How Warm is Too Warm?

Global warming, sea level rise, and the future of the polar ice sheets

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Second Lecture
The question, “How Warm...?” is essentially posed by the UN Framework Convention on Climate Change (US and Australia are parties).

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Article 2, UNFCCC

Kyoto, and subsequent protocols, are its children.
Avoiding a large sea level rise is a plausible answer...

• What is the history of global sea level?

• What may happen to sea level as the world warms?
Global Sea Level Rise since the last glacial maximum

C. Rapley 2005, British Antarctic Survey
Why Does Sea Level Rise (or Fall)?

Major Factors Worldwide:

- Thermal expansion/contraction of ocean water
- Melting/growth of mountain glaciers
- Shrinkage/growth of Greenland and Antarctic ice sheets
Sea Level Change now measured by satellite altimetry to high accuracy.
Recent Sea Level Changes: Satellite Altimetry

**Figure 5.** Global mean sea level variations from T/P and Jason.
Recent trends in sea level

Table 1: Components of Sea Level Rise (IPCC 2007).

Significant, unexpected contribution from ice sheets
Locally-important factors mean the average hides local differences

- Sediment supply changes/compaction
- Rebound of Earth’s crust (isostasy)
- Tectonic shifts
- Shifts in ocean currents
Local variations in sea level rise over a brief period.
Pervasive Coastal Changes due to Sea Level Rise

- Erosion and submergence of beaches, wetlands, other (agricultural) lowlands
- Undermining, flooding of infrastructure
- Salination of groundwater and agricultural soil
- Near-complete loss of some Pacific Island nations
- Episodic threat: Increased storm-flood risk
Bangladesh: a case study in high vulnerability (and some success at adapting)

• High population density
• Low income
• Low-lying agricultural land
• Over-taxed river system
• Tropical cyclones
• Unique ecosystems
Projected Sea Level Rise for Bangladesh

Shading Indicates Population Density

Sunderbans
High Vulnerability in Industrial Countries, too

- Coastal housing
- Highways, airports
- Beaches
- Wetlands
- New Orleans
Westhampton Beach, NY, 1992

High natural vulnerability combined with poor management decisions
Adaptations

- Withdraw / raise infrastructure and agriculture; enhance barrier beaches and wetlands
- Sea Walls (which themselves alter coastline)
- Recreational beach restoration (no more sand?)
- High cost, long lead times
- Warning systems (Bangladesh)
# Projection of 21st Century Sea Level Rise

**Table SPM-2.** Projected globally averaged surface warming and sea level rise at the end of the 21st century for different model cases. The sea level projections do not include uncertainties in carbon-cycle feedbacks, because a basis in published literature is lacking. (10.5, 10.6, Table 10.7)

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature Change (°C at 2090-2099 relative to 1980-1999)</th>
<th>Sea Level Rise (m at 2090-2099 relative to 1980-1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best estimate</td>
<td>Likely range</td>
</tr>
<tr>
<td>Constant Year 2000 concentrations</td>
<td>0.6</td>
<td>0.3 – 0.9</td>
</tr>
<tr>
<td>B1 scenario</td>
<td>1.8</td>
<td>1.1 – 2.9</td>
</tr>
<tr>
<td>A1T scenario</td>
<td>2.4</td>
<td>1.4 – 3.8</td>
</tr>
<tr>
<td>B2 scenario</td>
<td>2.4</td>
<td>1.4 – 3.8</td>
</tr>
<tr>
<td>A1B scenario</td>
<td>2.8</td>
<td>1.7 – 4.4</td>
</tr>
<tr>
<td>A2 scenario</td>
<td>3.4</td>
<td>2.0 – 5.4</td>
</tr>
<tr>
<td>A1FI scenario</td>
<td>4.0</td>
<td>2.4 – 6.4</td>
</tr>
</tbody>
</table>

Notes:

- a These estimates are assessed from a hierarchy of models that encompass a simple climate model, several EMICs, and a large number of AOGCMs.
- b Year 2000 constant composition is derived from AOGCMs only.
10-foot flood line = 100yr return of flood

Notice Newark Airport

FIGURE 3-15 Flood risk zone, New York City metropolitan area.
Future response of ice sheets is the big unknown:
What is an ice sheet?

- Mass accumulates in the cold center of continent

- Ice piles up in center, flows under influence of gravity toward warmer edges (near ocean, lower altitude)…

- … where ice loss occurs due to melting and iceberg formation
So, ice can melt and ice can move

• Melting at the surface is slow or nil at center

• But ice surface can melt at fringes where it also floats in the warmer ocean, where melting is fast.

• Movement can be slow or fast
The Hazard...

West Antarctic Ice Sheet
East Antarctica (WAIS)
5m
60m

Greenland Ice Sheet
7m

Equivalent sea level rise contained in ice sheets
WAIS + GIS + other sources ---> ~ 50 feet
Key Issues

• Why have ice sheets receded recently?

• What is the role of the buildup of greenhouse gases in these changes?

• Prognosis for polar ice and sea level in a warmer world: how much and how fast might polar ice melt?

• The issue of “How Warm..? (or Article 2 of UNFCCC): What temperature change would lead to a “dangerous” sea level rise from ice sheets?
Why are ice sheets shrinking?

- Ice loss that is twice as fast for Greenland as expected due to dynamical response to warming (movement) as opposed to melting only.

- Antarctica apparently shrinking *rather than growing*, due to fast loss in WAIS, lack of added accumulation overall. Both movement and melting implicated.
Short-term trend in surface melting, Greenland

But surprisingly, dynamical loss is equally important (recently)
Greenland Ice Elevation Changes: 1993-4 versus 1998-9

loss rate ~ 0.13mm/yr

Other values:

GRACE (2002-4) ~ 0.2mm/yr
(2002-5) ~ 0.5mm/yr
Satellite radar (1996)~0.2
(2000)~0.5
But it’s not simple...

Howat et al Science 2007
Lubrication at base a reason for rapid changes in movement of ice in Greenland?
Changes in Antarctica: melting at a couple of locations...

Surface melting

Warm water reaching under ice shelves in Amundsen sea

Mass balance 2002-2005 from GRACE

Movement also widespread

Ice Streams: Movement is a key to the size of WAIS
Fig. 2. Landsat image of Ice Stream E. (Two images from Landsat TM band 4; path 14 row 117 and path 114 row 118, acquired 17 January 1987.) The approximate outline of the finite-element mesh is indicated by the heavy line. The prominent linear feature which slashes obliquely across the ice stream and which contains a small crater-like depression is of interest in assessing the plausibility of a simulated Landsat image given in Figure 12.

Ice streams are tied closely to ice dynamics far inland.

Figure 1. (A) Balance velocities for part of the Siple Coast covering parts of Ice Streams B, C, D, and E. The area to the left of the black line marks the limit of the ERS-1 satellite-derived elevation data. (B) Surface velocities derived from feature tracking (16) and RADARSAT SAR images with the use of a combination of interferometric and "speckle tracking" techniques (8). m a\textsuperscript{\textcircled{1}}, m year\textsuperscript{\textcircled{1}}.
Ice shelves: may partially control flow rate of ice streams.

Key issue: If ice shelves were removed, would land-based ice accelerate?

A way that warming could accelerate movement.
Projecting the Future

• Projection by extrapolation of past behavior is unreliable, so...

• One needs a computer model of ice sheets to simulate their response to warming, but...

• We don’t have valid models!

*What to do instead?*
The Antarctic Peninsula. Locations of the main stations on the peninsula are marked, together with the period of observation in years, the temperature trend in degrees Celsius per century, and the significance of the trend. (Inset) Location of Amundsen-Scott Base (A-S), East Antarctica (EA), and West Antarctica (WA).
Glacier acceleration where ice shelf lost, lack thereof elsewhere

- Larsen A - x3 increase in flow speed of 2 feed glaciers

- Larsen B - x2-x6 increase in flow speed of 4 feed glaciers
- Hektoria glacier lowered by ~40m in 6 mo
- Glaciers south of collapse region unaffected
- "cork from bottle" analogy
- ~ 0.06mm/y global msl contribution? Work in progress

Slide 13  C.Rapley, BAS
Avoiding Dangerous Climate Change: Exeter Feb 2005
Two ways to destroy an ice shelf

- **Surface melting**: requires a warming of ~5°C on major ice shelves holding back most of WAIS’ ice

- **Basal melting** due to warm circumpolar waters: is destroying Amundsen Sea ice shelves already (1.5m SLR possible), accelerating loss of ice to the sea. Will this continue? ??? warming to destroy large ice shelves
Alternative 2:
Look to the past for clues

\( \text{CO}_2 \) Today
Greenland during LIG

Source: IPCC AR4 WGI Fig 6.6
Last Interglacial

- Ice sheets *smaller* than now
- Poles were significantly warmer: +2-5°C (summer) vs present.
- Sea level was (plus or minus) 4-6m higher
- Greenland ice extent was probably smaller by 2-4m SLR-equivalent, so WAIS may have shrunk, too
- Rates of SLR of >1m/century even in approach to final stand
Fig. 12. (a) Diagram showing the effects of hydro-isostacy at a far-field ‘stable’ continental margin site such as the Western Australian. For a step-function increase in eustatic sea level, there is an initial overshoot in the relative sea level that decays exponentially due to the coastal margin re-adjusting to the increased water load. Isostatic effects are thus more pronounced at the commencement of the LI. (b) The observed relative sea level curve for Western Australia and the corrected eustatic curve.
How much global warming would return poles to LIG condition?

- Sustained global warming of 2-4°C could return polar temperatures comparable to LIG.

- This is consistent with (deficient) ice sheet models that project slow loss of entire Greenland ice sheet for 1-4°C global warming.

- Same models project no net loss from Antarctica for such warming.

- But both “slow” for Greenland and “no loss” for Antarctica must be doubted due to model limitations.
Putting observations, model-based and paleo evidence together:

“There is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1- 4°C (relative to 1990-2000), causing a contribution to sea level rise of 4-6 m or more.”

IPCC Fourth Assessment  WGII
In other words...

- A plausible definition of dangerous warming lies between 1-4°C future global warming

- A “precautionary” definition lies between 1-2°C
A precautionary approach to “dangerous anthropogenic interference”
Possible emissions futures:
AA and AB may get us where we need to go