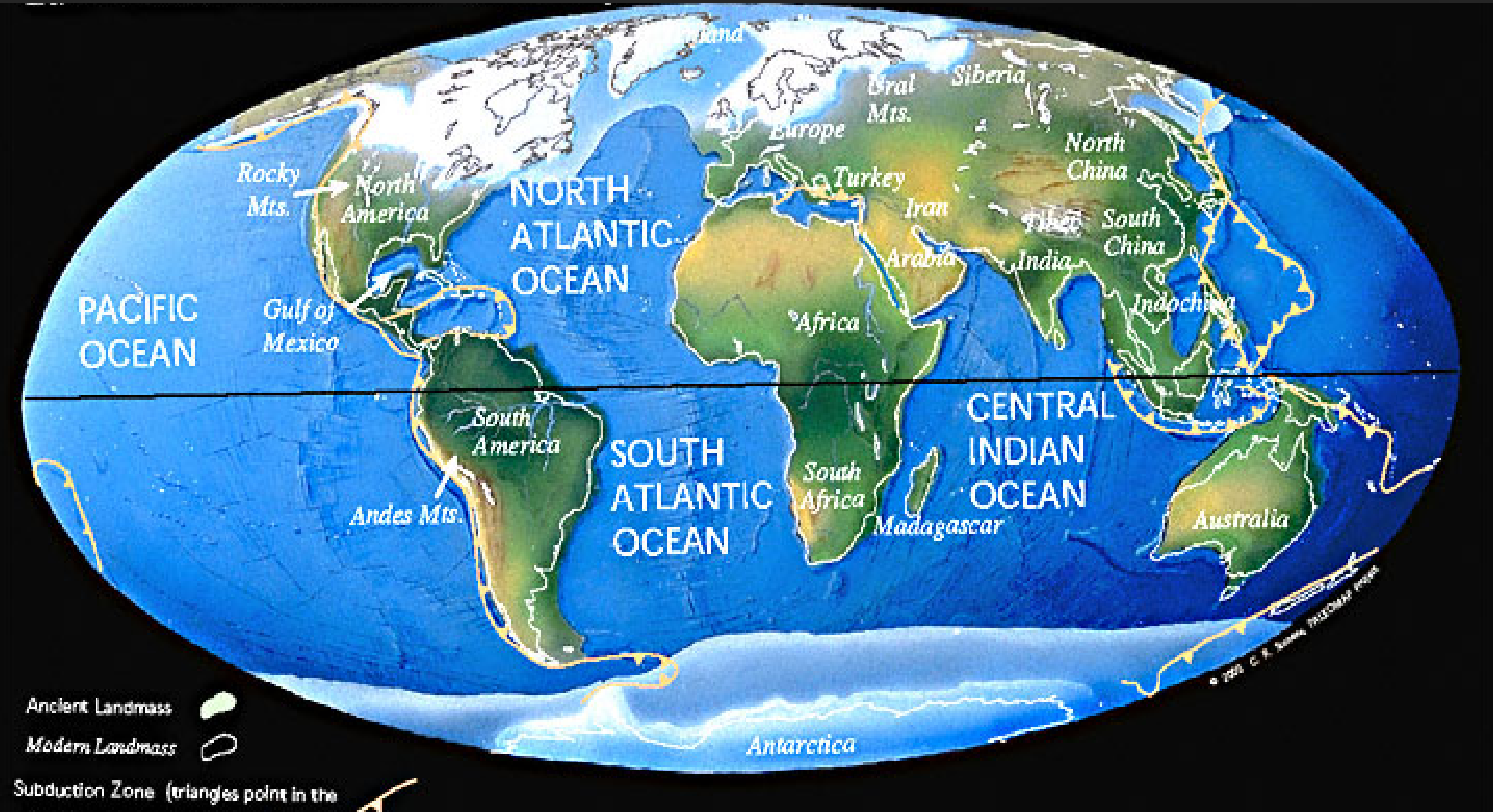
- Global mean temperature was 1-2° higher than today
- Global sea level was 3-6 m higher
- Much of the Greenland ice sheet may have melted



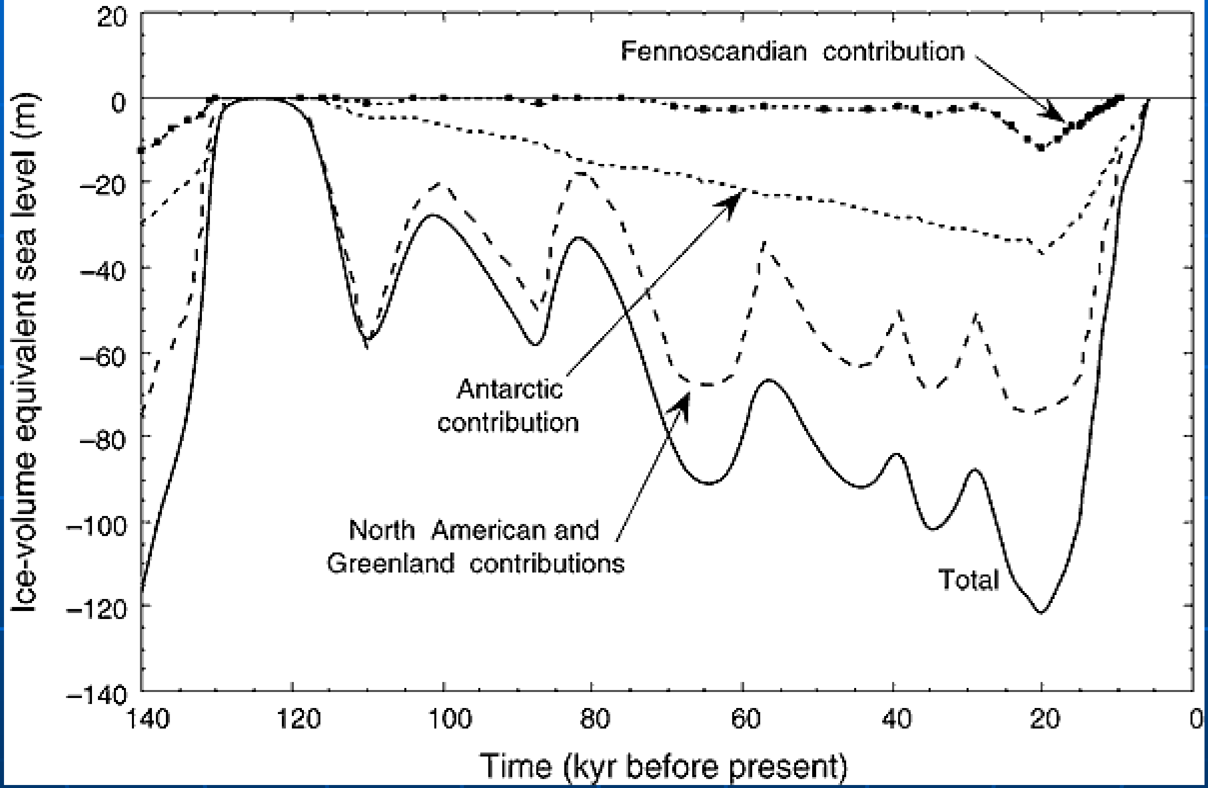
Greenland minimum extent
(Cuffey and Marshall, 2000)

Last Glacial Maximum: ~21 kyr ago

- Laurentide, Fennoscandian ice sheets covered Canada, northern Europe
- Sea level ~120 m lower than today



Sea level change since Eemian



IPCC TAR (2001), from Lambeck (1999)

- Current rate of increase is ~18 cm/century
- Past rates were up to 10 times greater

IPCC Third Assessment Report: Sea level change

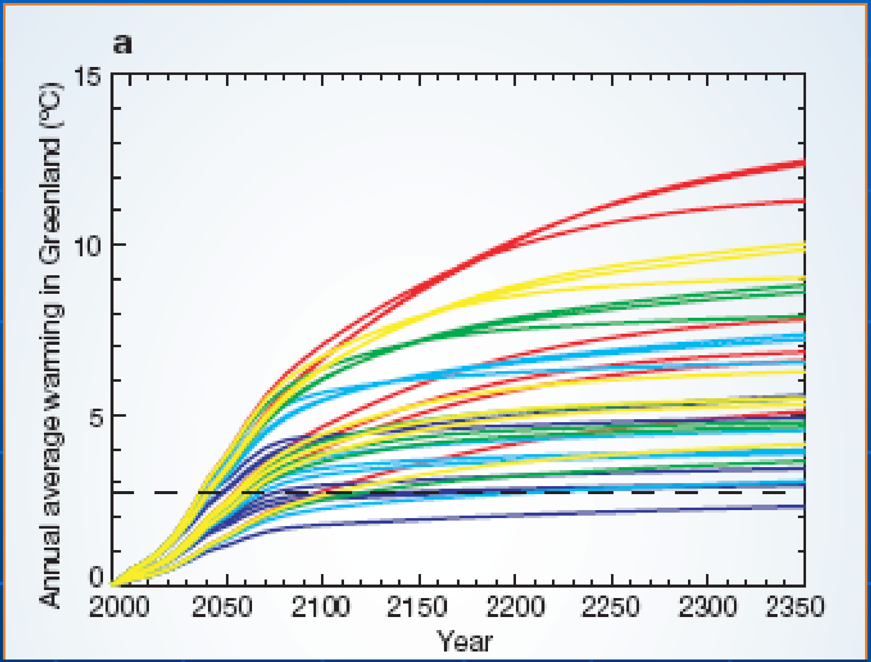
- Global mean sea level rose 10-20 cm during the 20th century, with a significant contribution from anthropogenic climate change.
- Sea level will increase further in the 21st century, with ice sheets making a modest contribution of uncertain sign.

	20th century	1990-2100
Thermal expansion	3 to 7 cm	11 to 43 cm
Ice caps & glaciers	2 to 4 cm	1 to 23 cm
Greenland	0 to 1 cm	-2 to 9 cm
Antarctica	-2 to 0 cm	-17 to 2 cm

IPCC TAR: Stability of Greenland

- "Models project that a local annual-average warming of larger than 3°C, sustained for millennia, would lead to virtually a complete melting of the Greenland ice sheet."
- This projection is based on standalone ice sheet models (Huybrechts & De Wolde, 1999; Greve, 2000). 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.

Effect of 6 m sea level rise

Florida; h < 6 m in green region

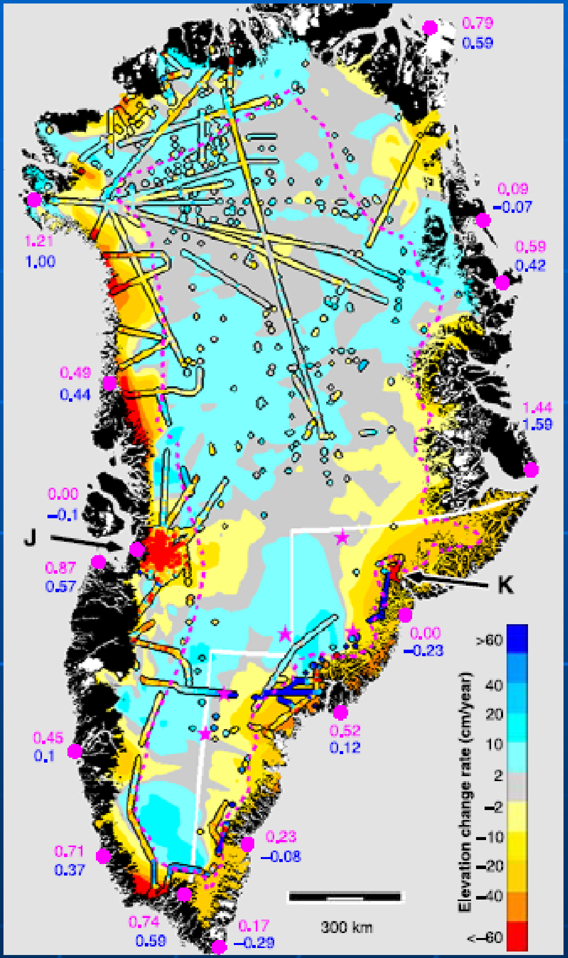
Composite satellite image taken by Landsat Thematic Mapper, 30-m resolution, supplied by the Earth Satellite Corporation. Contour analysis courtesy of Stephen Leatherman.

IPCC TAR: Ice sheet dynamics

- “A key question is whether ice-dynamical mechanisms could operate which would enhance ice discharge sufficiently to have an appreciable additional effect on sea level rise.”
- Recent altimetry observations suggest that dynamic feedbacks are more important than previously believed.

Recent observations: Greenland

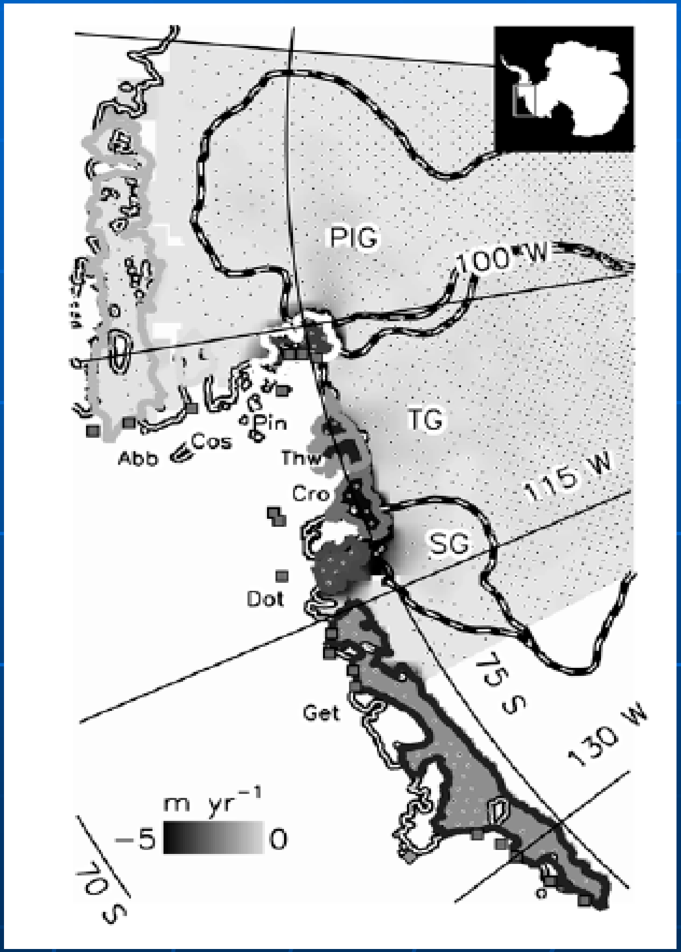
- Laser altimetry shows rapid thinning near Greenland coast: ~0.20 mm/yr SLE
- Thinning is in part a dynamic response: possibly basal sliding due to increased drainage of surface meltwater.
- Ice observed to accelerate during summer melt season (Zwally et al., 2002)



Ice elevation change
(Krabill et al., 2004)

Recent observations: West Antarctica

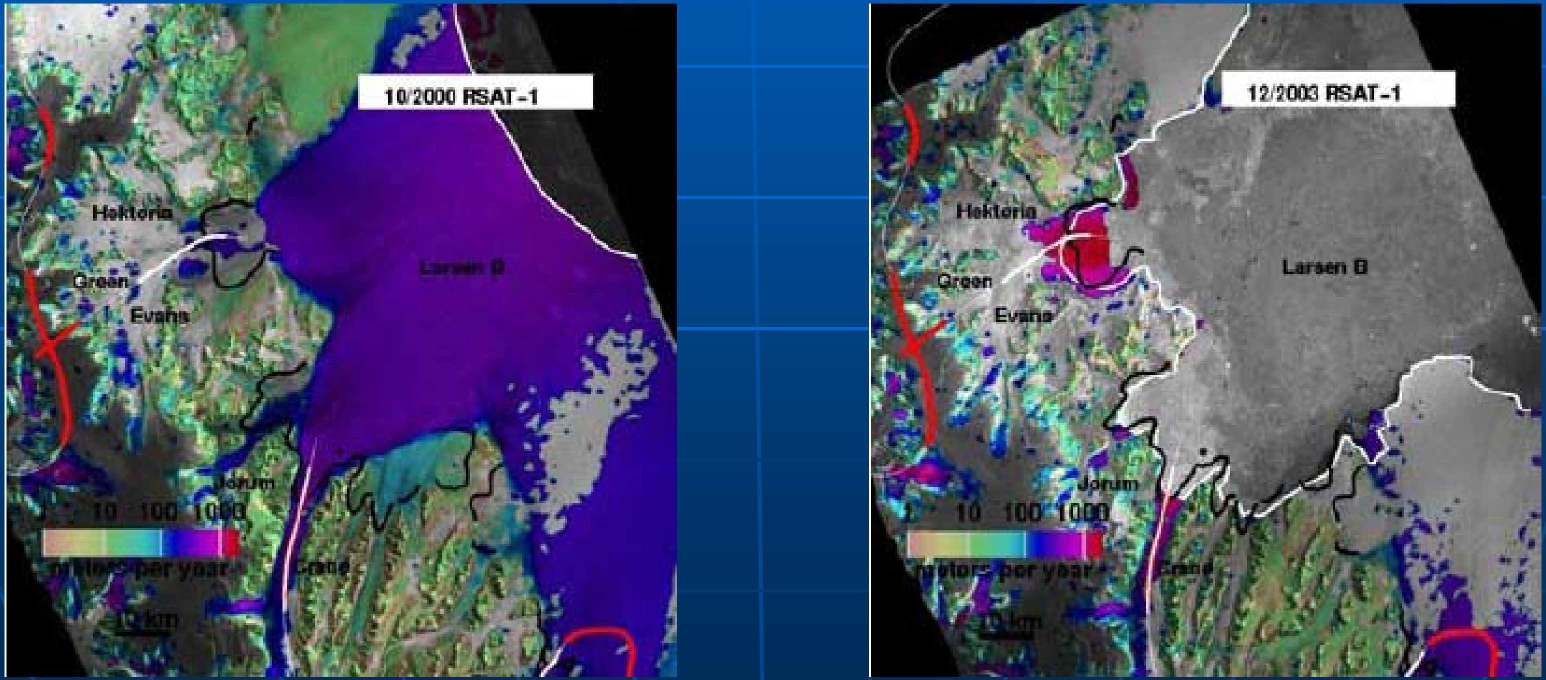
- Large glaciers (Pine Island, Thwaites, Smith) flowing into the Amundsen Sea are thinning, probably because of warm ocean water eroding ice shelves (Payne et al., 2004; Shepherd et al., 2004)
- Thinning extends ~200 km inland
- Sea level rise ~ 0.16 mm/yr from West Antarctic thinning



Ice thinning rate
(Shepherd et al., 2004)

Recent observations: Antarctic peninsula

- Glaciers accelerated by up to a factor of 8 after the 2002 collapse of the Larsen B ice shelf (Scambos et al., 2004; Rignot et al., 2004)

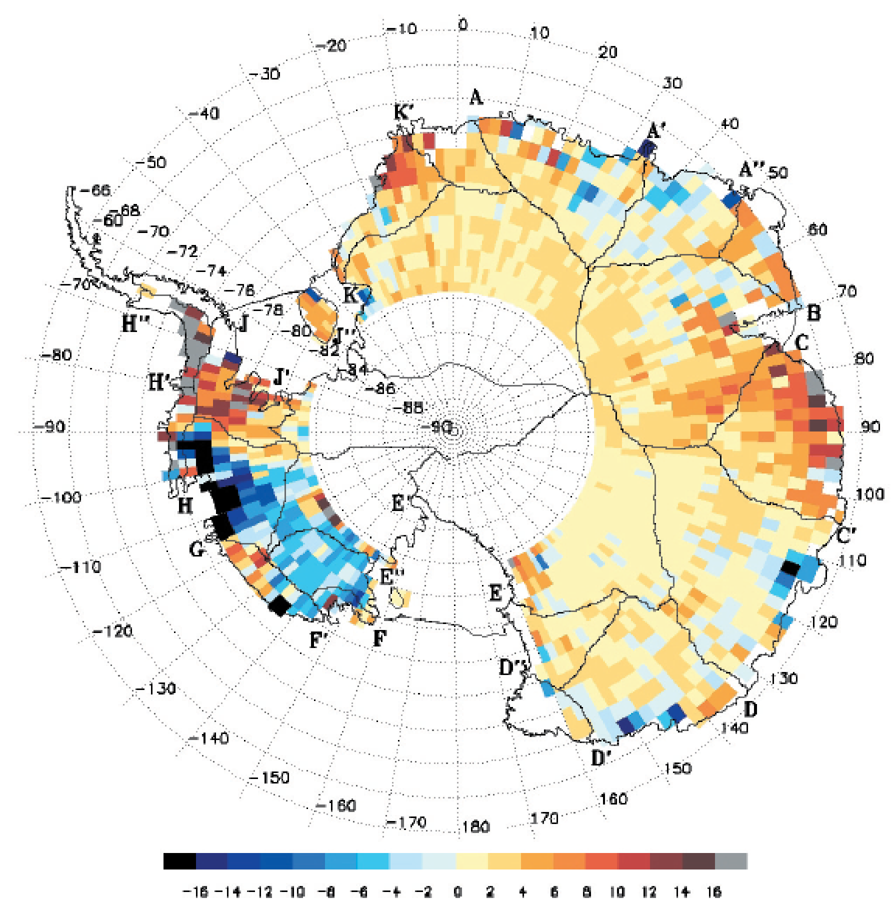


Oct. 2000

Dec. 2003

(Rignot et al., 2004)

Recent observations: East Antarctica



Ice elevation change, 1992-2003
(Davis et al., 2005)

- SAR measurements suggest that East Antarctica is thickening by ~1.8 cm/yr , probably because of increased snowfall
- SLE ~ -0.12 mm/yr; could cancel out West Antarctic thinning

Slippery slope?

- Ice sheets can respond more rapidly to climate change than previously believed.
- We need to better understand the time scales and mechanisms of deglaciation.

Photo by R. J. Braithwaite.

From Science, vol. 297, July 12, 2002.

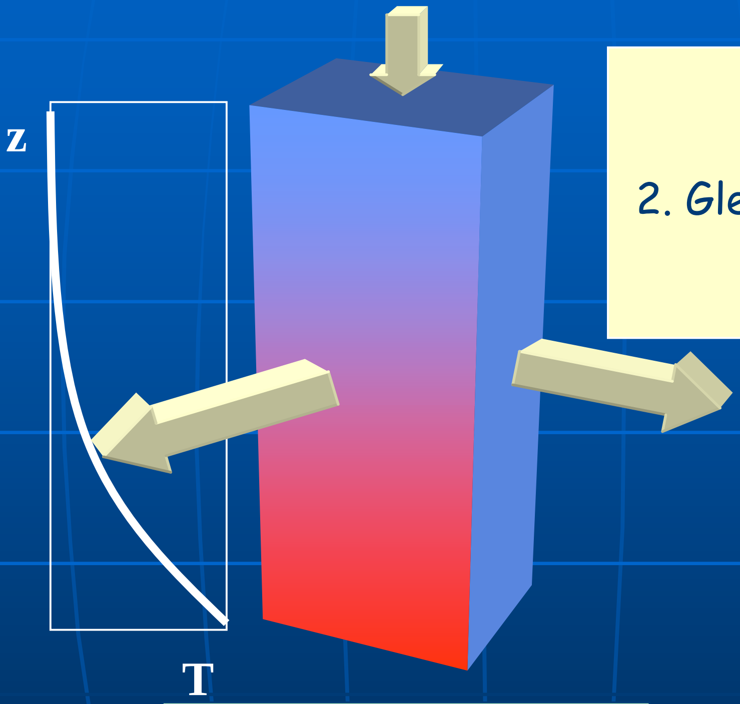
Thermomechanical ice sheet models

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 divergence

Thickness evolution

1. Horizontal flow divergence
2. Accumulation

Lower boundary

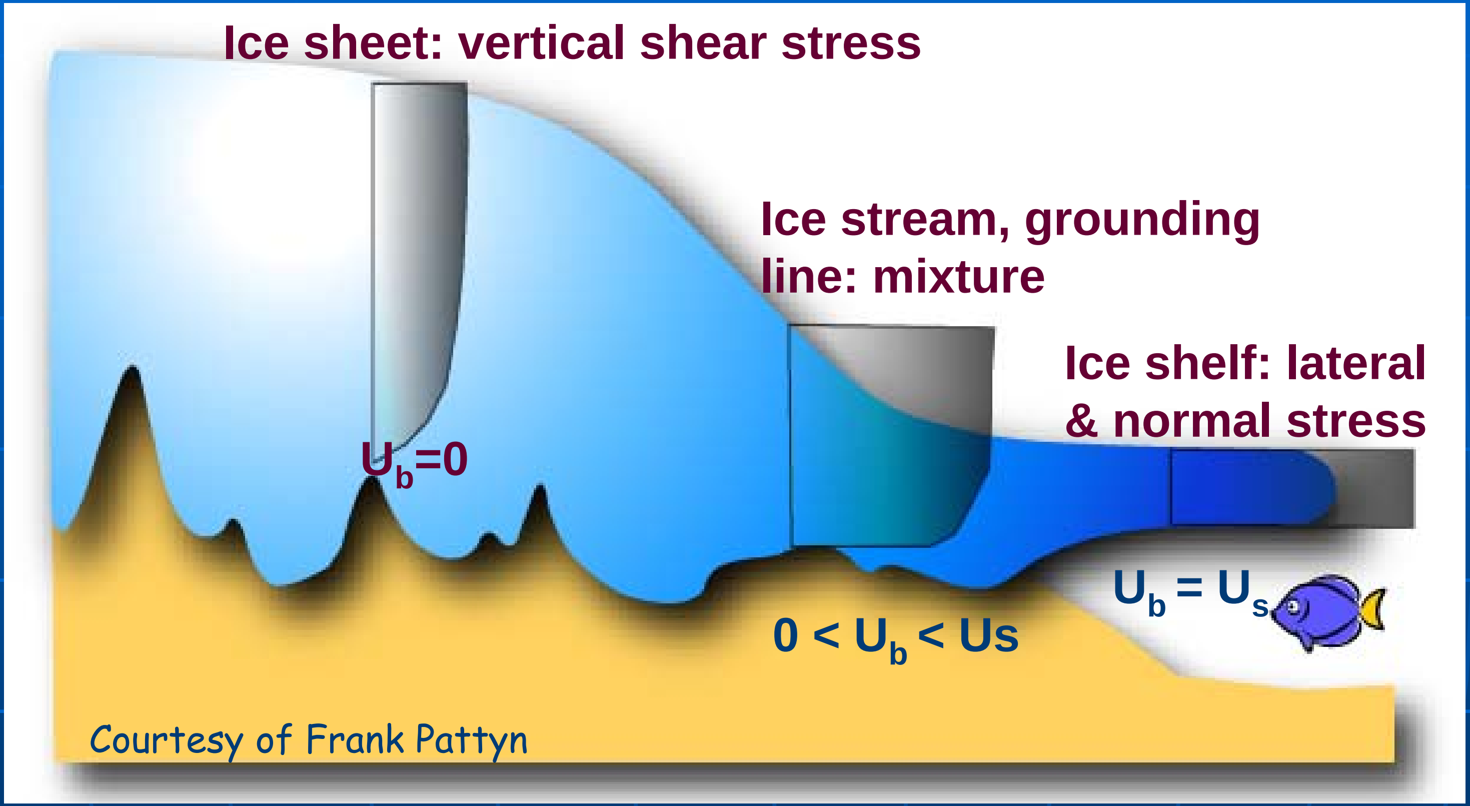
1. Slip velocity
2. Basal friction
3. Geothermal heat flux

Isostasy

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

Courtesy of Tony Payne

Ice sheet dynamics



Courtesy of Frank Pattyn

- Ice sheet interior: Gravity balanced by basal drag
- Ice shelves: No basal drag or vertical shear
- Transition regions: Need to solve complex 3D elliptic equations—still a research problem (e.g., Pattyn, 2003)

Ice sheet mass balance

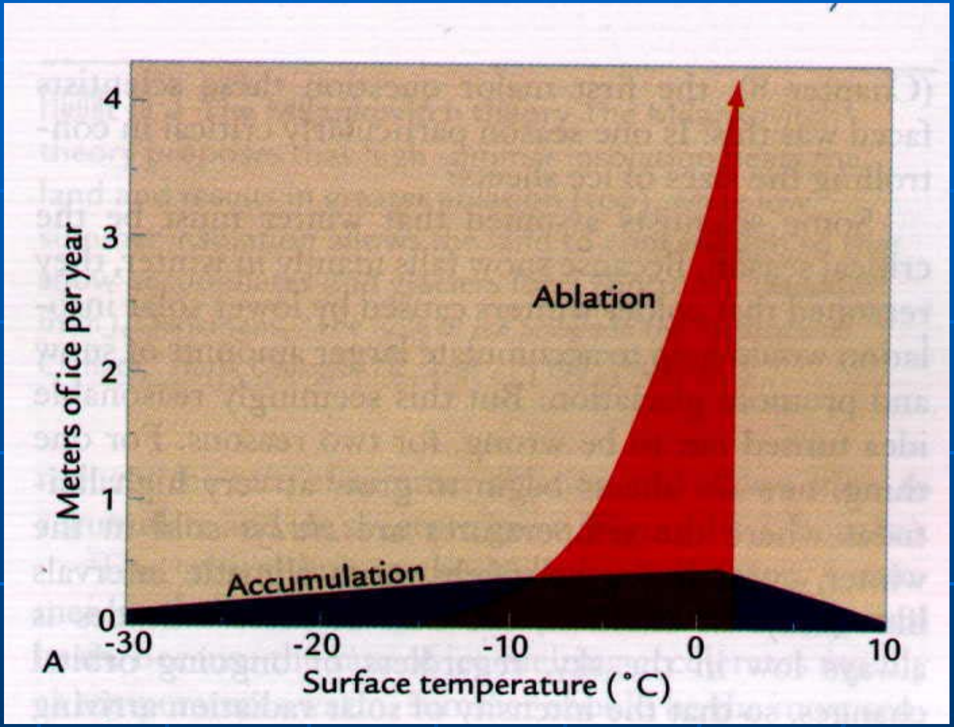
$$b = c + a$$

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

Coupling ice sheet models and GCMs

Why couple? Why not just force ice sheet models offline with GCM output?

- 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.

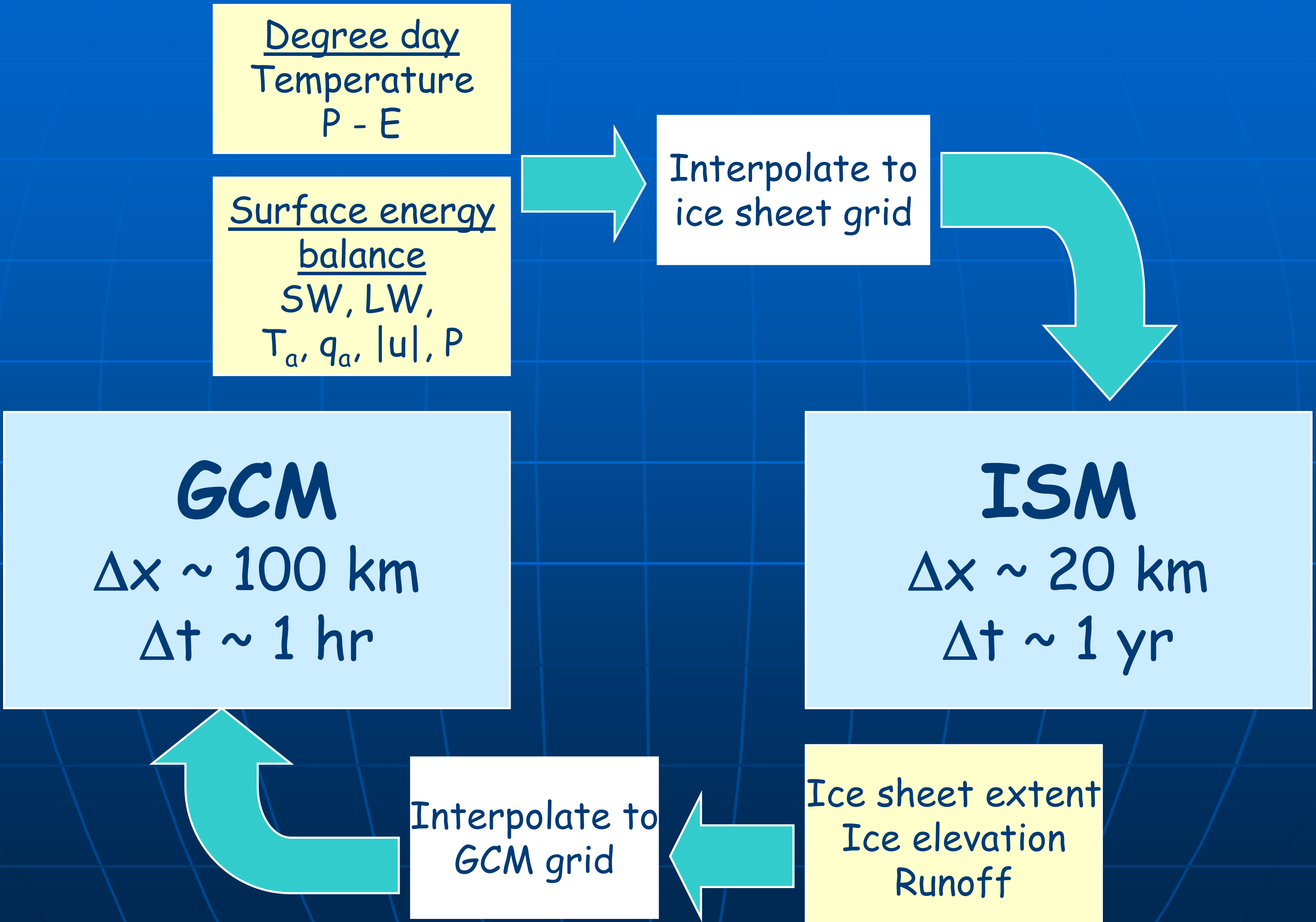
Time and spatial scales

- Ice sheet spatial scales are short compared to typical climate model components:
  - 10-20 km resolution needed to resolve ice streams
  - Similar resolution needed to resolve steep topography near ice edge (for accurate ablation rates)

- Ice sheet time scales are long:
  - Flow rates ~10 m/yr in interior, ~1 km/yr in ice streams
  - Typical dynamic time step ~ 1-10 yr
  - Response time ~ 10^4 yr

- Cf. GCM scales: $\Delta x \sim 100$ km, $\Delta t \sim 1$ hr

Coupling ice sheet models and GCMs



Degree day
Temperature
P - E

Surface energy balance
SW, LW,
T_a, q_a, |u|, P

Interpolate to ice sheet grid

ISM
$\Delta x \sim 20$ km
$\Delta t \sim 1$ yr

Ice sheet extent
Ice elevation
Runoff

Interpolate to GCM grid

GCM
$\Delta x \sim 100$ km
$\Delta t \sim 1$ hr

Challenges: Model biases

Problem: GCM temperature and precipitation may not be accurate enough to give realistic ice sheets.

Solution: Apply model anomaly fields with an observed climatology.

Caveat: The model may not have the correct sensitivity if its mean fields are wrong.

Challenges: Asynchronous coupling

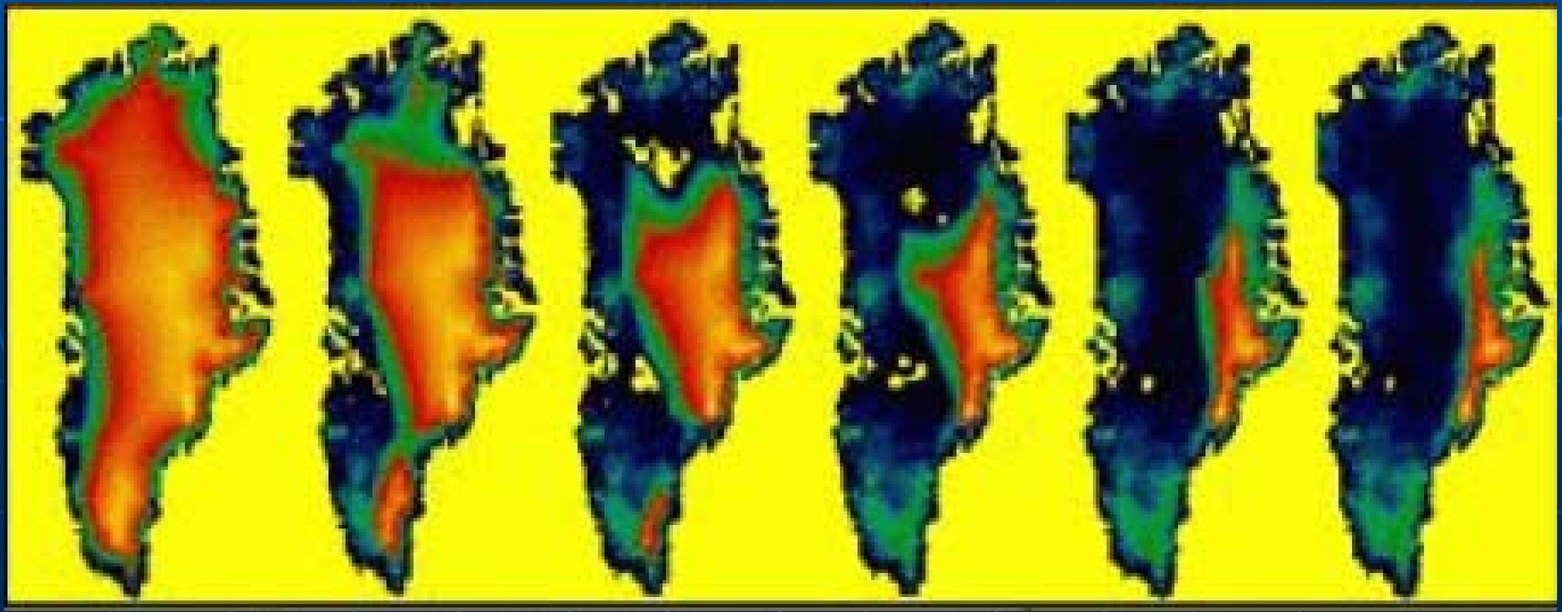
Problem: Fully coupled multi-millennial runs are not currently feasible.

Solution: Couple the models asynchronously, e.g. 10 GCM years for every 100 ISM years.

Caveat: May not conserve global water, may not give the ocean circulation enough time to adjust.

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.



SGER proposal

- I will couple Glimmer, an ice sheet model, to CCSM.
  - Developed by Tony Payne and colleagues at the University of Bristol
  - Includes shelf/stream model, basal sliding, and iceberg calving
  - Designed for flexible coupling with climate models
- Initial coupling will use a positive degree-day scheme.
- Future versions could include a surface energy balance scheme and full 3D stresses.

Key questions

- How fast will the Greenland and Antarctic ice sheets respond to climate change?

- At what level of greenhouse gas concentrations are existing ice sheets unstable?

- Can we model paleoclimate events such as glacial-interglacial transitions?

- To what extent will ice sheet changes feed back on the climate?

The End