Deep Uncertainties in Future Sea Level Rise: Threshold Behavior in Glaciers and Ice Sheets

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Where are the principal unquantified uncertainties in land ice ("barystatic" or "new water") SL contributions?

What has been done about these to date?

What is being done to reduce overall SLR uncertainty?

What should we be doing differently?
Components of Sea Level Rise (SLR)

1. Steric (thermal expansion)
   - a. Upper ocean (top 700 m)
   - b. Deep ocean

2. Barystatic (new water)
   - a. Antarctica
   - b. Greenland
   - c. Glaciers and Ice Caps (GIC)
     - d. Terrestrial storage
       - 1. Ground water
       - 2. Surface water
         - a. Reservoir storage

3. Relative (local)
   - a. Dynamics (winds/currents)
   - b. Gravitational (fingerprinting)
   - c. Isostatic rebound
   - d. Coastal subsidence
     - 1. Infrastructure loading
     - 2. SLR loading
     - 3. Upstream sediment trapping
     - 4. Groundwater depletion

(very long-term components, e.g. tectonics, are not considered here)
Observed Sea Level Change (satellite altimetry)

Inverse barometer applied, GIA corrected

Rate = 3.1 ± 0.4 mm/yr
Seasonal signals removed

Observed Sea Level Rise – Nerem Group, University of Colorado, V 16 April 2012
Observed components of globally-averaged Sea Level Rise

20th C Rate: ~ 0.20 m/C
~2000-2010 Rate: ~ 0.30 m/C

- Glaciers, Ice Caps exclusive of ice sheets
- Greenland, Antarctic Ice Sheets
- Thermal expansion of ocean water
- Changes in land storage (ground water, reservoirs)

thermosteric / barystatic
Optimal assessment of global glacier (excluding ice sheets) loss rates over 50 years

Actual loss rate is actually highly variable on ~ 5 year time scale, but significant noise is also present from lack of basic measurements.
2007 IPCC AR4 Sea Level Projection: Less than 1 m, but with caveats concerning ‘rapid dynamics’
“These confusions are a result of the IPCC’s decision for its AR4 report to provide actual predictions for only some of the causes of sea level rise (those it could predict with mathematical models). It produced predictions based on sea level rise from thermal expansion and mountain glacier melting while refusing to assign numbers – because committee members didn’t have a mathematical model they agreed on – to what is likely to be the most important source of sea level rise in the twenty-first century: ice sheet melting.”

(pg. 50, The Rising Sea, Pilkey and Young, Shearwater, 2009)
Sea Level Rise projections to 2100 as of 2007
Including Rapid Dynamics kludge
Rapid Dynamics (RD) Assessment AR4:

Two future RD scenarios:

1. Presently (2007) observed RD are transient and will fade.
2. Presently (2007) observed RD will continue and scale in magnitude with modeled future global average Temperature $T_{GM}$ according to:

$$SLR_{RD} = 0.32 \times \left( \frac{T_{GM}(t)}{0.63^\circ C} \right) \text{ mm yr}^{-1}$$

Range of RD Result:

Added SL Increment of -0.1 to +0.17 m SLR by 2100
Increased SLR Rate of 0.0 to 3.9 mm/yr
Sea Level Rise projections to 2100 as of 2007
Including Rapid Dynamics kludge
**IPCC AR4 Sea Level Rise**

Projections by forcing scenario:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Range of SLR (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.18 - 0.38</td>
</tr>
<tr>
<td>A1T</td>
<td>0.20 - 0.45</td>
</tr>
<tr>
<td>B2</td>
<td>0.20 - 0.43</td>
</tr>
<tr>
<td>A1B</td>
<td>0.21 - 0.48</td>
</tr>
<tr>
<td>A2</td>
<td>0.23 - 0.51</td>
</tr>
<tr>
<td>A1F1</td>
<td>0.26 - 0.59</td>
</tr>
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Total Range  0.18 - 0.59 m

**Vermeer and Rahmstorf 2009**

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</tr>
<tr>
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<td>0.97 - 1.58</td>
</tr>
<tr>
<td>B2</td>
<td>0.89 - 1.45</td>
</tr>
<tr>
<td>A1B</td>
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</tr>
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<td>0.98 - 1.55</td>
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<tr>
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Total Range  0.81 - 1.79 m

**Observational record**

- Rahmstorf 2007

Pfeffer et al 2008
- High-End (2.00 m)
- Low-End (0.78 m)

**IPCC AR4 Sea Level Rise Projections by forcing scenario:**

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**IPCC AR4 projections**

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**Simple Average of 15 Semi-Empirical Models**

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**Hansen, etc up on the ceiling somewhere**
National Research Council, 2012  Total Sea Level Projection

![Graph showing sea level rise projections from different sources.](image-url)
“Rapid Dynamics:”

Changes in glacier or ice sheet geometry, speed, mass, rate of mass change modulated by internal dynamical interactions at rates faster than accompanying rates of environmental mass balance.
Surface Mass Balance and Glacier Equilibrium

Gain: Snowfall exceeds Melt

Loss: Melt exceeds Snowfall

Equilibrium Line Altitude (ELA)

Downslope flow may or may not compensate for surface mass balance
Surface Mass Balance and Glacier Equilibrium

The Continuity Equation

\[ \frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = \dot{b} \]
Flow of the ice under gravity redistributes mass through the ice sheet....
Ice Sheet in equilibrium

Normally, flow balances gains and losses and keeps the size and shape of the ice sheet roughly constant.

... and under ‘steady’ conditions, everything balances.

\[ \text{Gains} = \text{Losses: No change in ice sheet volume} \]
Ice Sheet warming

If a sustained imbalance develops between gains and losses, the ice sheet will change size....

When Losses exceed Gains, the ice sheet shrinks, and the difference goes into the ocean, either via iceberg calving or melt and runoff.

\[ \frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = \dot{b} \]

Mass balance is calling the shots
Ice Sheet accelerating: Rapid Dynamics

But the rate of ice flow is not *obliged* to balance the rates of gain and loss; the ice could (and sometimes does) accelerate…

\[ \frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = b \]

*Flux divergence is calling the shots*

Again, Losses exceed Gains, and the ice sheet shrinks, with the difference going into the ocean.
1982-2009: 8 km of retreat, 400+ m of thinning
The Future
Methods of cryospheric projection in use or in development:

1. Full processed-based models (e.g. Navier-Stokes)
2. Extrapolation based models (fully empirical)
3. Semi-empirical models (empirical fit of output to modeled input)
4. Hybrid models (semi-empirical components in process models)
5. Assessment/Compilation (e.g. IPCC, NCA)
Radic and Hock, 2011
Process-based glacier contribution to projected sea level rise, AOGCM forced surface mass balance, no dynamic response
Extrapolation assumes statistical stationarity: whatever is driving accelerated mass loss today continues into the future.
Projected Sea Level to 2100 from all components.

An example of projection by extrapolation – Projection observed present-day rates forward into the future.

Assign declining overall confidence in projection with time: Projected ± uncertainty represents “known unknowns” only.

National Research Council, 2012
Vermeer and Rahmsdorf, 2009

Projected total sea level rise, undifferentiated sources, observation record of sea level rise scaled to observational record of temperature and projected into future using modeled temperature
Price et al, 2011
Hybrid semi-empirical model
Projected sea level rise, Greenland ice sheet only, dynamics modeled, but timing simulated empirically
National Climate Assessment/Copilation, USGCRP, 2012
End points only assessed from literature; simple curves drawn from present
Stranded iceberg, Columbia Glacier, Alaska

W.T. Pfeffer
The current state of the art on sea level projection from the policy maker’s perspective:

**SLR at 2100 Could Be About Anything**
(i.e. the uncertainties are too large)

Why?

1. Wide range of potential forcings (RCPs).

2. Fundamental process knowledge lacking in certain areas: **rapid dynamics** via ice/rock interface interaction, iceberg calving. Also snow and englacial hydrology effects on surface mass balance.

3. Observations missing (but attainable in principal). e.g. detailed subglacial topography.

but also…
The time scales are poorly defined, and in conflict with planner’s needs.

1. Most SLR projections done by geoscientists (including IPCC) tend to be focused on 2100 and beyond.

2. Research strategies are pure-science driven, and result (coincidentally) is focus on processes with long lead times (hence focus on 2100 and beyond)

3. Processes critical in short-term (decades to 2100) but possibly insignificant in long-term (after 2100) very poorly represented.

4. Geoscientists response to AR4 “Rapid Dynamics” problem was to work harder on the same problems they’d pursued for the past 30 years.
Why Rapid Dynamics for Ice Sheets only?

- Ocean-terminating glaciers account for 38% of global glacier area (ca. 280,000 km²)
- Alaska, currently discharges 17 GT/yr via calving, accounting for 36% of Alaska’s mass loss, from only 13% of Alaska’s glacier-covered area.
- Alaska contains only 4% of the world’s ocean-ending area outside of the icesheets. No estimates exist of the global calving fraction.
Alternative strategies could include:

Set goals based on obtaining certain projected values (e.g. global mean SLR),

with quantified uncertainty (target tolerance),

for specific dates in the future (e.g. 2030, 2050, 2100),

to be delivered early enough to be of use (ideally before it happens).

Need to decide:

What time periods do we project for?  
What is an acceptable level of uncertainty?  
How much advance notice do we need?
SLR projections will ideally be delivered as a PDF.

The full suite of SL contributors required to establish *most likely* value are not being evaluated.

Extreme events on ice sheets fall into “fat tail”

This weakness is *more* pronounced at *nearer* forecast target dates.
The short-term is important, but don’t forget about the long term...

*from MOMA Rising Currents (September 2010)*

Image courtesy Architecture Research Office and dlandstudio
Battery Breakwater

from A New Urban Ground, Cassell and Yarinsky, Architectural Research Office, 2010
Time scales matter:

Long scales (100 yrs +) important for major long-term infrastructure replacement

Short scales (10 – 50 yrs) important for far more numerous infrastructure maintenance and replacement over normal lifetime-of-infrastructure (50 – 75 years).

<table>
<thead>
<tr>
<th>Average or interval of life expectancy</th>
<th>Estonia</th>
<th>Sweden</th>
<th>Austria</th>
<th>France</th>
<th>Germany</th>
<th>Spain</th>
<th>The Netherlands</th>
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<tbody>
<tr>
<td>Buildings</td>
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<td>10-35</td>
<td>25</td>
<td>50</td>
<td>10-50</td>
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<td>Civil engineering works</td>
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<td>Superstructure</td>
<td>8-50</td>
<td>40</td>
<td>25</td>
<td>30-50</td>
<td>20-25</td>
<td>18-40</td>
<td>33</td>
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<tr>
<td>New construction in progress</td>
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<td>N/a</td>
<td>N/a</td>
<td>N/a</td>
<td>N/a</td>
<td>N/a</td>
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<tr>
<td>Transmission lines</td>
<td>8-50</td>
<td>10-35</td>
<td>15</td>
<td>20</td>
<td>20-20</td>
<td>33</td>
<td>11</td>
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<tr>
<td>Signalling equipment</td>
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<tr>
<td>Telecommunications equipment</td>
<td>5-20</td>
<td>4</td>
<td>15</td>
<td>5-20</td>
<td></td>
<td></td>
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<tr>
<td>Safety installations</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Vehicles / rolling stock</td>
<td>3-15</td>
<td>5</td>
<td>5</td>
<td>15-30</td>
<td>10-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant and machinery</td>
<td>3-15</td>
<td>3-25</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office, computer and other equipment, tools</td>
<td>3-5</td>
<td>3-25</td>
<td>4</td>
<td>3-7</td>
<td>2-20</td>
<td>5-40</td>
<td></td>
</tr>
</tbody>
</table>

*from* Infrastructure Expenditures and Costs (Eur. Comm., 2005)
Predictions and Cost of uncertainty (value of reducing uncertainty) varies over time

What are time scales C and D?

C: Possibly ~ 1 year (reducing uncertainty in sea level forecast on much shorter time scales isn’t useful).

D: Possibly 50-100 years (reducing uncertainty in sea level forecast 500 years from now isn’t politically/economically usable).

*Long-term determinations not useful in the absence of medium-short term determinations*

What are the optimal windows for making projections? Is it better to have a more uncertain 50-year projection for 2050 now, or wait until 2025 and get a better 25-year projection?
A few Advantages to Rapid Dynamic Response

The biggest events have comparatively long time scales: West Antarctic Ice Sheet collapse (2-3 m/century SLE) requires removal of major ice shelves first; requires 100-200 years (Maybe? – requires investigation). We get advance warning.

Greenland Ice Sheet contains ca. 6 m SLE but no capacity for catastrophic West Antarctic style collapse. Could reach high loss rates, but not by an exceptionally non-linear path.
Projected Sea Level to 2100 from all components.

Cryospheric losses projected by **uncertainty-weighted generalized least squares interpolation** from observations:
- 1992-2009 (ice sheets)
- 1961-2009 (glaciers)

**National Research Council, 2012**

*Projected in red:* Best estimate of what *will* happen
*Projected in black:* What could happen if RD occurs, but no probability occurrence attached to this.
Modeling improvements/alternatives:

1. Model all sources, not just the biggest ones.

Uncertainty for glacier and ice sheet projections are approximately equal.
Pursue parallel modeling tracks. Embrace non-deterministic modeling and hybrid models.

- **Stationary process**: continued acceleration
- **Transitional process**: stabilizes at new steady state
- **Transient process**: returns to initial state after period of fast change

Model Rapid Dynamics but handle initiation of RD as a *parameter*.

Price et al (PNAS) have started this.
Pursue parallel modeling tracks. Embrace non-deterministic modeling and hybrid models.

Extend Semi-empirical strategy to hybrid models:

\[
\begin{align*}
T_{\text{global}} \rightarrow & \text{ Rahmsdorf, etc} \rightarrow \text{Sea Level} \\
\text{Observed/Modeled time constants for outlet glacier response} \rightarrow & \text{Semi-empirical outlet glacier component} \rightarrow \text{Initiation and duration of RD by basin} \\
\text{Experimental determination of } A \& n \rightarrow & \text{Glenn's Flow Law } \dot{\varepsilon} = A\sigma^{n-1}_{e} \sigma_{ij} \rightarrow \text{Calculated Strain Rate}
\end{align*}
\]
Sea Level forecasting can be substantially improved simply by thinking carefully about **goals** and communicating them.

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A Comment

GLACIOLOGY NEEDS TO COME OUT OF THE IVORY TOWER

W. Tad Pfeffer

What happens when a field of scientific inquiry that starts out as a subject motivated purely by curiosity and driven by the simple desire to understand how the world works, is turned rather suddenly into a field with applications of the most urgent nature? This has happened in the study of glaciers and sea-level rise. Thus, we glaciologists need to change how we view, practice and report our science. What we say and do matters.

Fifty years ago, the study of the dynamics of glaciers and ice sheets was sufficiently arcane for the term “glaciology” to merit an entry in “Mrs. Byrne’s Dictionary of Unusual, Obscure, and Preposterous Words.” Today, with the growing prominence of climate change and the role of glaciers in sea-level rise, what was once a research topic pursued by a relatively small, scattered community of geoscientists working at a comparatively leisurely pace, is now a vast enterprise with applications that are as far reaching as the consequences of climate change itself. The assessment authors were very clear about the limitations of the sea-level projections, as well as what they were estimating using some simple approximations, and the need for improvements in basic knowledge of glacier dynamics, glacier-ocean interactions, and computer models to simulate them.

W. Tad Pfeffer is a glaciologist, photographer and author.

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