Scaling Techniques for Simultaneously Modeling 300,000+ Glaciers and Ice Caps

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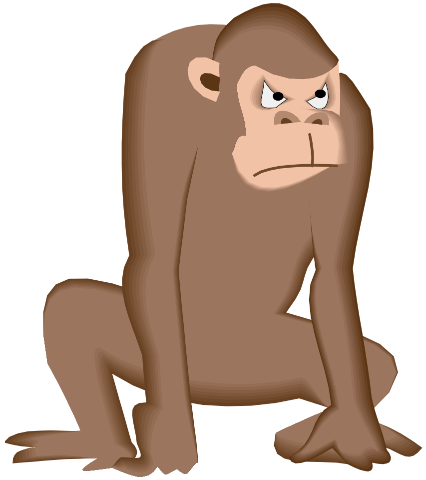
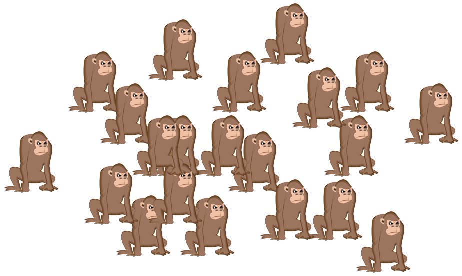
Why Bother Including GIC?

- 300,000 to 400,000 glaciers and ice caps (GIC) *all* melting.



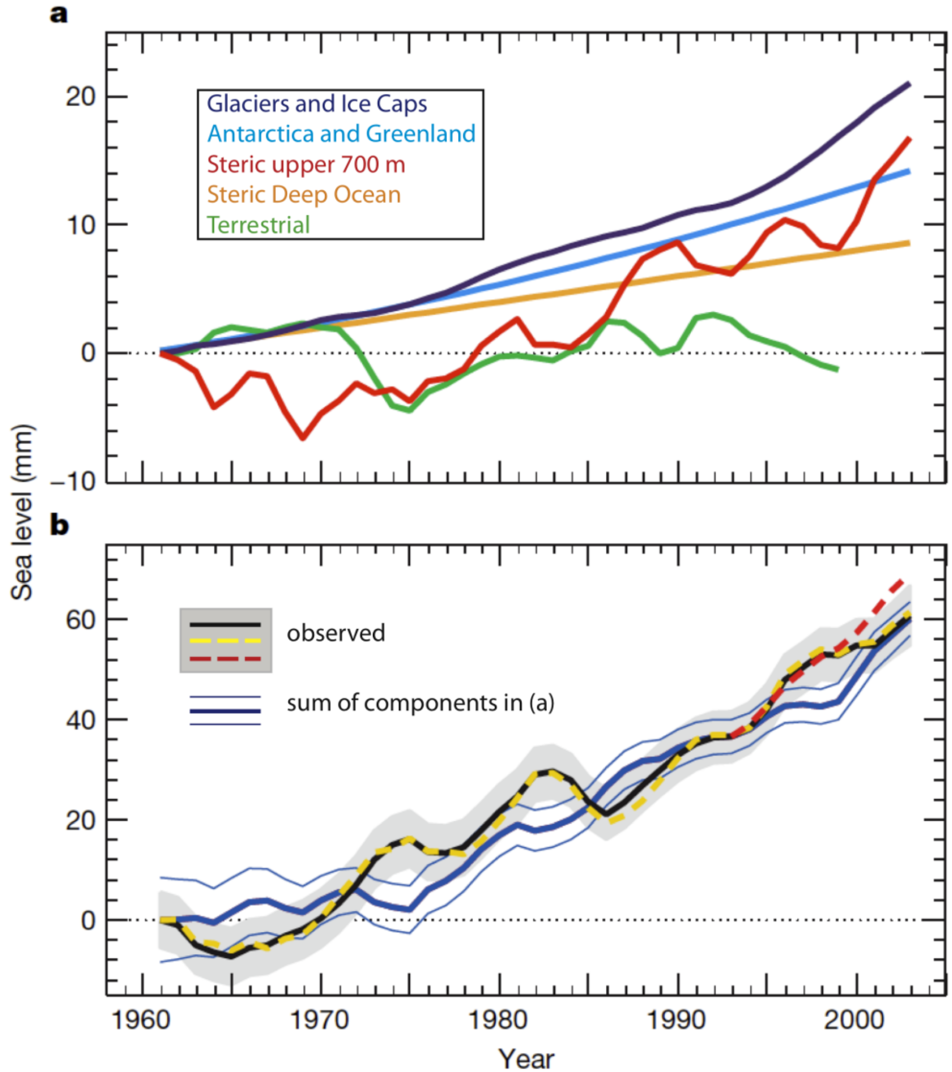
Greenland and Antarctica = “300,000 pound” gorillas



GIC = 300,000 individual “1 pound” gorillas. They add up!

GIC Big Contributors Today

from Domingues et al, Nature 2008



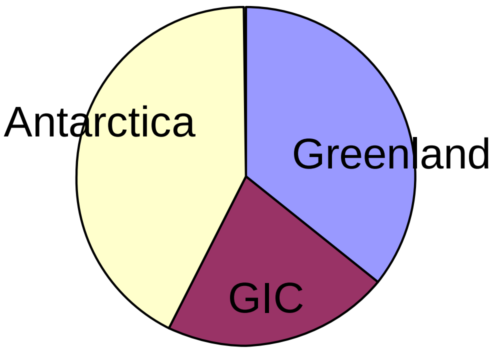
Glaciers and ice caps (GIC) are leading term in today's sea-level rise (SLR).

GIC Big Contributors in Future

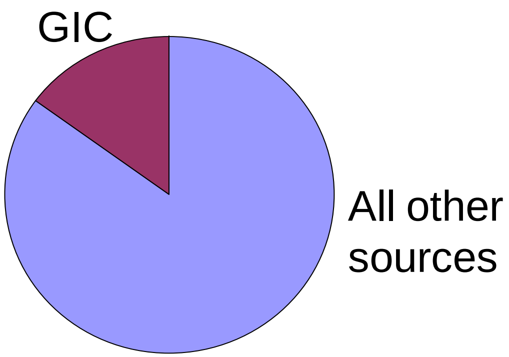
Glaciers and Ice Caps (GIC) will continue to be major contributors to sea level.

- 2.0m is highest plausible total from *all* sources over next 100 years (*Pfeffer et al, Science 2008*).
  - 0.54m Greenland
  - 0.62m Antarctica
  - 0.3m GIC

- Predicted GIC contribution over next 100 years
  - 0.4m SLE (Bahr et al, *GRL*, 2009)
  - 0.6m SLE (Radic and Hock, in press)
  - 0.15 to 0.37m (Church et al, *Sustain. Sci*, 2008)

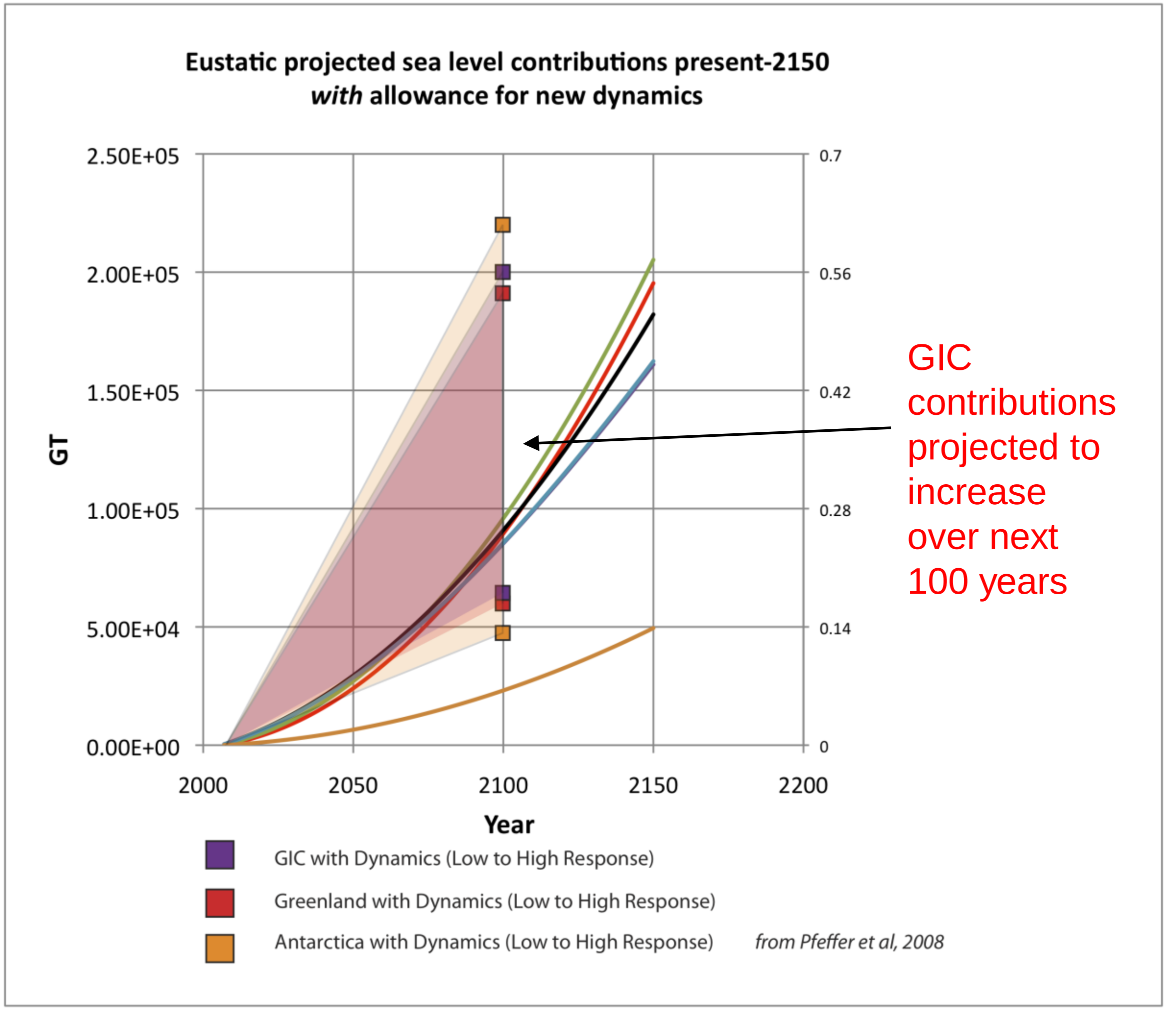


Approx. SLR contributions from ice over next 100 years



Approx. contributions to total SLR over next 100 years

GIC Have Staying Power



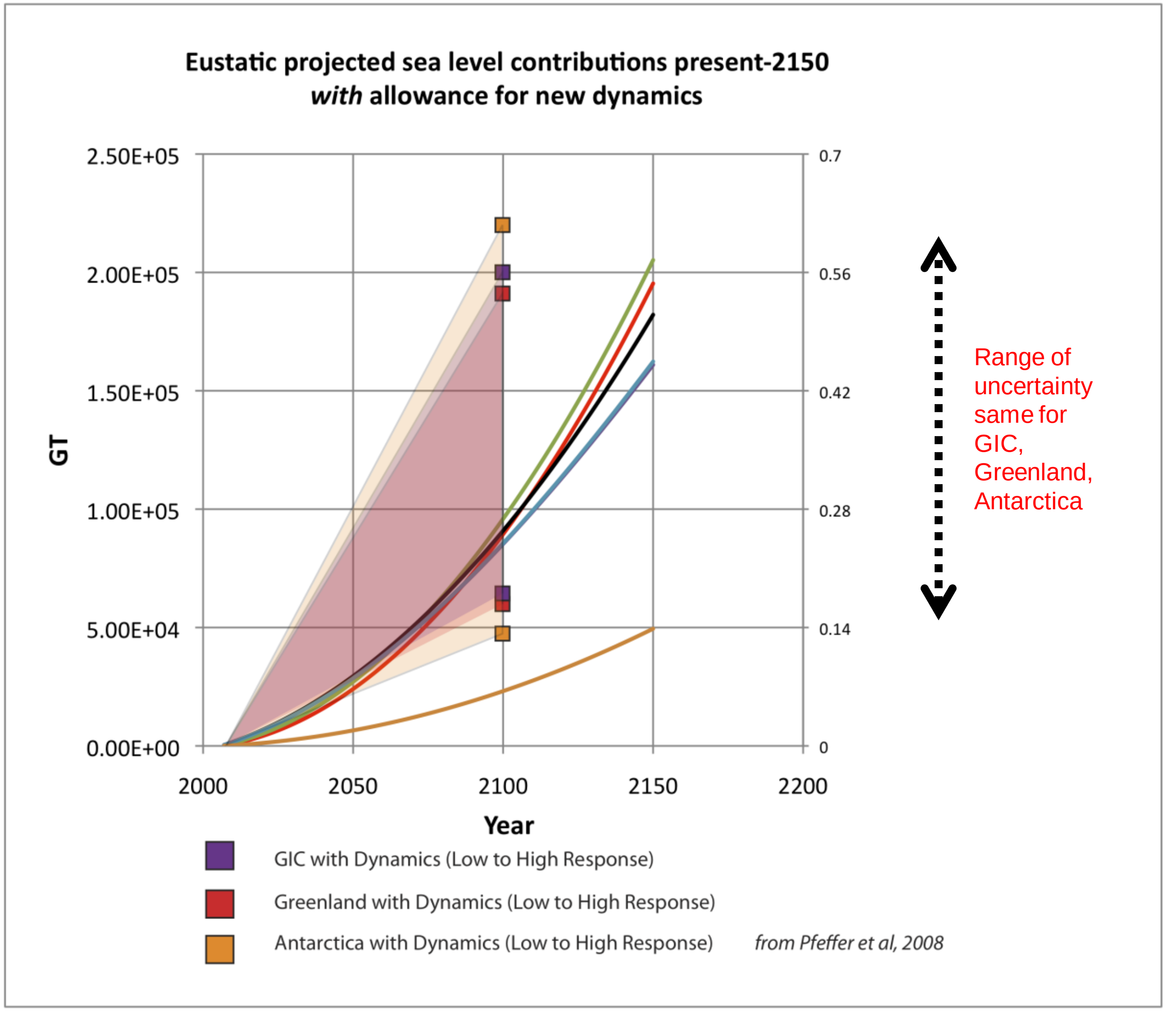
Contributions will not diminish rapidly.

Will last 550 years if GIC continue to melt at present rate (1.1mm/a).

GIC volume depleted only 6% over next 100 years at present day *acceleration* rate.

Yes, will lose smallest GIC soon, but glaciers come in all sizes. Will have big glaciers for many years.

Really Need a Handle on GIC Uncertainties



Over next 100 years GIC uncertainties comparable to ice sheet uncertainties.

Need SLR forecasts with meaningful uncertainties, so must include GIC.

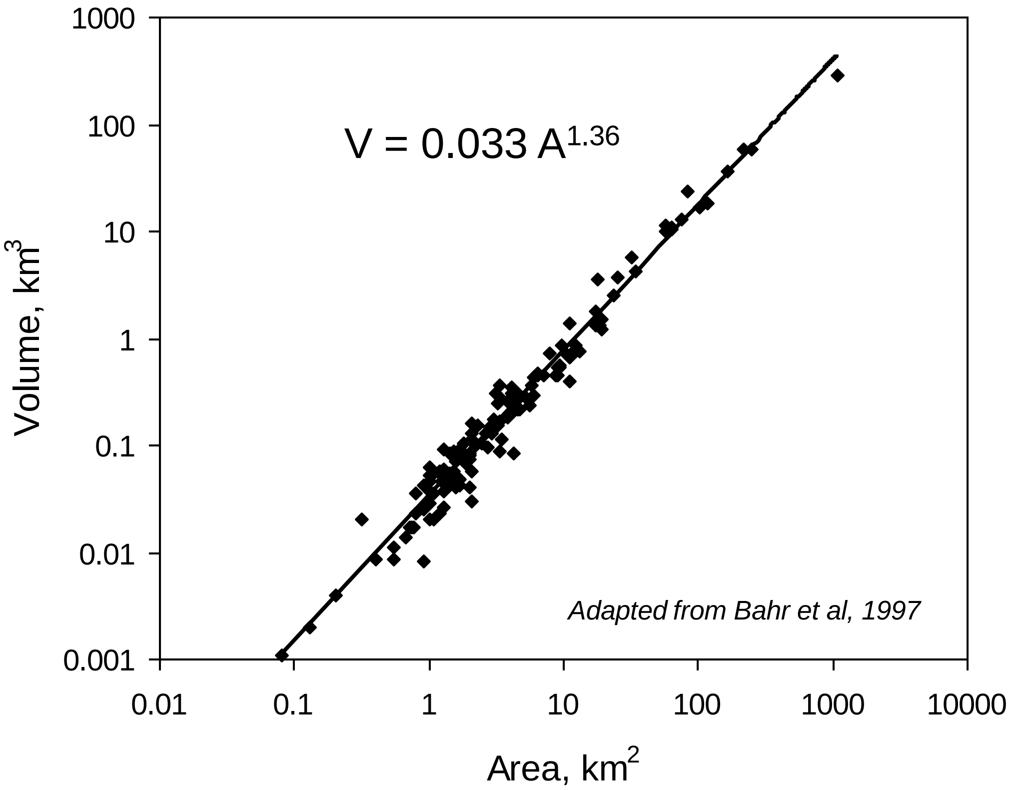
Yes, over next 1000 years, ice sheet uncertainties are larger, but 100 years is relevant to policy makers, engineers, planners, etc.

So How Model GIC?

- Goal:
  - Estimate GIC melt water contributions to SLR as a function of time.
- Challenge:
  - 300,000 to 400,000 glaciers.
  - Can’t model dynamics for each.
- Solution:
  - Collapse dynamics with scaling laws.
    - Only need GIC volume changes to estimate SLR.
    - CESM can give surface mass balance and Δarea.
    - Then use scaling relationships which give Δvolume = f(Δarea).

Volume-Area Scaling

$$V = c\,A^{1.375}$$



Collapse complex glacier dynamics to scaling relationship between volume and area.

Derived mathematically from dynamics.

Derivations and modeling show scaling is valid in both steady state *and* non-steady state. i.e., scaling is valid in past, present, and future.

Empirically established from data.

Bahr et al, 1997

Also Need Response-Time Scaling

Response-time scaling: $T = k A^{\beta}$

Relaxes exponentially towards new state with characteristic time T.

South Cascade Glacier, WA

Small area, fast response to climate changes

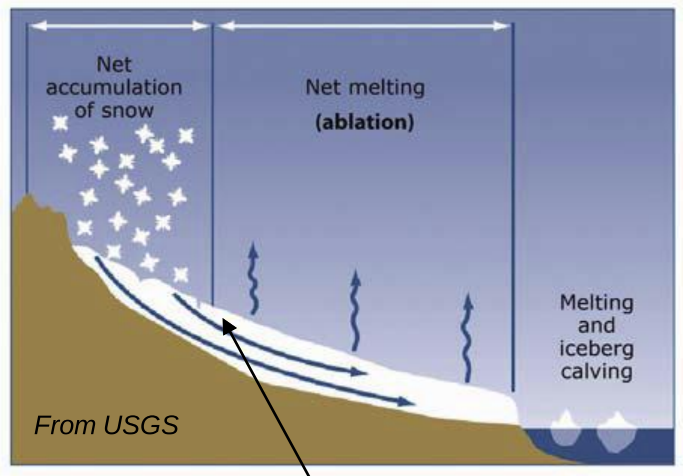
Columbia Glacier, AK (Photo: James Balog)

Large area, slow response to climate changes

Bahr et al, 1998; Pfeffer et al, 1998

Also Need AAR Scaling

Accumulation Area Ratio (AAR) – fraction of glacier that is accumulating mass



Equilibrium line altitude, ELA, where balance = 0.

Glaciers in equilibrium have $AAR_{eq} = 0.57$.

Glaciers with net mass loss have $AAR < AAR_{eq}$.

AAR-Volume scaling: $1+\Delta V/V = (1+AAR/AAR_{eq})^{1.375}$

A change in surface mass balance will change the AAR.

This will result in a change in volume.

Bahr et al, 2009

Finally, Need Hypsometry

Aletsch Glacier, Switzerland

- Average shape of a glacier
  - Long.
  - Nearly linear.
    - More data/analysis forthcoming.
  - Constant width.
    - Width given by (what else), $W = c_w A^\alpha$

Vatnajokull Ice Cap, Iceland

- Average shape of an ice cap
  - Round.

Bahr, 1997

Putting it all in CESM

- Place all GIC in CESM (at their correct elevations and locations).
- Run model forward one time step.

- *For each glacier:*

1. Use CESM to estimate change in surface mass balance Δb (for each glacier).
2. Δb gives ΔV.
3. ΔV gives ΔA (volume-area scaling).
4. ΔV gives new AAR (AAR scaling).
5. AAR combined with canonical hypsometry gives the new ELA.
6. Adjust position of newly-sized glacier so its new ELA matches model's predicted ELA (zero surface balance).
7. But wait, don't adjust all the way – glaciers take time to respond.
   - Relax exponentially toward final glacier area with characteristic time T (response time scaling).
   - $A(t) = (A_0 - A_{final})\, e^{-t/T} + A_{final}$

- Run model another time step and repeat.

Nagging Problem

- This deterministic approach requires knowledge of every glacier’s position.
    - We don’t have that yet (funding please :-).
    - Major pain in the keister to place each of 300,000 to 400,000 glaciers in the model.
    - Computationally expensive to loop over all glaciers.
    - Have to keep track of 400,000 glaciers in the model.

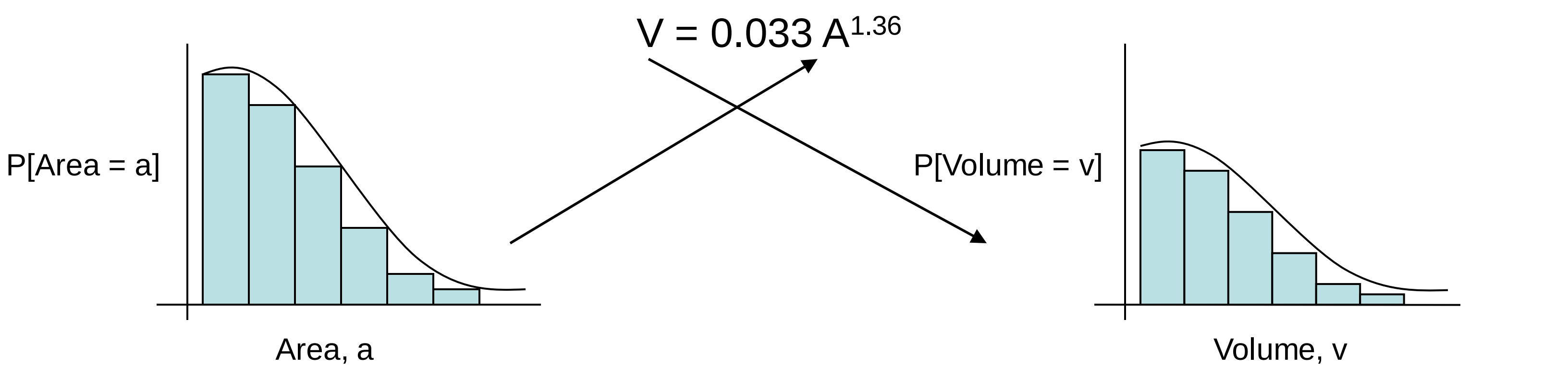
Stochastic Solution

- Forget about placing each glacier in its precise location.
- Instead select a region of the world (Alps, AK, Himalaya, etc.).
- Deal with all of the glaciers in that region simultaneously.
- How? Bin the glaciers to build a distribution of sizes.

Track Changes in Distributions

(essence of statistical physics)

Visually, we take the original distribution and scale it to a new distribution.

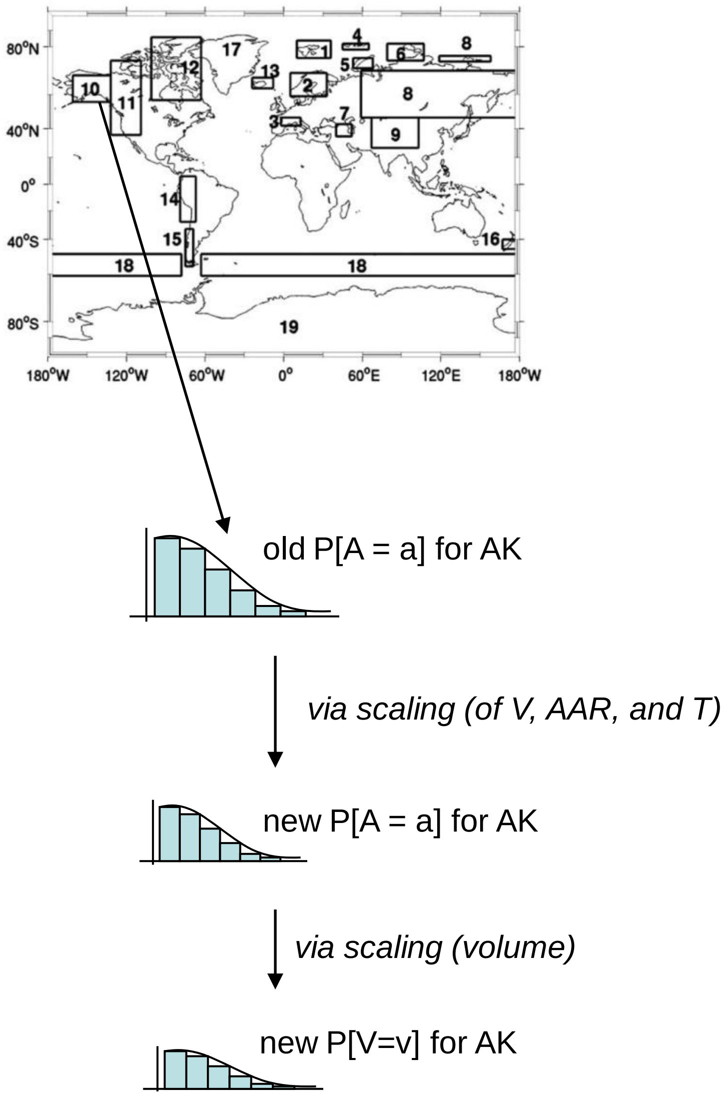


Binned areas – the probability distribution or PDF

Binned volumes – the probability distribution or PDF

Now use *all* of volume, AAR, and response-time scaling to get distributions for *changes* in volume and SLR.

Stochastic Details



Select a region of the world (Alps, AK, Himalaya, etc.).

Find distribution of glacier sizes for that region.

Run model one step and apply scaling to get new distribution of sizes.

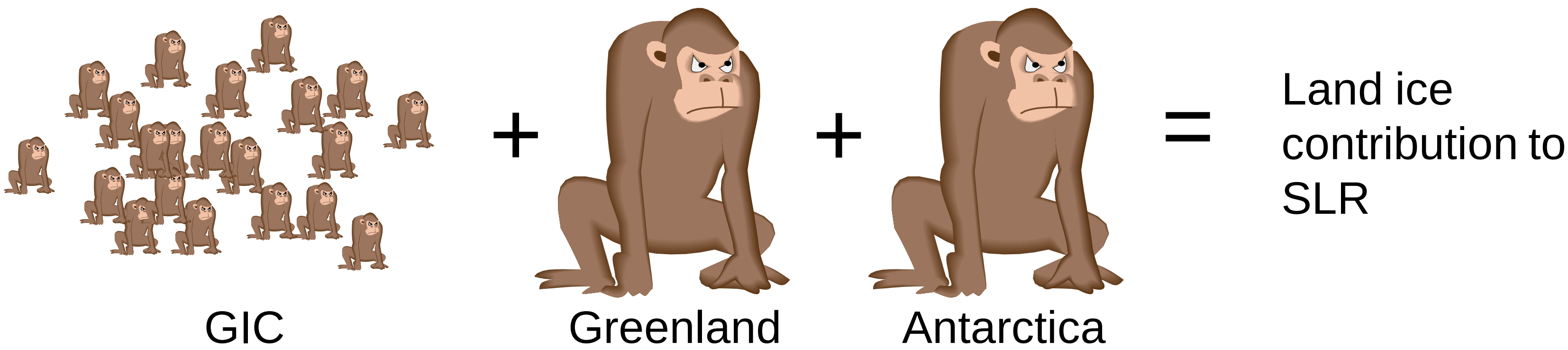
Apply scaling to get new volume distribution. Compare to old volume distribution to calculate sea level change.

Repeat.

Stochastic Advantages

- Don’t need to know each glacier’s precise locations.
  - Just need distribution of sizes.
  - Theoretical considerations can fill in a distribution when incomplete. (*Bahr and Meier, 2000*)
  - Model only stores the distribution rather than zillions of individual glaciers.
- All calculations are analytical.
  - CESM supplies surface balance.
  - Everything else is just functional transformations.
  - Computationally efficient.
- Disadvantages?
  - Assumes an ELA for a region. (Could be generalized with care.)
  - And teensy-eensy bit more complicated ☺

Summary



- Essential to model GIC component of SLR.
    - Need to quantify contribution and timing.
    - Need to estimate uncertainties.

- Scaling provides a means of tracking 400,000 glaciers simultaneously.
    - Deterministic approach simpler but complex to model.
    - Stochastic approach complex but simpler to model.