Model Projection Strategies for Glaciers and Ice Caps and Complete Assessment of Sea Level Rise

Columbia Glacier, 2004 W.T. Pfeffer

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15 February 2012

with thanks to
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Christina Hulbe and Scott Waibel, Portland State University, Portland, Oregon, USA

Previous Evaluation of Glacier Loss Rates

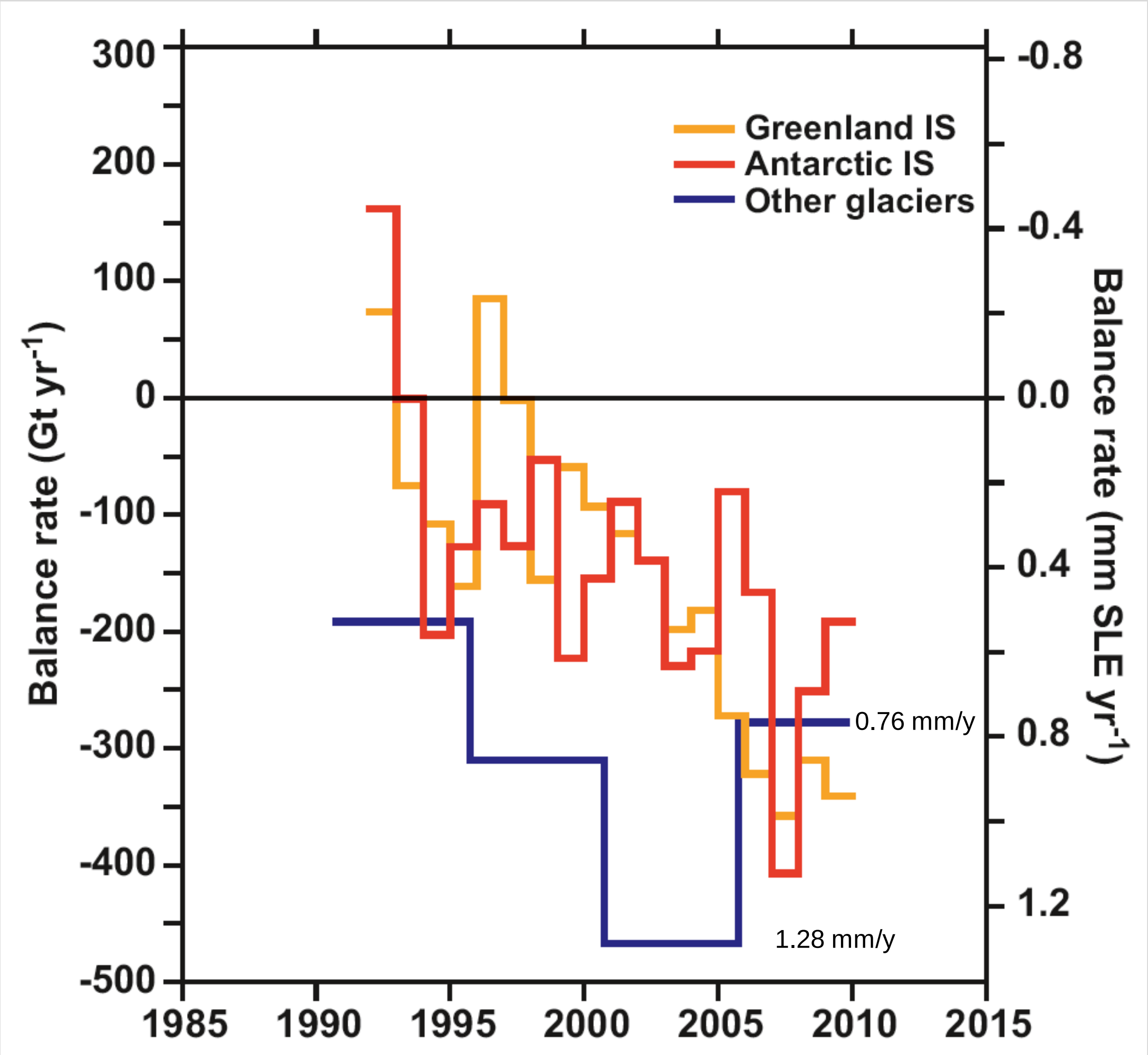
Cazenave and Llovel, 2010

Table 1 Sea level budget for two time spans (1993–2007, 2003–2007)*

Sea level rise (mm $year^{-1}$)	1993–2007	2003–2007
Observed	3.3 ± 0.4	2.5 ± 0.4 (Ablain et al. 2009)
Thermal expansion	1.0 ± 0.3 (mean of Levitus et al. 2009 and Ishii & Kimoto 2009 values)	0.25 ± 0.8 (Argo) (mean of Willis et al. 2008, Cazenave et al. 2009, and Leuliette & Miller 2009 values)
Ocean mass	2.3 ± 0.5 (observed rate minus thermal expansion)	2.1 ± 0.1 (GRACE with a −2 mm $year^{-1}$ GIA correction, Cazenave et al. 2009)
Glaciers	1.1 ± 0.25 (based on Kaser et al. 2006 and Meier et al. 2007)	1.4 ± 0.25 (Cogley 2009)
Total ice sheets (Greenland & Antarctic)	0.7 ± 0.2 0.4 ± 0.15 0.3 ± 0.15 (compilation of published results)	1.0 ± 0.2 0.5 ± 0.15 0.5 ± 0.15 (compilation of published results)
Land waters	—	−0.2 ± 0.1 (W. Llovel, K. DoMinh, A. Cazenave, J.F. Cretaux, M. Becker, unpublished manuscript)
Sum of (2 + 4 + 5 + 6)	2.85 ± 0.35	2.45 ± 0.85
Observed rate minus sum	0.45	−0.05

* Quoted errors are one standard deviation. The observed sea level rate is GIA corrected (−0.3 mm $year^{-1}$ removed).

Current Evaluation of Glacier Loss Rates



Cogley, 2012

Current Evaluation of Glacier Loss Rates

Table 1 | Inverted 2003–2010 mass balance rates

Region	Rate (Gt yr^{-1})
1. Iceland	−11 ± 2
2. Svalbard	−3 ± 2
3. Franz Josef Land	0 ± 2
4. Novaya Zemlya	−4 ± 2
5. Severnaya Zemlya	−1 ± 2
6. Siberia and Kamchatka	2 ± 10
7. Altai	3 ± 6
8. High Mountain Asia	−4 ± 20
8a. Tianshan	−5 ± 6
8b. Pamirs and Kunlun Shan	−1 ± 5
8c. Himalaya and Karakoram	−5 ± 6
8d. Tibet and Qilian Shan	7 ± 7
9. Caucasus	1 ± 3
10. Alps	−2 ± 3
11. Scandinavia	3 ± 5
12. Alaska	−46 ± 7
13. Northwest America excl. Alaska	5 ± 8
14. Baffin Island	−33 ± 5
15. Ellesmere, Axel Heiberg and Devon Islands	−34 ± 6
16. South America excl. Patagonia	−6 ± 12
17. Patagonia	−23 ± 9
18. New Zealand	2 ± 3
19. Greenland ice sheet + PGICs	−222 ± 9
20. Antarctica ice sheet + PGICs	−165 ± 72
Total	−536 ± 93
GICs excl. Greenland and Antarctica PGICs	−148 ± 30
Antarctica + Greenland ice sheet and PGICs	−384 ± 71
Total contribution to SLR	1.48 ± 0.26 mm yr^{-1}
SLR due to GICs excl. Greenland and Antarctica PGICs	0.41 ± 0.08 mm yr^{-1}
SLR due to Antarctica + Greenland ice sheet and PGICs	1.06 ± 0.19 mm yr^{-1}

Uncertainties are given at the 95% (2σ) confidence level.

Jacob et al, 2012

As reported:
Glaciers – PGIC: 148 GT/yr = 28%
Greenland IS + PGIC: 222 GT/yr = 41%
Antarctic IS + PGIC: 165 GT/yr = 31%

Using estimated fraction of ice sheet
Signal coming from peripheral glaciers
and ice caps around the ice sheets (PGIC)
Glaciers + PGIC: 229 GT/yr = 43%
Greenland IS - PGIC: 192 GT/yr = 36%
Antarctic IS - PGIC: 111 GT/yr = 21%

Current Evaluation of Glacier Loss Rates

Jacob et al, 2012

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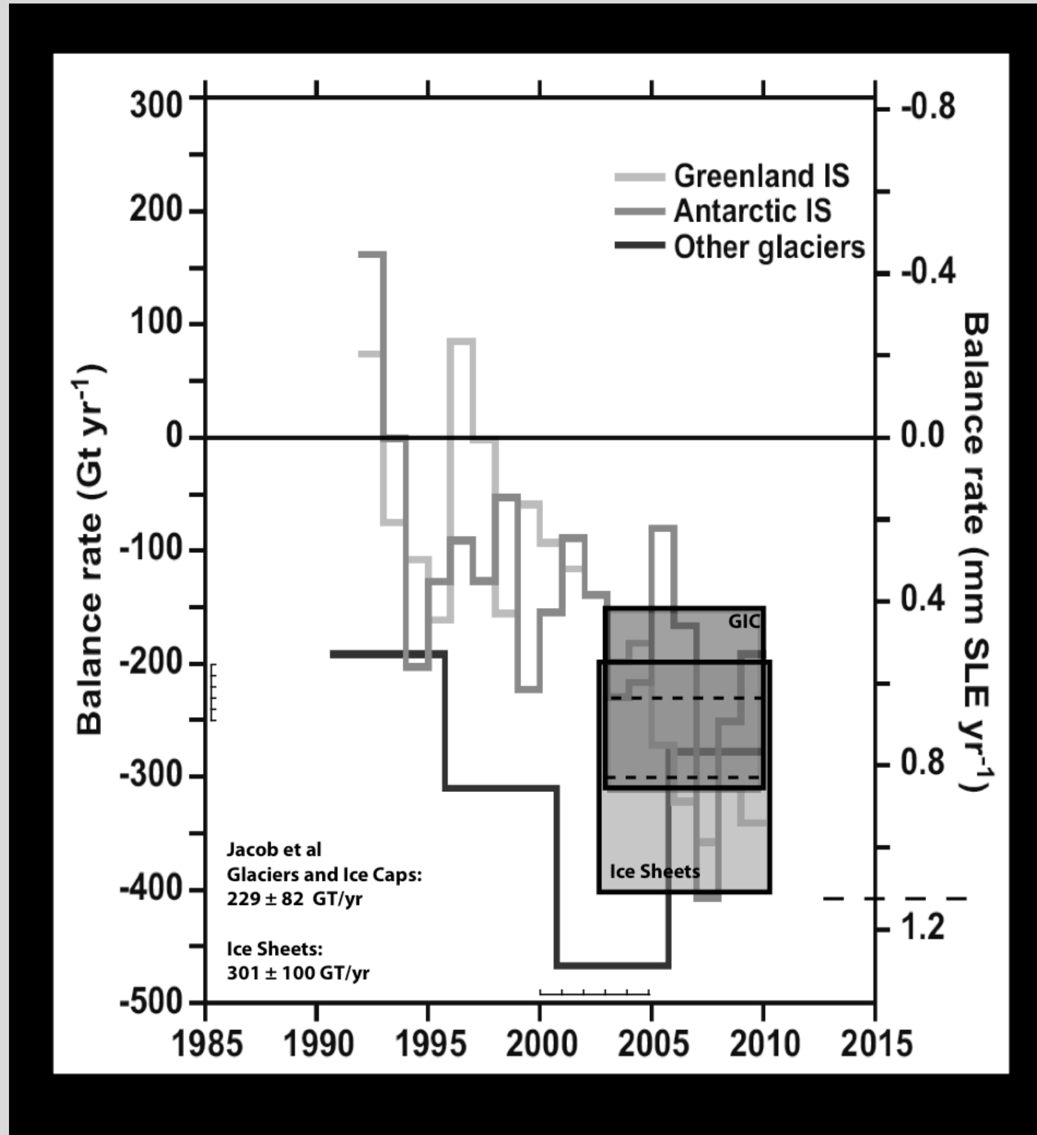
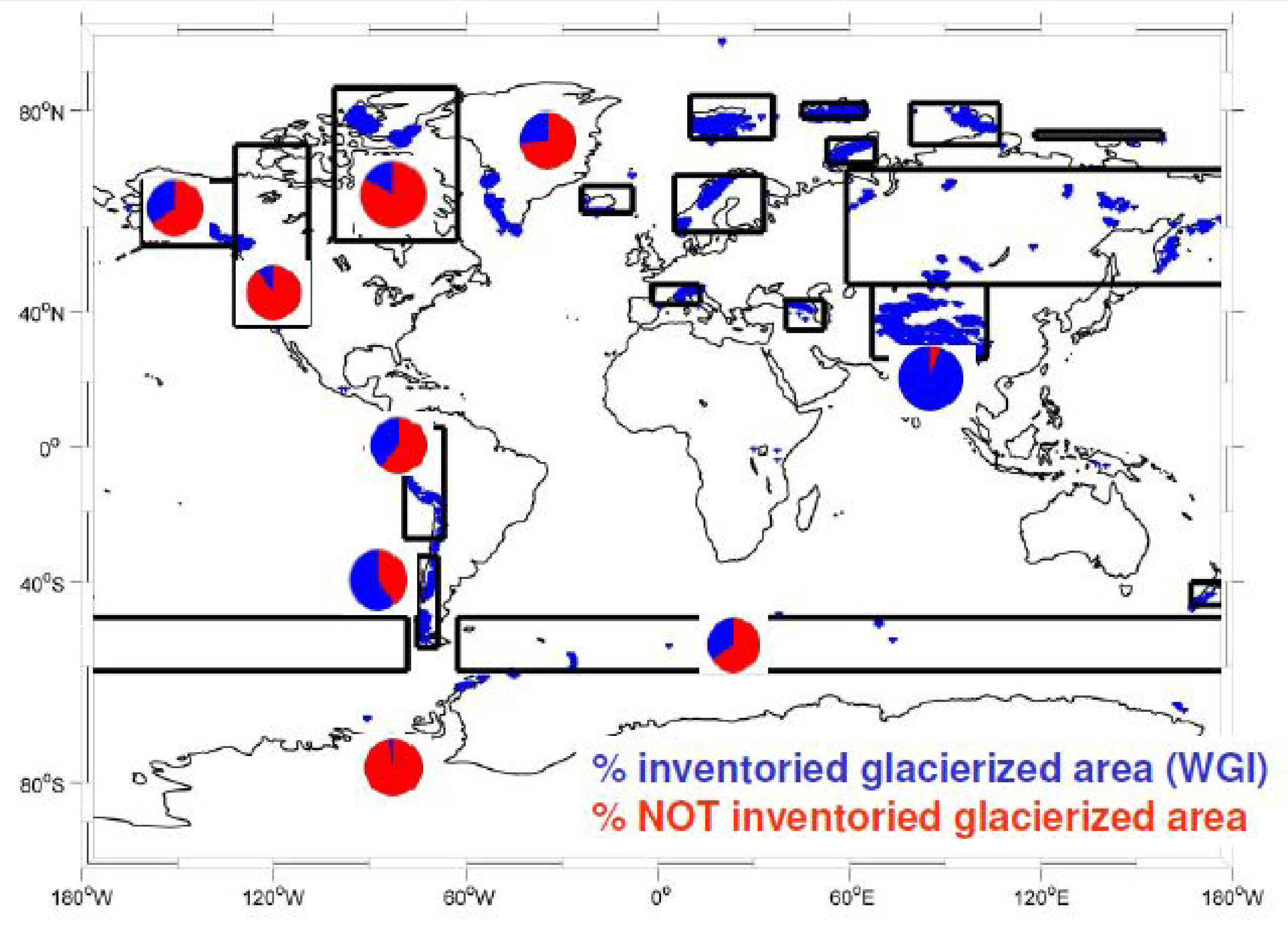


OLD Inventory as of 2010: Regions included/not included in WGI.
Image courtesy V. Radic



Data compilation: G. Cogley

Randolph Glacier Inventory

http://glims.org:8080/RGI/randolph.html

GLIMS

Randolph Glacier Inventory 1.0

- Home
- More About GLIMS
- Data Access
- Documentation / RC Resources
- Publications and Presentations
- Workshops and Meetings
- Mailing List
- Software (GLIMSView)
- Contact

Dataset Description

The Randolph Glacier Inventory (RGI 1.0) is a global inventory of glacier outlines. It is supplemental to the Global Land Ice Measurements from Space initiative (GLIMS). Production of the RGI was motivated by the forthcoming Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) and is being released initially with little documentation in view of the IPCC's tight deadlines during 2012. Updates beyond the IPCC 2012 deadlines will take the form of additions to the GLIMS Glacier Database. As resources allow, all these data will be incorporated into the GLIMS Glacier Database.

For more details, please see the RGI 1.0 Technical Report (DRAFT, PDF format).

List of contributors

See this list.

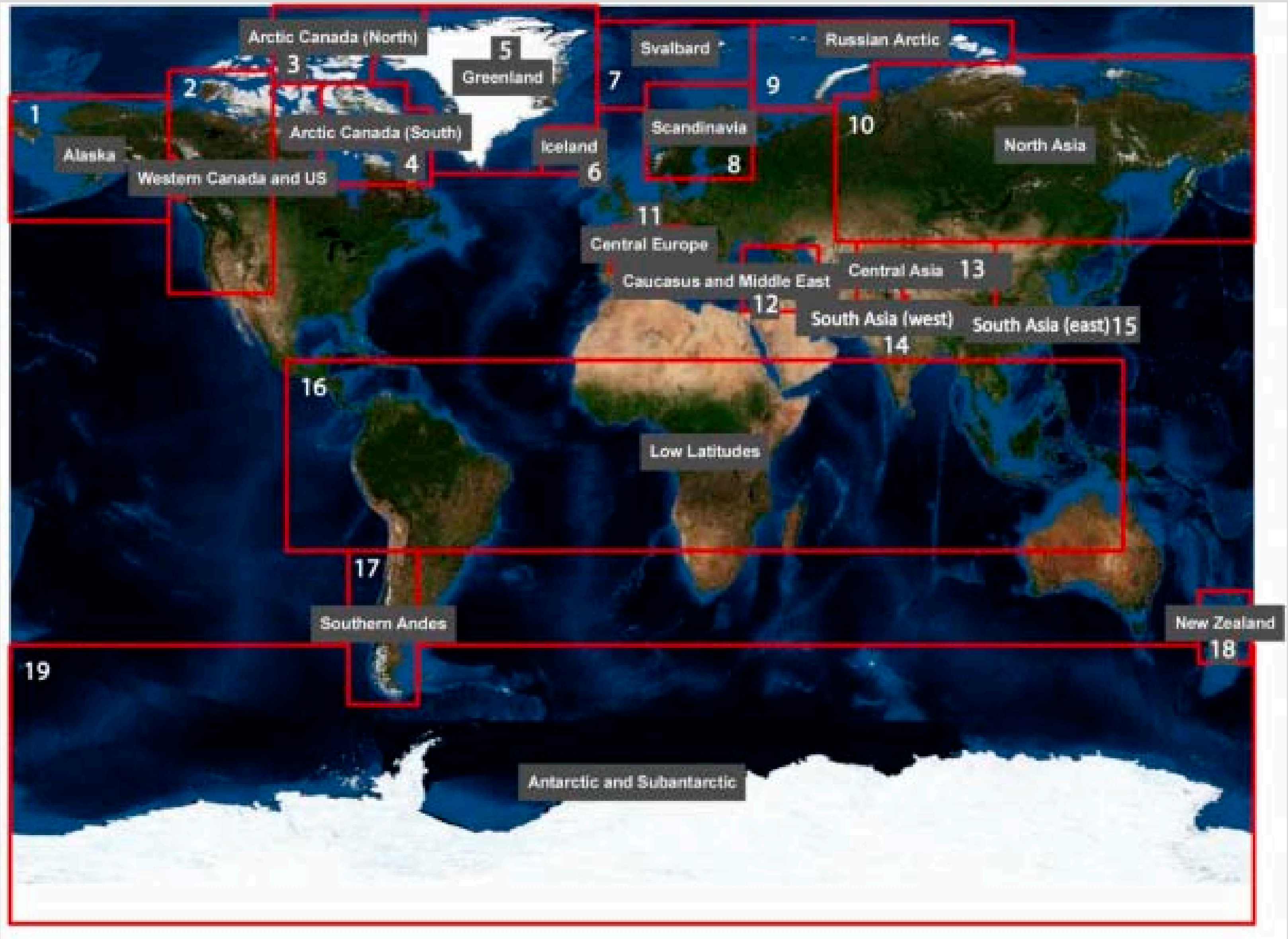
Provisional release schedule

- RGI Version 1.0: release date Jan 18, 2012(?)
- RGI Version 2.0: proposed release date April 30, 2012. Version 2.0 will include metadata on source imagery, outlining techniques and will incorporate any newly available outlines.

Data Access

Register and get the RGI 1.0

Randolph Glacier Inventory



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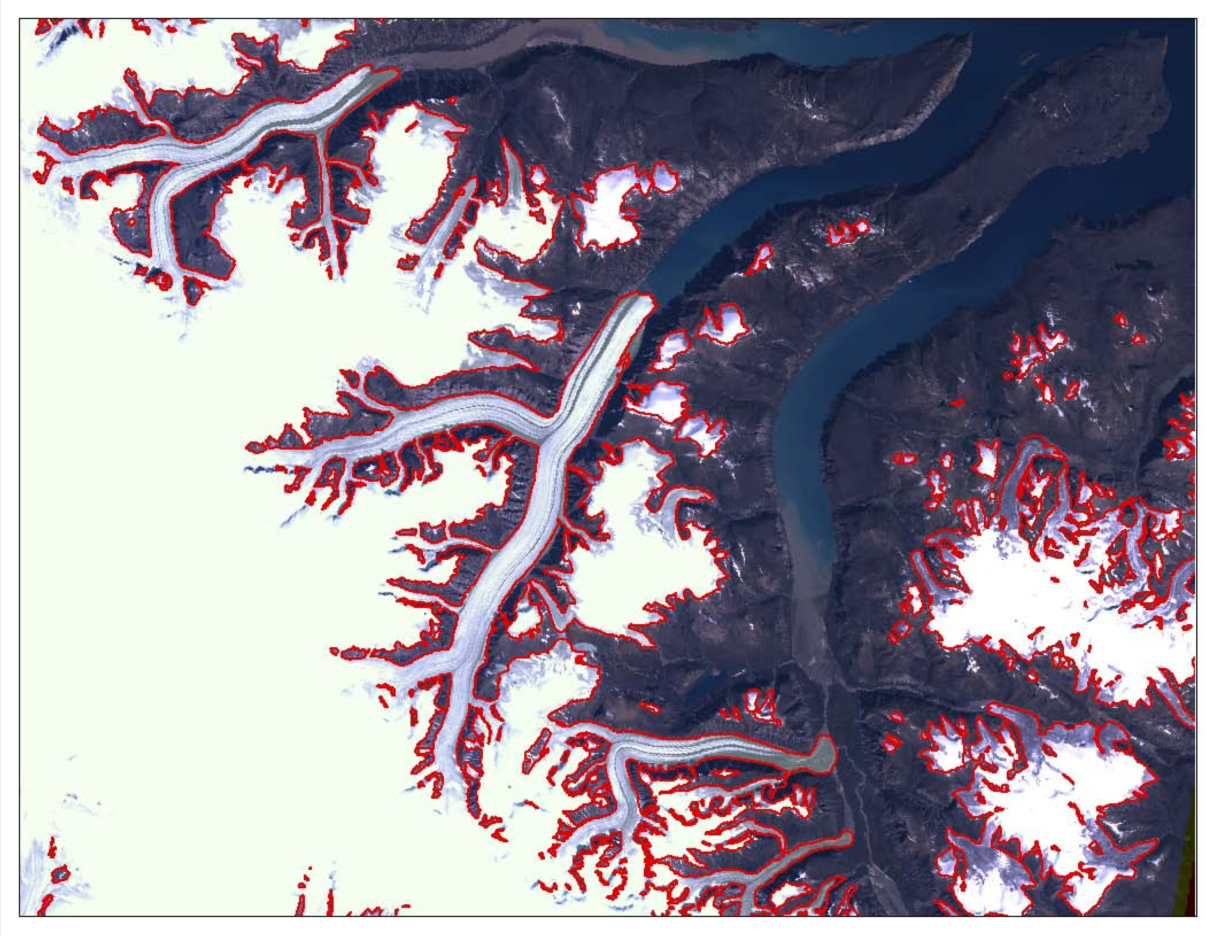
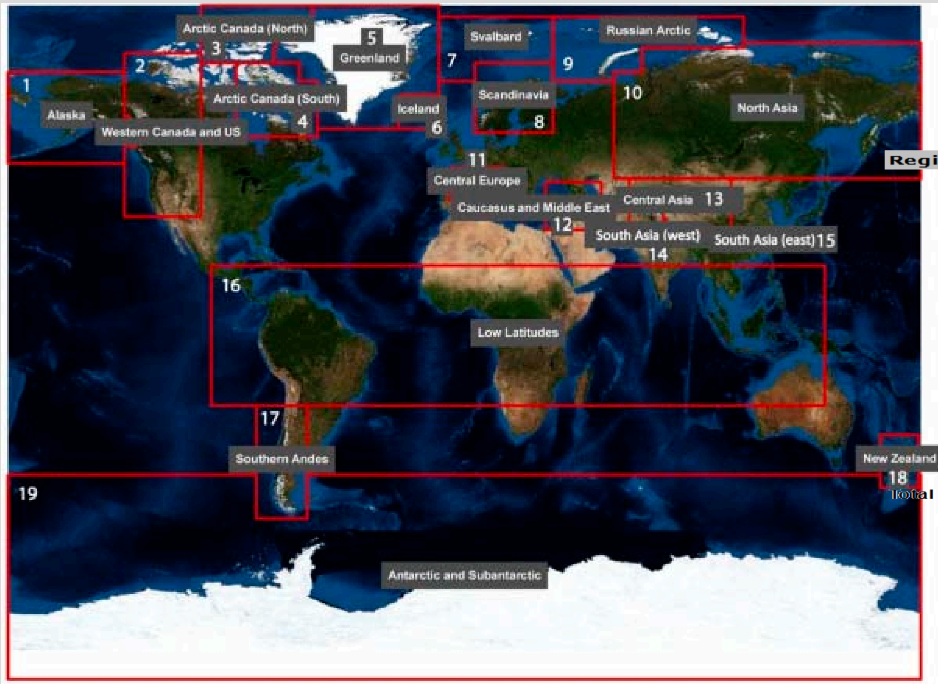
Randolph Glacier Inventory

"Zero-order inventory:" glacier outlines only. Combined with DEM this gives Areas, Area Distribution, Area-Elevation Distribution; basic domain variables needed for modeling with minimal upscaling.



Outline example – Penny Ice Cap, Baffin Island, Canada

Randolph Glacier Inventory



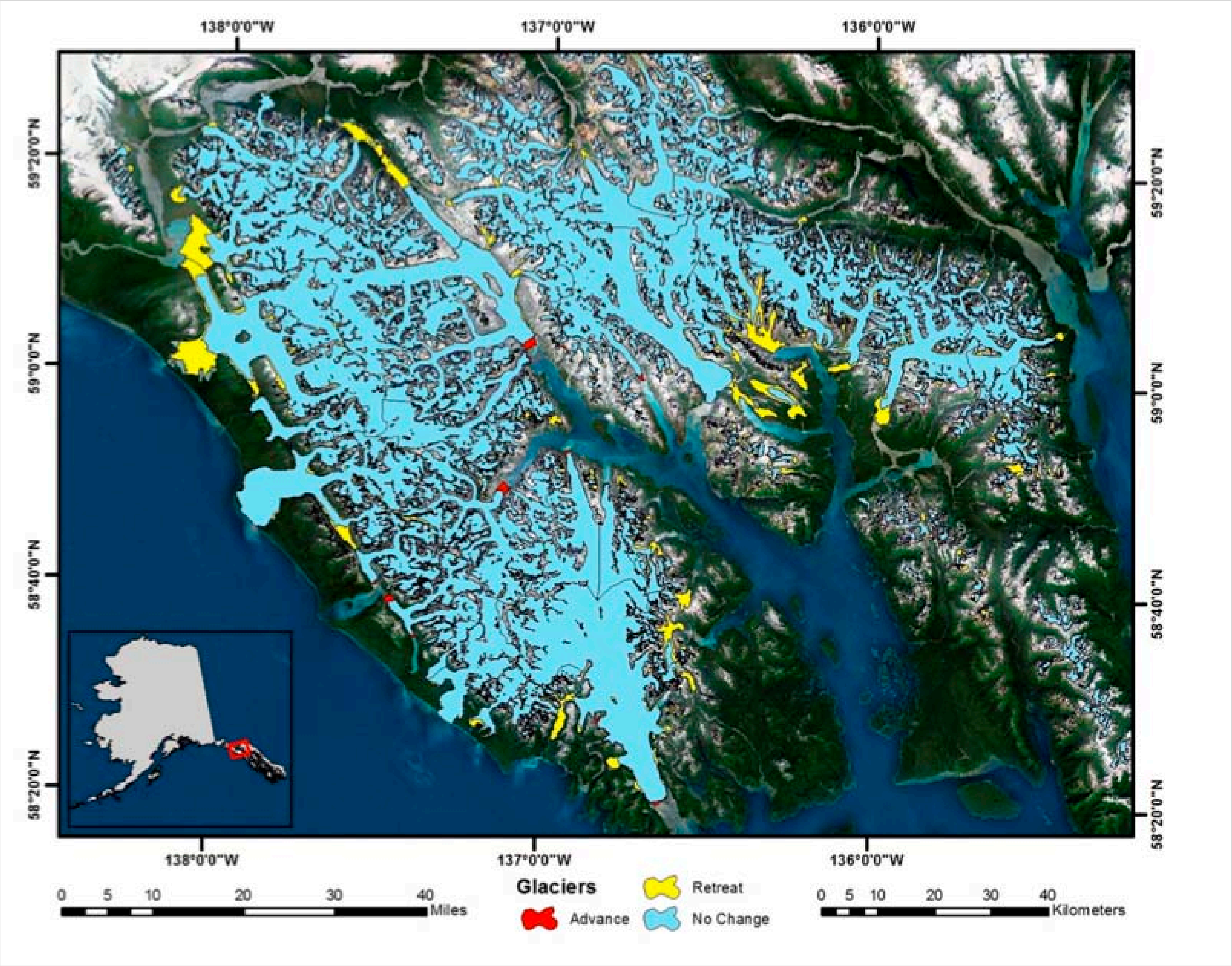
Region #	ID	Region Name	glacier area [km²]
1	ALA	Alaska	88952
2	WNA	Western Canada and US	14505
3	CDN	Arctic Canada (North)	104864
4	CDS	Arctic Canada (South)	40855
5	GRE	Greenland	53547
6	ICE	Iceland	11119
7	SVB	Svalbard	33210
8	SCA	Scandinavia	2852
9	RAI	Russian Arctic	51789
10	NAS	North Asia	2999
11	CEU	Central Europe	4553
12	CAU	Caucasus and Middle East	1439
13	CAN	Central Asia (North)	51452
14	CAW	Central Asia (West)	33859
15	CAS	Central Asia (South)	21775
16	TRP	Low Latitudes	5040
17	AND	Southern Andes	34260
18	NEZ	New Zealand	1164
19	ANT	Antarctic and Subantarctic	124370
Total			**682605**

Net GIC Volume:
0.60 ± 0.07 m SLE (Radic and Hock, 2010); No update yet.

Previous value: 741± 68 x 10^3 km^2 (Radic and Hock, 2010)
(~8% reduction)

All values include peripheral glaciers surrounding Greenland and Antarctic Ice Sheets

Randolph Glacier Inventory



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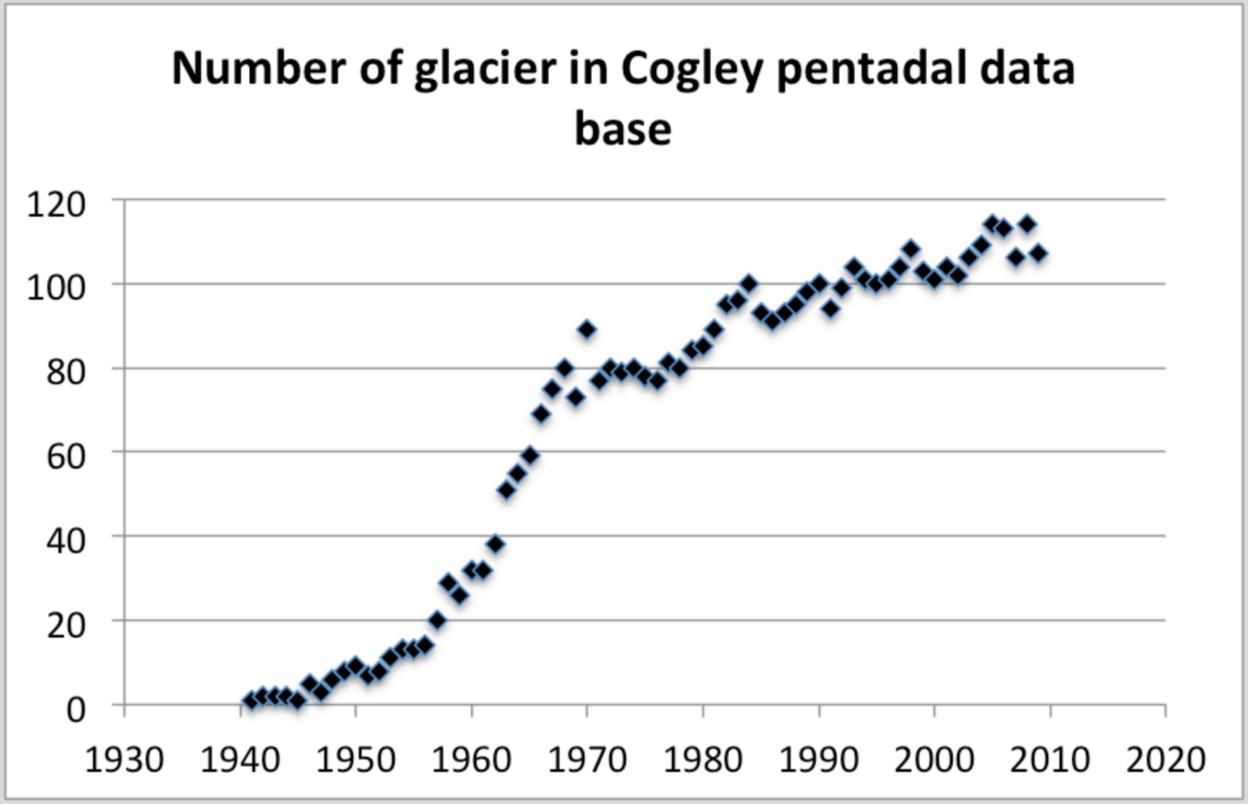
Glacier loss rate assessment requires:

1. Inventory: Glacier location, size, area-elevation distribution. Done once with periodic updates as distribution changes.

2. Mass Balance Observations: Gain/loss on annual or periodic basis;

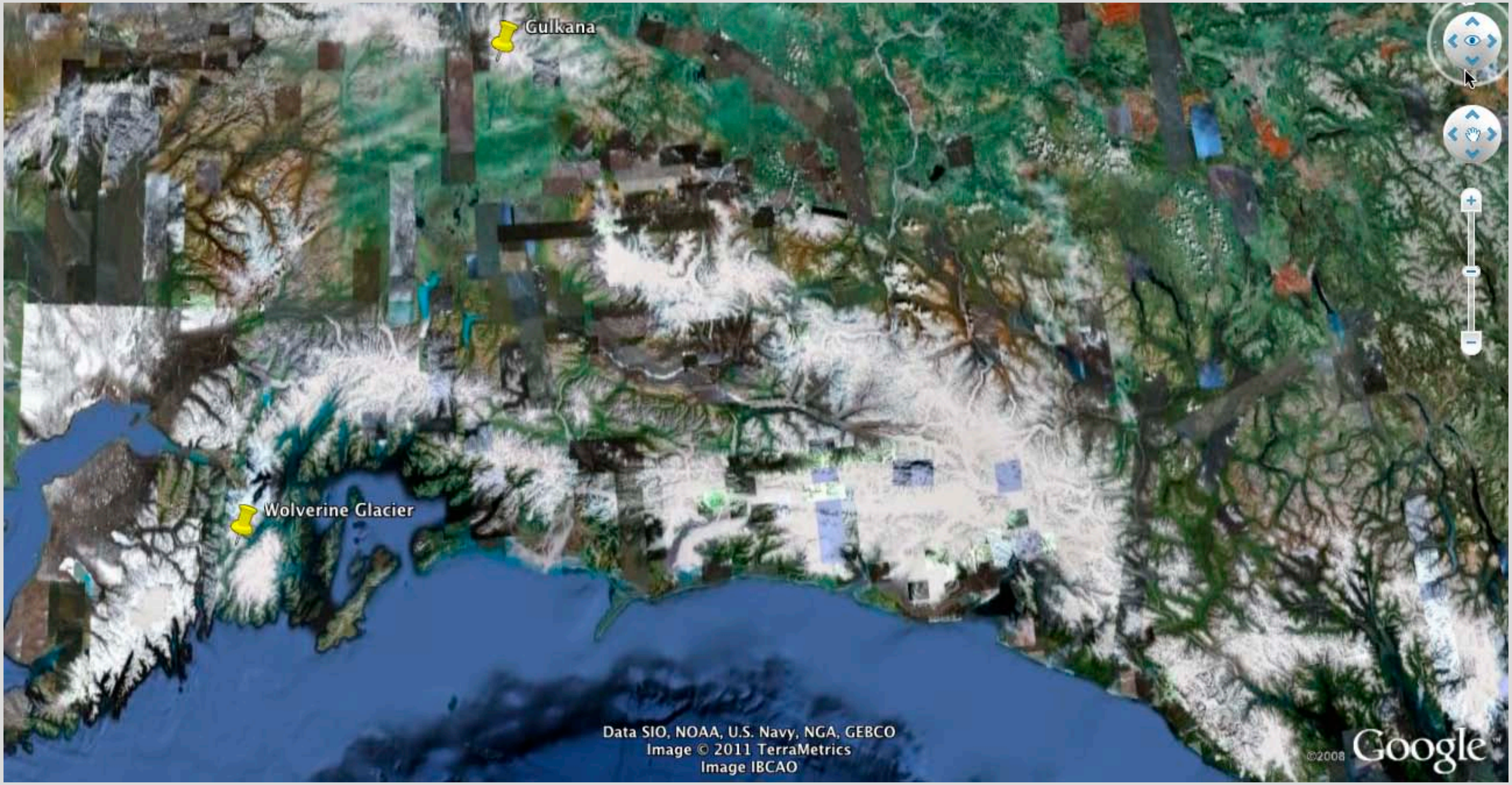
- Net volume change (e.g. altimetry, repeat mapping)
- Net mass change (e.g. GRACE)
- Mass balance components (e.g. direct observation of accumulation/ablation)
- Requires regular (ideally annual) updates

Mass balance observations



Sources of GIC uncertainty: very limited number of glaciers in mass balance observational data base

Mass balance observations



Biased representation of glaciers: glaciers large, high-altitude, and tidewater glaciers are strongly *underrepresented* in weak sample

Alaska Mass Balance records: Gulkana and Wolverine glaciers (ca.36 km^2 combined area, representing Alaska's ca. 79,260 ± 1076 km^2 (Radic and Hock, 2010)

Projections

Table 3. Projected contribution to sea level by 2100 (cm)

Year	Study	Source (1983 EPA did not separate land ice sources)			
		Low	Mid-Range Low	Mid-Range High	High
1983	EPA (Hoffman et al., 1983)	+56.2	+144.4	+216.6	+345.0

Year	Study	Source		
		Greenland Ice Sheet	Antarctic Ice Sheets	Glaciers and Ice Caps
1984	NRC/DOE (Committee on Glaciology, 1985)	+10 to +30	−10 to +100	+10 to +30
1990	IPCC First Assessment[1] (Houghton et al., 1990)	+0.5 to +3.7	−0.8 to 0.0	+2.3 to +10.3
1995	IPCC Second Assessment[2] (Houghton et al., 1996)	+6	−1	+16
2001	IPCC Third Assessment[3] (Church et al., 2001)	0 to +7	−7 to +2	+3 to +23
2007	IPCC Fourth Assessment[4] (Lemke et al., 2007)	+8 to +17	−14 to −3	+2 to +12

[1] Projection to 2030 using BAU Forcing Scenario; NOTE: 1990 Projection to 2030 only.
[2] Projection using IS92a Forcing Scenario.
[3] Using Forcing Scenario CGCM1 GS; 1990–2100.
[4] Total land ice contribution 4 to 23 cm; with "scaled-up ice sheet contribution," add ca. 10 to 20 cm.
NOTE: Highest ("fastest burn") emission scenario only for each Assessment chosen for comparison.

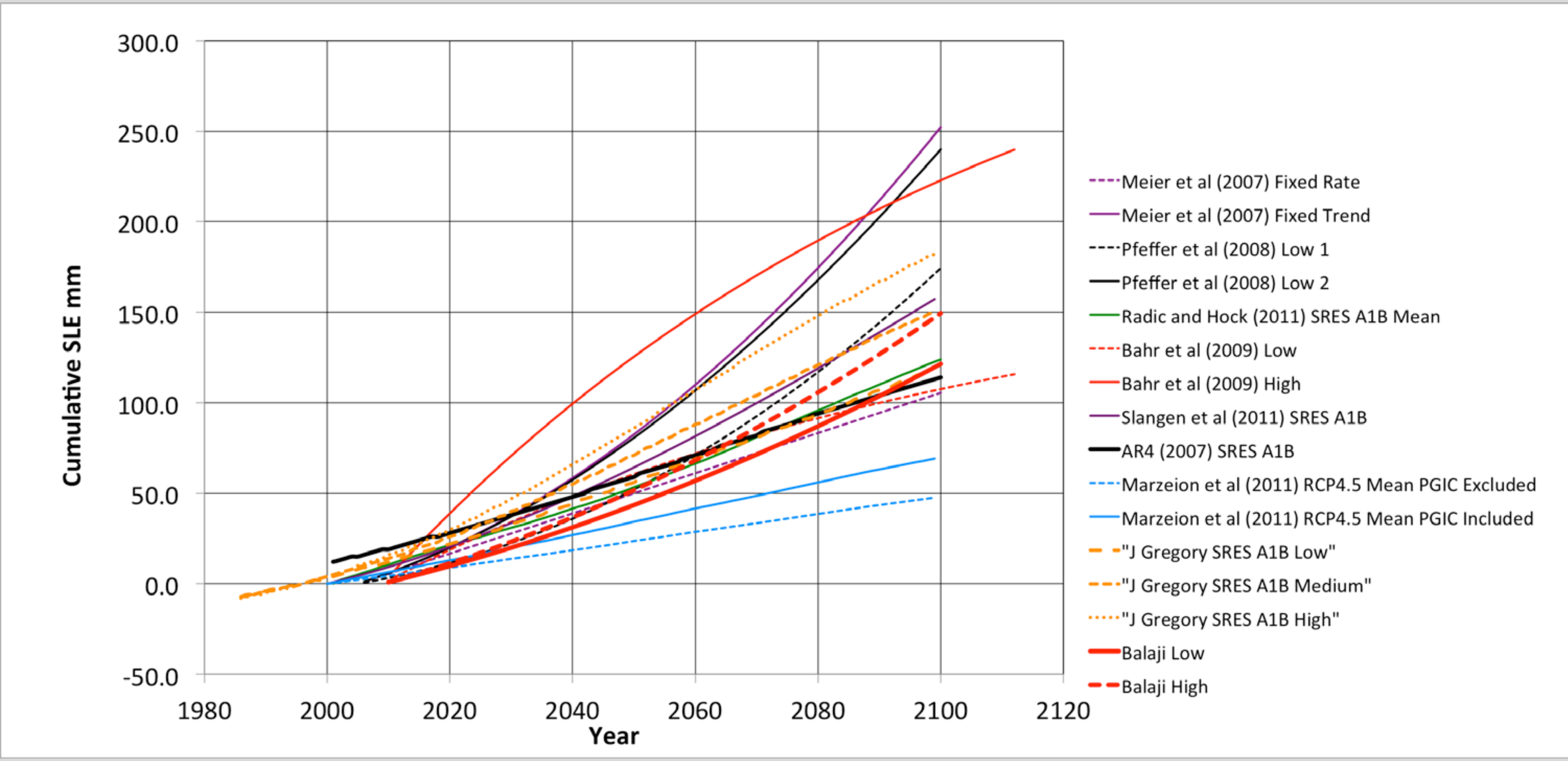
Projection types:

1. Explicit numerical model (don’t really exist for 300,000+ glaciers)

2. Combined numerical model/power-law upscaling (Radic and Hock, 2010; Marzeion et al, 2011, Slangen et al, 2011)

3. Extrapolation (Meier et al, 2007; Pfeffer et al, 2008; Pfeffer and Balaji, in prep)

4. Relaxation to equilibrium ($AAR > AAR_0$) (Bahr et al, 2009; Mernild [in review?])



Newest GIC model projections

- None use new inventory
- None consider dynamic response except extrapolation models
- Scaling models can be improved

Reference	Projected SLR at 2100 (m)	Notes
Radic and Hock (2011)	0.09–0.16	A1B scenario Average of 10 GCMs Calving excluded
Meier et al. (2007)		
Fixed rate	0.08–0.12	Extrapolation
Fixed trend	0.11–0.37	Calving included
Pfeffer et al. (2008)		
Low projection 1	0.17	Limit seeking analysis
Low projection 2	0.24	Calving included
Bahr et al. (2009)		
Present AAR	0.12	Exponential approach to long-term steady-state
Continued AAR decline	0.24	Calving excluded
Slangen et al. (2011)	0.16	A1B scenario Calving excluded
Marzeion et al. (2011)		
Excluding glaciers peripheral to ice sheets	0.035–0.063	A1B Scenario Average of 10 GCMs
Excluding glaciers peripheral to ice sheets	0.046–0.082	Calving excluded
Gregory Method		
Low	0.12	A1B scenario
Medium	0.15	
High	0.18	
Full Range of projections	**0.035–0.37**	

Non-deterministic GIC projections

Projection: Bahr, Meier, and Dyurgerov (GRL 2009):

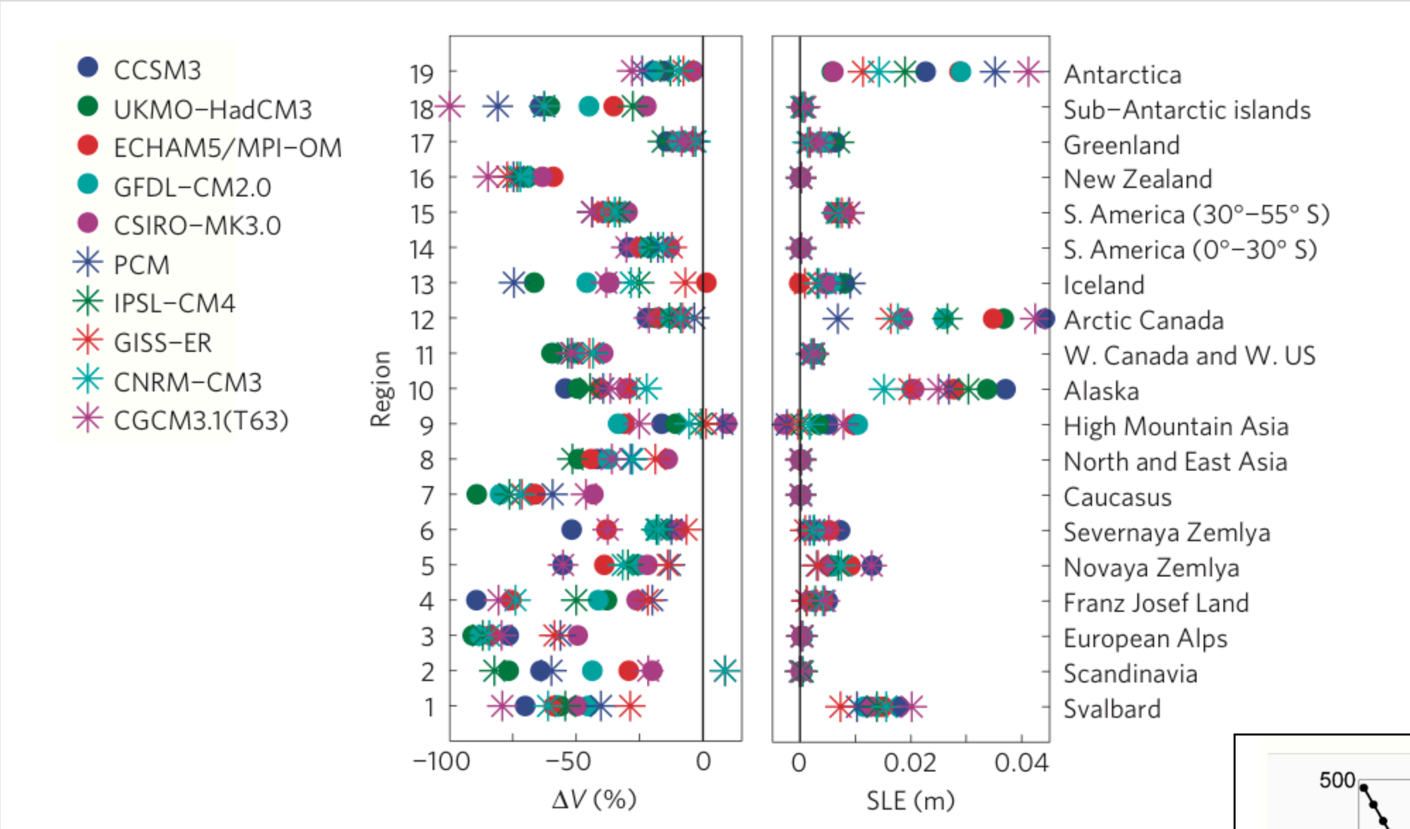
GIC contribution to sea level 18.0 ± 3 cm by 2100 with no further warming
37.0 ± 2 cm by 2100 with further warming

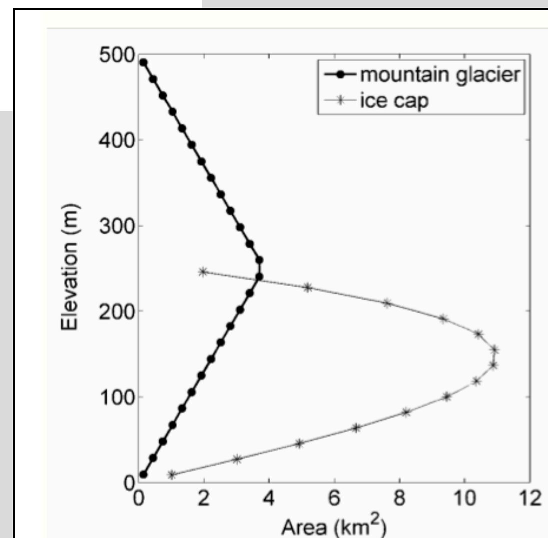
Method uses re-equilibration to equilibrium AAR_0 = 0.57

Limitation: Relies upon assumption that AAR = 0.57 is an intrinsic equilibrium value. Observations support this, but a theoretical reason is lacking.

No choice of coefficient c required (factored out in analysis)
Hypsometry is variable

Non-deterministic GIC projections





Projection: Radic and Hock, Nature Geoscience 2011
GIC contribution to sea level 12.4 ± 3.7 cm by 2100

Limitations:
1.No account made for dynamic response
2.Requires choice of c in V = cS©
3.Hypsometry fixed with AAR = 0.5

Non-deterministic GIC projections

Another non-deterministic scaling model (proposed, Bahr, Pfeffer):

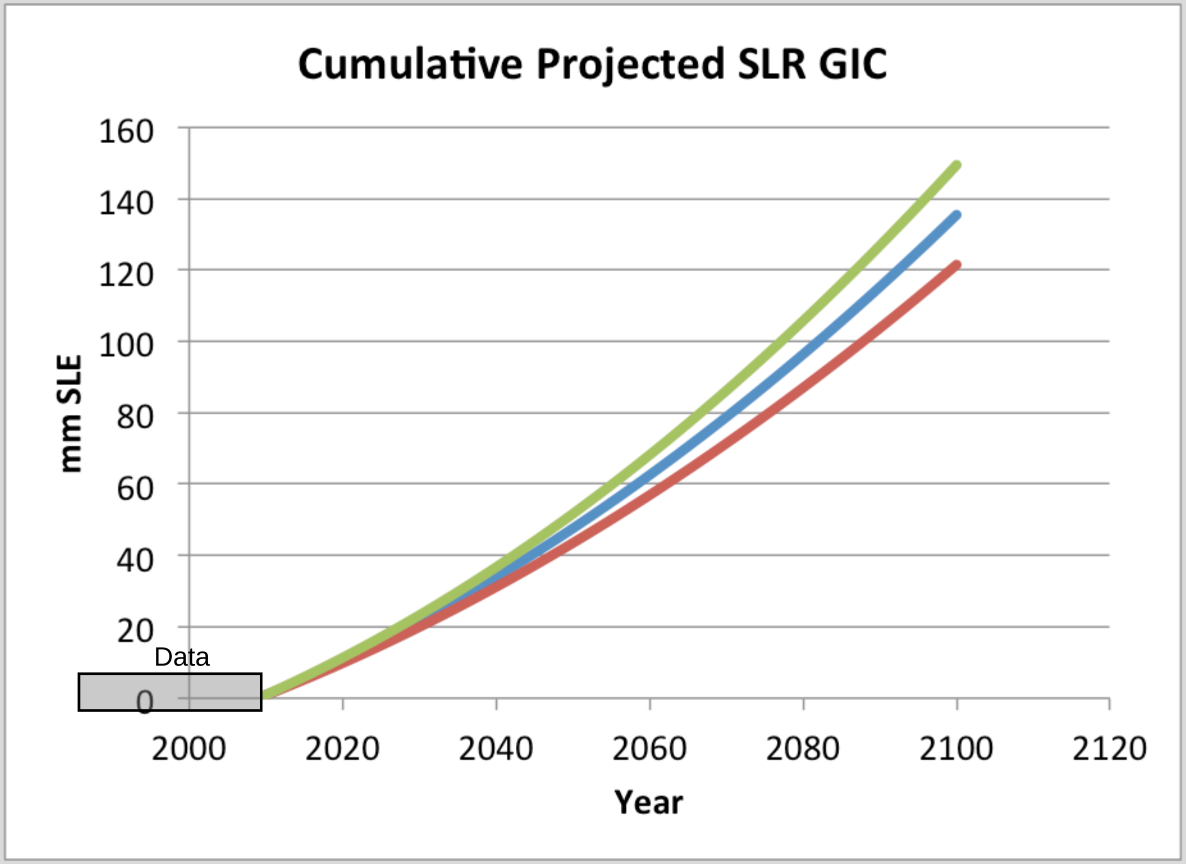
Use Volume-Area scaling: $V = cA^{\gamma}$
Area-Response Time scaling: $T = kA^{\beta}$
AAR scaling: $(1 + \Delta V/V) = (1+AAR/AAR_0)^{\gamma}$

Need initial GIC distribution and hypsometry (i.e. inventory)

1. GCM provides surface mass balance (SMB) as function of position & time.
2. SMB provides ΔV, Volume-Area scaling provides ΔA.
3. AAR scaling provides new distribution of areas (i.e. new hypsometry), hypsometry + new ELA from GCM provides new distribution of glaciers for next step.
4. Response time scaling allows partial adjustment during time step to reflect dynamics.

Do not model each of 300,000+ glaciers! Generate glacier populations stochastically as needed.

Alternate projection by Generalized Linear Model



Extrapolated SLE from Glaciers and Ice Caps (GIC)

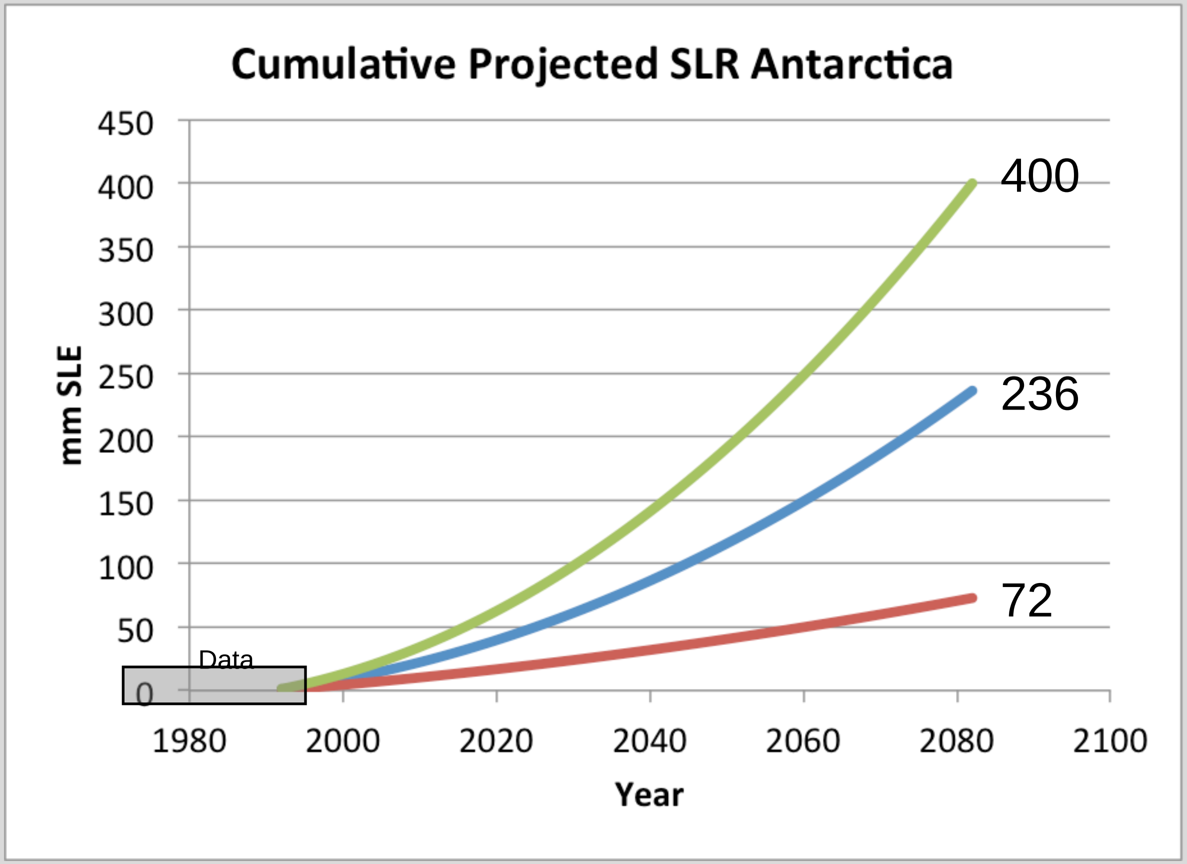
by 2030:
21.6 ± 2 mm

By 2050:
47.6 ± 4 mm

GIC data: GLM-weighted Gogley, Dyurgerov (2010) and Meier et al (2007) compilation

Projected SLR from Rignot data using GLM methods – GIC
Data from ~1960 - 2005

Alternate projection by Generalized Linear Model



Extrapolated SLE from Antarctica

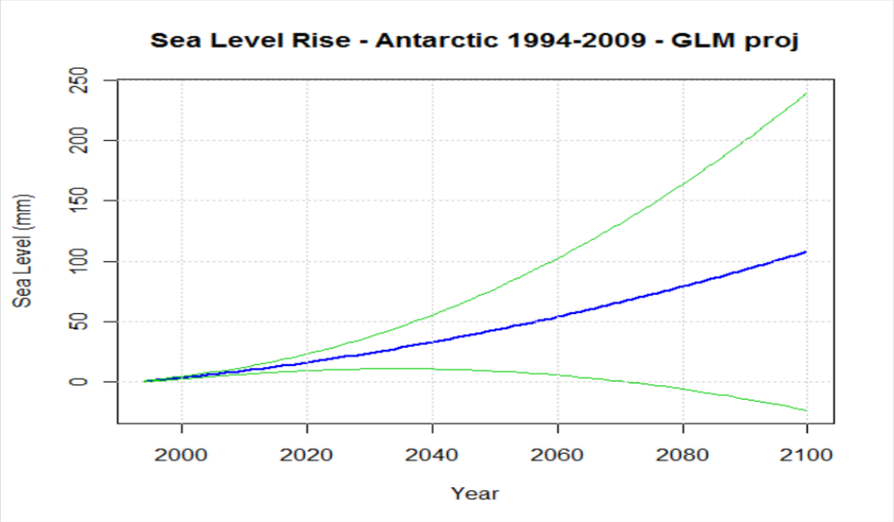
by 2030:
19.0 ± 5 mm

By 2050:
52.0 ± 13 mm

By 2100:
236.0 ± 163 mm

Projected SLR from Rignot data using GLM methods – Greenland
Data from 1992-2009

Alternate projection by Generalized Linear Model



Rignot data taken at the midpoint of each year (1992-2009)

240

110

-20

SLE by 2100:
110.0 ± 130 mm

Effect of dropping first 2 years of 17 year data series

Projected SLR from Rignot data using GLM methods – Antarctica
Data from 1994-2009

Problems with GIC projections:

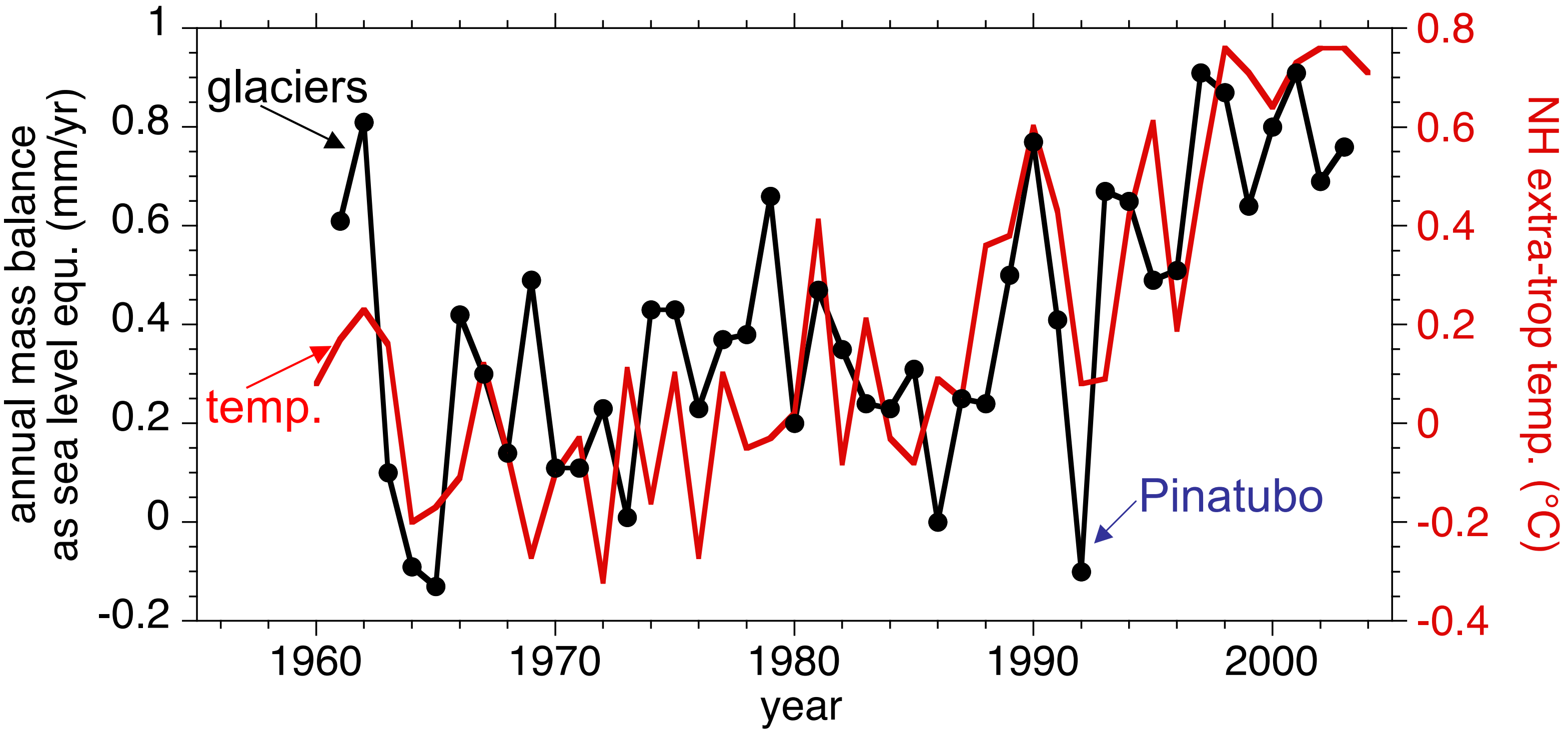
1)Numerical models well developed, and will get better with new inventory, but:

- At present dependent upon primative AAR model
- Models SMB only
- Still strongly dependent on weak observational data

2) Extrapolation and Semi-empirical models may be better for GICs to the extent that GICs may be less influenced by dynamics;

3) But we don’t know what role dynamics plays or will play in GIC loss rates. What fraction of global GIC area is drained through marine outlets? (it’s 14% in Alaska). How much of present-day GIC loss is dynamic? (in Alaska, 10% comes from Columbia Glacier alone. Will this last?)

global“small” glaciers vs. temperature

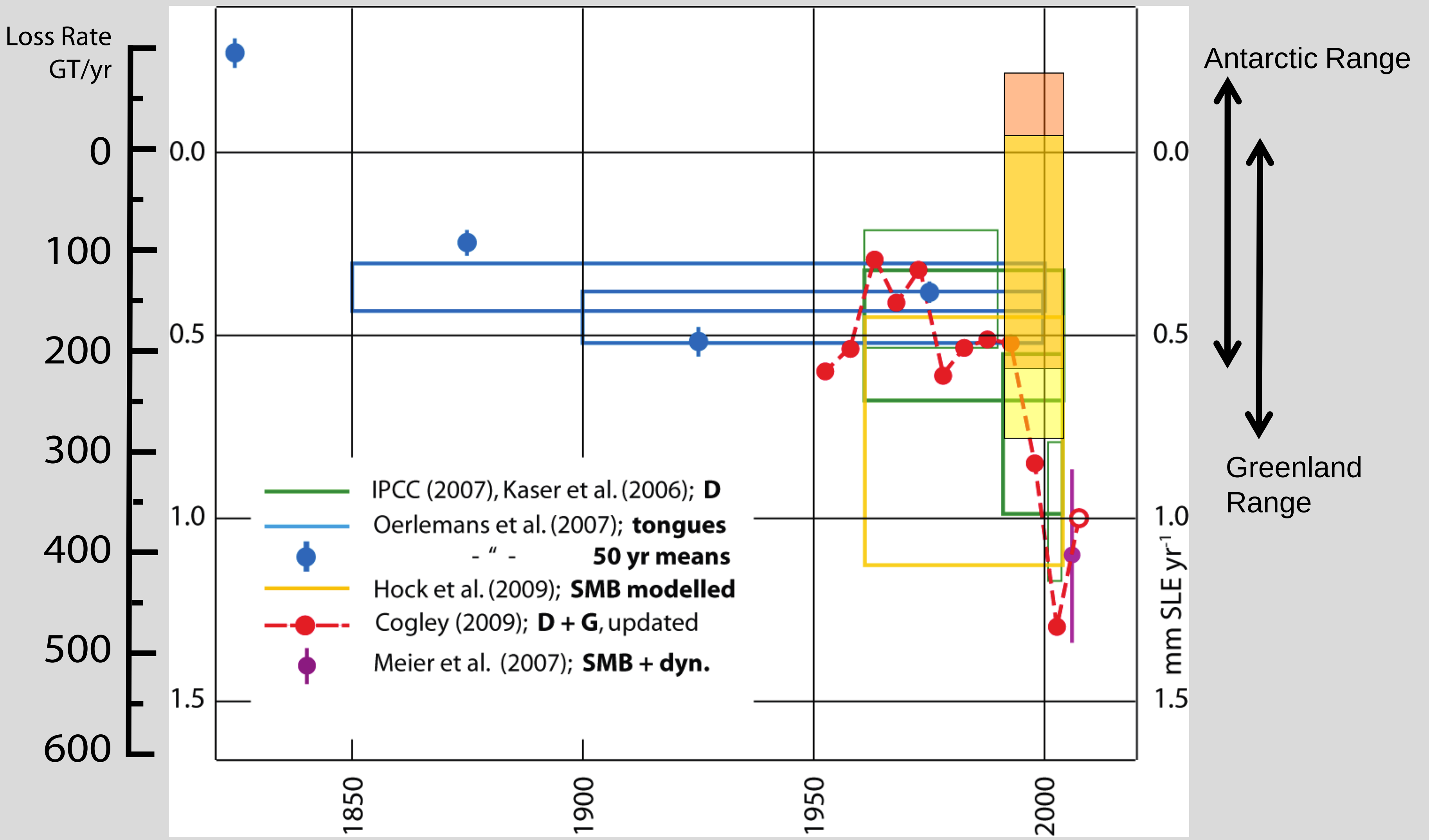


annual global small glacier melting (or growth), given here as equivalent annual change in sea-level, follows temperature change of extra-tropical NH (from GISS)

global glacier melting appears v. sensitive to warming

glacier data of Dyurgerov (CU), analysis of Lehman & Knutti

W. T. Pfeffer, Columbia Glacier, Alaska 2006



Compilation figure courtesy Georg Kaser

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