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

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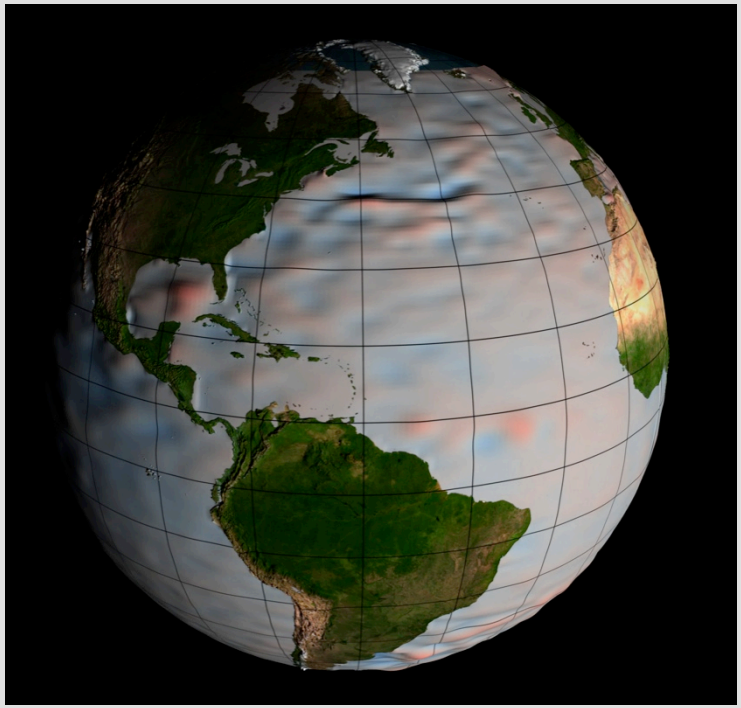
Where are the principal unquantified uncertainties in land ice (“barystatic” or “new water”) SL contributions?

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

Global

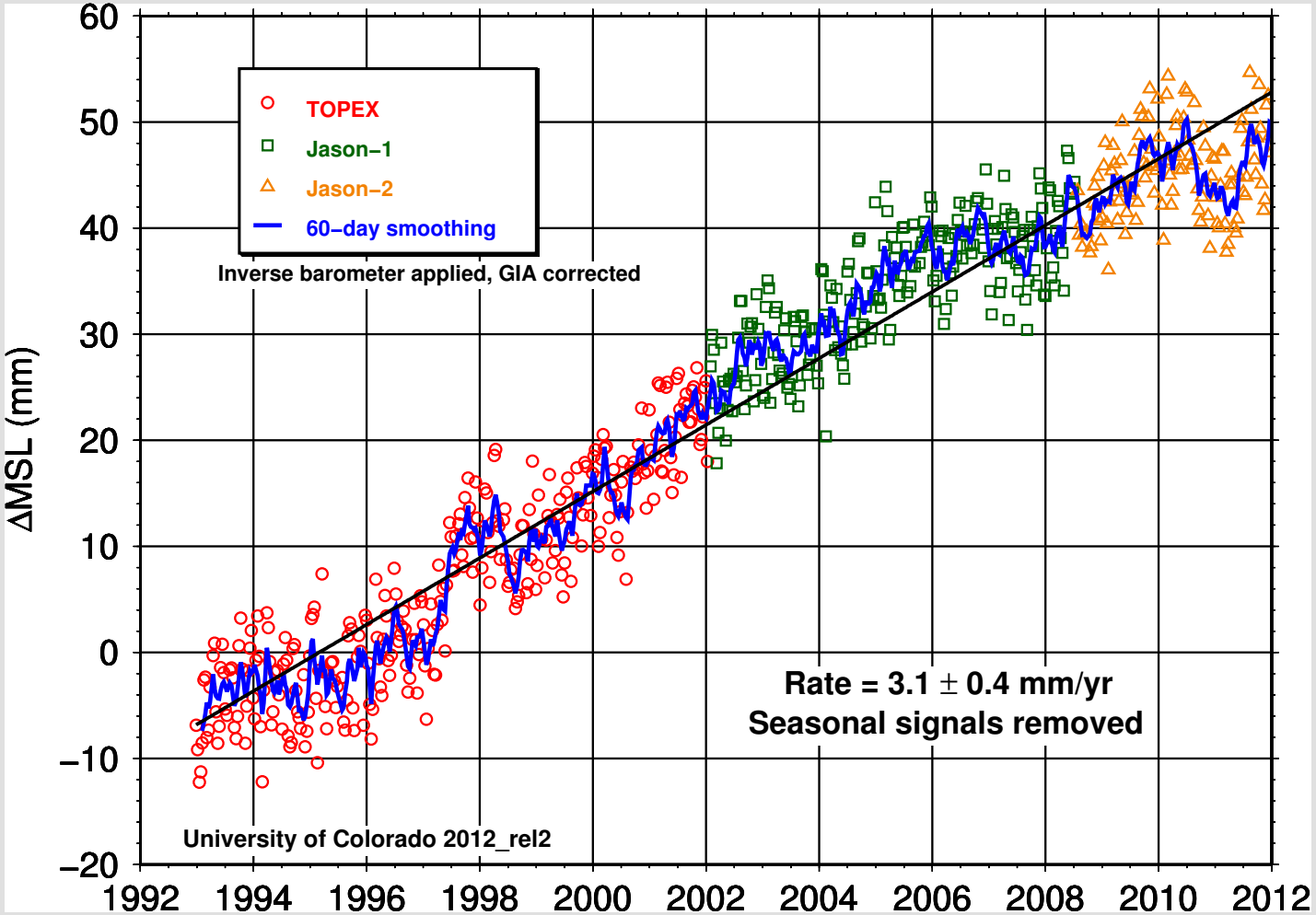
3.Relative (local)

   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

May dominate locally

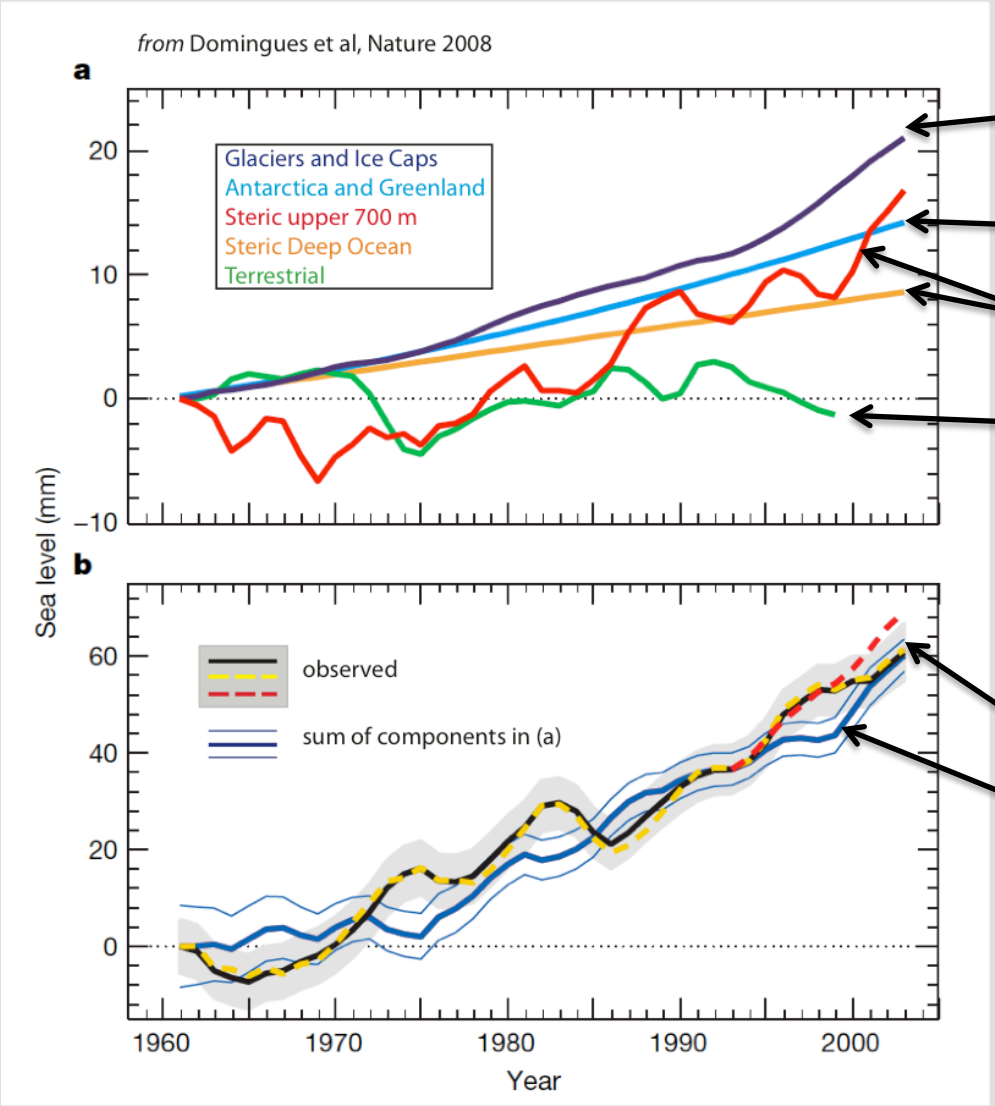
(very long-term components, e.g. tectonics, are not considered here)

Observed Sea Level Change (satellite altimetry)



Observed Sea Level Rise – Nerem Group, University of Colorado, V 16 April 2012

Observed **components** of globally-averaged Sea Level Rise



[thermosteric / barystatic]

Glaciers, Ice Caps exclusive of ice sheets

Greenland, Antarctic Ice Sheets

Thermal expansion of ocean water

Changes in land storage (ground water, reservoirs)

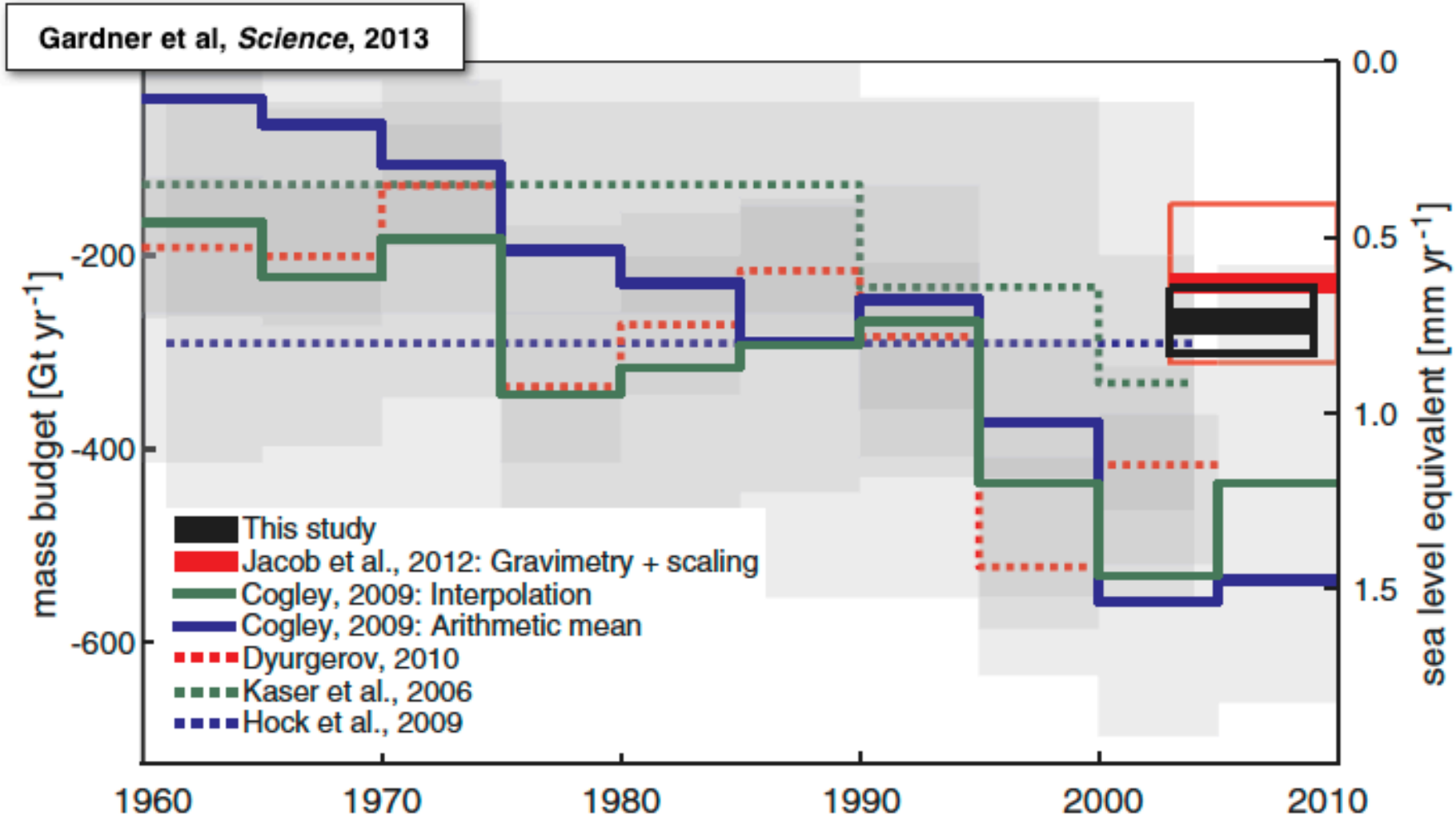
Observed SLR from gauges, altimetry

Sum of components

20th C Rate: ~ 0.20 m/C

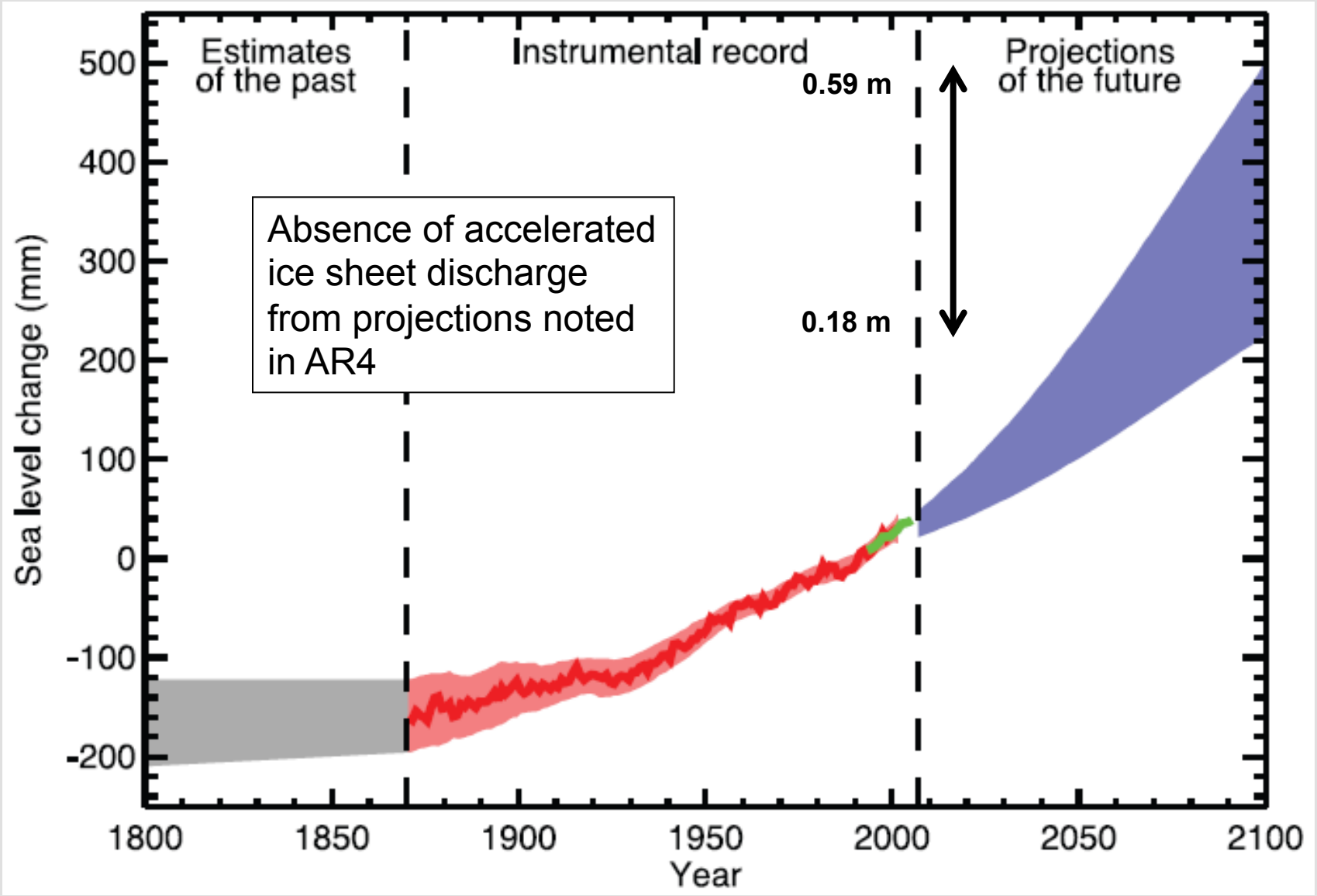
~2000-2010 Rate: ~ 0.30 m/C

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

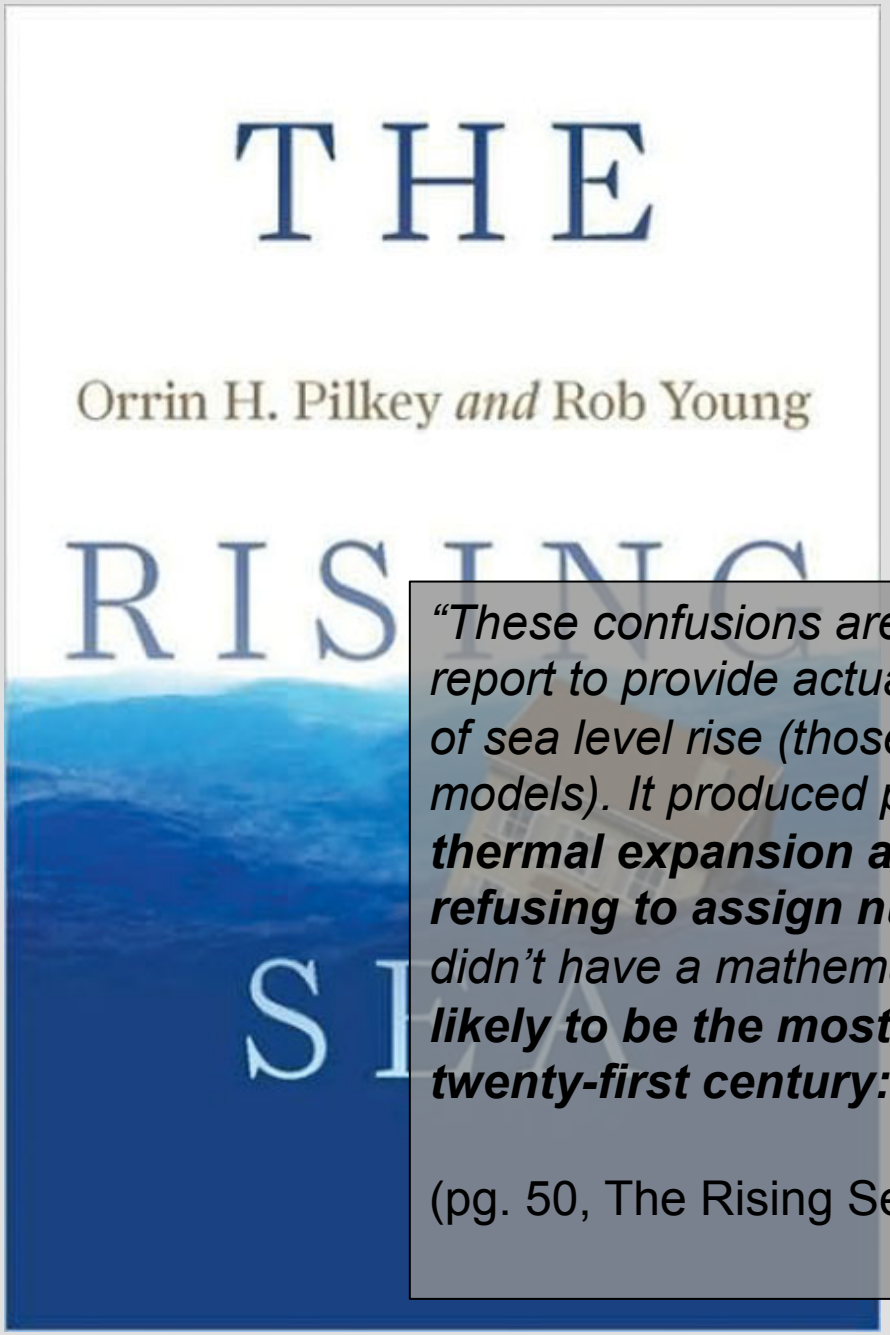


Actual loss rate is actually highly variable on ~ 5 year time scale, but significant noise is also present from lack of basic measurements

2007 IPCC AR4 Sea Level Projection



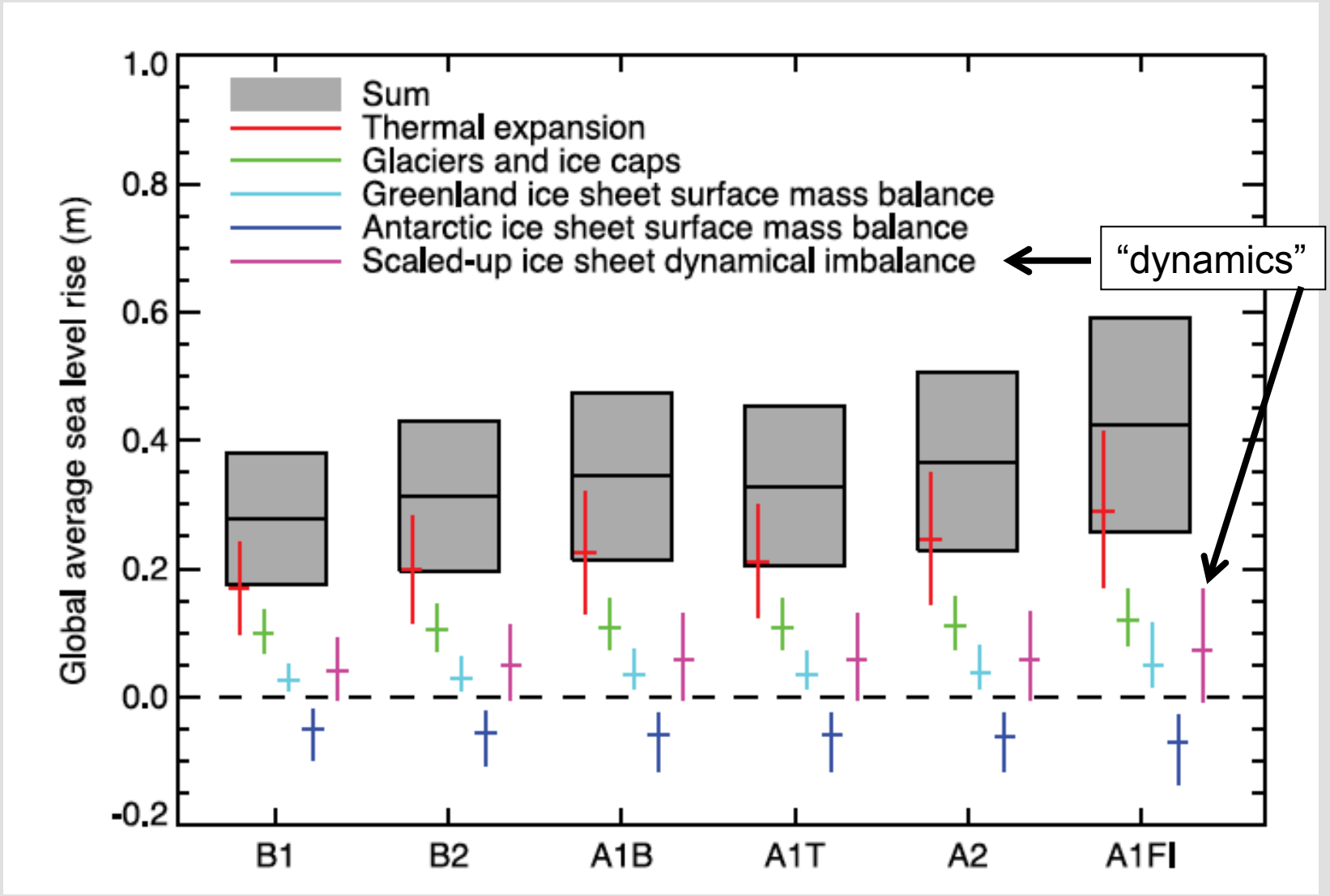
IPCC AR4 2007 Sea Level Projection: Less than 1 m,
but with caveats concerning 'rapid dynamics'



"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)

2007 IPCC AR4 Sea Level Summary Figure 10.33



Sea Level Rise projections to 2100 as of 2007
Including Rapid Dynamics kludge

Rapid Dynamics (RD) Assessment AR4:

Two future RD scenarios:

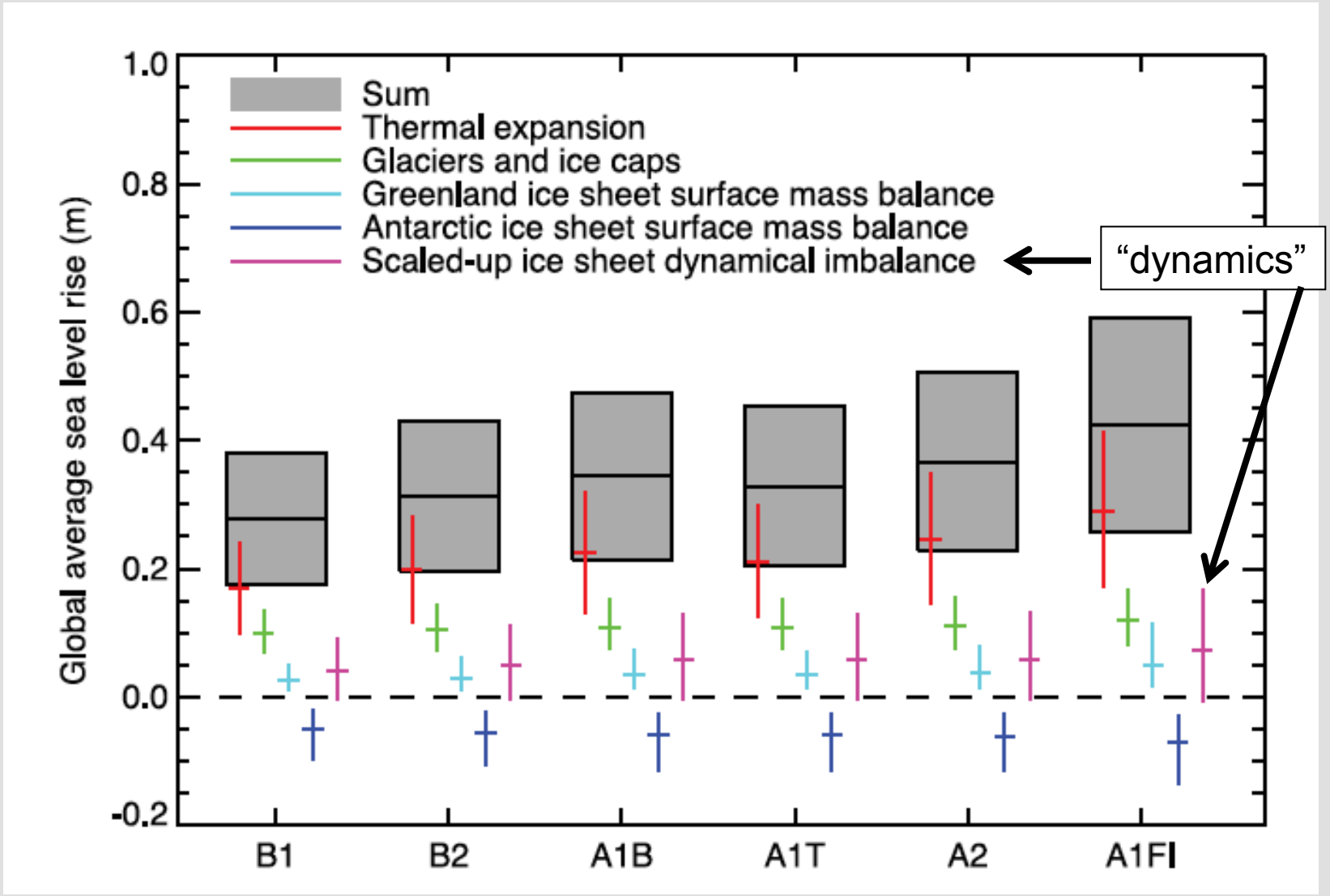
1. Presently (2007) observed RD are transient and will fade.
2. Presently (2007) observed RD will continue and scale in magnitude with modeled future global average Temperature T_{GM} according to:

$$SLR_{RD} = 0.32 \times (T_{GM}(t) / 0.63^{\circ}\mathrm{C}) \quad mm\,yr^{-1}$$

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

2007 IPCC AR4 Sea Level Summary Figure 10.33



Sea Level Rise projections to 2100 as of 2007
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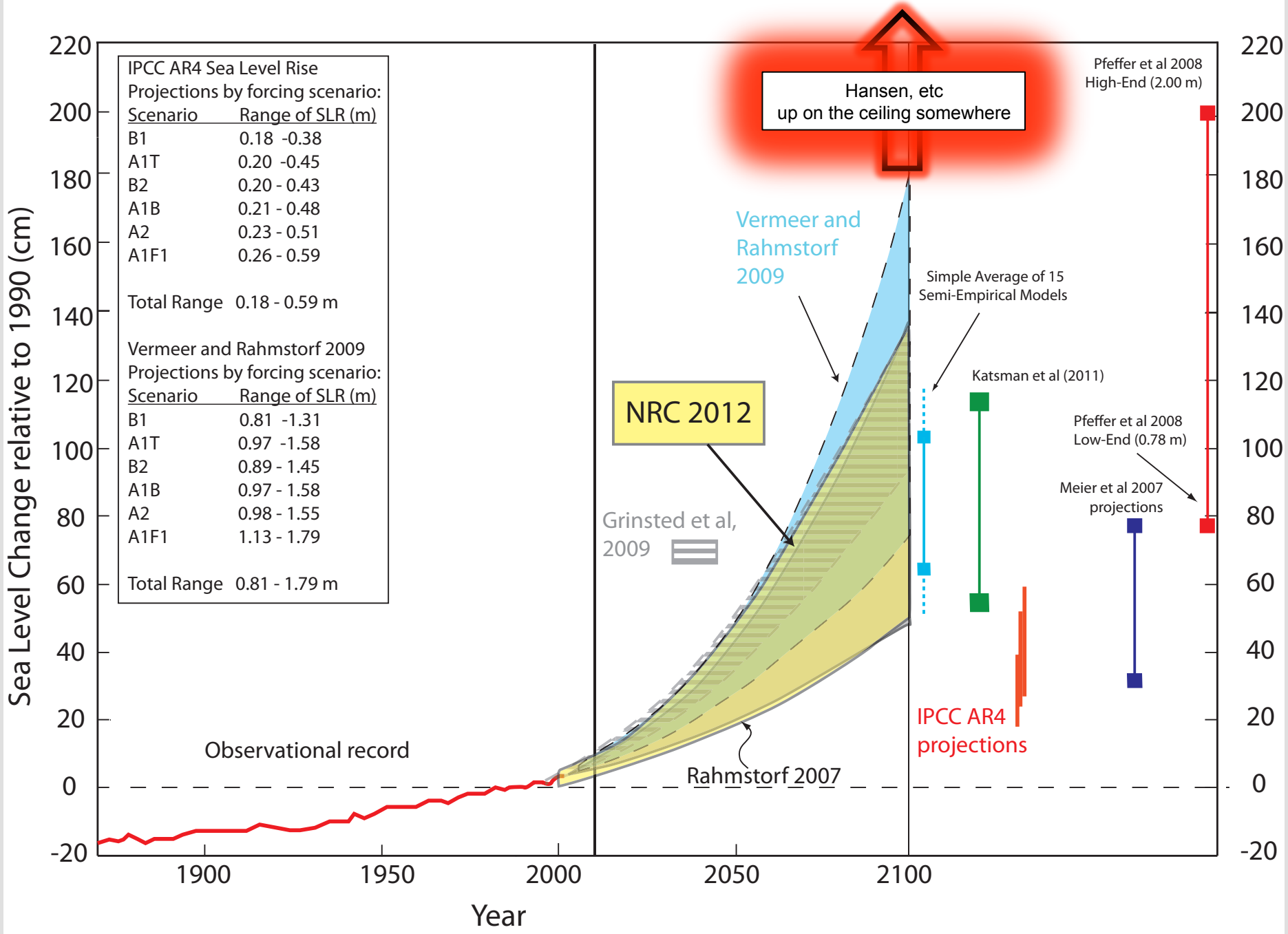
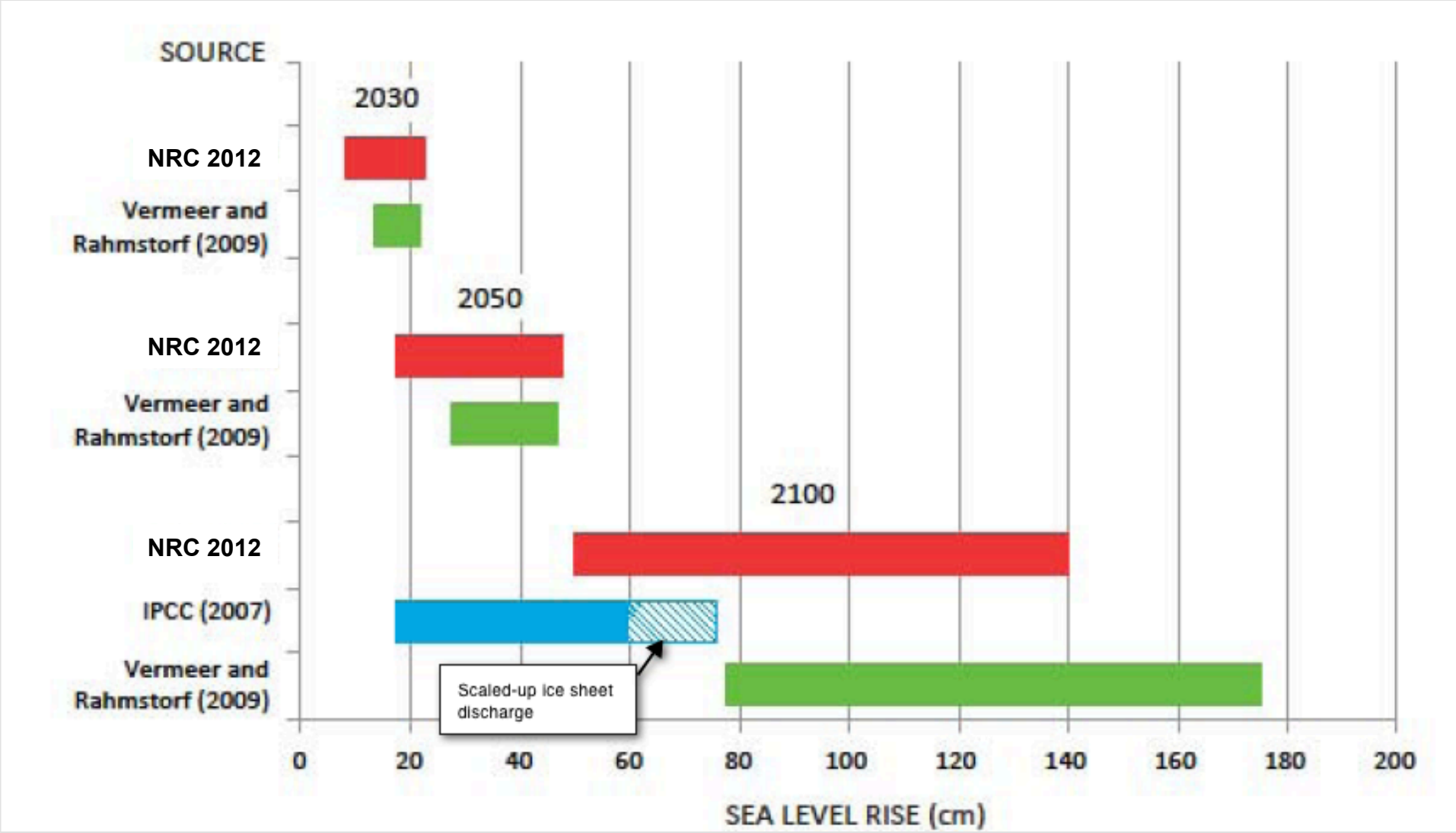

IPCC AR4 Sea Level Rise
Projections by forcing scenario:
Scenario Range of SLR (m)
B1 0.18 -0.38
A1T 0.20 -0.45
B2 0.20 - 0.43
A1B 0.21 - 0.48
A2 0.23 - 0.51
A1F1 0.26 - 0.59
Total Range 0.18 - 0.59 m
Vermeer and Rahmstorf 2009
Projections by forcing scenario:
Scenario Range of SLR (m)
B1 0.81 -1.31
A1T 0.97 -1.58
B2 0.89 - 1.45
A1B 0.97 - 1.58
A2 0.98 - 1.55
A1F1 1.13 - 1.79
Total Range 0.81 - 1.79 m
Hansen, etc
up on the ceiling somewhere
Pfeffer et al 2008
High-End (2.00 m)
Vermeer and
Rahmstorf
2009
Simple Average of 15
Semi-Empirical Models
Katsman et al (2011)
NRC 2012
Pfeffer et al 2008
Low-End (0.78 m)
Meier et al 2007
projections
Grinsted et al,
2009
IPCC AR4
projections
Observational record
Rahmstorf 2007
Sea Level Change relative to 1990 (cm)
Year
220
200
180
160
140
120
100
80
60
40
20
0
-20
1900
1950
2000
2050
2100

National Research Council, 2012 Total Sea Level Projection



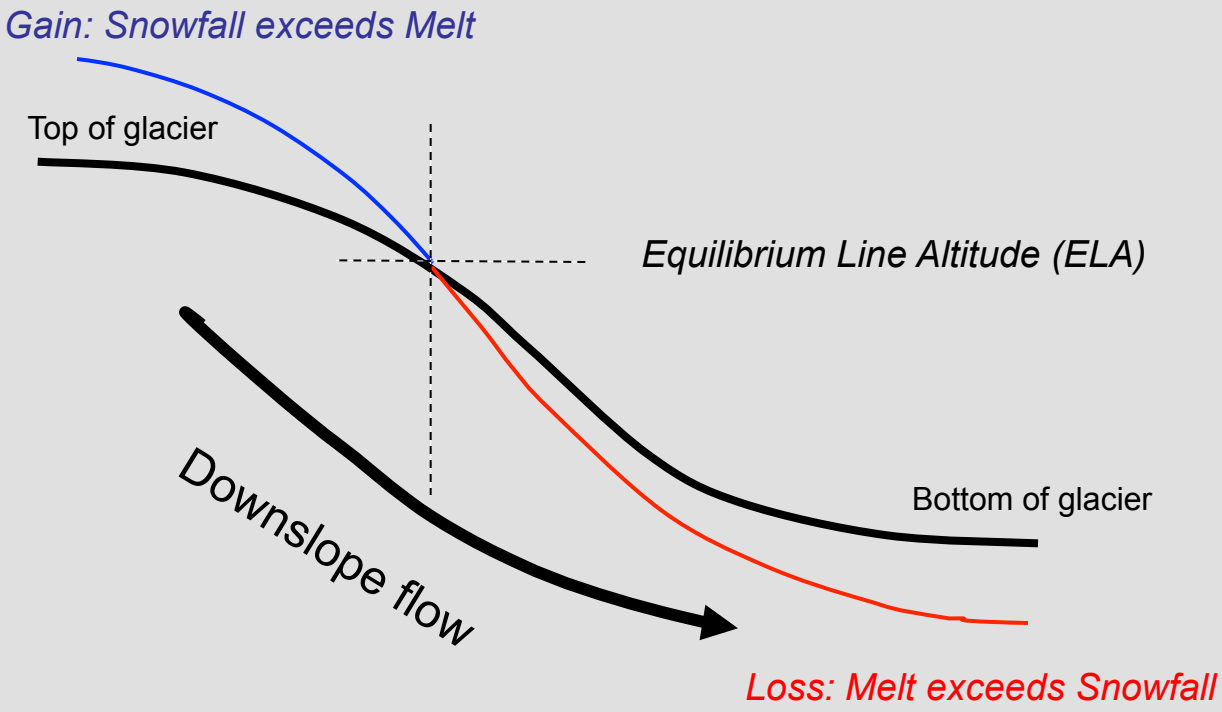
"Rapid Dynamics:"

Changes in glacier or ice sheet geometry, speed, mass, rate of mass change

modulated by internal dynamical interactions

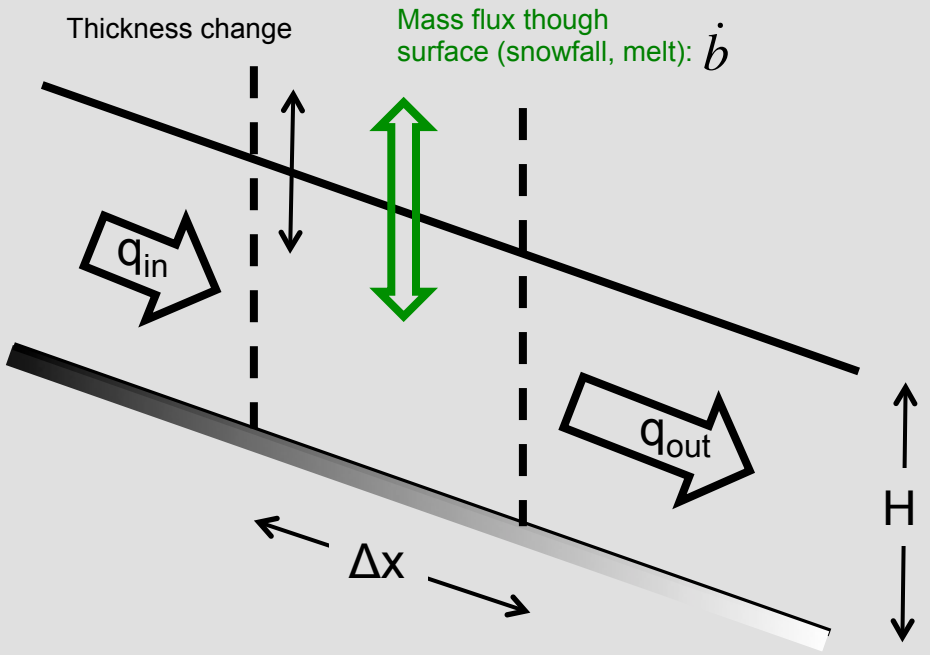
at rates faster than accompanying rates of environmental mass balance

Surface Mass Balance and Glacier Equilibrium



Downslope flow *may or may not* compensate for surface mass balance

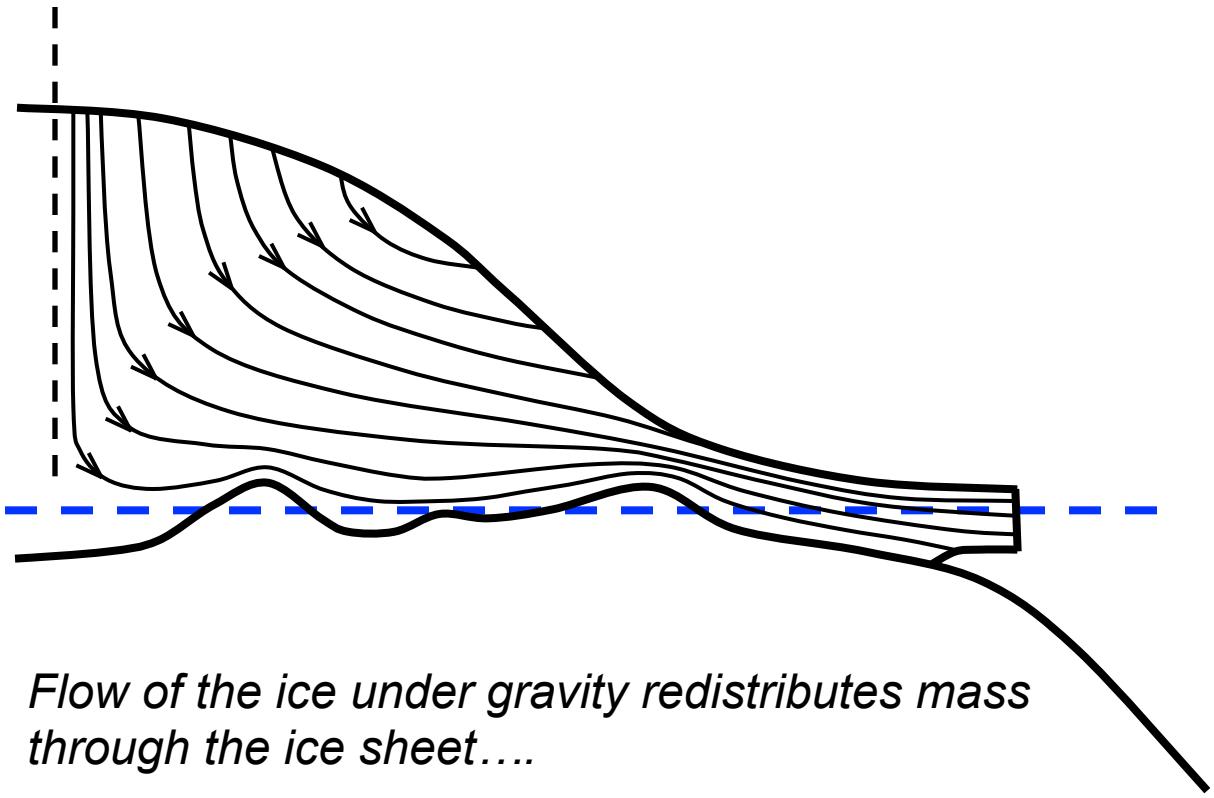
Surface Mass Balance and Glacier Equilibrium



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

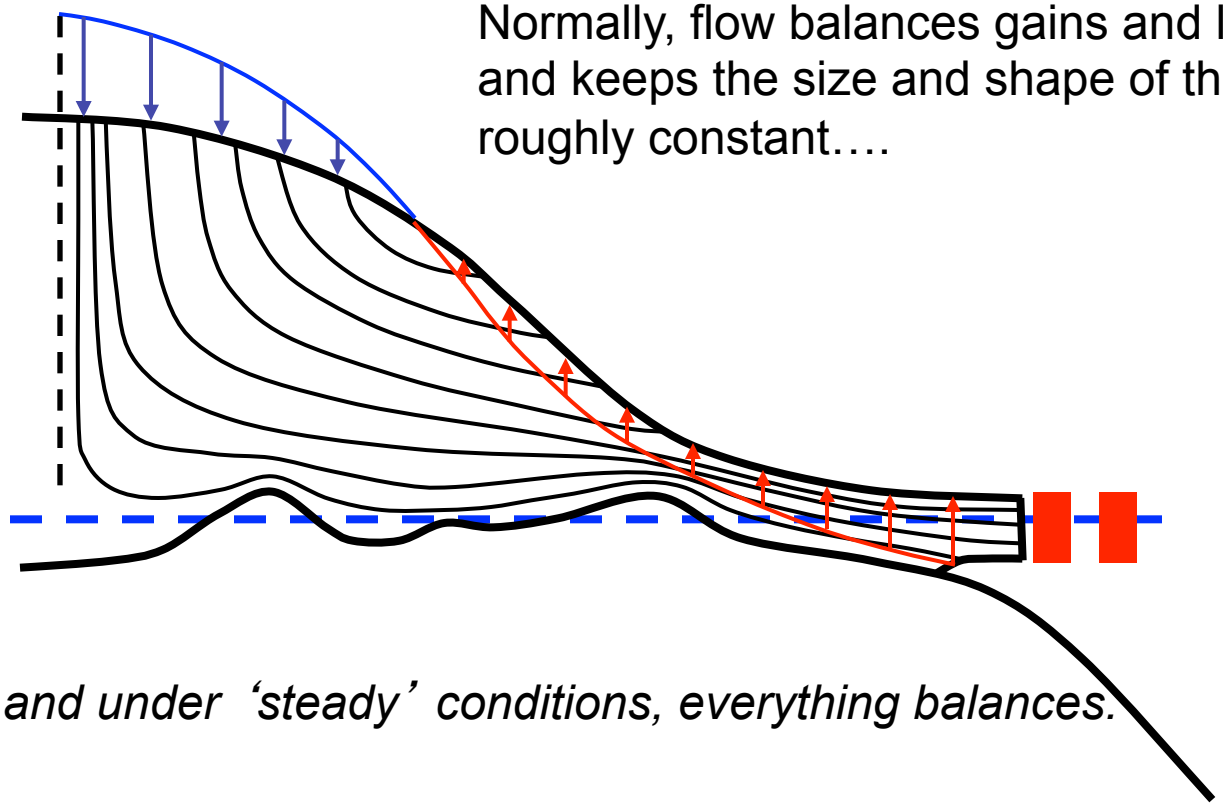
The Continuity Equation

Ice Sheet flow



Flow of the ice under gravity redistributes mass through the ice sheet….

Ice Sheet in equilibrium

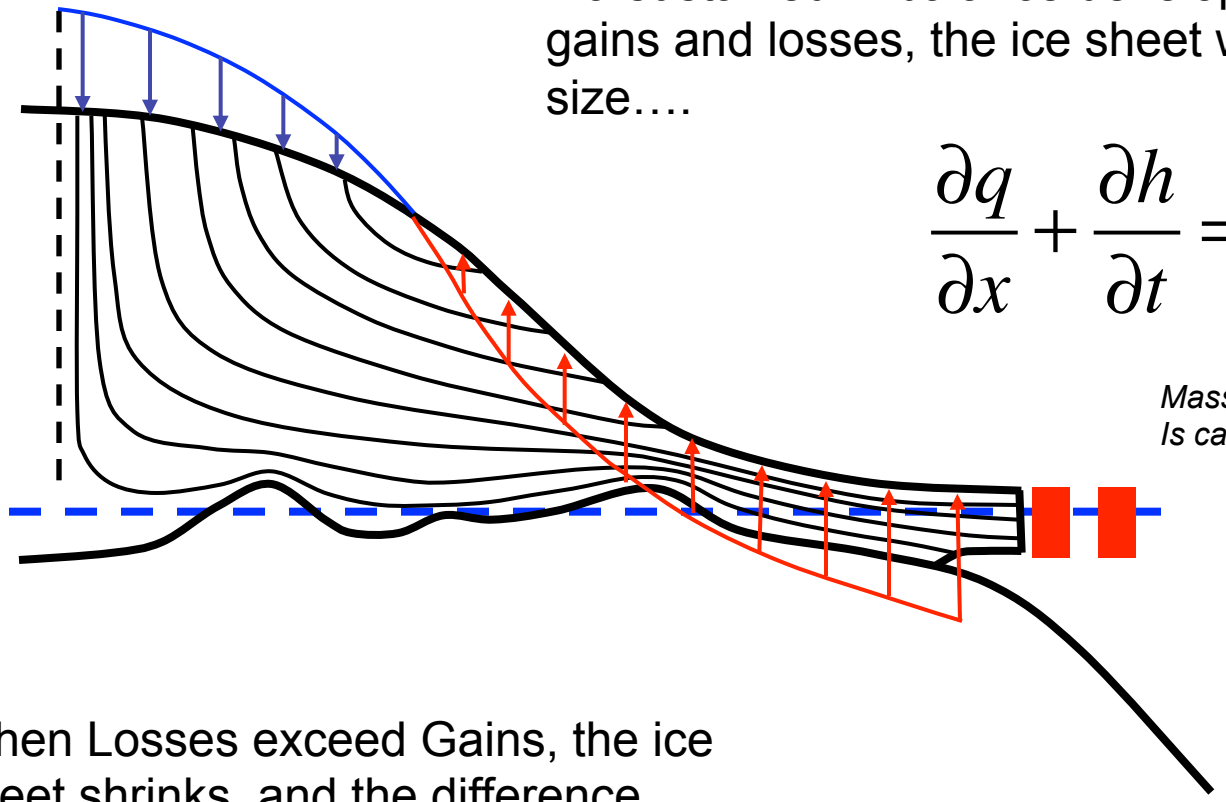


Normally, flow balances gains and losses and keeps the size and shape of the ice sheet roughly constant….

… and under 'steady' conditions, everything balances.

Gains = 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….

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

Mass balance
Is calling the shots

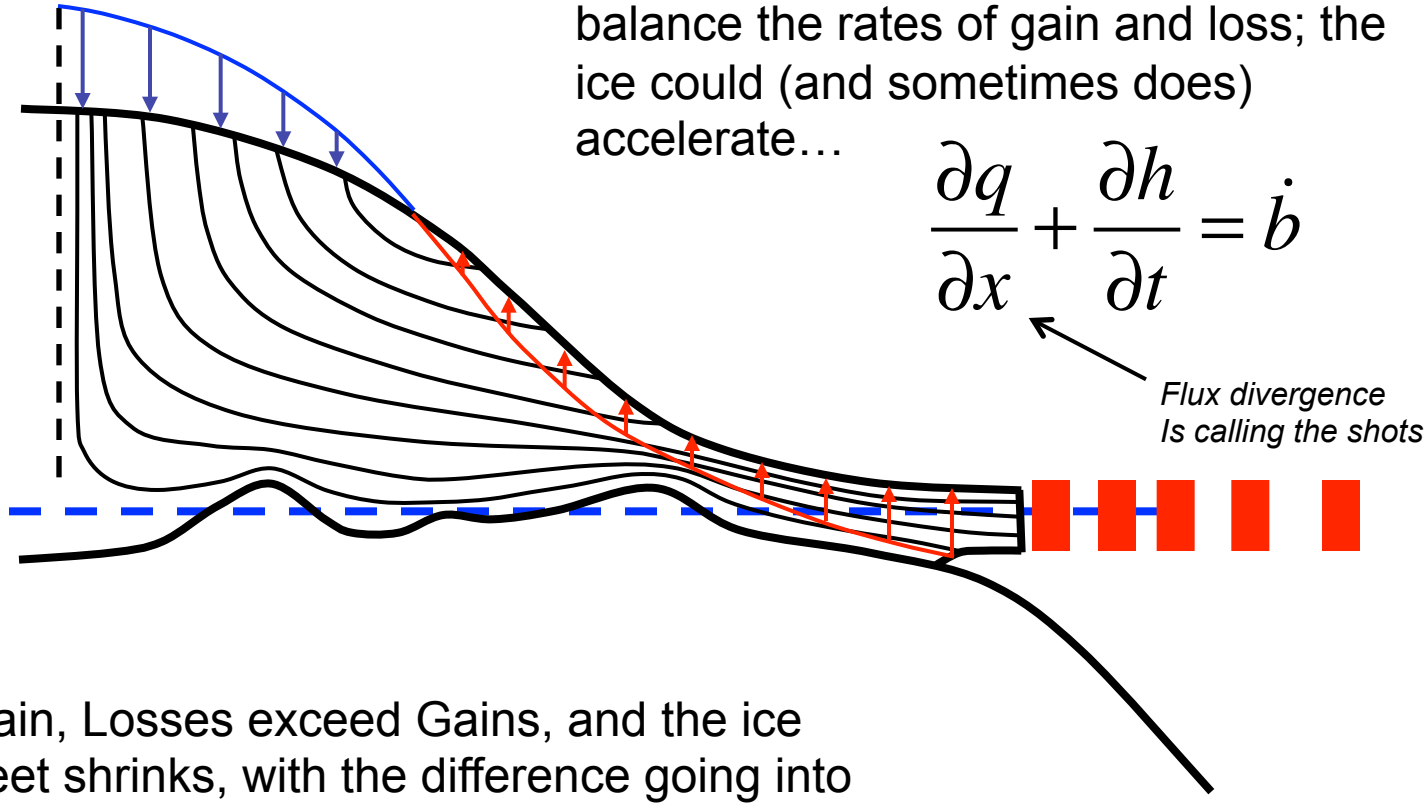
When Losses exceed Gains, the ice sheet shrinks, and the difference goes into the ocean, either via iceberg calving or melt and runoff.

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…

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

Flux divergence
Is calling the shots



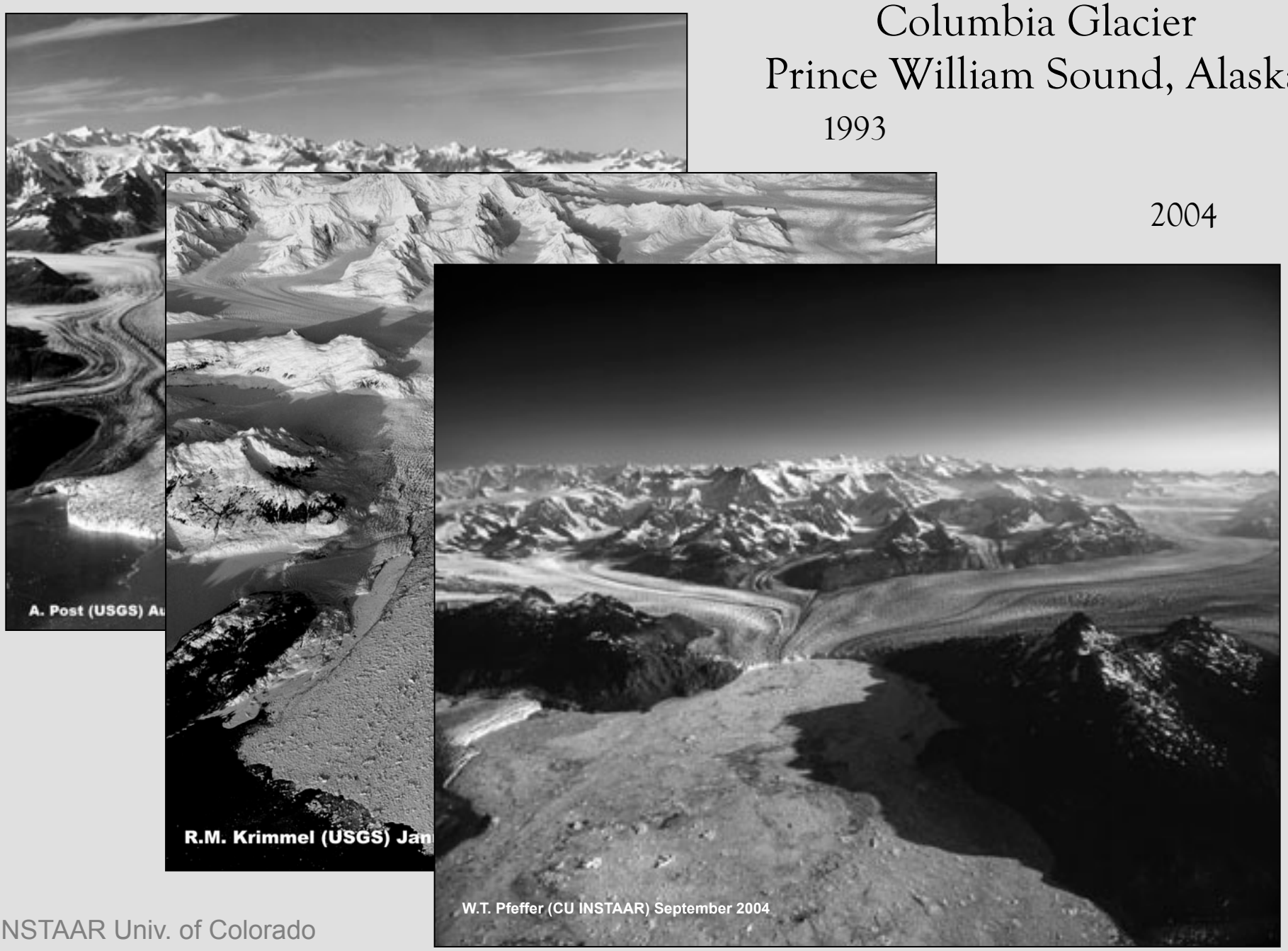
Again, Losses exceed Gains, and the ice sheet shrinks, with the difference going into the ocean.

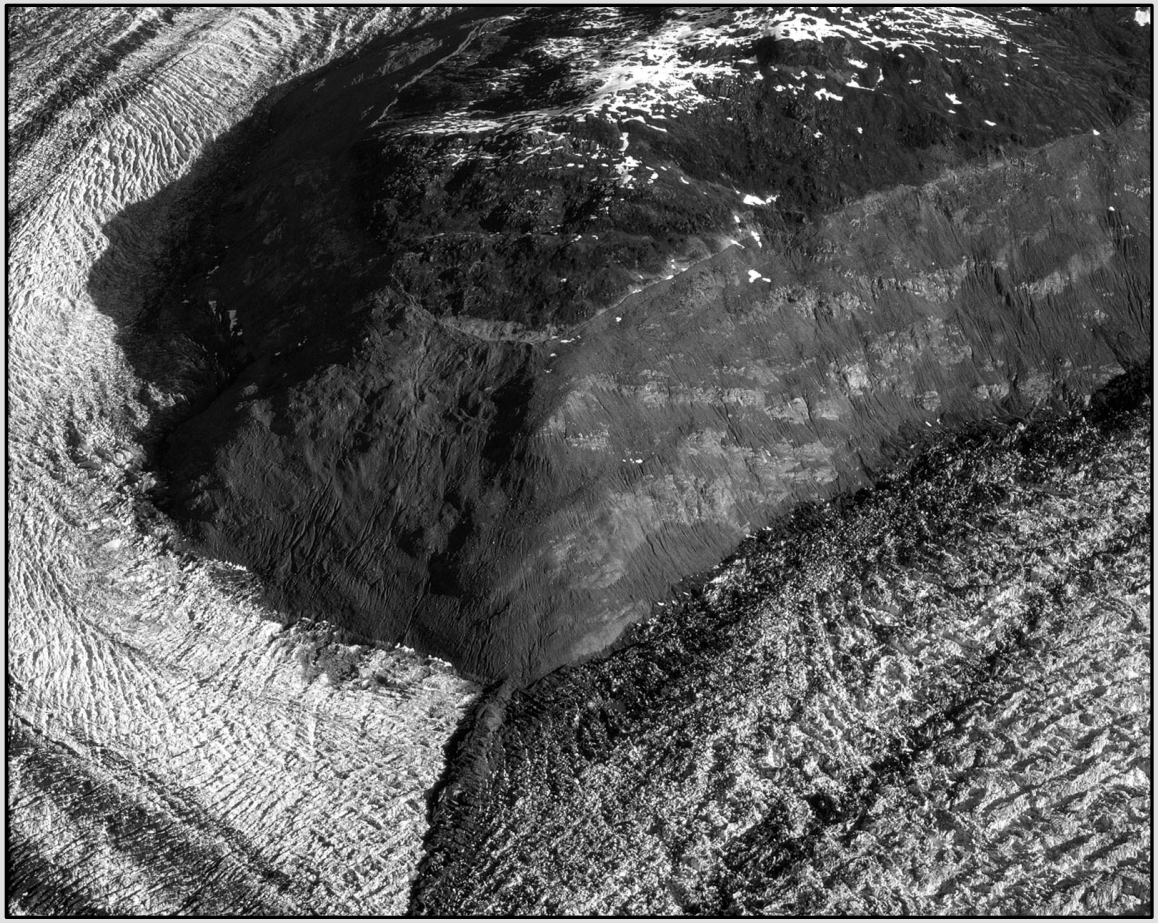
1979

Columbia Glacier
Prince William Sound, Alaska

1993

2004





Trimline at Juncture, Columbia glacier, 2005 W.T. Pfeffer

1982-2009: 8 km of retreat, 400+ m of thinning

The Future

Methods of cryopsheric projection in use or in development:

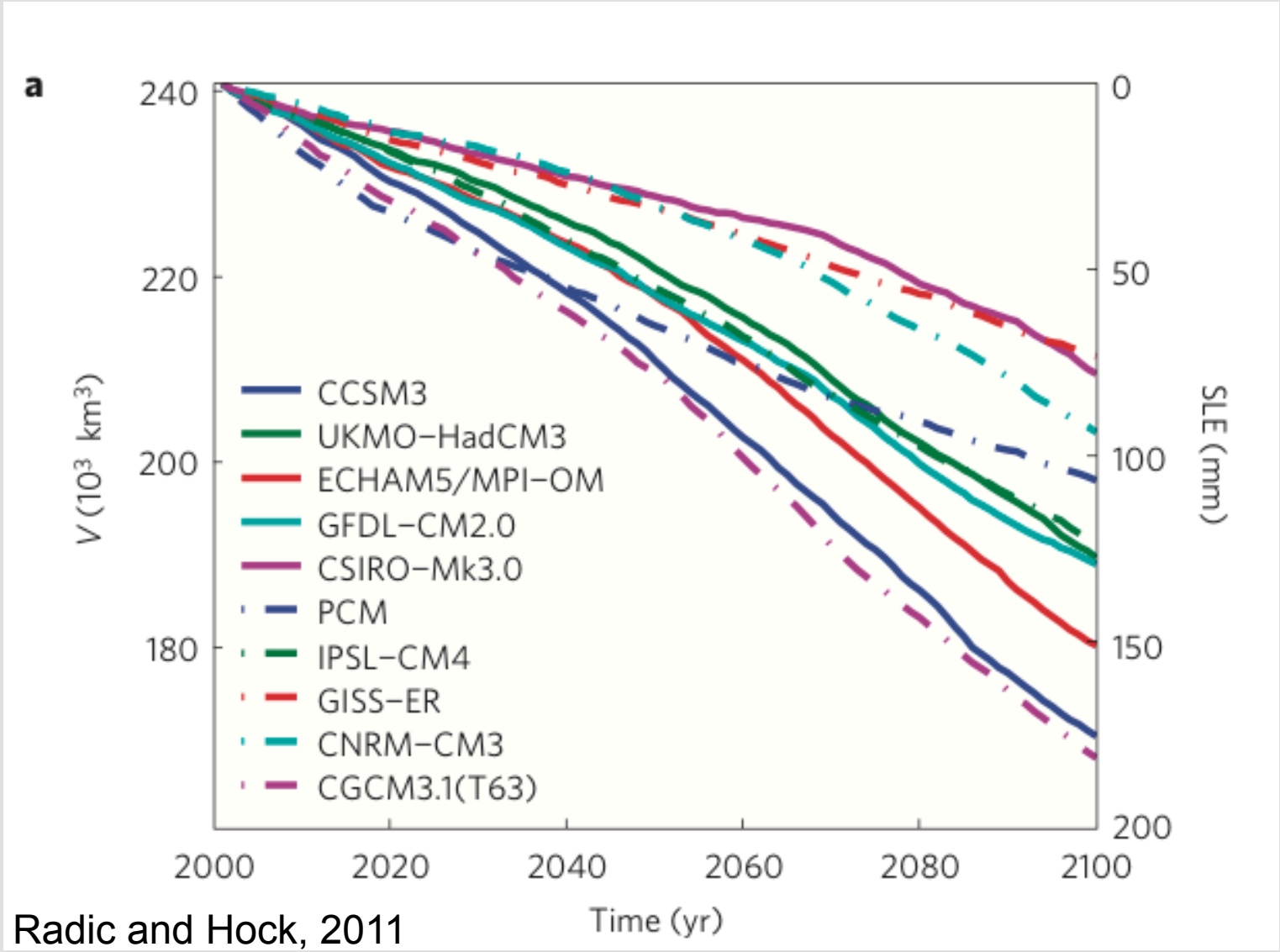
1. Full processed-based models (e.g. Navier-Stokes)

2. Extrapolation based models (fully empirical)

3. Semi-empirical models (empirical fit of output to modeled input)

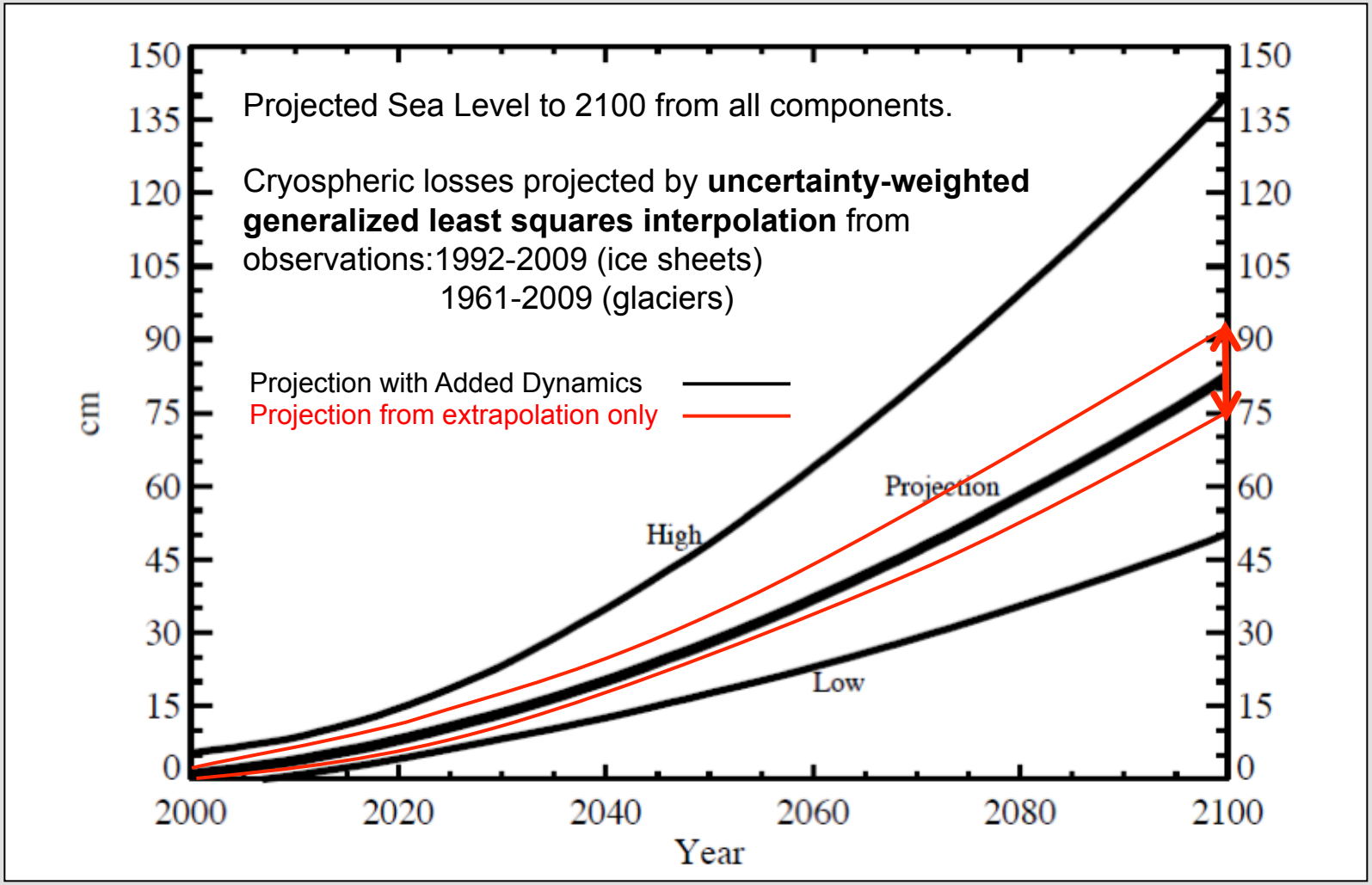
4. Hybrid models (semi-empirical components in process models)

5. Assessment/Compilation (e.g. IPCC, NCA)



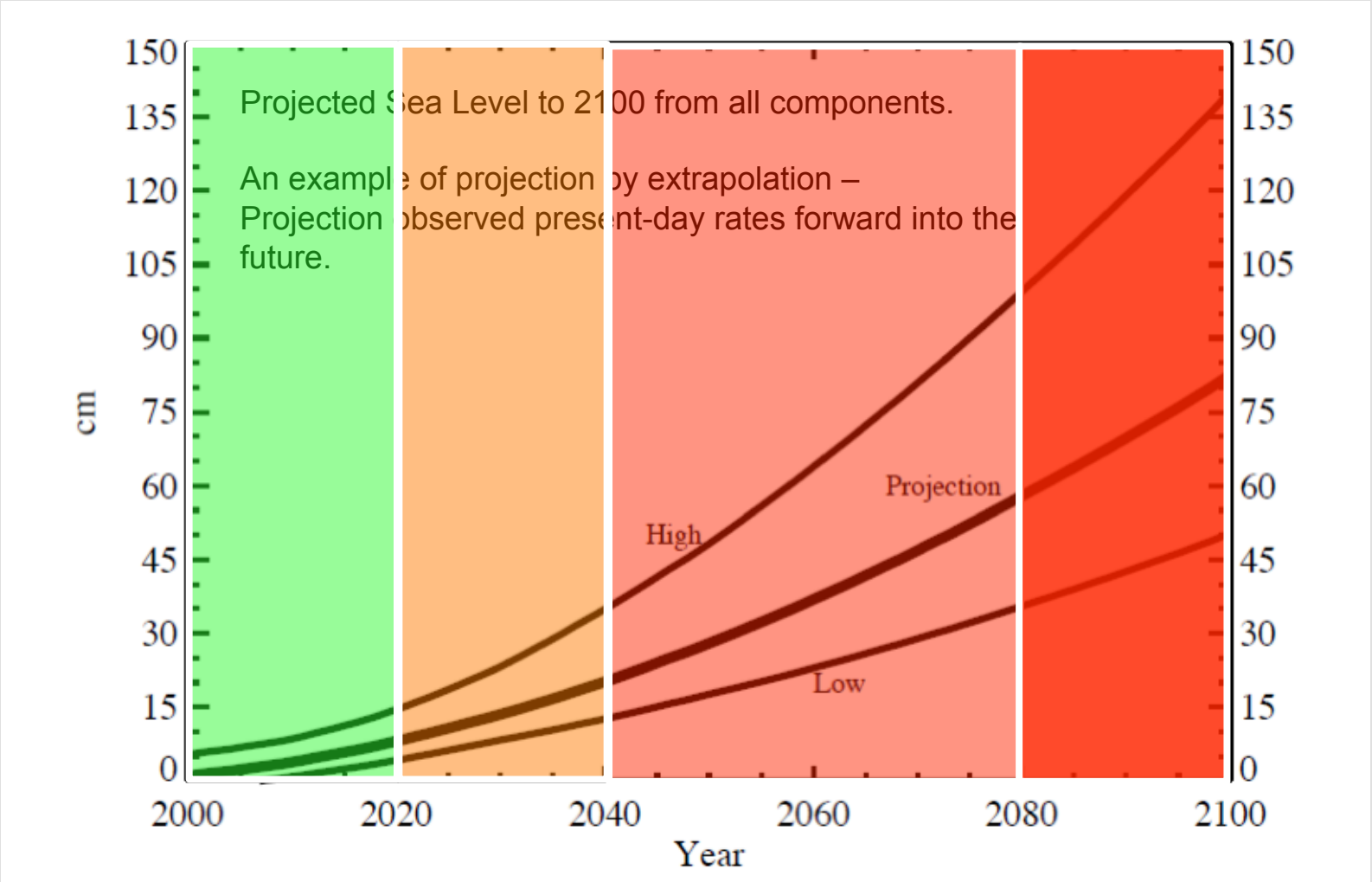
Radic and Hock, 2011

Process-based glacier contribution to projected sea level rise, AOGCM forced surface mass balance, no dynamic response



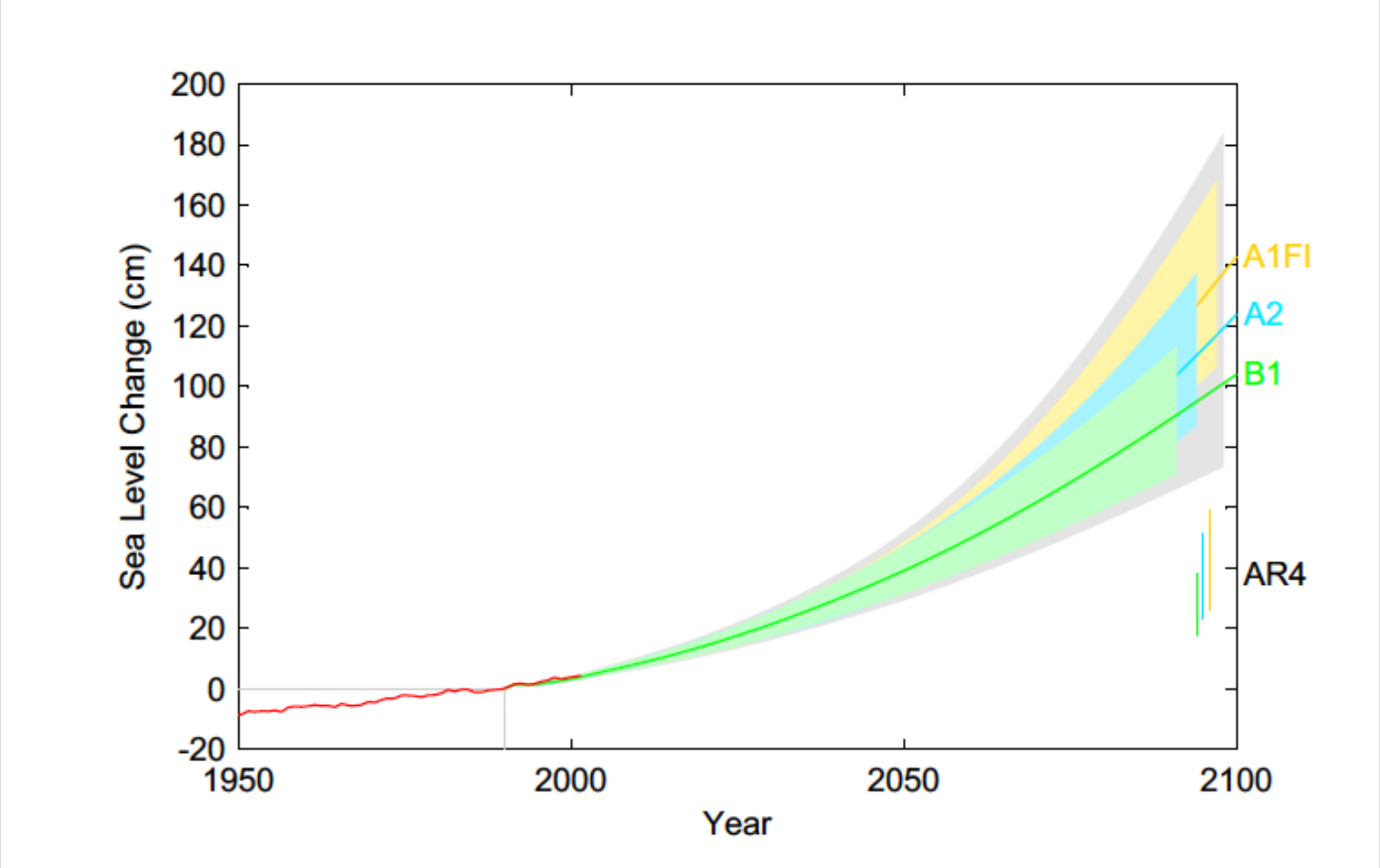
National Research Council, 2012

Extrapolation assumes statistical stationarity: whatever is driving accelerated mass loss today *continues* into the future



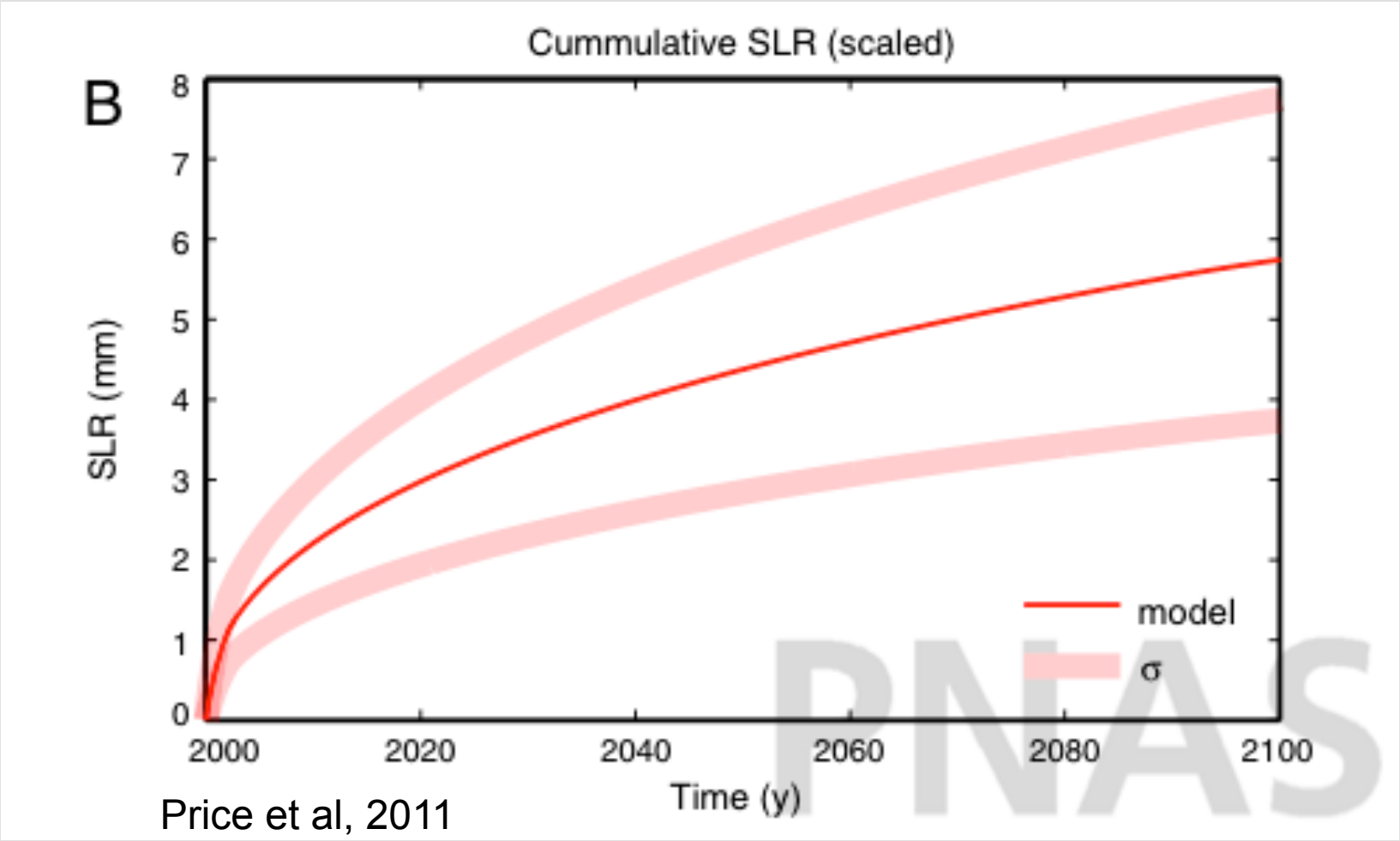
National Research Council, 2012

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



Vermeer and Rahmsdorf, 2009

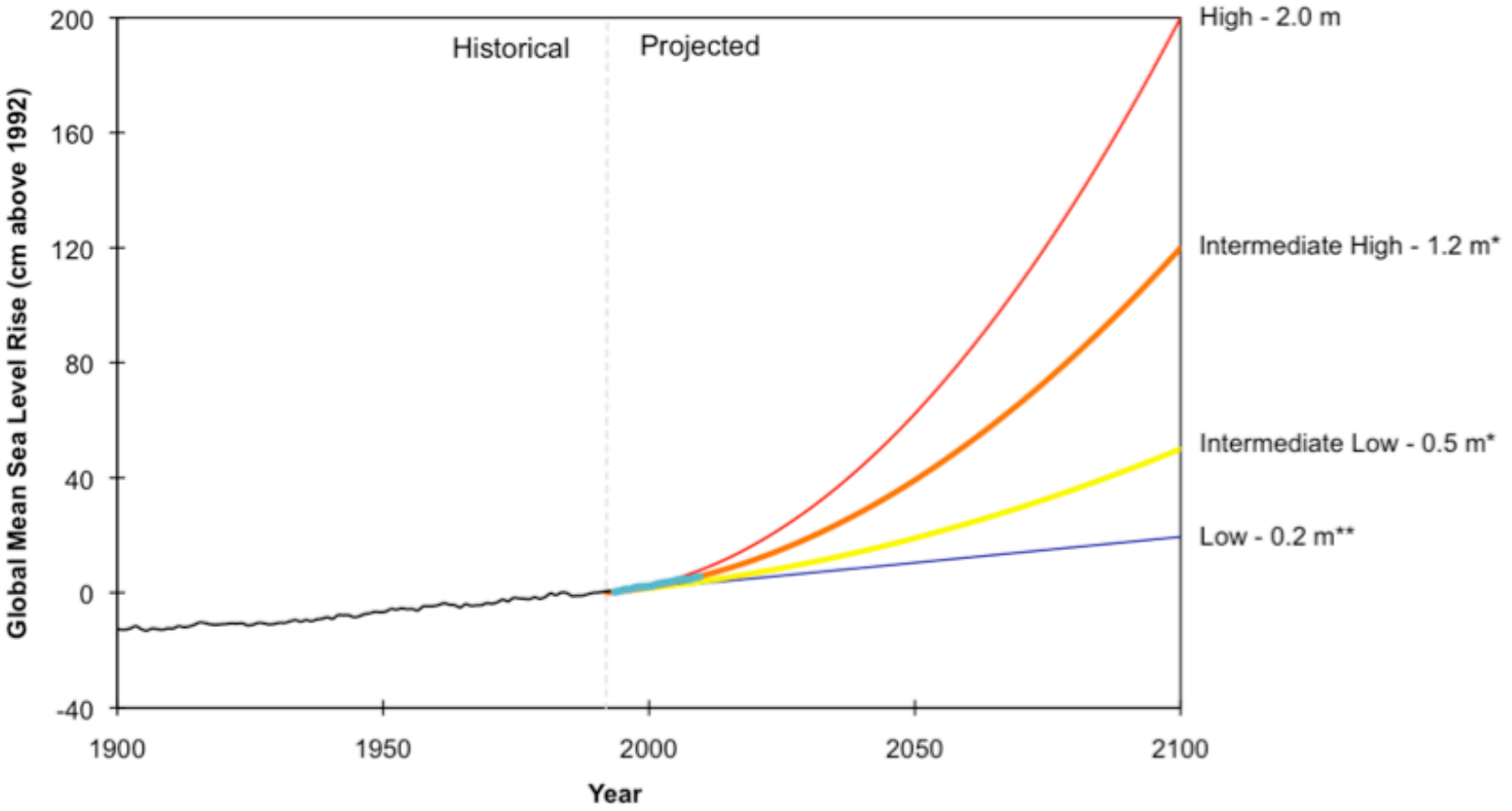
Projected total sea level rise, undifferentiated sources, observation record of sea level rise scaled to observational record of temperature and projected into future using modeled temperature



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 km^2)
- 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.

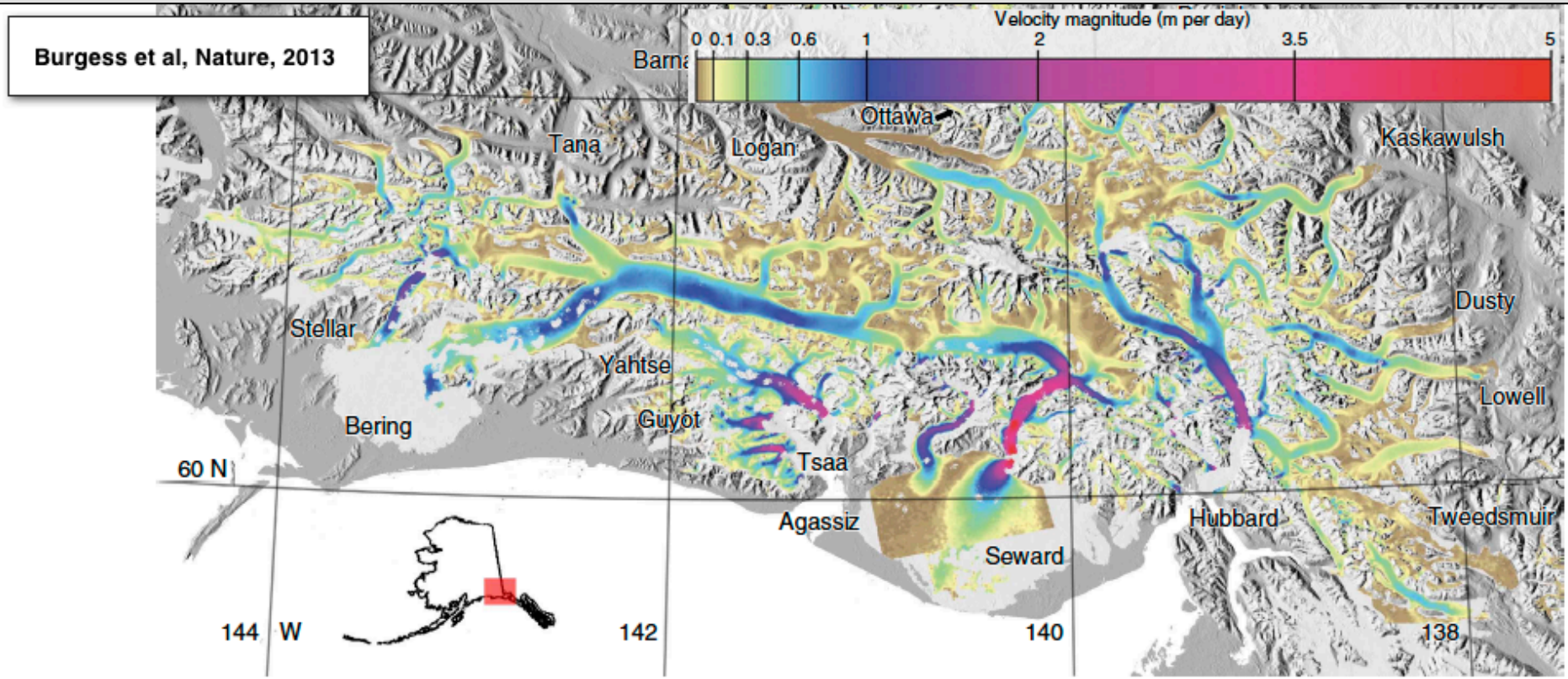


Figure 1 | Surface velocity map of the Wrangell and St Elias Ranges. Light grey glacier outlines[47] indicate missing data.

Alternative strategies could include:

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

with quantified uncertainty (target tolerance),

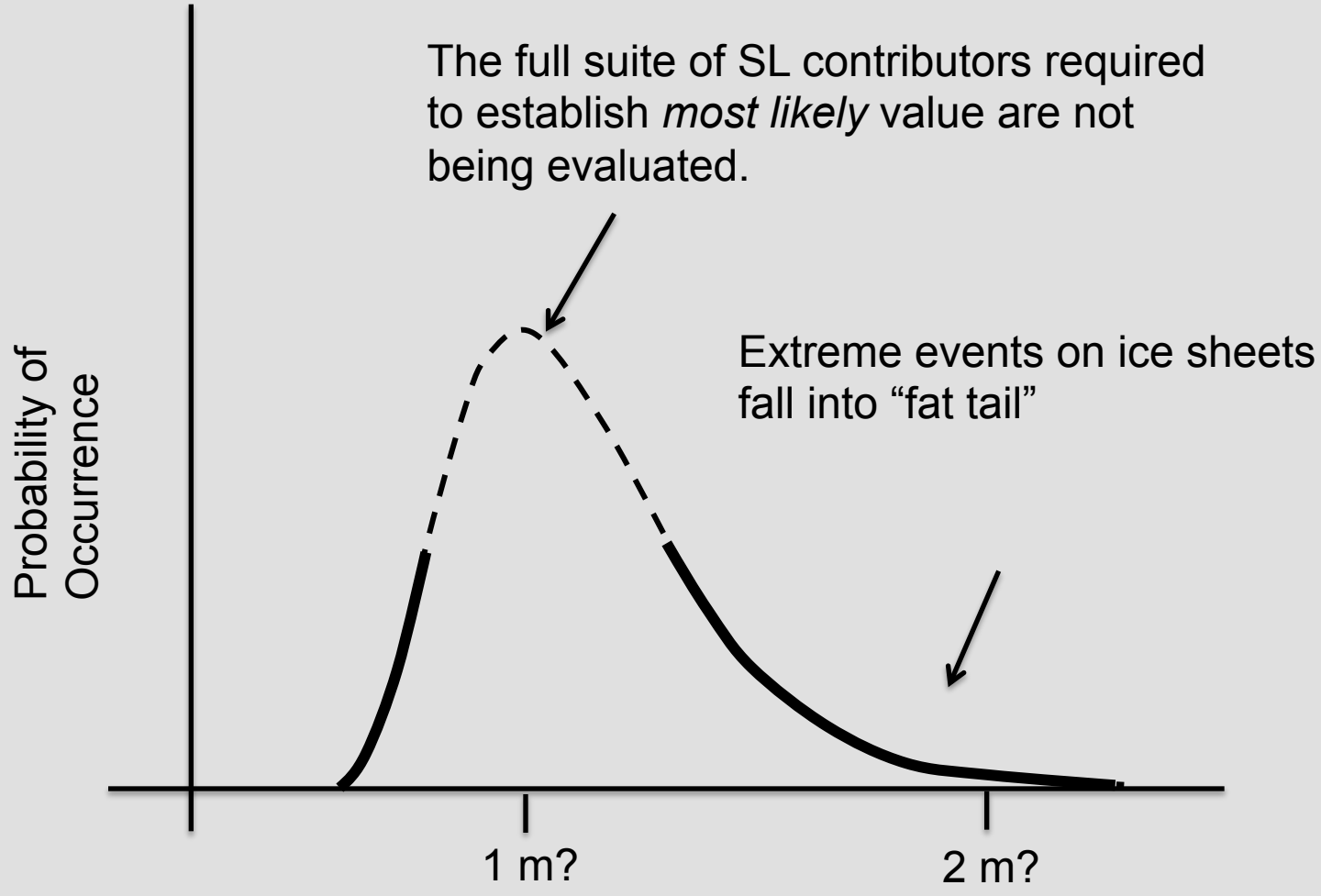
for specific dates in the future (e.g. 2030, 2050, 2100),

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.

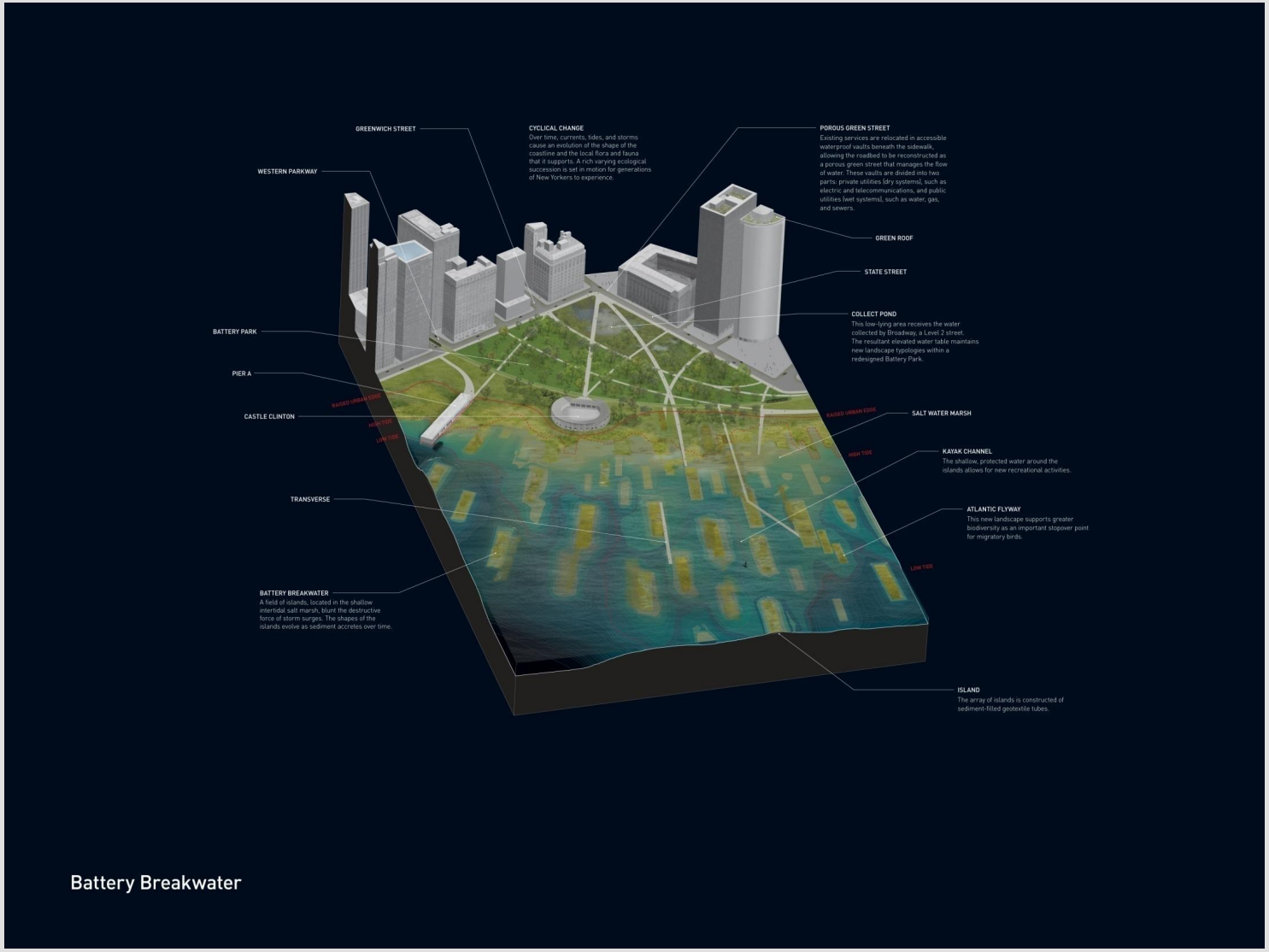


This weakness is *more* pronounced at *nearer* forecast target dates

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



from A New Urban Ground, Cassell and Yarinsky,Architectural Research Office, 2010

Time scales matter:

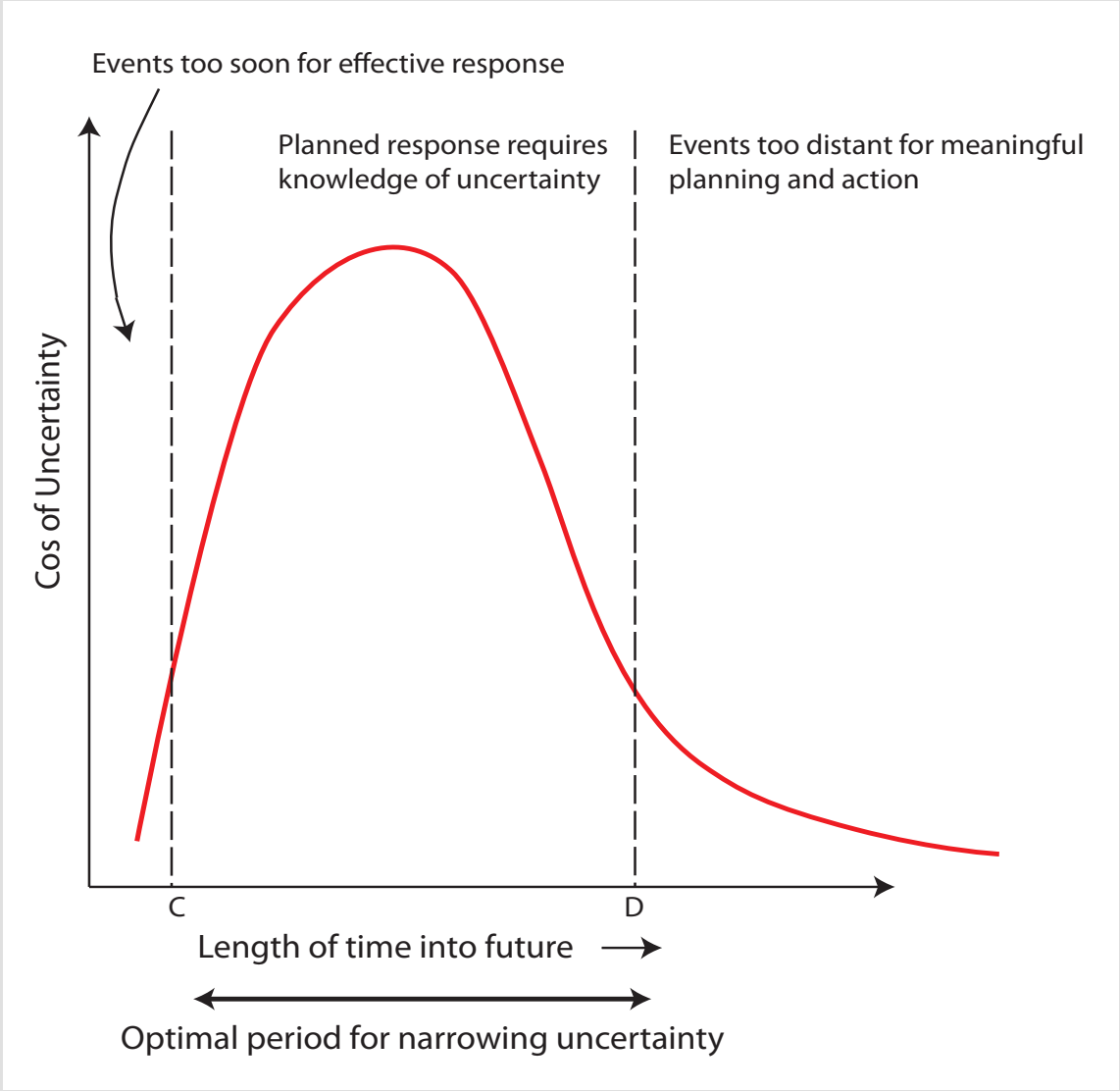
Long scales (100 yrs +) important for major long-term infrastructure replacement

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

Average or interval of life expectancy	Estonia	Sweden	Austria	France	Germany	Spain	The Netherlands
Buildings	8-50	10-35	25	50	10-50	50	
Civil engineering works			20	70	75-75	75	
Superstructure	8-50	40	25	30-50	20-25	18-40	33[38]
New construction in progress	N/a	N/a	N/a	N/a	N/a	N/a	N/a
Transmission lines	8-50	10-35	15	20			33
Signalling equipment					20-20		11
Telecommunications equipment		5-20	4	15	5-20		
Safety installations			4	15			25
Vehicles / rolling stock	3-15		5	5	15-30	10-30	
Plant and machinery	3-15	3-25	9				
Office, computer and other equipment, tools	3-5	3-25	4	3-7	2-20	5-40	

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).

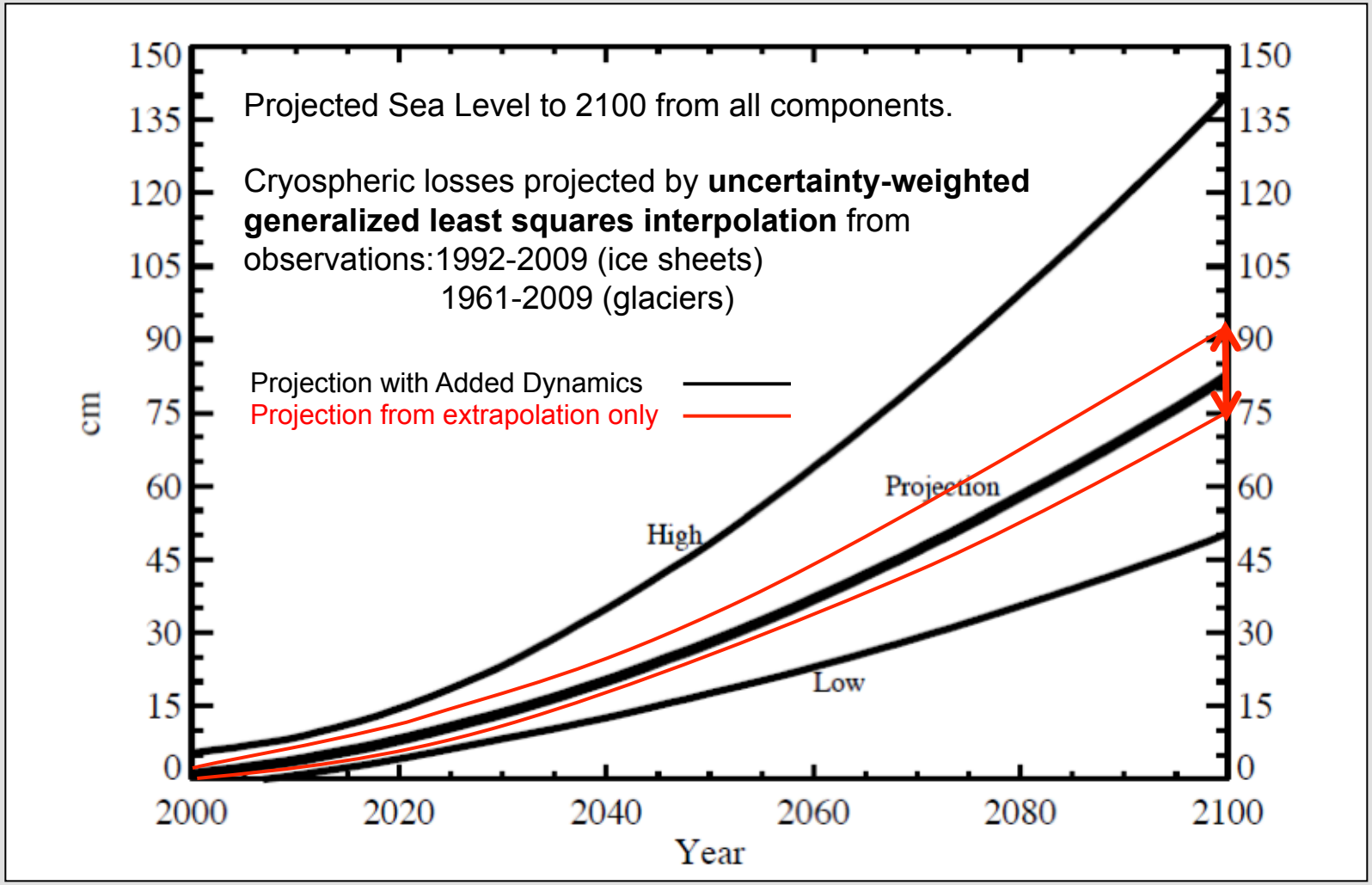
Long-term determinations not useful in the absence of medium-short term determinations

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.

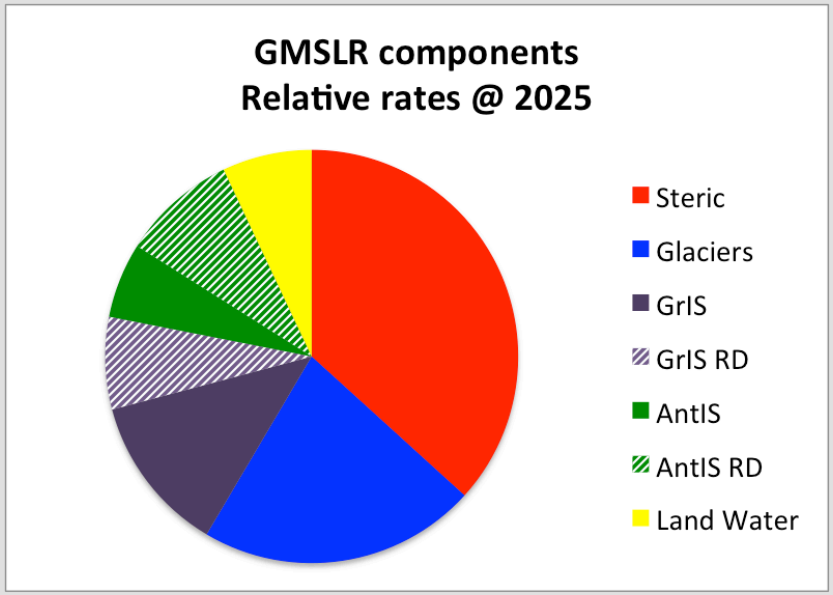


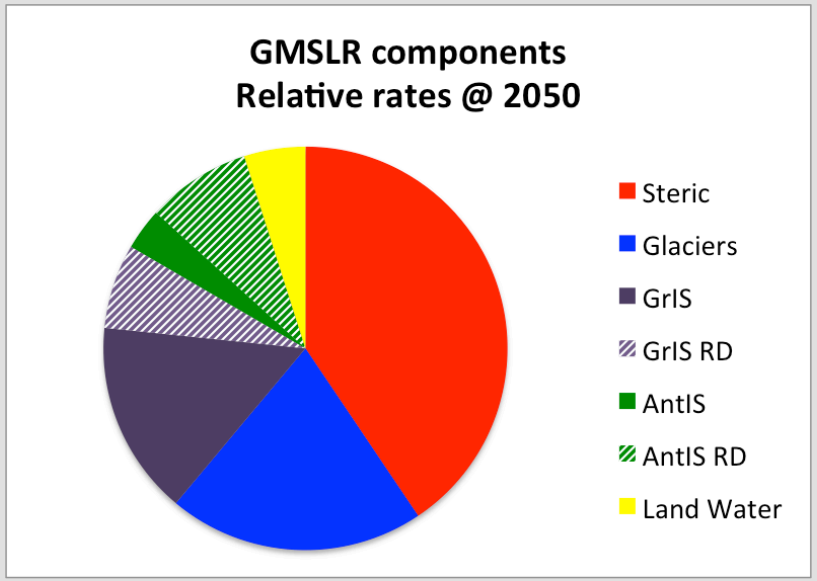
National Research Council, 2012

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

Modeling improvements/alternatives:

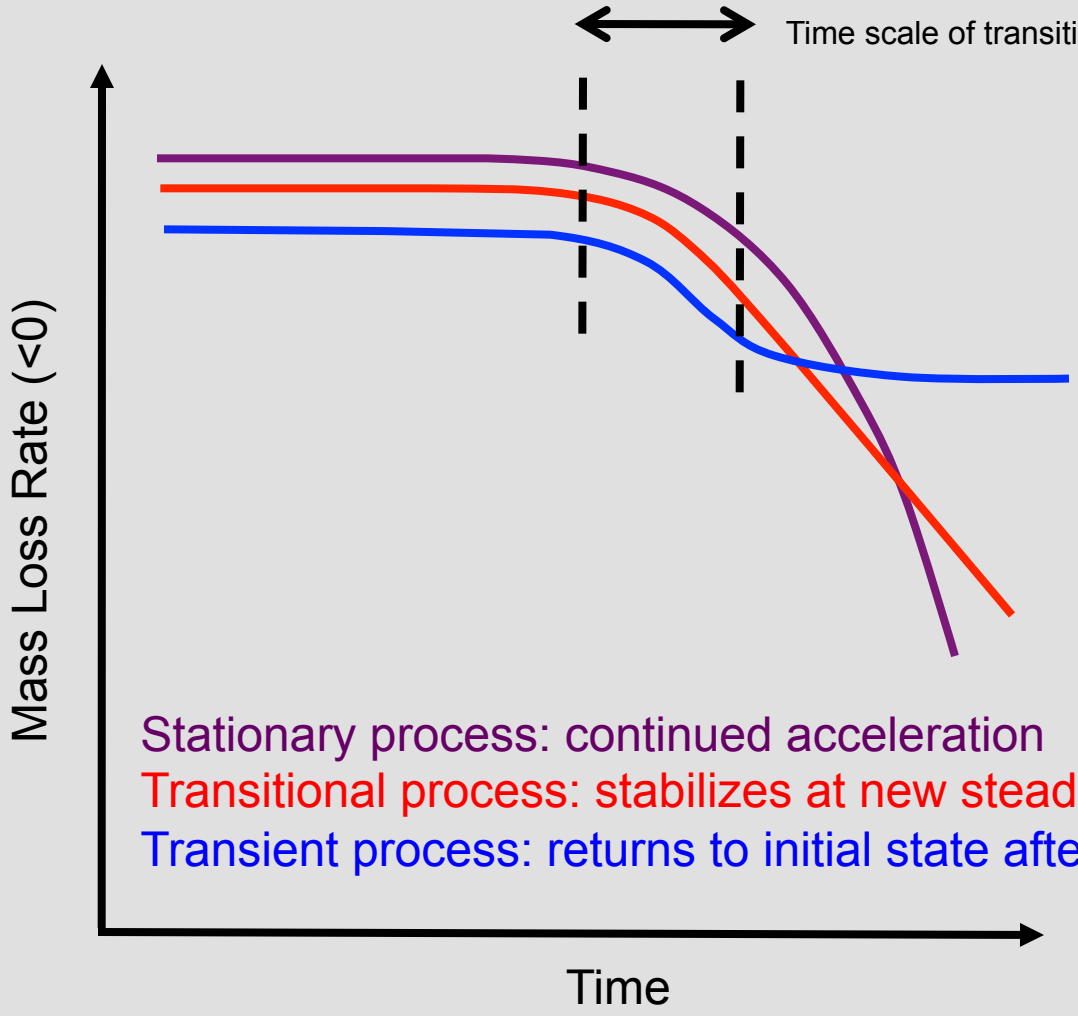
1. Model all sources, not just the biggest ones.





Uncertainty for glacier and ice sheet projections are approximately equal

Pursue parallel modeling tracks. Embrace non-deterministic modeling and hybrid models



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

Price et al (PNAS) have started this.

Stationary process: continued acceleration

Transitional process: stabilizes at new steady state

Transient process: returns to initial state after period of fast change

Pursue parallel modeling tracks. Embrace non-deterministic modeling and hybrid models

Extend Semi-empirical strategy to hybrid models:

Something new

Observed/Modeled time constants for outlet glacier response → Semi-empirical outlet glacier *component* → Initiation and duration of RD by basin

Experimental determination of A & n → Glenn's Flow Law $\dot{\varepsilon} = A\sigma_e^{n-1}\ \sigma_{ij}$ → Calculated Strain Rate

Sea Level forecasting can be substantially improved simply by thinking carefully about **goals** and communicating them.

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.

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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

were estimated using some simple approximations, and the need for improvements in basic knowledge of glacier dynamics, glacier-ocean interactions, and computer models to simulate them stood out as paramount goals for future investigation.

The assessment authors were very clear about the limitations of the sea-level projections, as well as what they

ago in the study of the hydrology and dynamics of mountain glaciers. Much of

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W.T. Pfeffer

Stagnant landlobe terminus, Columbia Glacier, 2006

W.T. Pfeffer