Pine Island Glacier - did we solve it?

Andrew Shepherd
University of Edinburgh
IPCC Assessment reports (1990, 1995, 2001)

Global warming
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Global warming

0.6 °C rise since 1900
IPCC Assessment reports (1990, 1995, 2001)
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15 cm rise since 1900

Global sea level rise
According to tide gauges, global sea levels have risen by 1.5 mm per year during the 20th century. This rise is ten times greater than at any other time during the past 3000 years.

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In 2001, only 50% of measured rise explained by central estimates.
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21st C projection (2 x CO₂):
- Ocean expansion (× 3)
- Glaciers (× 3/4)
- Ice sheets (× 1/2)
- Rivers (?)
IPCC Assessment reports (1990, 1995, 2001)

- 21st C projection (2 x CO
\textsubscript{2}):
  - Ocean expansion (\times 3)
  - Glaciers (\times \frac{3}{4})
  - Ice sheets (\times \frac{1}{2})
  - Rivers (?)

- \(~ 0.5\) m total sea level rise
- Major contribution is ocean expansion
UK today

No Polar Ice Sheets
Water cycle

Atmospheric Circulation

Precipitation → Evaporation → Snow → Sublimation

Accumulation & Wind Redistribution

Equilibrium Line

Ice Flow

Melt and Runoff

Heat → Ocean Circulation
L3 – Pine Island Glacier

West Antarctic Ice Sheet

East Antarctic Ice Sheet

Antarctica & sea level
L3 – Pine Island Glacier

Continental Antarctica & sea level
Geometry of marine based ice sheets are unstable to advance or retreat – either event would be accelerating.
West Antarctica is drained through three sectors.
Only Amundsen Sea sector has no ice shelf barrier and is grounded below sea level.
1992-2004

35 day repeat

ERS footprint ~ 10 km

Orbit limit ~ 81.5°

Density $\propto$ latitude
Antarctic mass balance

- 1992-2004
- 35 day repeat
- ERS footprint ~ 10 km
- Orbit limit ~ 81.5°
- Density $\propto$ latitude

- Trends $\sim \pm 20$ cm yr$^{-1}$
### Antarctic mass balance

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**ERS elevation rate (cm yr$^{-1}$)**

-20 \[ \text{ERS elevation rate (cm yr}^{-1}\text{)} \]

**ESA Summer School 2006**
\[ \frac{\partial h}{\partial t} = \frac{\partial \Delta_B}{\partial t} + \int_0^M dm \frac{\partial}{\partial t} \left( \frac{1}{\rho_f(m)} \right) + \left( \frac{1}{\rho_{\text{ice}}} \right) (\dot{M}_s + \dot{M}_b + \nabla.(Mv)) \]
Elevation trends are due to either snowfall or ice flow.

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Snowfall typically fluctuates about a long term mean on decadal timescales by ~ 25 %
On average, Amundsen Sea sector has deflated by 7 cm yr$^{-1}$.

Snowfall variability is 6 cm yr$^{-1}$.

Although mean deflation is comparable to snowfall variability, signal is highly coherent and peak rate is 50 times greater.
Amundsen Sea Sector is 40% of WAIS

Drained by the Pine Island, Thwaites, and Smith glaciers

Ice volume sufficient to raise sea levels by 1.1 m
Deflation is highly correlated with ice flow.

I. Elevation change (m/year)

-3 0

II. Ice speed (km/year)

0 2.5

Pine Island Glacier

Thwaites Glacier

Smith Glacier
Deflation peaks at 3 m yr\(^{-1}\) at grounding line, and extends 200 km inland.
Consistent with InSAR grounding line retreat
Consistent with 20% glacier acceleration

Joughin et al, GRL, 2003
L3 – Pine Island Glacier

Origin of imbalance?

Geothermal

- No activity

Ocean

- External

Deglaciation

- Internal

Surge

Shepherd

Bindschadler

Huybrechts

Post

ESA Summer School 2006
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ESA Summer School 2006
Simulated perturbation of PIG

- 3d model of PIG stress regime (longitudinal, lateral, vertical, gravitational)
- Glen’s flow law
- Simplify by assuming down-stream component of velocity dominates
- Equations solved numerically by finite differences

\[ \tau = \beta^2 u \]
- Retreat of GL by 5 and 10 km, decrease ice plain traction by 50%
- Instant response is thinning up to 70 km from GL
- Insufficient to explain observed rates inland

Payne et al., 2004
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen’s flow law
- Thickness evolution from ice flow perturbations
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Simulated perturbation of PIG

7 years
Simulated perturbation of PIG

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50 years
Simulated perturbation of PIG

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- Thickness evolution from ice flow perturbations
Accumulated thinning matches observed changes inland

Conclude that a reduction in ice thickness at the grounding line is sufficient to trigger inland thinning
Amundsen Sea glaciers terminate in short floating ice shelves
**Bathymetry shows deep troughs channel water to glacier grounding lines**
Pine Island Bay gyre draws water from continental shelf
Circumpolar Deep water is 4 C above freezing point
Warm CDW infiltrates Pine Island Bay and reaches glacier grounding lines.
Ice shelf thinning mirrors that of tributary glaciers
Thinning is correlated with melt potential of ocean current (10 m yr$^{-1}$ C$^{-1}$)
2d plume model of ice-ocean interaction beneath PIG reproduces observed pattern of steady-state ice melting.
Perturbation experiment shows a 0.5 °C warming of ocean temperature is sufficient to cause observed ice shelf thinning
Dynamic thinning ongoing in all submarine sectors of Antarctica.
Retreat of submarine glaciers is supposed to be an accelerating process.
PIG deflation *is* accelerating.
Ocean temperatures are set to rise by 1.0 C around Antarctica
Amundsen Sea glaciers are losing 30 Gt of ice each year

- Equivalent to a sea level contribution of 0.1 mm yr\(^{-1}\)
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20\(^{th}\) century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21\(^{st}\) century response not in current sea level projections
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50% of Antarctic thinning is within 148 km of coast

89% of coastal 100 km remains unsurveyed