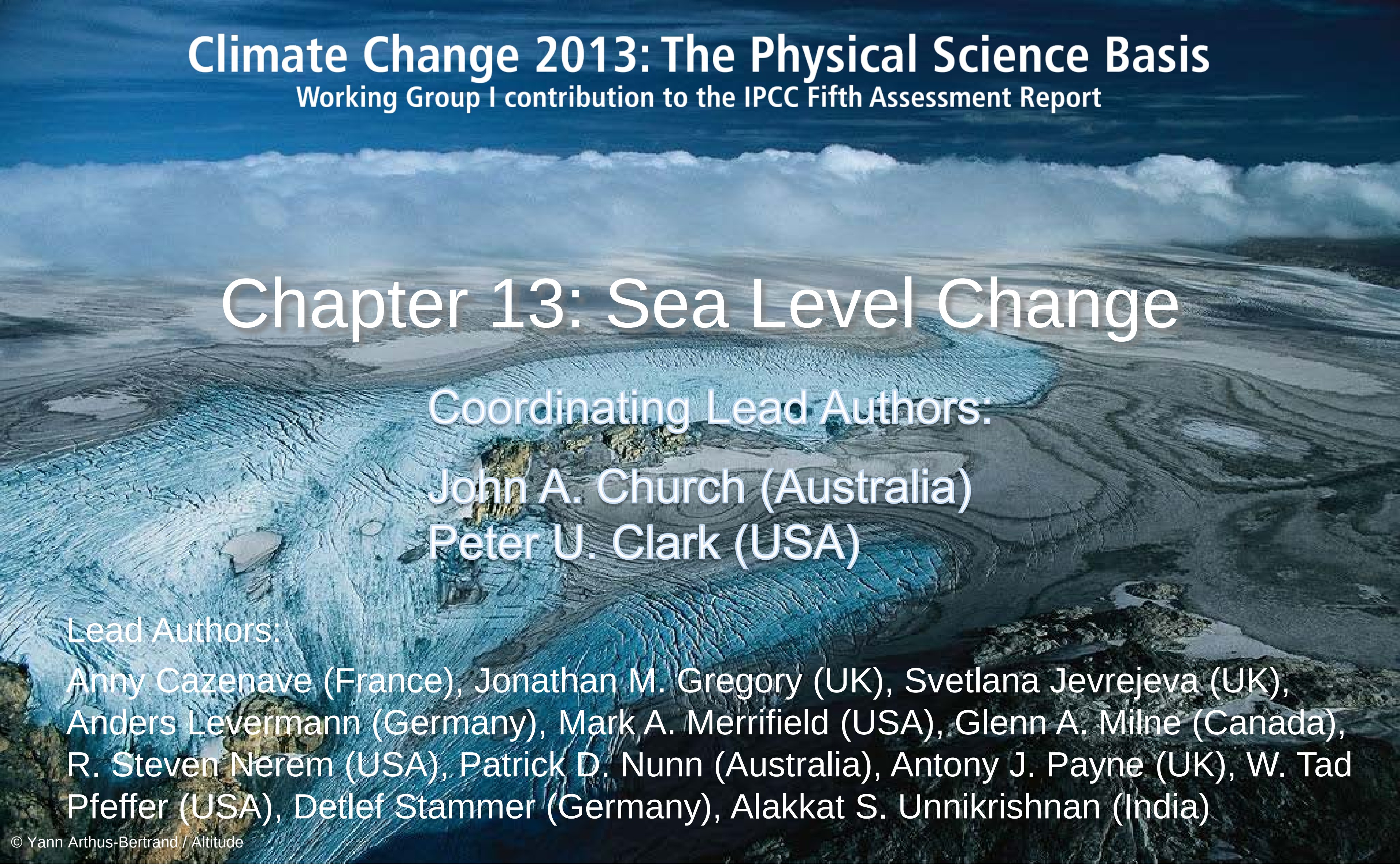

Climate Change 2013: The Physical Science Basis

Working Group I contribution to the IPCC Fifth Assessment Report

Chapter 13: Sea Level Change

Coordinating Lead Authors:

John A. Church (Australia)
Peter U. Clark (USA)

Lead Authors:

Anny Cazenave (France), Jonathan M. Gregory (UK), Svetlana Jevrejeva (UK), Anders Levermann (Germany), Mark A. Merrifield (USA), Glenn A. Milne (Canada), R. Steven Nerem (USA), Patrick D. Nunn (Australia), Antony J. Payne (UK), W. Tad Pfeffer (USA), Detlef Stammer (Germany), Alakkat S. Unnikrishnan (India)

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Contributing Authors: (57 from 15 countries)

David Bahr (USA), Jason E. Box (Denmark/USA), David H. Bromwich (USA), Mark Carson (Germany), William Collins (UK), Xavier Fettweis (Belgium), Piers Forster (UK), Alex Gardner (USA), W. Roland Gehrels (UK), Rianne Giesen (Netherlands), Peter J. Gleckler (USA), Peter Good (UK), Rune Grand Graversen (Sweden), Ralf Greve (Japan), Stephen Griffies (USA), Edward Hanna (UK), Mark Hemer (Australia), Regine Hock (USA), Simon J. Holgate (UK), John Hunter (Australia), Philippe Huybrechts (Belgium), Gregory Johnson (USA), Ian Joughin (USA), Georg Kaser (Austria), Caroline Katsman (Netherlands), Leonard Konikow (USA), Gerhard Krinner (France), Anne Le Brocq (UK), Jan Lenaerts (Netherlands), Stefan Ligtenberg (Netherlands), Christopher M. Little (USA), Ben Marzeion (Austria), Kathleen L. McInnes (Australia), Sebastian H. Mernild (USA), Didier Monselesan (Australia), Ruth Mottram (Denmark), Tavi Murray (UK), Gunnar Myhre (Norway), J.P. Nicholas (USA), Faezeh Nick (Norway), Mahé Perrette (Germany), David Pollard (USA), Valentina Radić (Canada), Jamie Rae (UK), Markku Rummukainen (Sweden), Christian Schoof (Canada), Aimée Slangen (Australia/Netherlands), Jan H. van Angelen (Netherlands), Willem Jan van de Berg (Netherlands), Michiel van den Broeke (Netherlands), Miren Vizcaíno (Netherlands), Yoshihide Wada (Netherlands), Neil J. White (Australia), Ricarda Winkelmann (Germany), Jianjun Yin (USA), Masakazu Yoshimori (Japan), Kirsten Zickfeld (Canada)

Review Editors:

Jean Jouzel (France), Roderik van de Wal (Netherlands), Philip L. Woodworth (UK), Cunde Xiao (China)

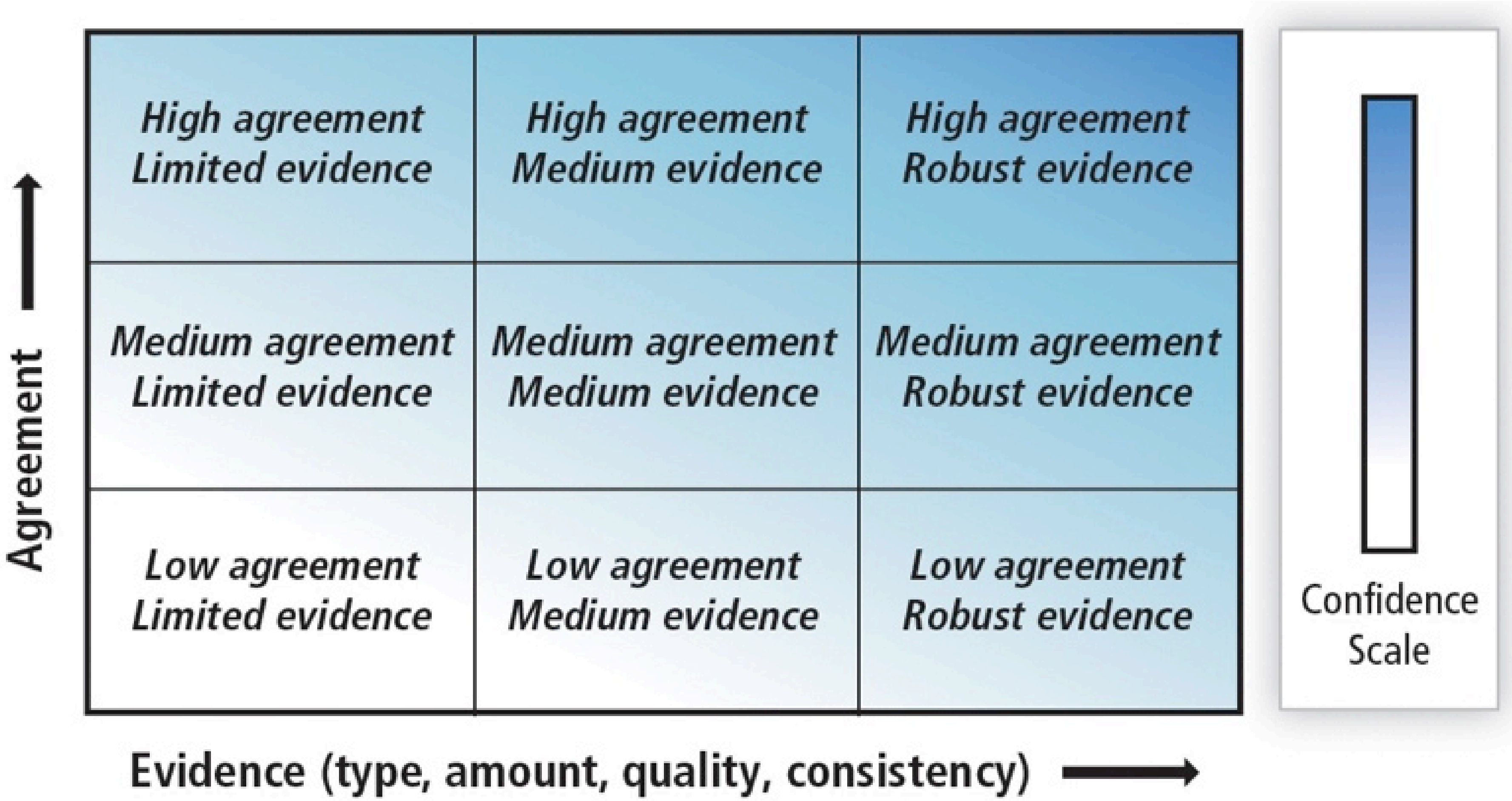
Working Group I Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis

Outline

1. Communicating uncertainty.
2. Contributions to global mean sea level rise (GMSLR).
3. Observations of sea level change.
4. Basis for improved understanding of recent GMSLR.
5. Projections of GMSLR for the 21st century and beyond.
6. Regional sea level change.
7. Post-IPCC research.
8. Summary.

1. Communicating uncertainty

Confidence in validity of a finding.



1. Communicating uncertainty

Quantifying uncertainty.

Term	Likelihood of the Outcome
Virtually certain	99–100% probability

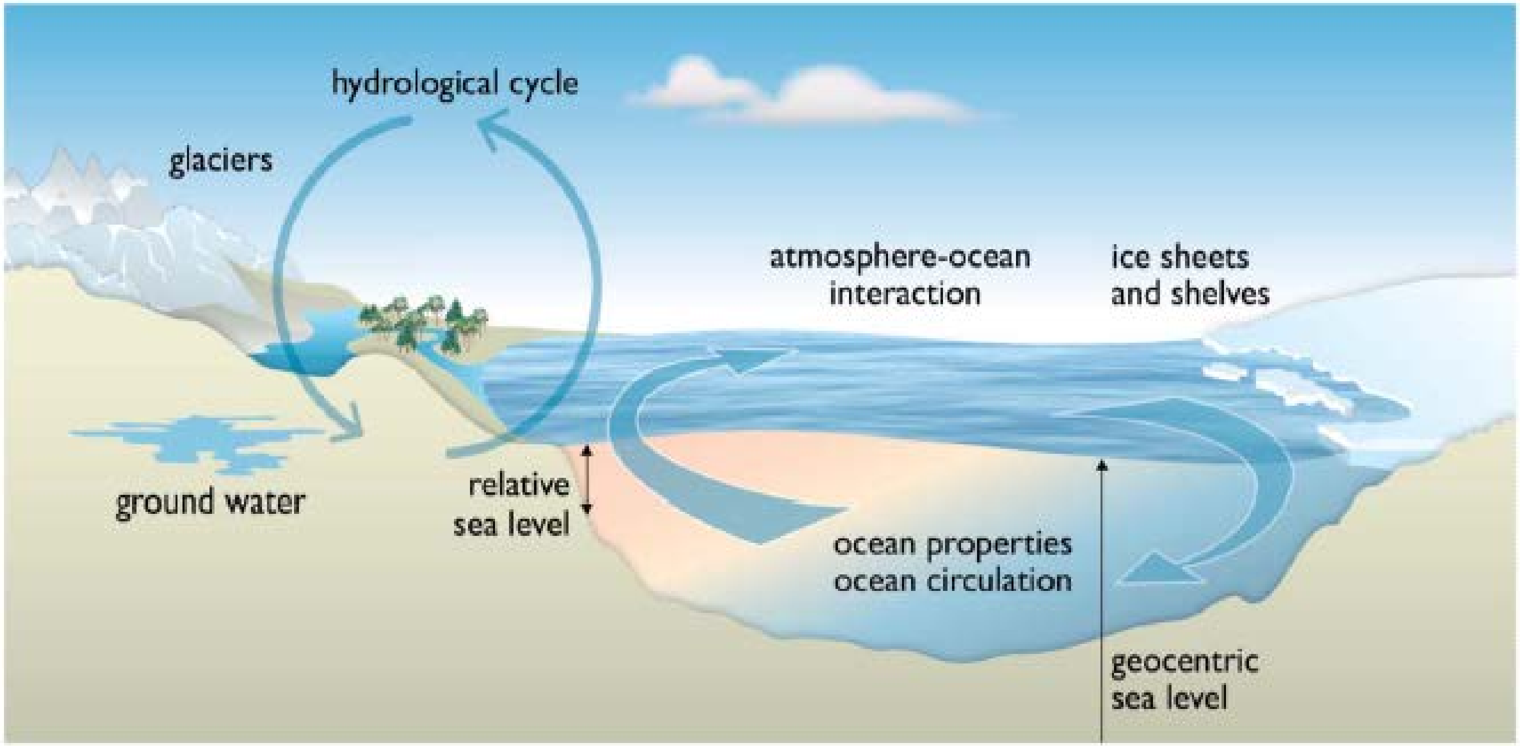
Example – a *likely* sea level range means that there is better than a two-in-three chance that the actual SLR lies in the range.

i.e. – does not exclude possibility of lower or higher sea levels.

Additional terms that were used in limited circumstances in the AR4 (*extremely likely* = 95–100% probability, *more likely than not* = >50–100% probability, and *extremely unlikely* = 0–5% probability) may also be used in the AR5 when appropriate.

2. Contributions to GMSLR

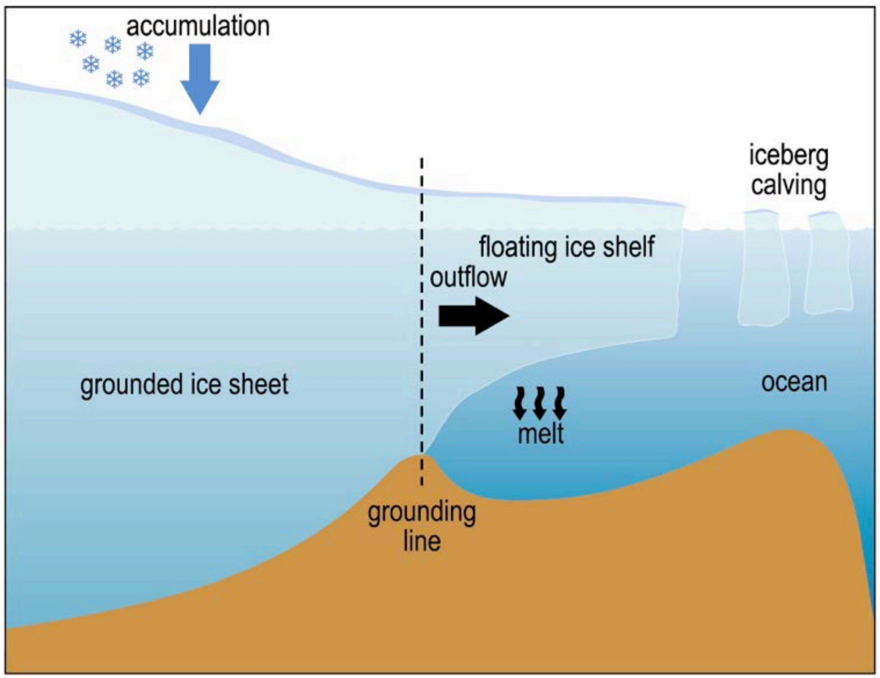
- Warming the ocean (thermal expansion).
- Loss of ice by glaciers and ice sheets (mass).
- Reduction of liquid water storage on land (mass).



2. Contributions to GMSLR

Glaciers and ice sheets

Surface mass balance Dynamics (outflow)



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2. Contributions to GMSLR

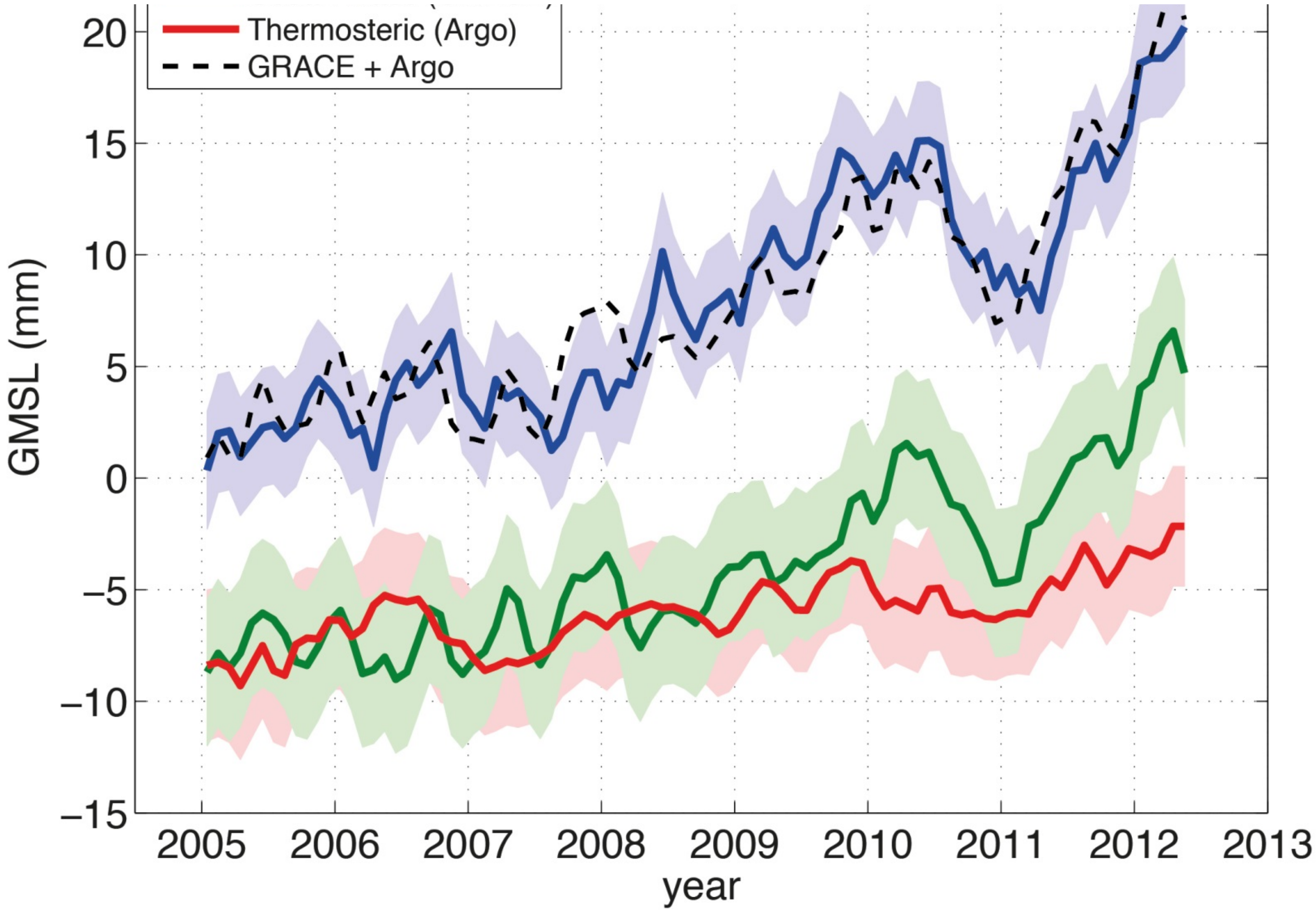
Land water storage

Reservoirs

Groundwater

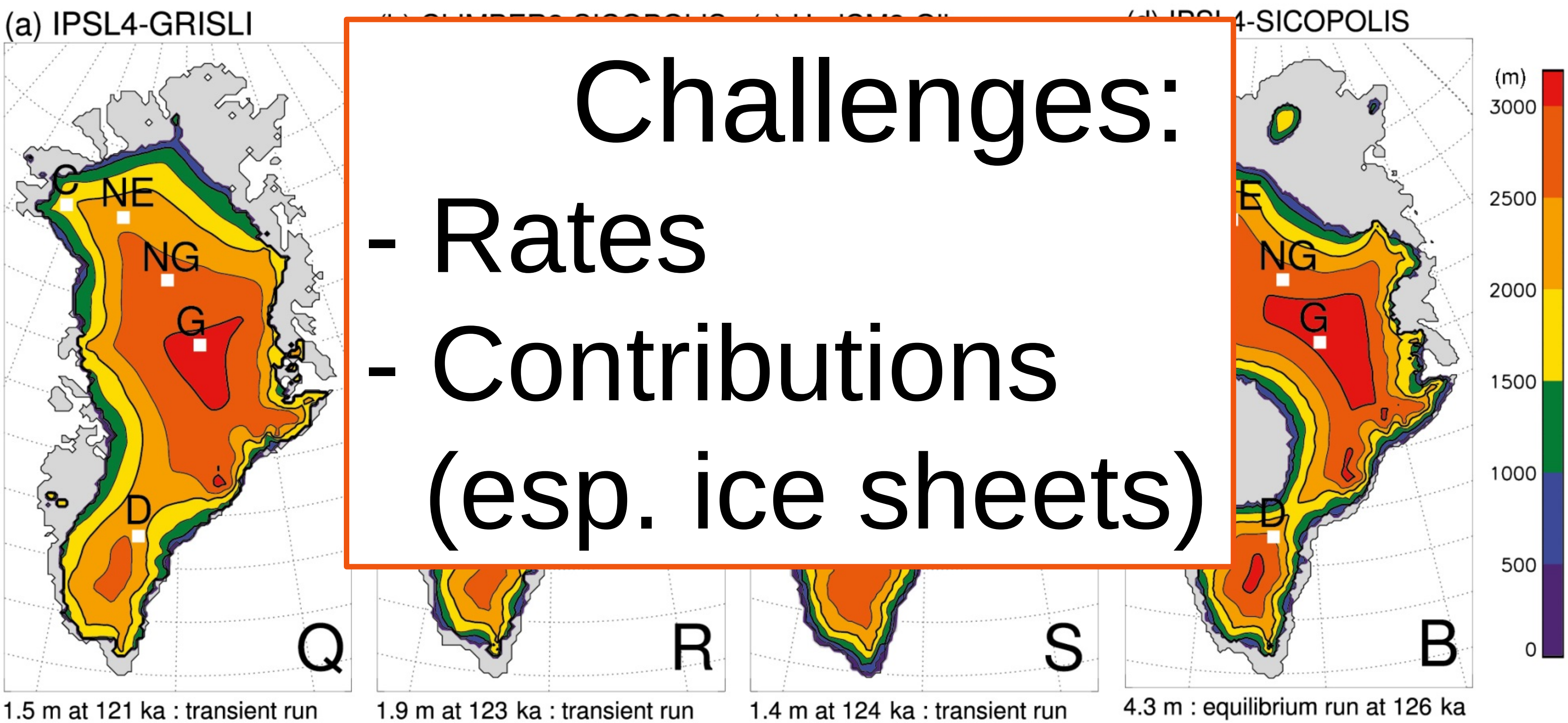
2. Contributions to GMSLR

Can be substantial interannual variability.



3. Observations

Paleo sea level was >5 m (*very high confidence*) when global mean temperature was up to 2ºC warmer (*medium confidence*).

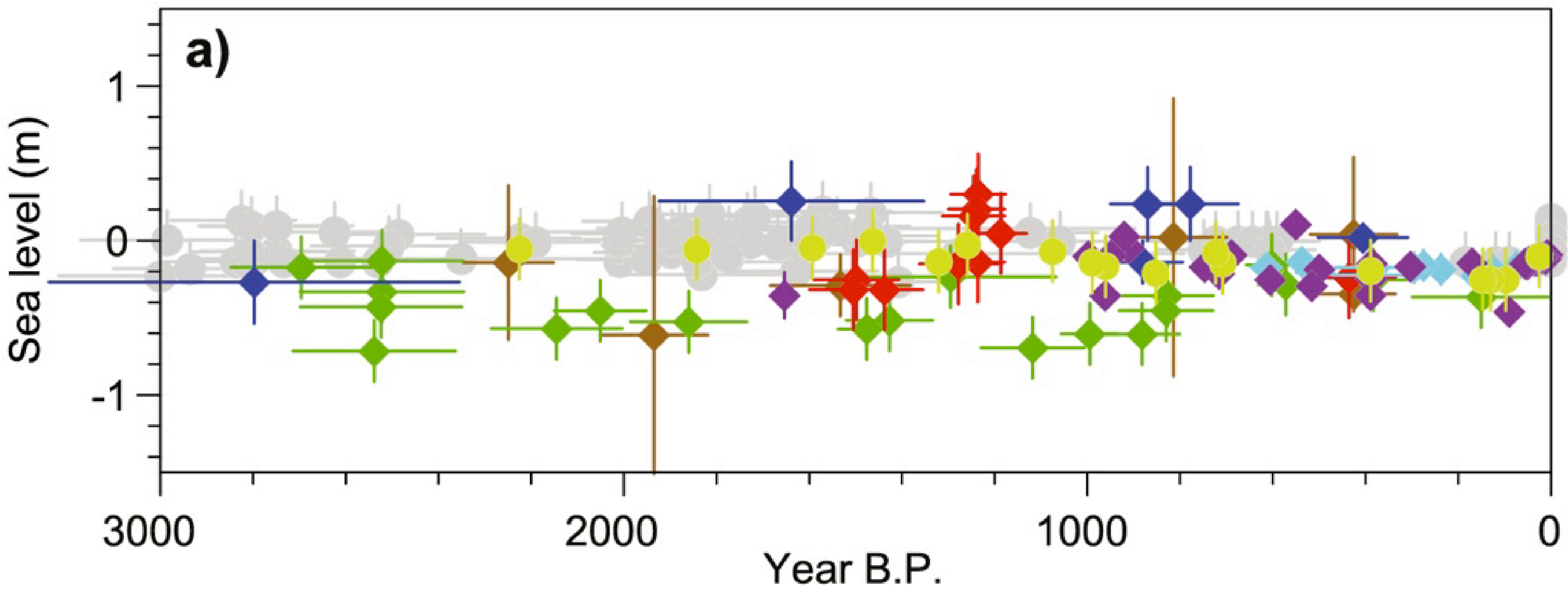


Challenges:

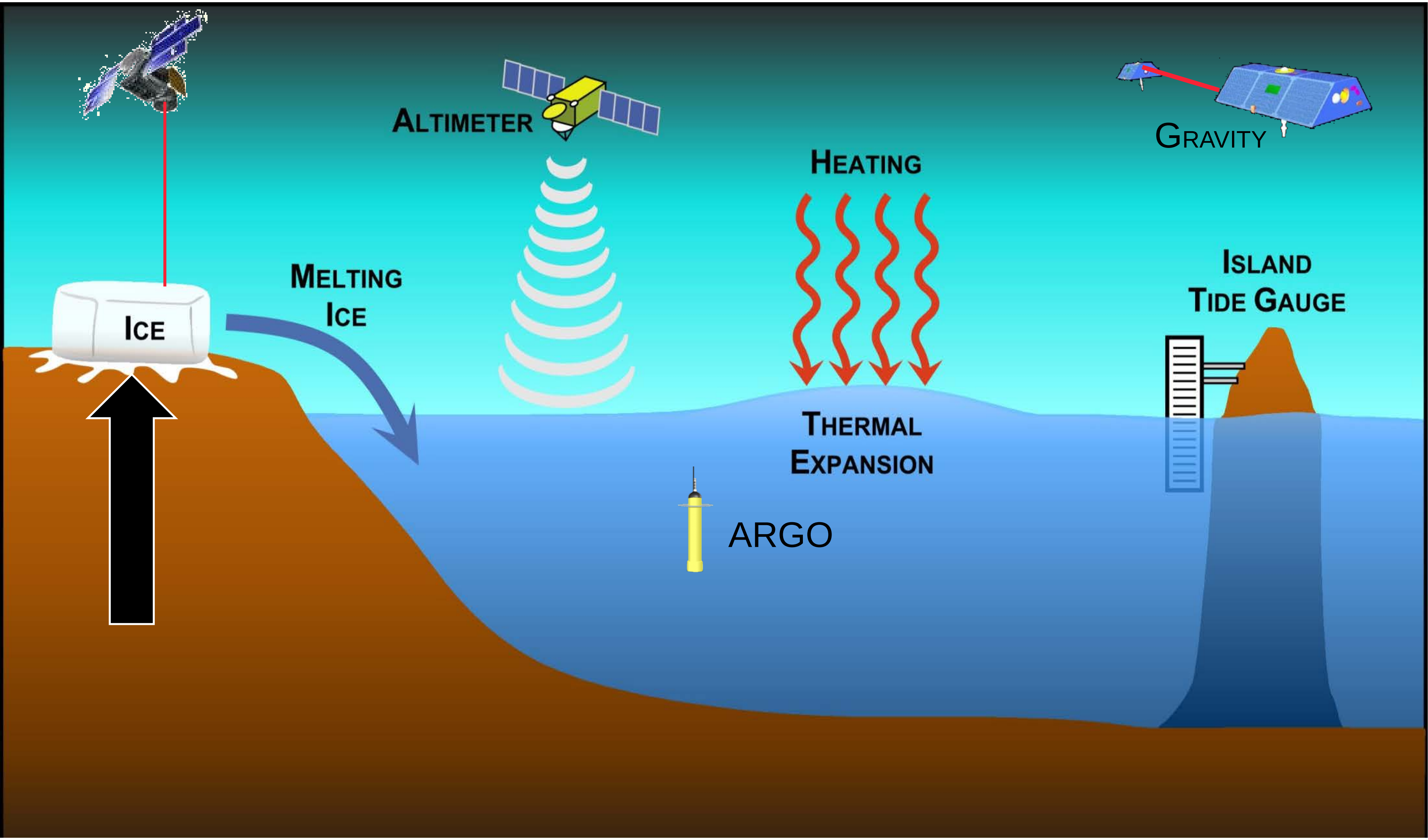
- Rates
- Contributions (esp. ice sheets)

3. Observations

Rate during the last two millennia was of order a few tenths of mm yr^{-1}.



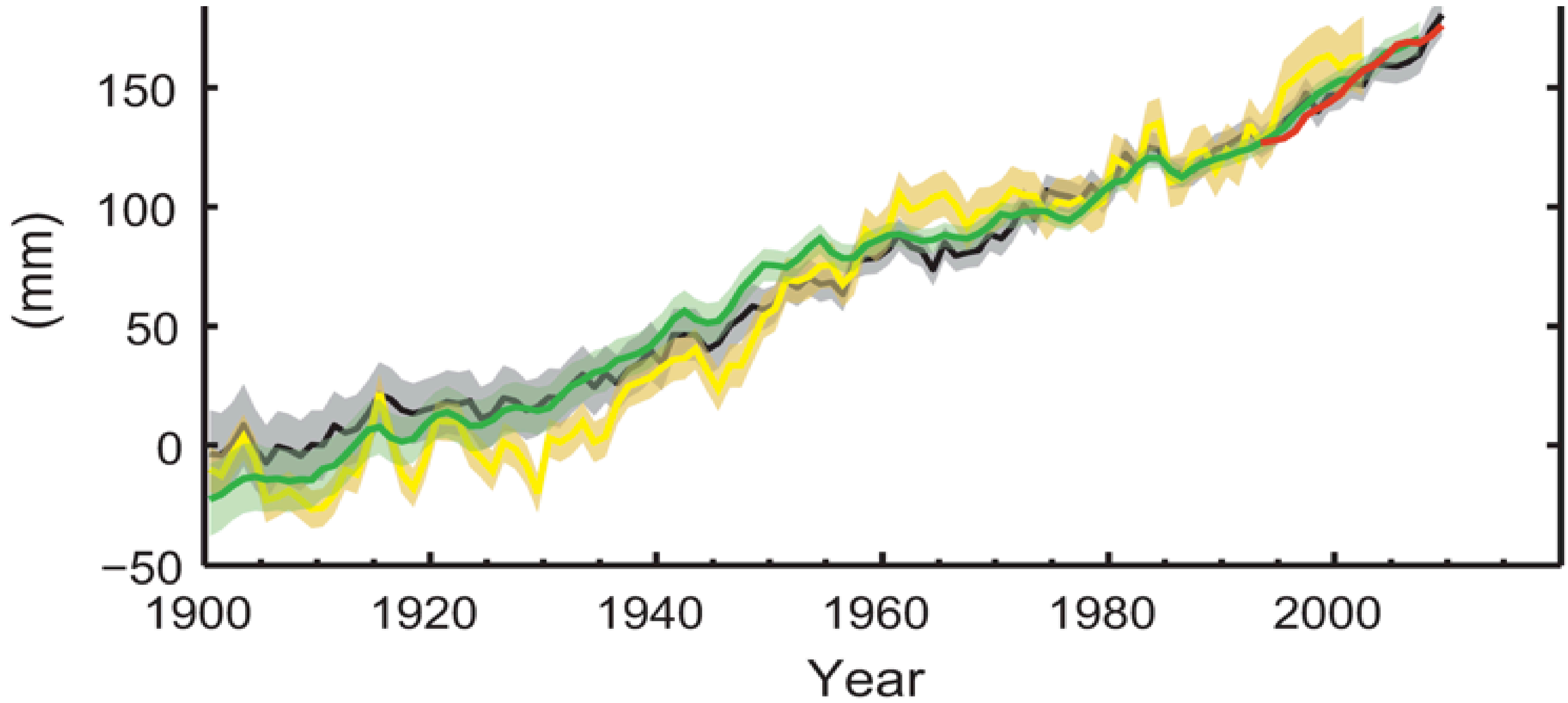
3. Observations



3. Observations

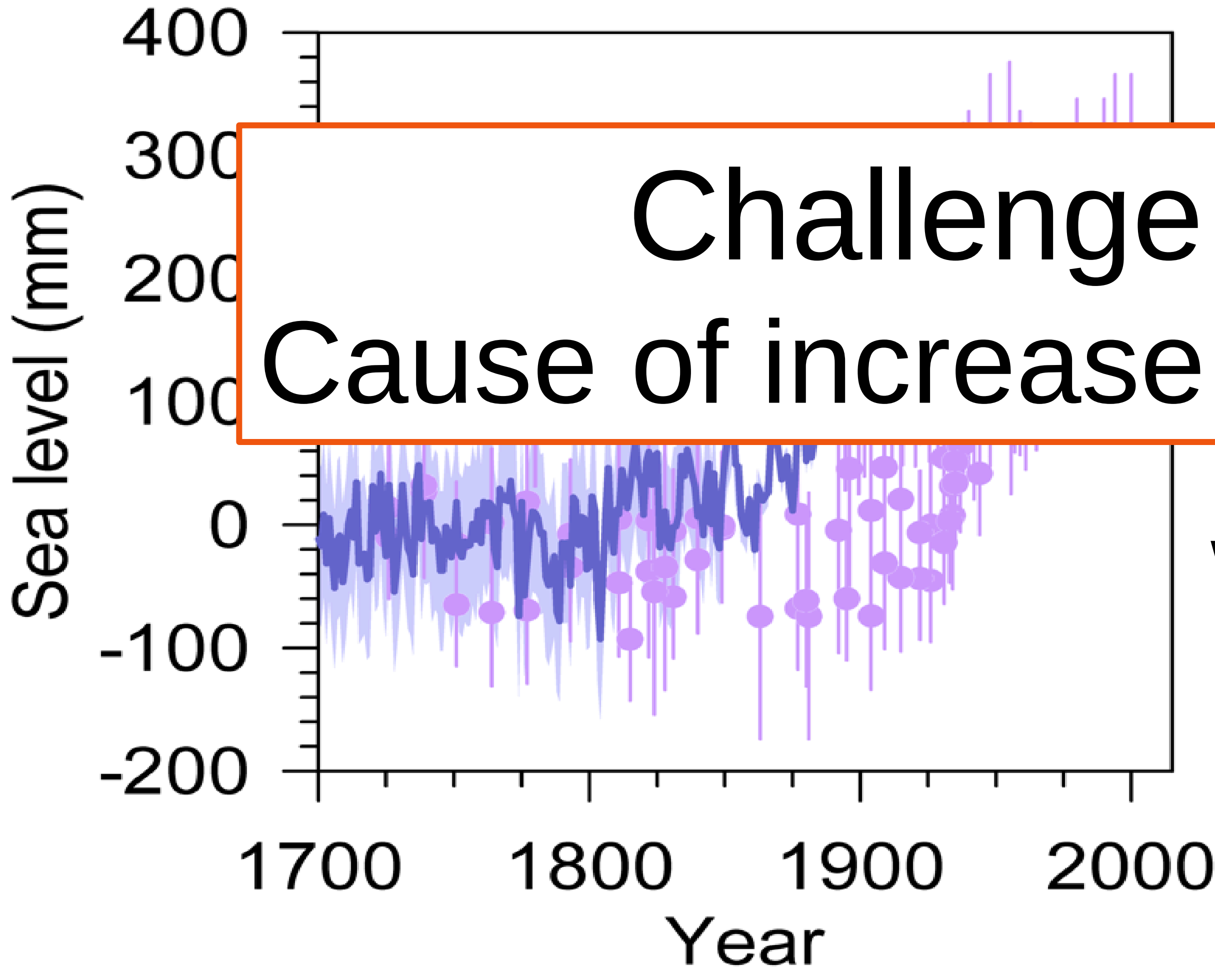
1901-2010: GMSL *very likely* rose 0.19 [0.17 to 0.21] m.

Likely that GMSL accelerated during this period.



3. Observations

Rate of GMSLR since early-20th century > rate during previous two millennia (*medium confidence*).



Challenge:
Cause of increase in rate.

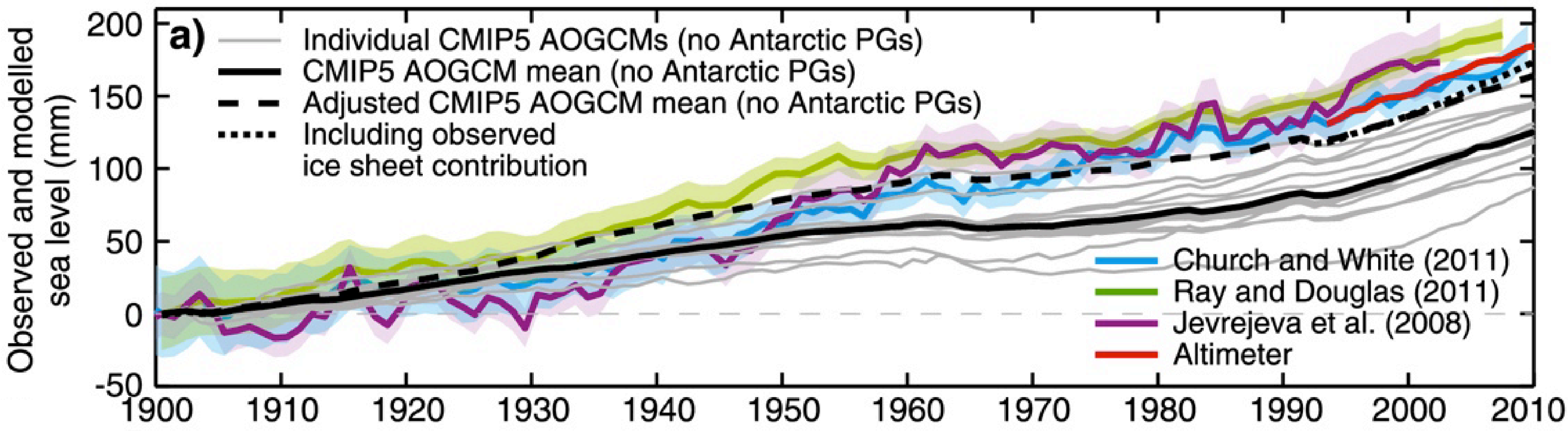
2010 was
n yr^{-1}.

Rate during previous 2 kyr was O(0.1) mm yr^{-1}.

4. Understanding

1901-1990: 1.5 [1.3 to 1.7] mm yr^{-1}

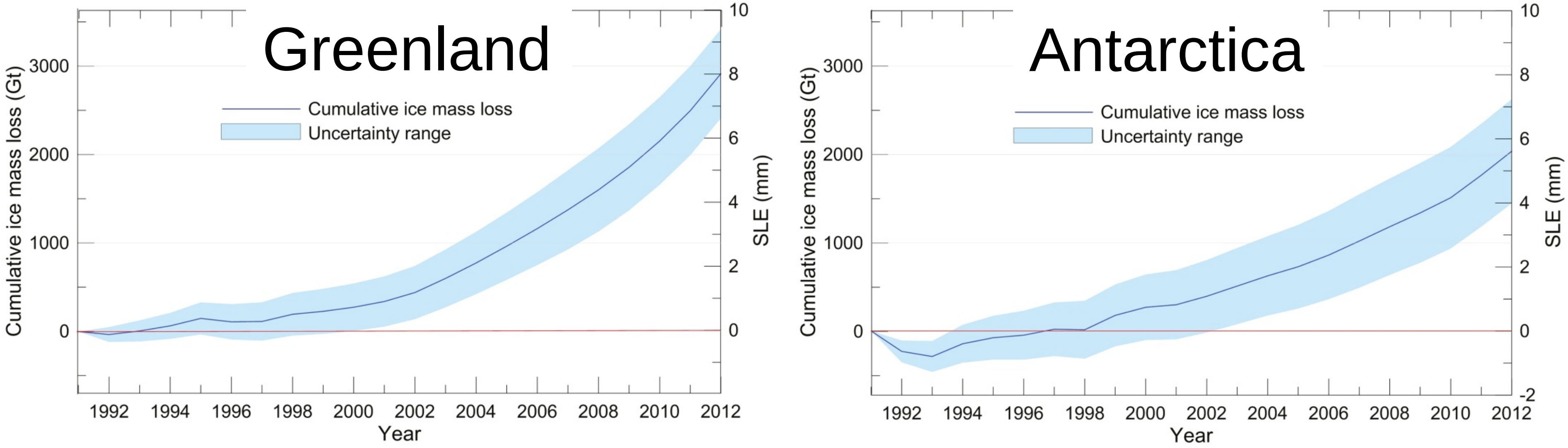
- Glaciers + expansion + LW storage = 65% GMSLR.
- Residual possibly by mass loss from Greenland and Antarctic ice sheets, but *no observational estimates*.



4. Understanding

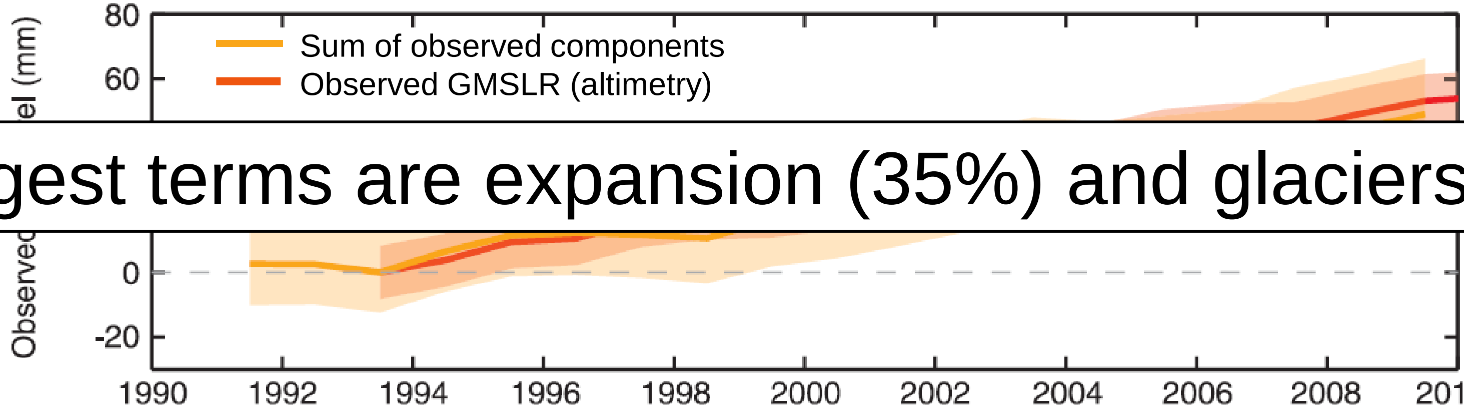
1993-2010: *vey likely* 3.2 [2.8 to 3.6] mm yr^{-1}

Observational estimates of ice sheets: recent increase in mass loss.



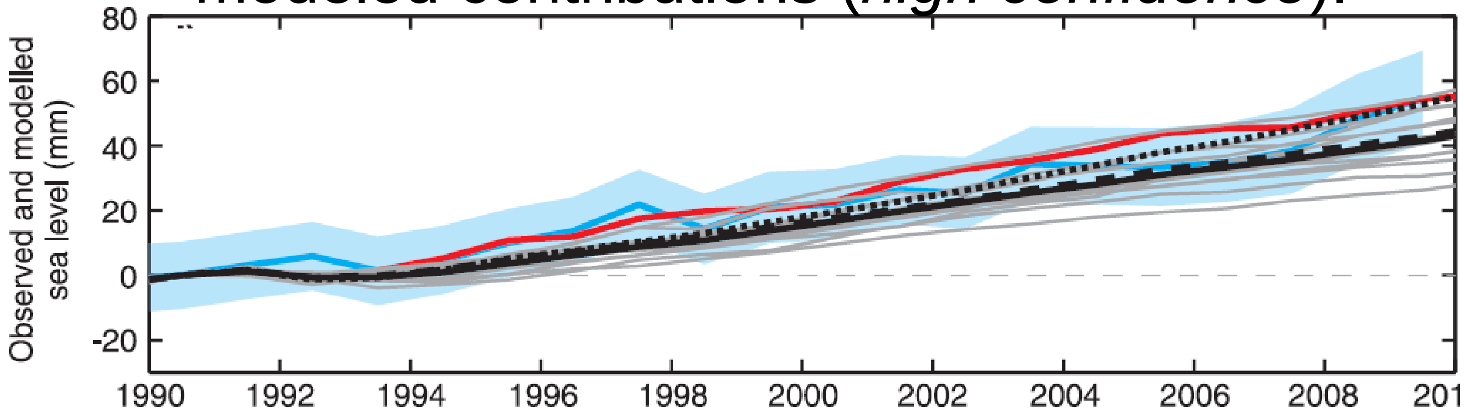
4. Understanding

1993-2010: Observed GMSLR is consistent with the sum of observed contributions (*high confidence*).



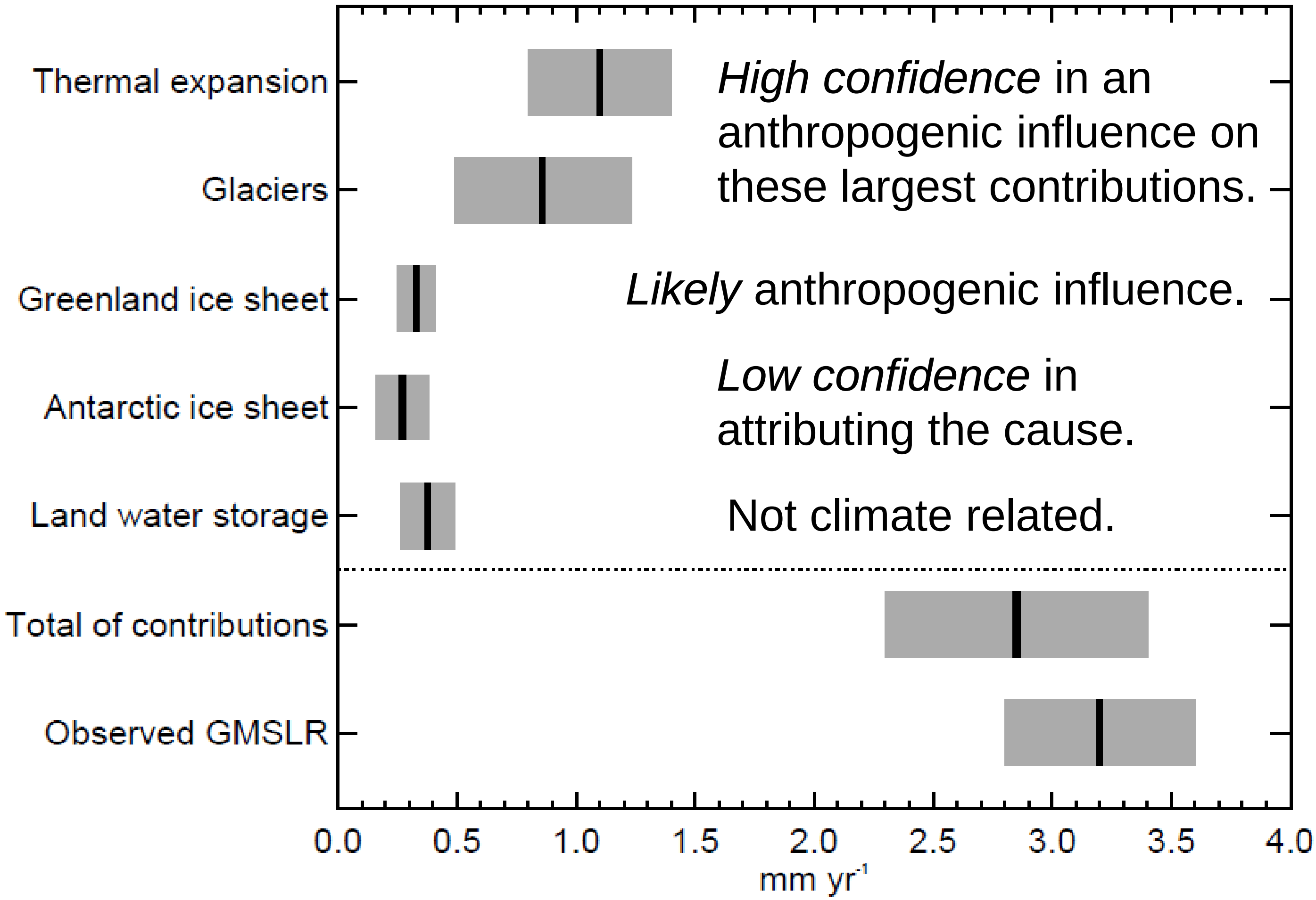
Largest terms are expansion (35%) and glaciers (25%)

1993-2010: Observed GMSLR is consistent with the sum of modeled contributions (*high confidence*).



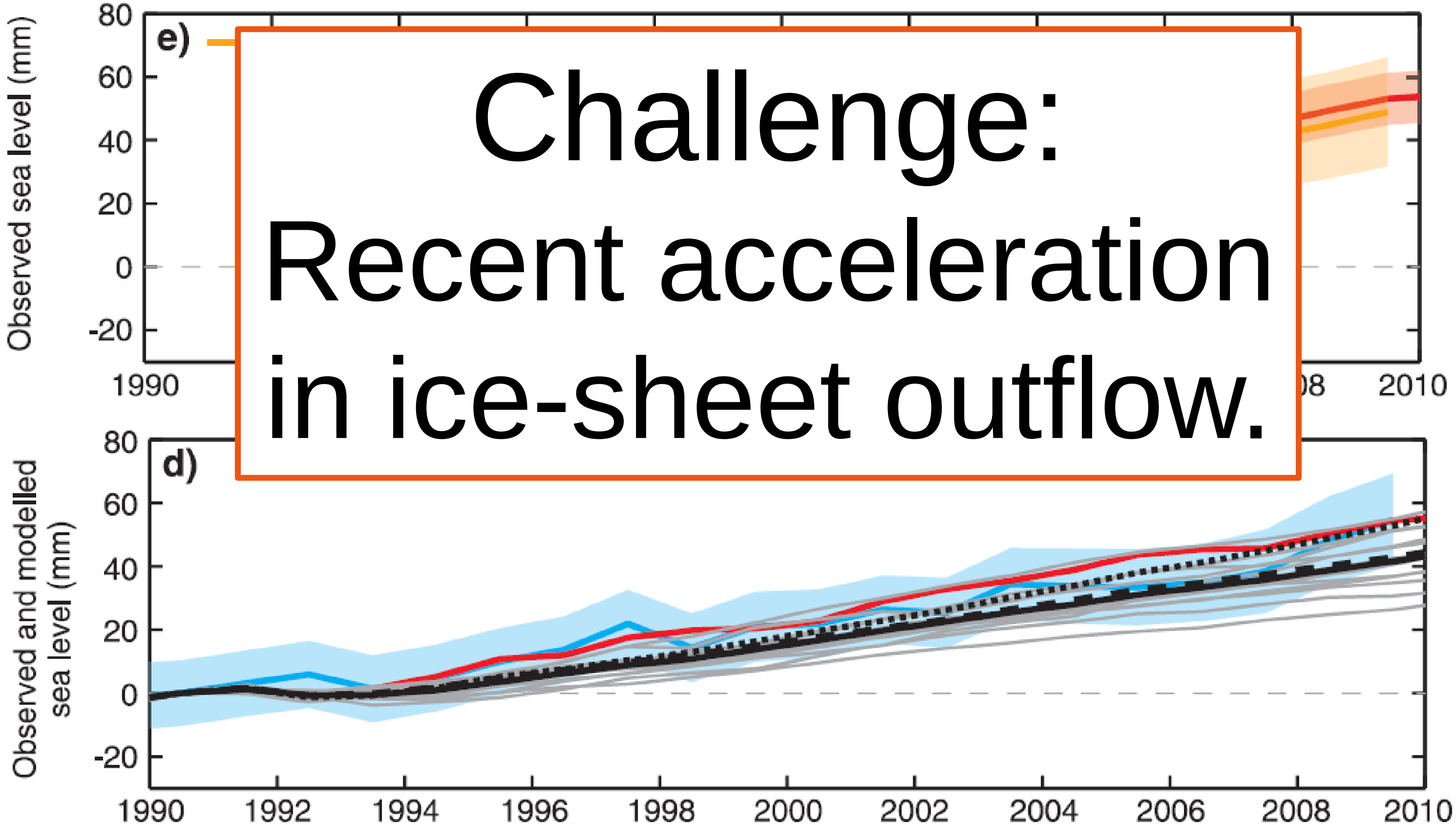
4. Understanding

Very likely that there is a substantial anthropogenic contribution to GMSLR since the 1970s.



4. Understanding

Closure of budget + consistency of models and observations = confidence in projections.

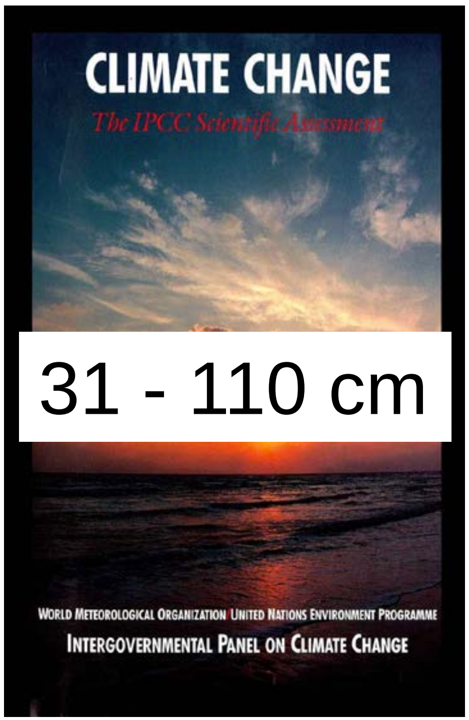


Challenge: Recent acceleration in ice-sheet outflow.

5. Projections

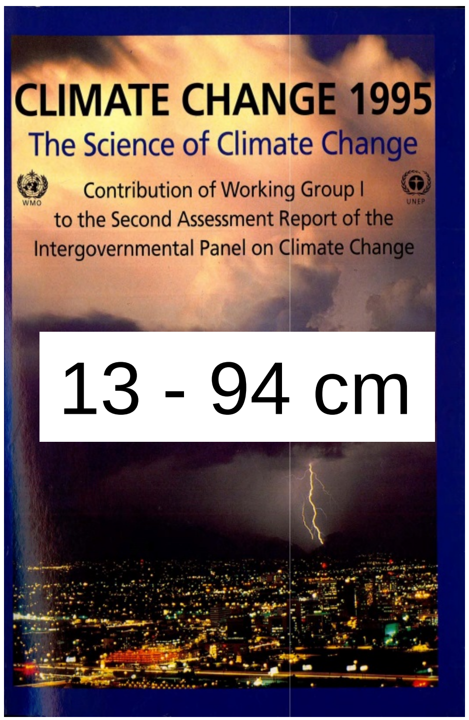
Range of sea-level projections for 2100

FAR (1990)



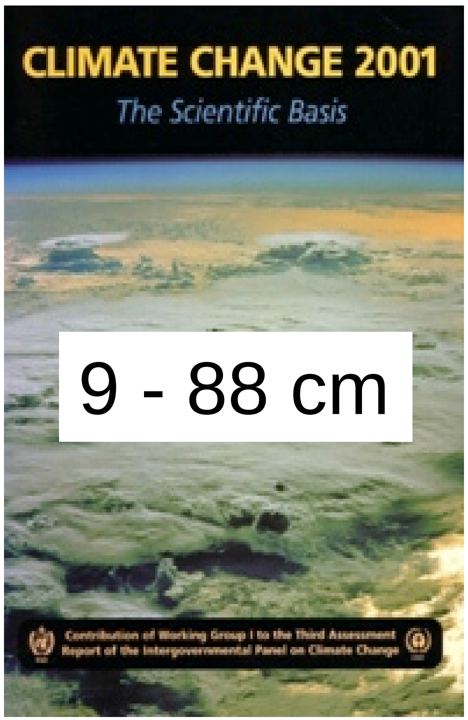
31 - 110 cm

SAR (1995)



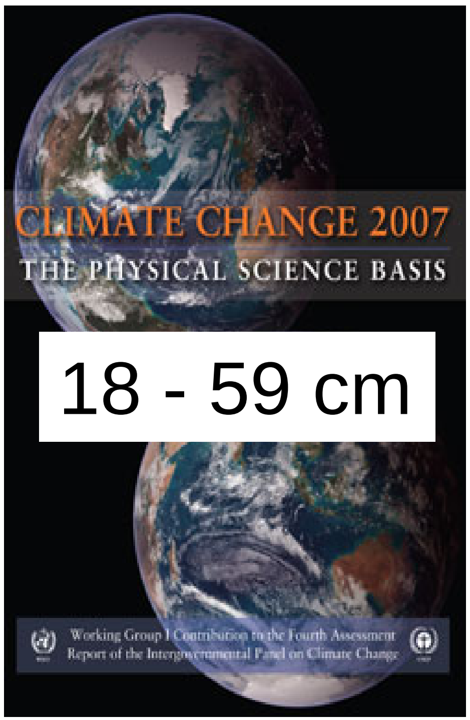
13 - 94 cm

TAR (2001)



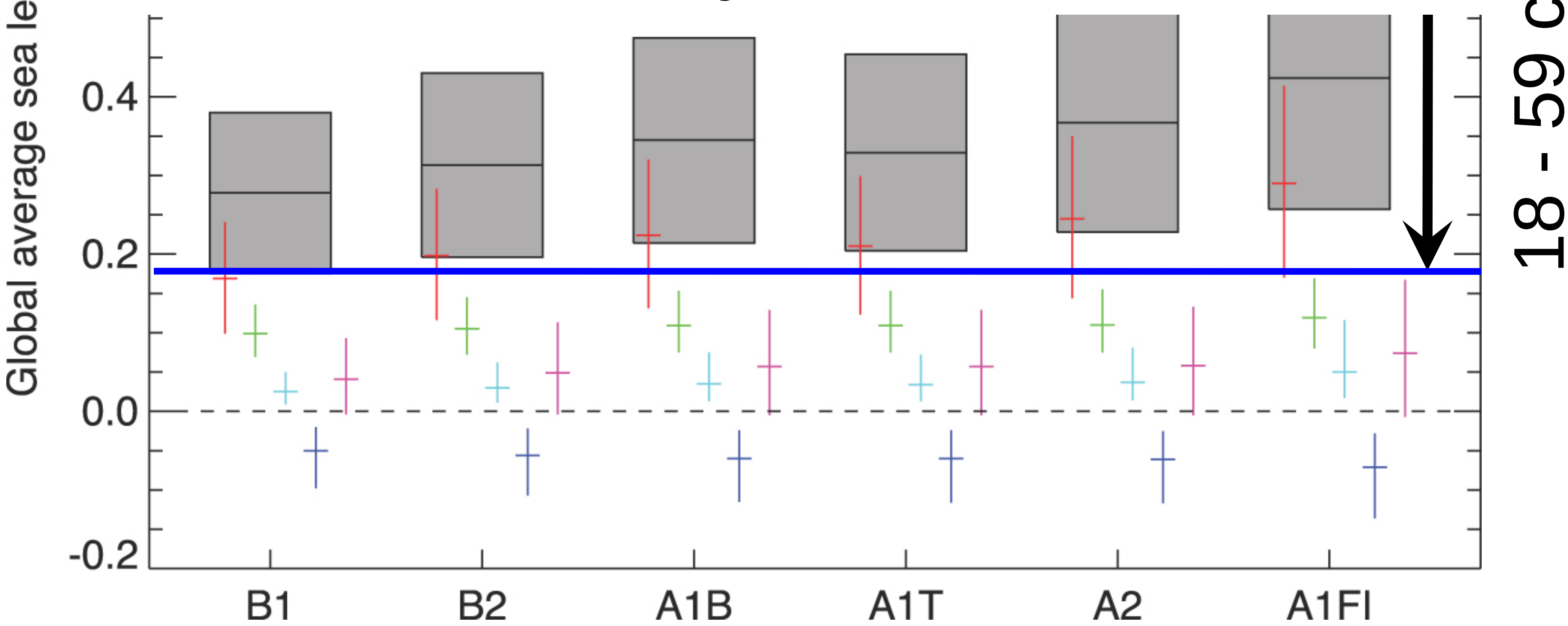
9 - 88 cm

AR4 (2007)



18 - 59 cm

Caveat: Understanding of ice-sheet dynamics was too limited to assess a *likely* range or best estimate for GMSLR under any scenario.



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5. Projections

AR5 assessed two approaches.

(1) Semi-empirical models – statistical relationship between observed GMSL and GM temperature of RF (no processes).

(2) Process-based models – sea level and land-ice models that simulate the underlying processes and interactions.

5. Projections

Semi-empirical models (SEMs)

Rate of sea level rise is proportional to global mean temperature (or RF) increase.

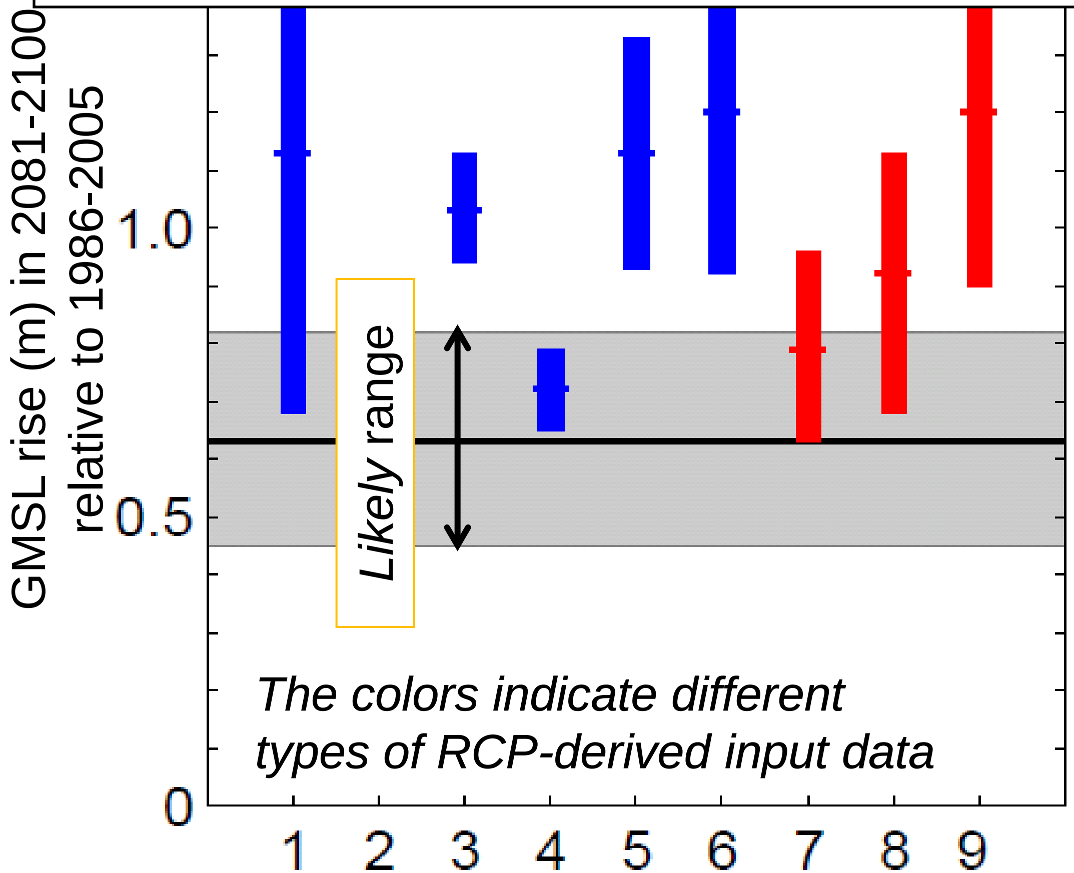
Assumption: same relationship used to construct SEMs holds for the future (i.e., statistical stationarity).

Two effects that may negate this assumption:
(1) Ocean heat uptake efficiency declines with warming.
(2) Glacier sensitivity to warming declines.

No consensus in scientific community.

5. Projections

Low confidence in the projections of semi-empirical models.



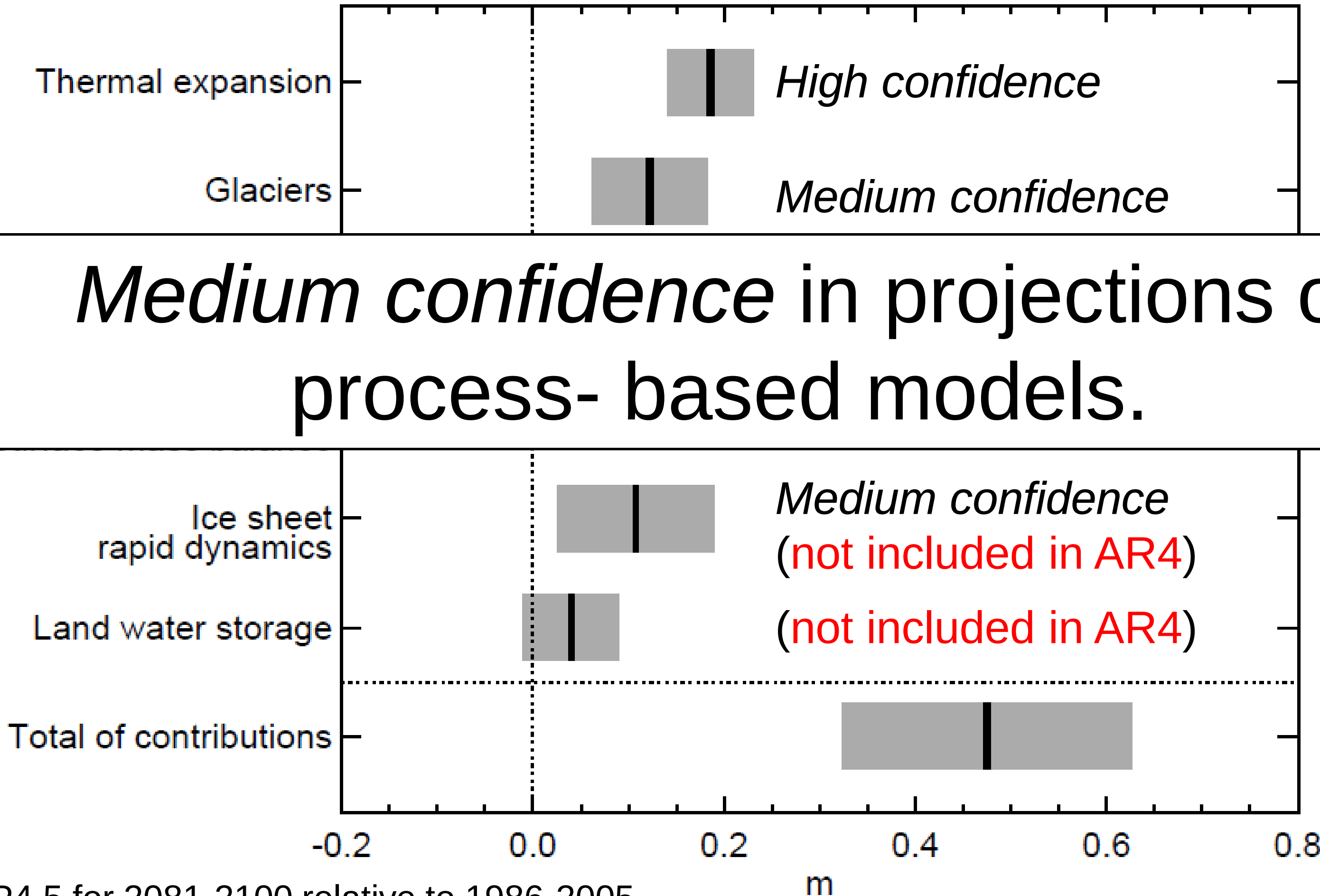
than the process-based *likely* range.

There is no evidence that glacier or ice-sheet dynamical change is the explanation for the higher projections.

- Not significant part of calibration period.
- Recent changes not clearly associated with global T or RF.

5. Projections

Process-based models.

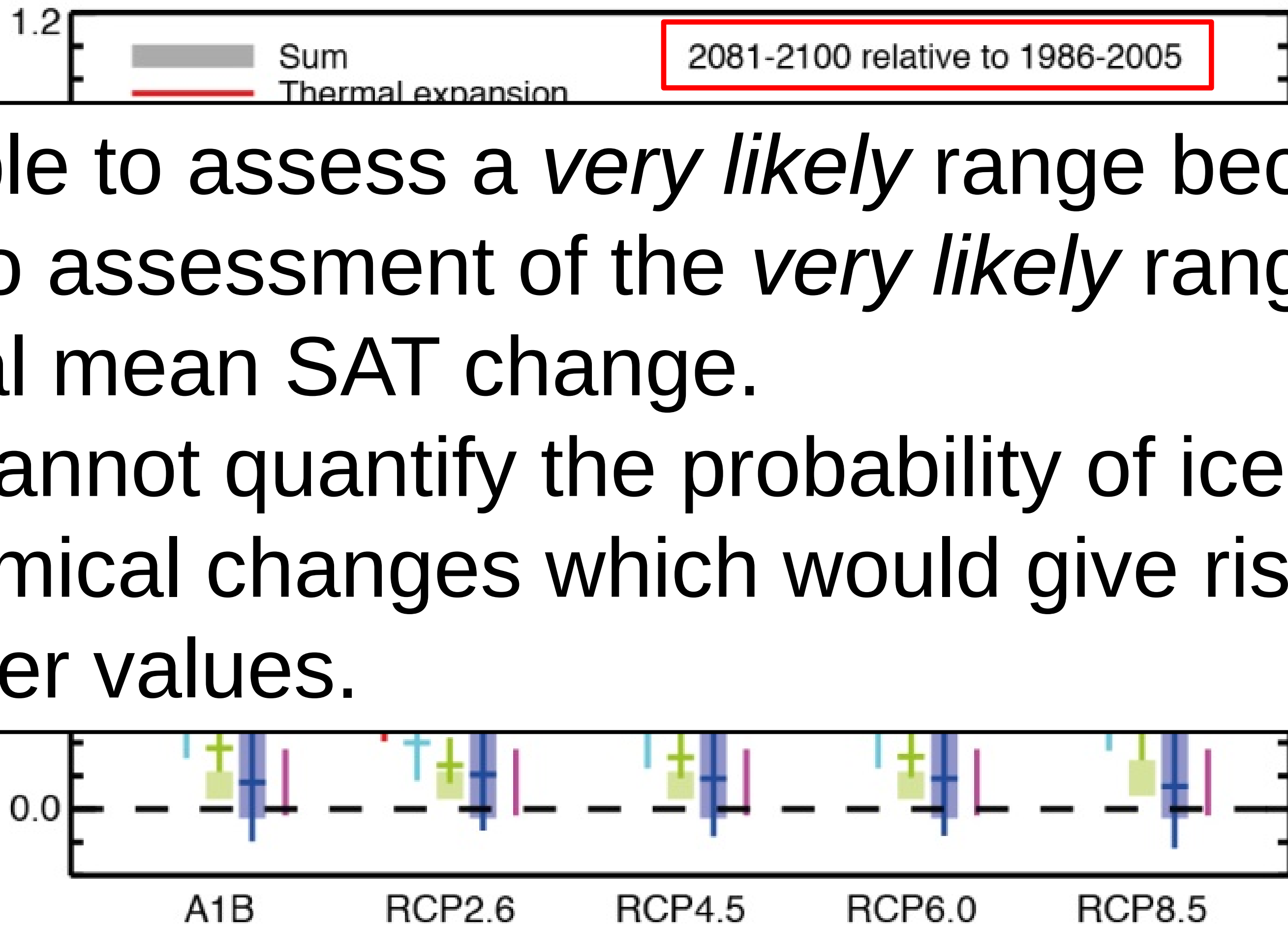


Medium confidence in projections of process- based models.

For RCP4.5 for 2081-2100 relative to 1986-2005.

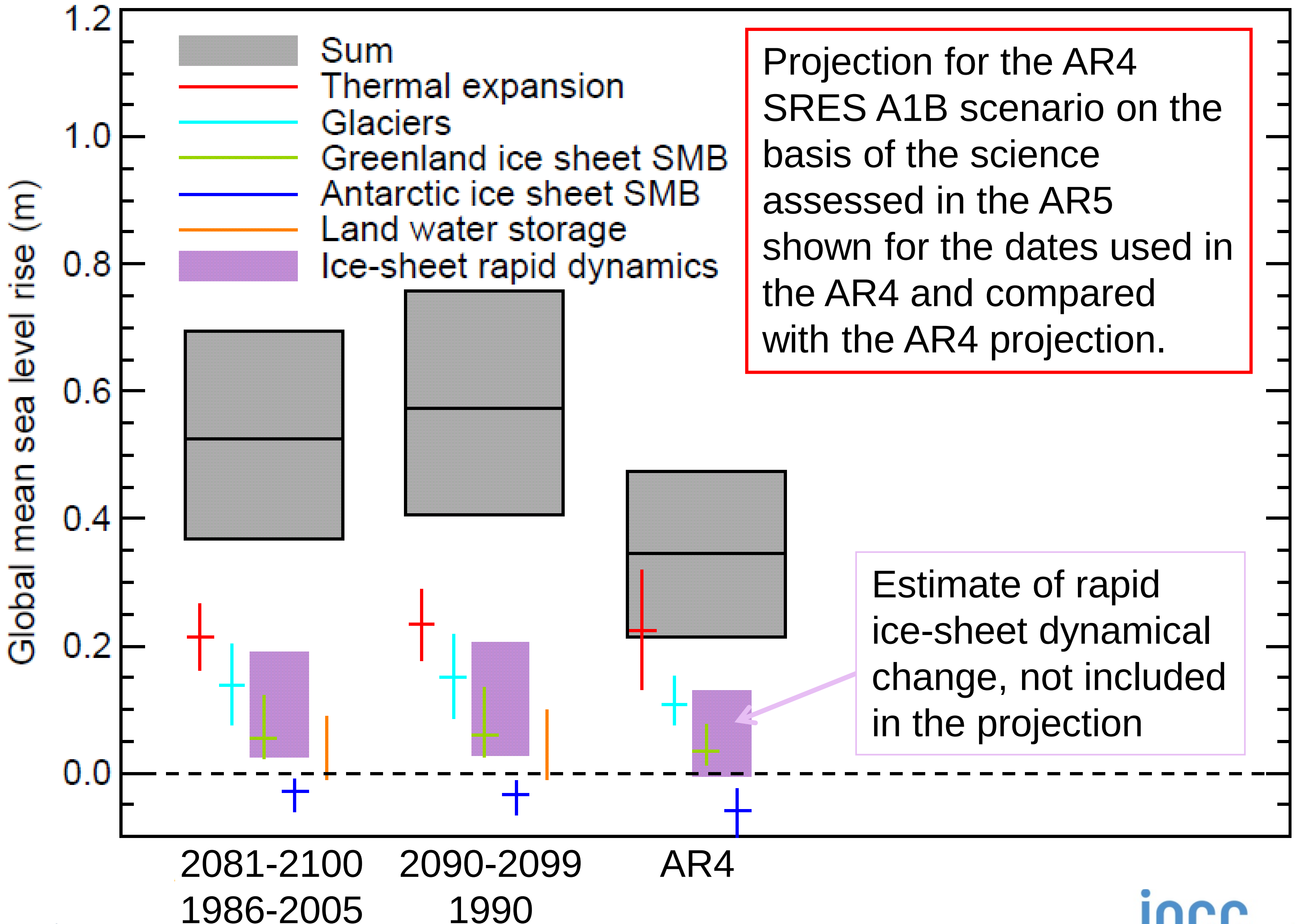
5. Projections

Process-based models – *likely* ranges.



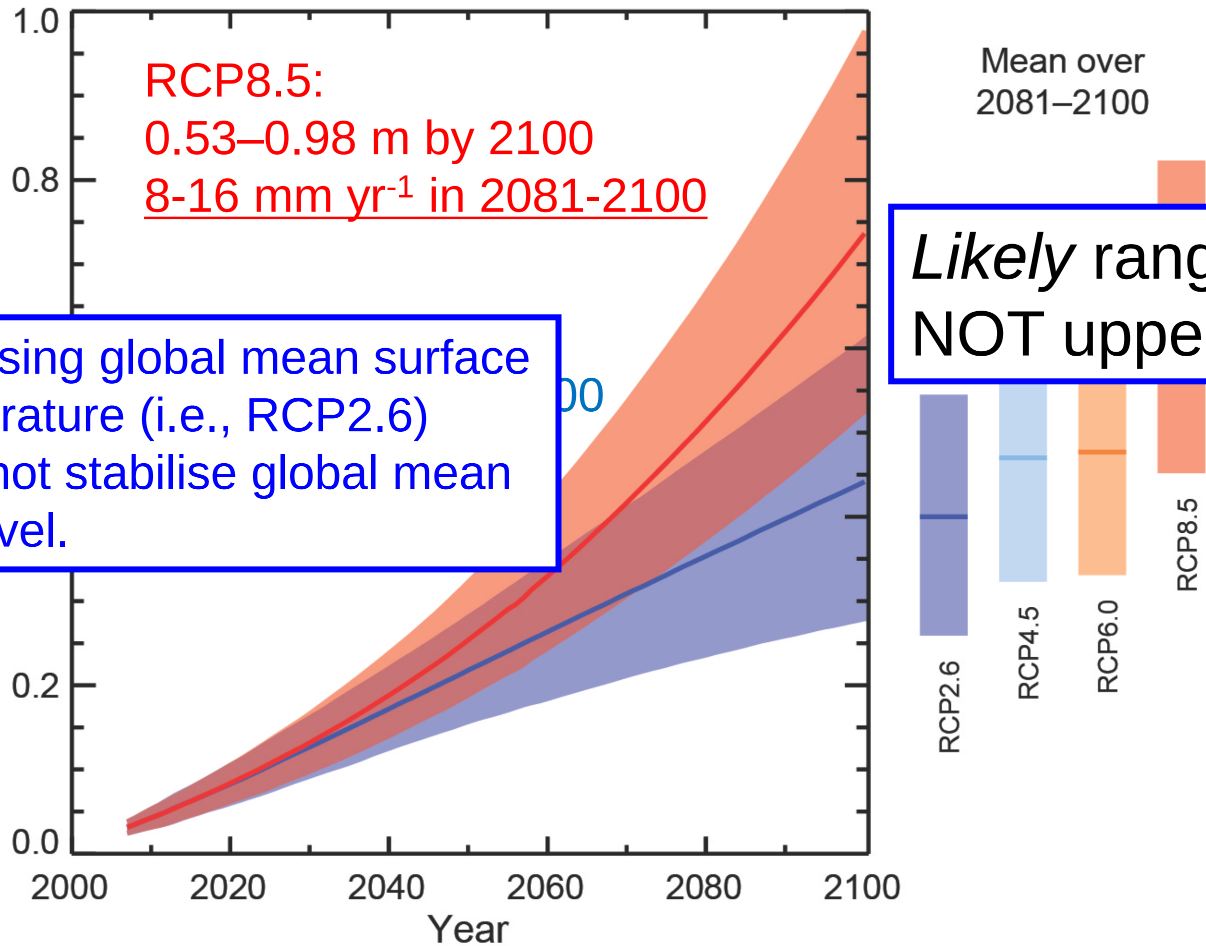
Unable to assess a *very likely* range because:
(1) no assessment of the *very likely* range for global mean SAT change.
(2) Cannot quantify the probability of ice-sheet dynamical changes which would give rise to greater values.

5. Projections



5. Projections

Under all RCPs the rate of GMSLR will *very likely* exceed that observed during 1971–2010.

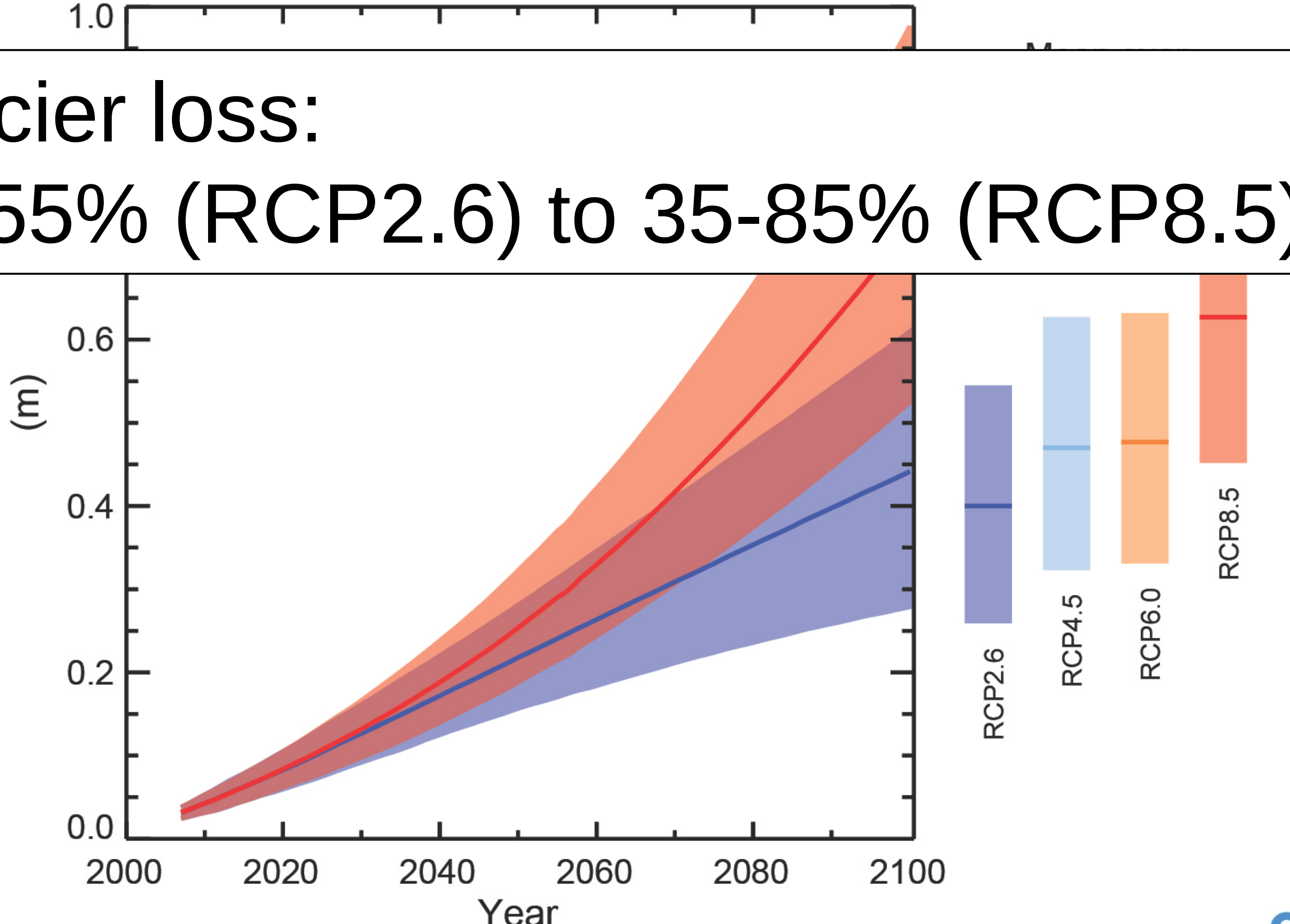


Stabilising global mean surface temperature (i.e., RCP2.6) does not stabilise global mean sea level.

Likely ranges – NOT upper bounds.

5. Projections

Thermal expansion accounts for 30 to 55% of 21st century GMSLR, and glaciers for 15 to 35%.

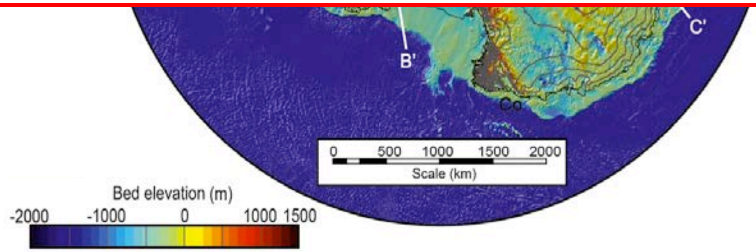


Glacier loss:
15-55% (RCP2.6) to 35-85% (RCP8.5)

5. Projections

- Only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century.

- The potential additional contribution cannot be precisely quantified, but *medium confidence* that this additional contribution would not exceed several tenths of a metre.



5. Projections

Challenges:

- Spread of climate models used for thermal and glacier projections.

- Modeling ice-sheet dynamics (MISI) and ice sheet-ocean-climate interactions.

- Current evidence and understanding do not allow a quantification of either the timing of onset of Antarctic collapse or of the magnitude of its multi-century contribution.

5. Projections

It is *virtually certain* that GMSLR will continue for many centuries beyond 2100.

Sustained warming above a certain threshold leads to near-complete loss of the Greenland ice sheet (*high confidence*).

The threshold is >1^{o}C (*low confidence*) but <4^{o}C (*medium confidence*) global mean warming w.r.t. pre-industrial.

5. Projections

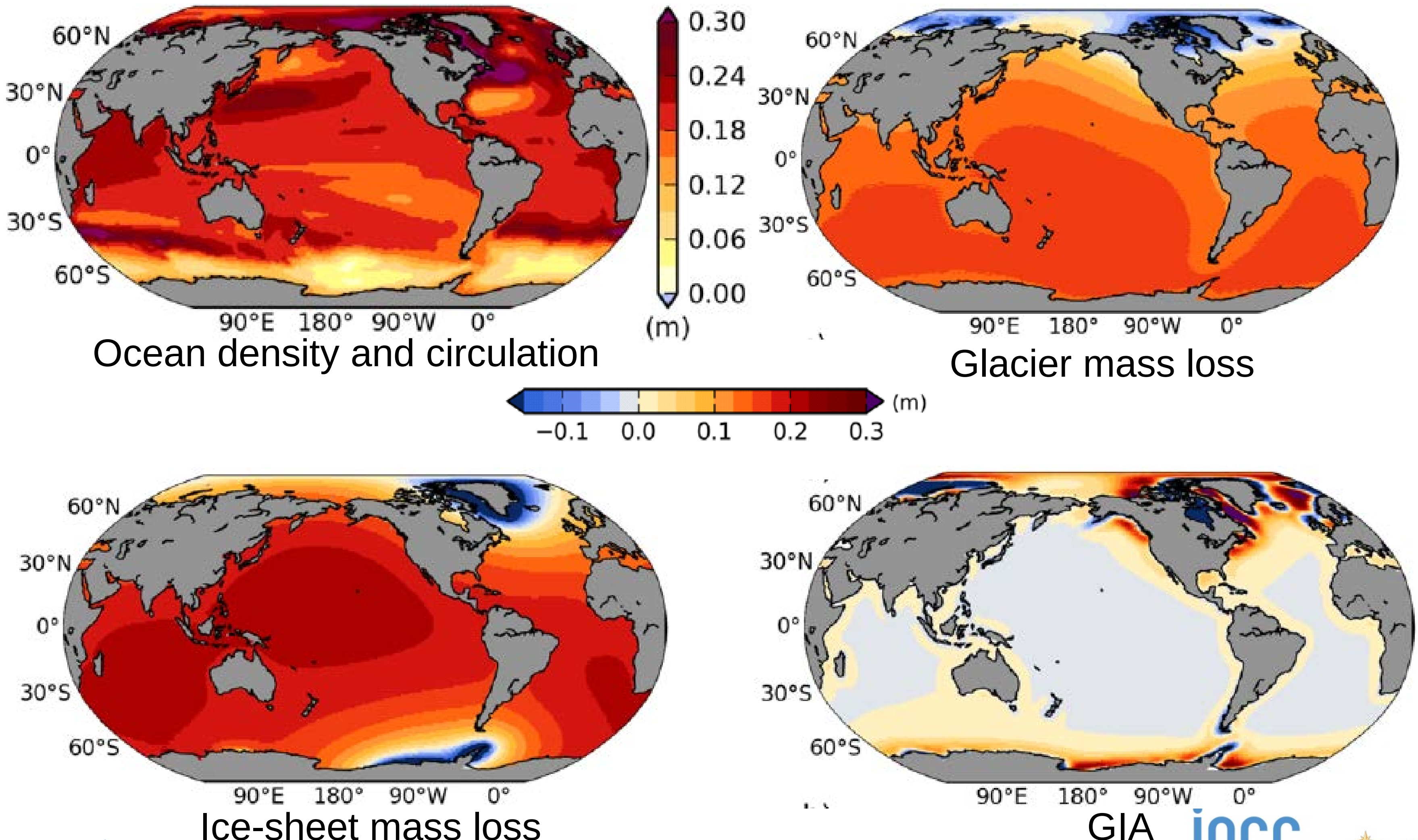
It is *virtually certain* that GMSLR will continue for many centuries beyond 2100.

Challenges:

- Large uncertainty in ice-sheet dynamical projections.
- Greenland threshold.

6. Regional Sea Level

Multiple causes for non-uniform sea level rise.



(for RCP4.5 2081-2100)

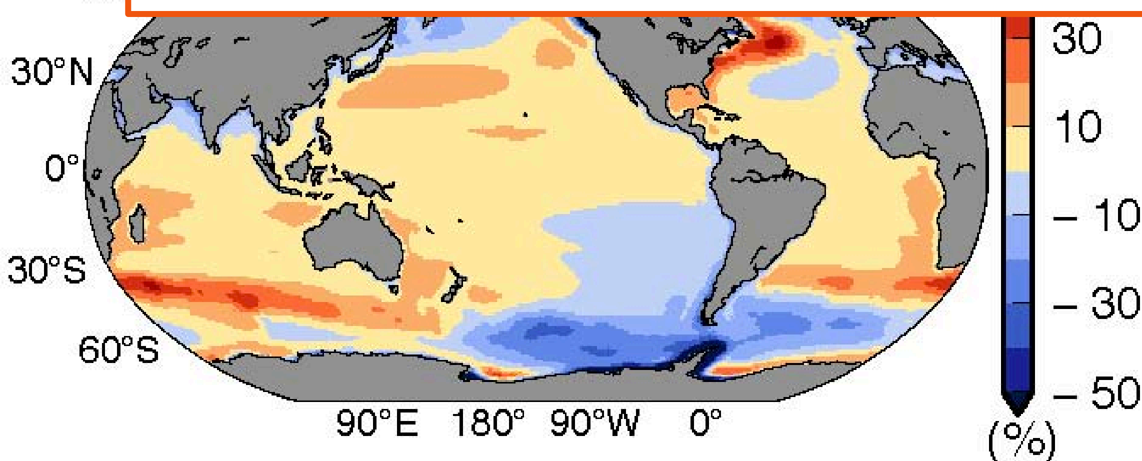
6. Regional Sea Level

Regional sea level rise by the end of the 21st century.

>95%
n area
kely).

Challenge:

Modeling ocean dynamics and circulation, rates of mass loss.



el
change for ~70% of coastlines within 20% of GMSL.

7. Post-IPCC Research

ARTICLES
PUBLISHED ONLINE: 16 MARCH 2014 | DOI: 10.1038/NCLIMATE2161
nature climate change

Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming

Shfaqat A. Khan[1*], Kurt H. Kjær[2], Michael Bevis[3], Jonathan L. Bamber[4], John Wahr[5], Kristian K. Kjeldsen[2], Anders A. Bjørk[2], Niels J. Korsgaard[2], Leigh A. Stearns[6], Michiel R. van den Broeke[7], Lin Liu[8†], Nicolaj K. Larsen[9] and Ioana S. Muresan[1]

The finding … will likely boost estimates of expected global sea level rise in the future...*

*From press release.

7. Post-IPCC Research

Assessed upper limit of *likely* range for GrIS dynamics.

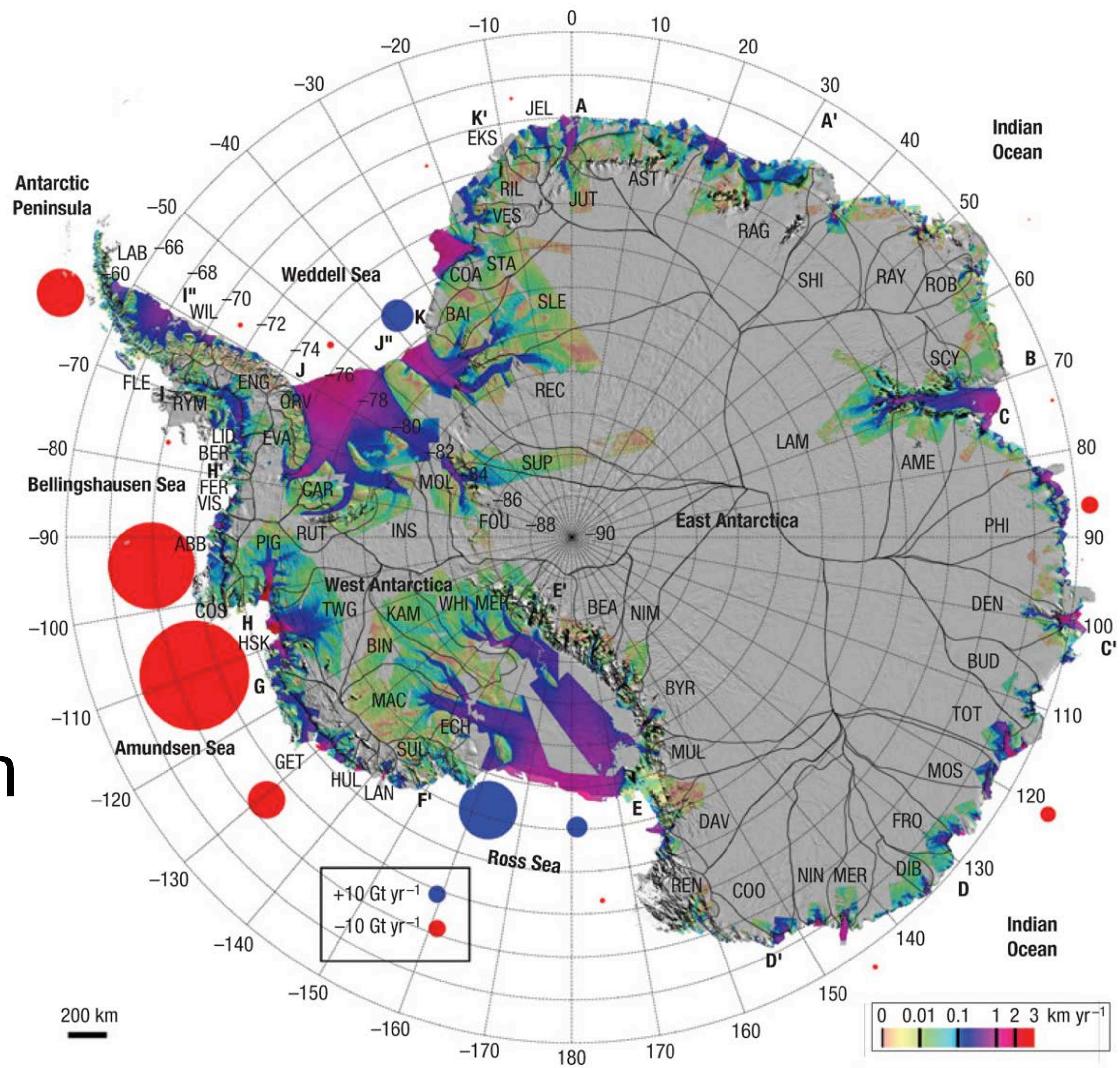
Based on forcing from scenarios A1B and RCP8.5, flowline modeling of four glaciers which drain 22% of GrIS gives (Nick et al., 2013):

A1B: 13 mm
RCP8.5: 18 mm

Scaling between modeled and <u>total</u> ice-sheet area (a factor of ~5) generalizes these numbers for the whole ice sheet (<u>including NE GrIS</u>) as:

A1B: 63 mm
RCP8.5: 85 mm

7. Post-IPCC Research



Amundsen Sea

Rignot et al. (2008)

7. Post-IPCC Research

nature climate change
LETTERS
PUBLISHED ONLINE: 12 JANUARY 2014 | DOI: 10.1038/NCLIMATE2094

Retreat of Pine Island Glacier controlled by marine ice-sheet instability

L. Favier[1,2], G. Durand[1,2]★, S. L. Cornford[3], G. H. Gudmundsson[4,5], O. Gagliardini[1,2,6], F. Gillet-Chaulet[1,2], T. Zwinger[7], A. J. Payne[3] and A. M. Le Brocq[8]

- Grounding line is probably engaged in an unstable 40 km retreat.
- Modeling: The associated mass loss increases up to and above 3.5–10 mm eustatic sea-level rise over the following 20 years.
- Mass loss remains elevated from then on, equivalent to 0.17–0.34 mm yr^{-1} [total of 15.5-34 mm if extrapolated to 2100].

7. Post-IPCC Research

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley   SCIENCE VOL 344 16 MAY 2014

"The new projections of sea-level rise are higher and potentially more devastating than earlier projections by the IPCC. The findings probably will force the IPCC to increase its current estimate of up to three feet of sea-level rise by 2100, said …"
Washington Post

7. Post-IPCC Research

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley

SCIENCE VOL 344 16 MAY 2014

"The recent reports from the IPCC don't include melt from West Antarctic in their projections and this would mean far more sea level rise, said …"
Scientific American

7. Post-IPCC Research

Summary

PIG = 34 mm by 2100

Thwaites = 21 mm by 2100

Total = 55 mm by 2100

Implications

- The AR5 assessment of upper limit of *likely* range for rapid AIS dynamics from these two drainages is 80 mm.
- Additional contribution from MISI limited to the large ice shelves (Ross and Ronne/Filchner).

8. Summary

1) The evidence now available gives a clearer account of observed GMSL change than in previous IPCC assessments, giving confidence in the 21st century sea level projections.

2) The AR5 assessment makes a complete projection of sea level rise, including ice-sheet dynamics, which is a big step forward from AR4.

3) Assessments were only possible at *medium confidence*, so much work remains, particularly with coupled ice sheet-climate models.

8. Summary

4) AIS marine instability is highlighted as the only mechanism that could raise sea level significantly above the *likely* range – a conditional assessment of magnitude is given but no probability could be attached to this. However, post-IPCC research indicates that the AR5 assessment of an additional few tens of cms is generous.

5) Post-2100 sea level projections require substantial improvements in modeling long-term ice-sheet dynamics.


Climate Change 2013: The Physical Science Basis
Working Group I contribution to the IPCC Fifth Assessment Report
Further Information
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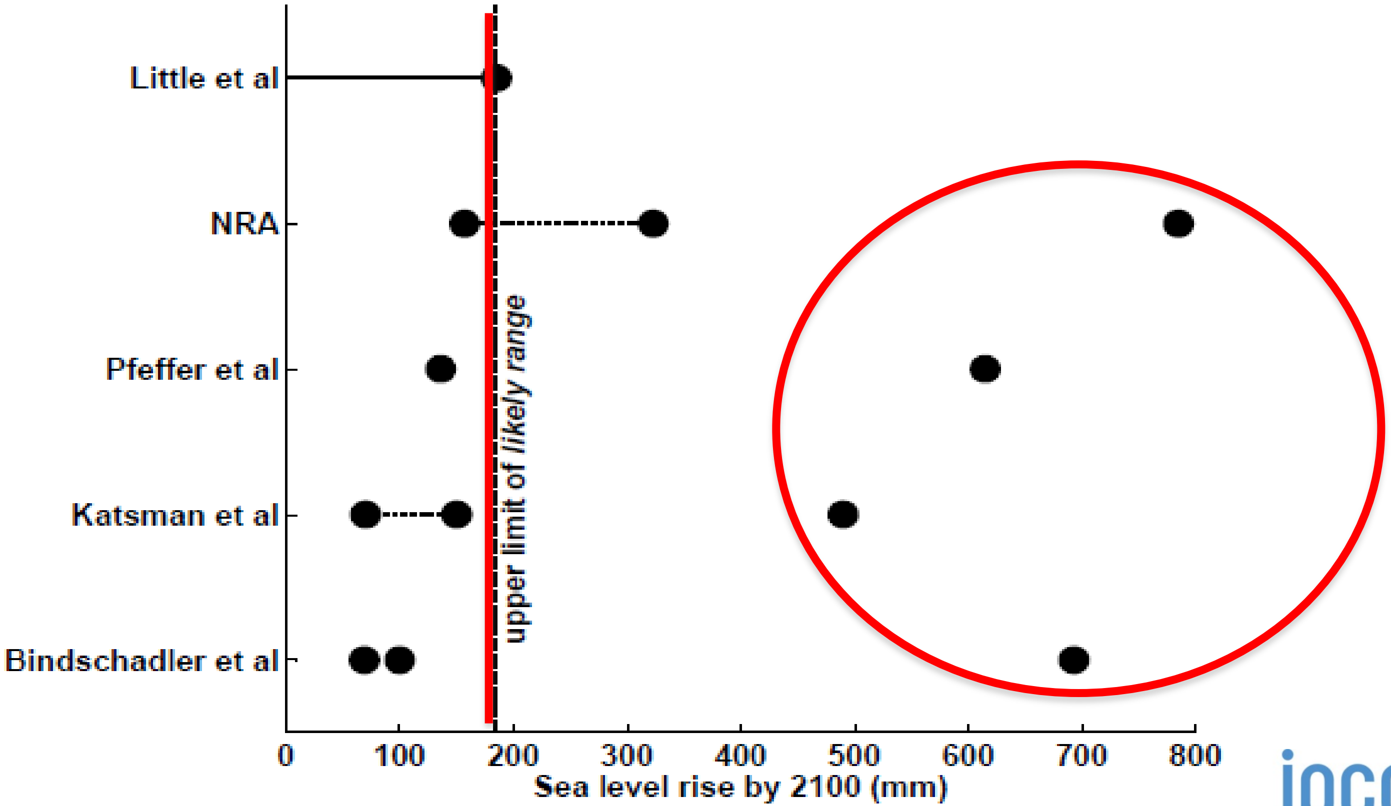
5. Projections

Upper limit of *likely* range for AIS dynamics is 185 mm: consistent with process-based modelling and physical intuition.

Projections above this level all relate to '*collapse*' scenarios.

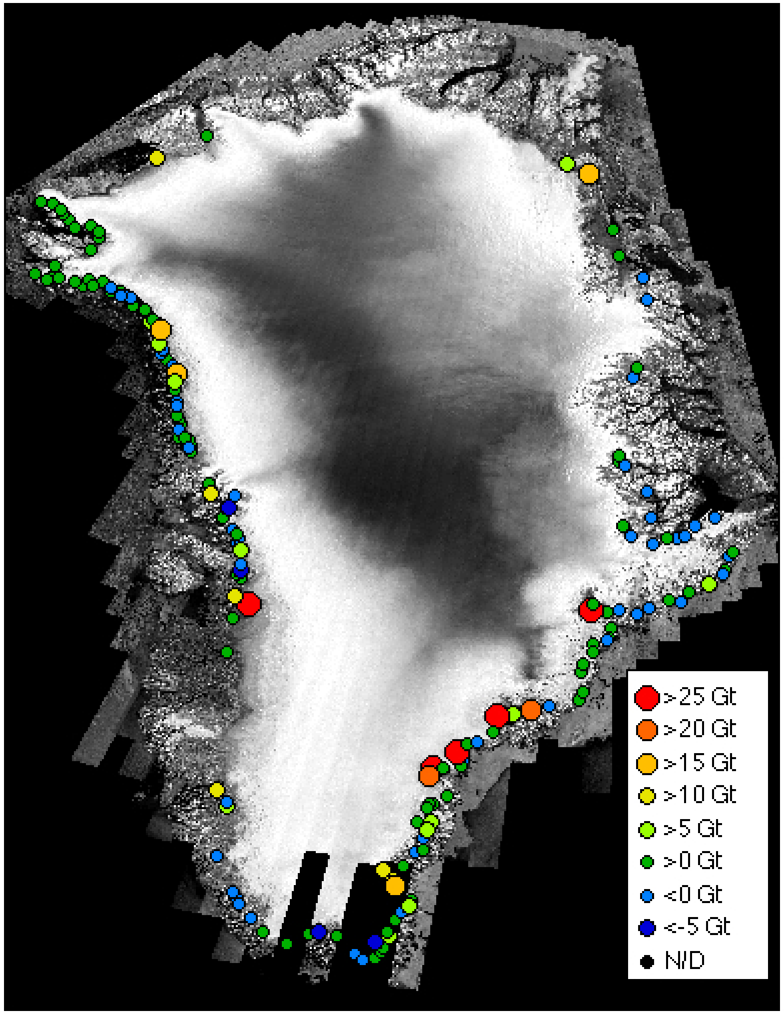


5. Projections

Probability that marine ice-sheet instability causing SLR outside the *likely* range.

1. Loss of Pine Island Glacier contributes ~cms and is therefore in *likely* range.
2. Grounds to believe Thwaites is less likely to retreat so lies above *likely* range. (see later)
3. Melt-ponds unlikely outside of Peninsula.
4. Ocean warming occurs too late in century to affect SLR substantially.
5. Grounding line may stabilize (i.e., instability not inevitable).

7. Post-IPCC Research



Sea level projection methods

- **Projection of thermal expansion, glaciers and SMB (both ice sheets)**

1. for each individual study, accumulated SL change (m) is related to integrated air temperature (K yr) using regression for each CMIP model and scenario
2. probability distribution (assumed normal or log-normal) fitted to these derived coefficients for SL component

- **Projection of ice sheet outflow**

1. Quadratic fitted to assessed SL by end of century for lower and upper limits of likely range
2. Assume uniform probability within likely range.

- **Joint ranges evaluated using Monte Carlo sampling from these parameter distributions for each contributor**

Derivation of global surface temperature and thermal expansion time series from CMIP5.

Annual time series for change in global mean surface air temperature (SAT) ('tas' in the CMIP5 archive) and global-mean sea level (GMSL) rise due to thermal expansion ('zostoga') in the historical period and during the 21st century under RCP scenarios were obtained from a set of 21 CMIP5 AOGCMs (ACCESS1-0, ACCESS1-3, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, CanESM2, GFDL-CM3, GFDL-ES-M2G, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M, NorESM1-ME, inmcm4).

Uncertainties were derived from the CMIP5 ensemble by treating the model spread as a normal distribution, and it was assumed that the 5 to 95% interval of CMIP5 projections for the 21st century for each RCP scenario can be interpreted as a *likely* range.

Glacier model

A parameterized scheme which was fitted separately to results from four global glacier models.

Glacier model:
$g_I(t) = fI(t)^p$
g_I = GMSL rise
I(t) = time integral of T to time t
f and p = constants

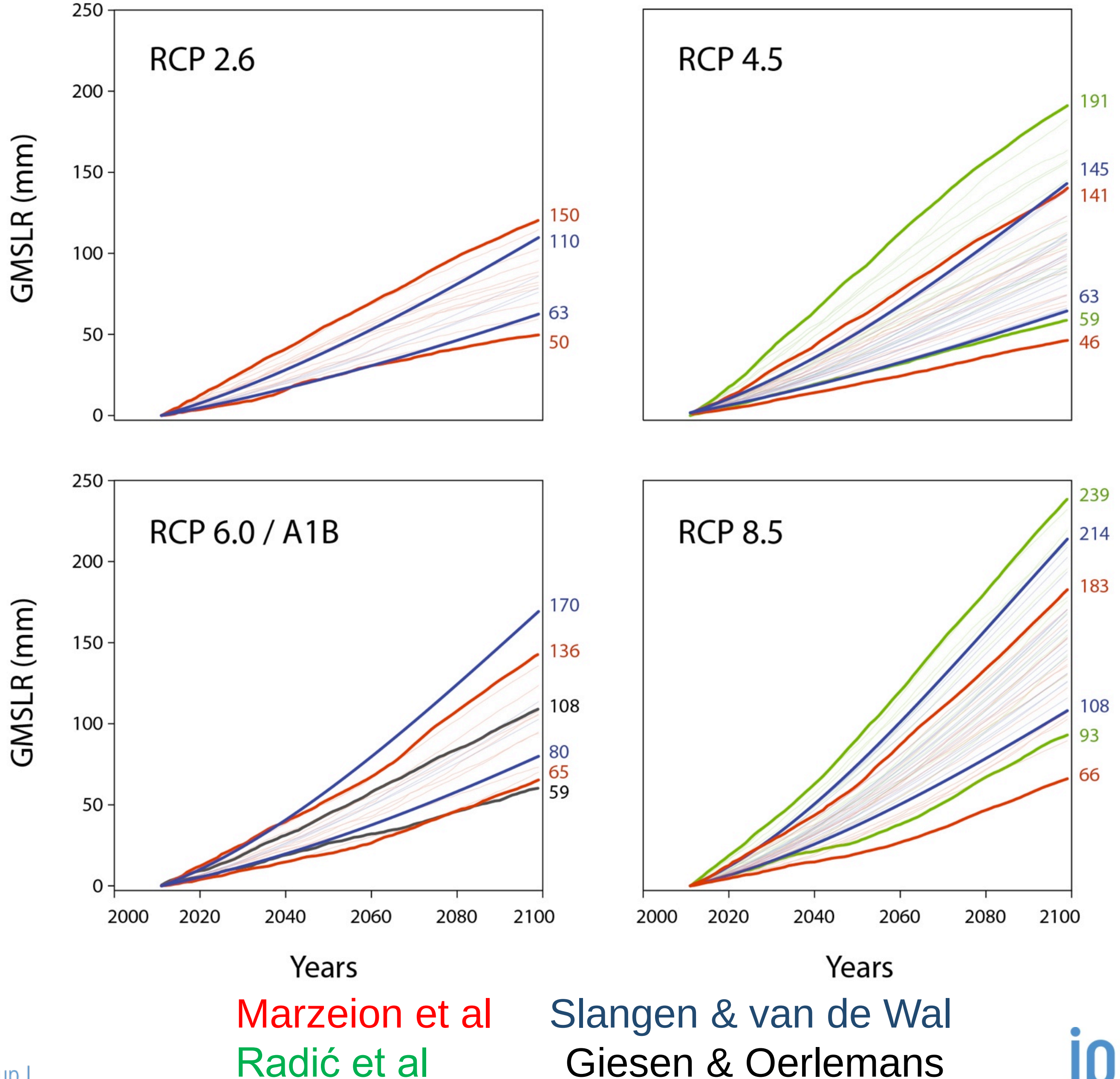
Table 13.SM.2 | Parameters for the fits to the global glacier models.

Global Glacier Model	f (mm °C^{-1} yr^{-1})	p (no unit)
Giesen and Oerlemans (2013)	3.02	0.733
Marzeion et al. (2012)	4.96	0.685
Radić et al. (2013)	5.45	0.676
Slangen and van de Wal (2011)	3.44	0.742

The spread of their results around the prediction of this formula has a coefficient of variation of 20% or less for decadal means for all glacier models and RCPs.

Therefore we take 20% of the projection of the formula made using the CMIP5 ensemble mean I(t) as the standard deviation of a normally distributed methodological uncertainty in the glacier projection for each global glacier model.

We give the four global glacier models equal weight in the projections.



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Ice-sheet projections

Separate ice sheet contributions into **SMB** and **outflow**

•SMB generally performed using regional climate models (RCMs) with energy-balance models forced by CMIP boundary conditions and fixed geometry

•confidence high (Greenland) or medium (Antarctic – projected increase in accumulation not observed)

Projections of **outflow** still in their infancy.

•range of techniques used including process-based modelling, physical intuition and statistical extrapolation.

•very limited ability to assess scenario dependence (hence assumed uniform across scenarios) and SRES forcing often used.

Ice-Sheet Surface Mass Balance

Greenland ice sheet SMB (Fettweis et al., 2013):

$G_e = -71.5T - 20.4T^2 - 2.8T^3$

$G_e = \text{Gt yr}^{-1}$

Antarctic ice sheet SMB:

solely to an increase in accumulation:

$5.1 \pm 1.5\%\ {}^{o}C^{-1}$

ratio of warming in Antarctic to global T = 1.1 ± 0.2

Rapid Ice-Sheet Dynamics

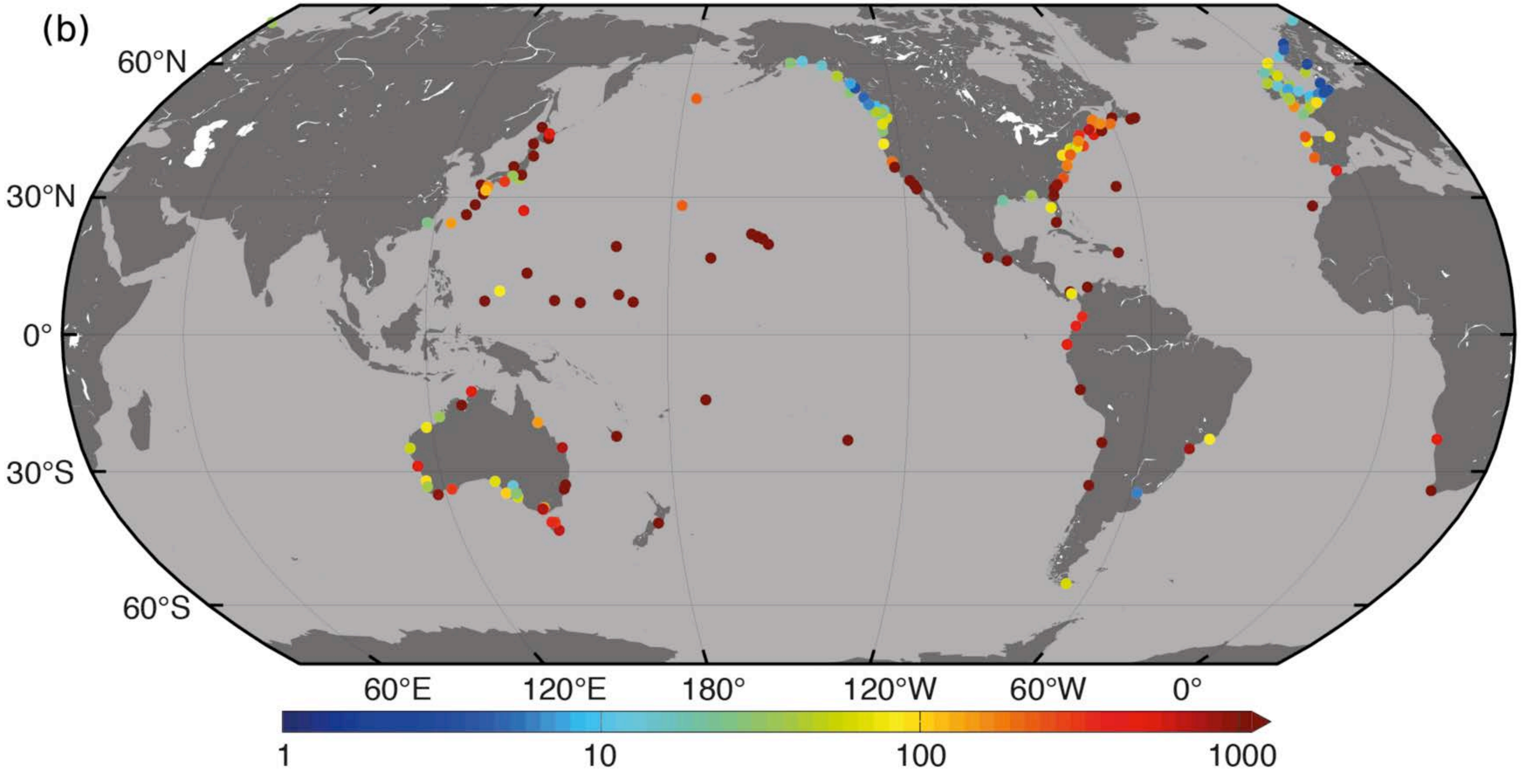
The contributions from rapid ice-sheet dynamics at the start of the projections were taken to be half of the observed rate of loss for 2005-2010 from Greenland (half of 0.46-0.80 mm yr-1) and all of that from Antarctica (0.21-0.61 mm yr-1).

The contributions reach the likely ranges from our assessment of existing studies (0.020 to 0.085 m at 2100 from Greenland for RCP8.5, 0.014 to 0.063 m for the other RCPs, and –0.020 to 0.185 m from Antarctica for all RCPs). For each ice sheet, a quadratic function of time was fitted which begins at the minimal initial rate and reaches the minimum final amount, and another for the maxima.

9. Regional Sea Level

Significant increase in sea level extremes.

This is primarily the result of an increase in local mean sea level which can lead to large increases in the frequency of extreme events.

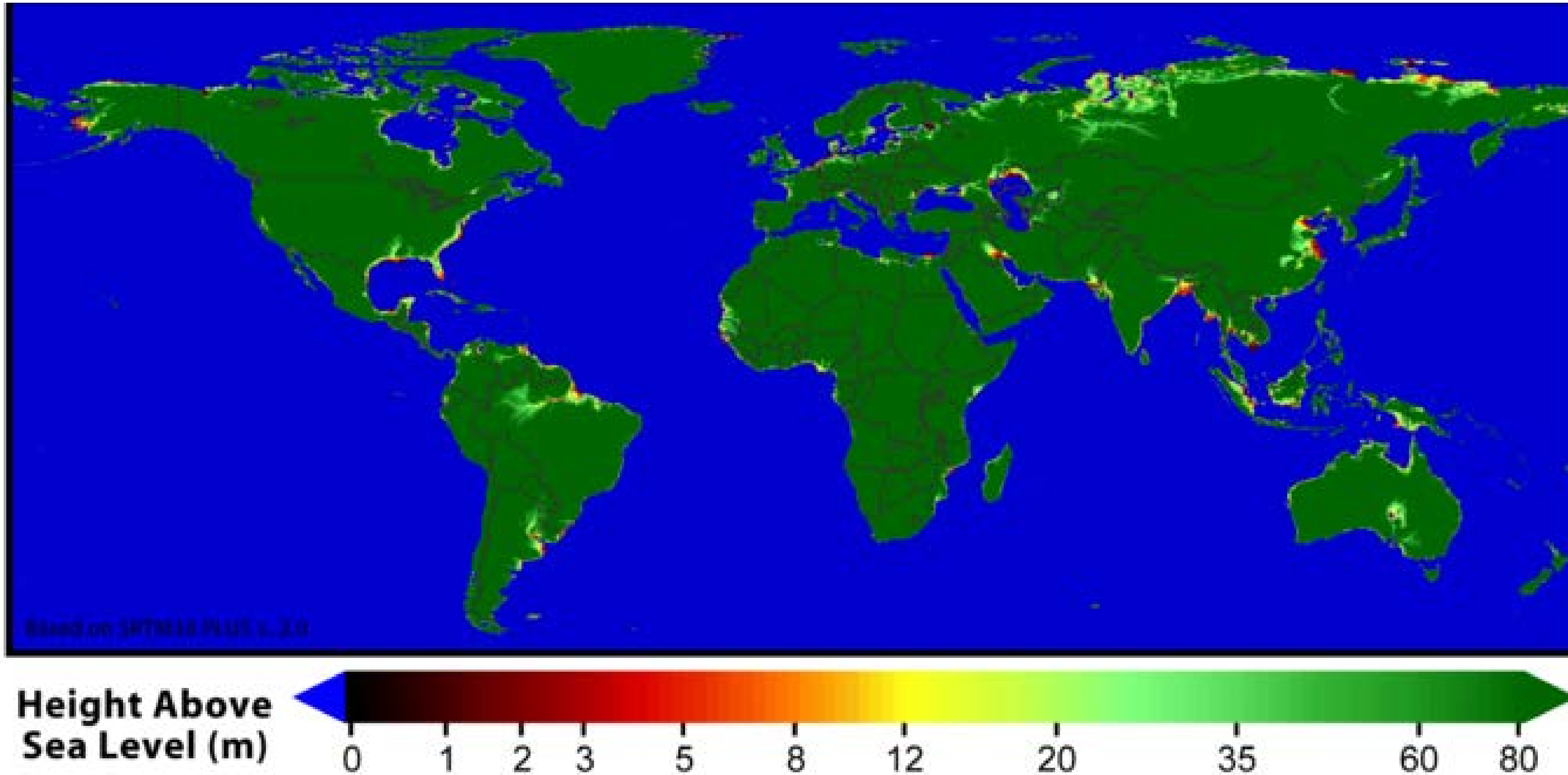


Multiplication factor for the frequency of a given sea level extreme.

2. Impacts of sea level change

2. Impacts of sea level change

10% of world's population lives below 10 m elevation.



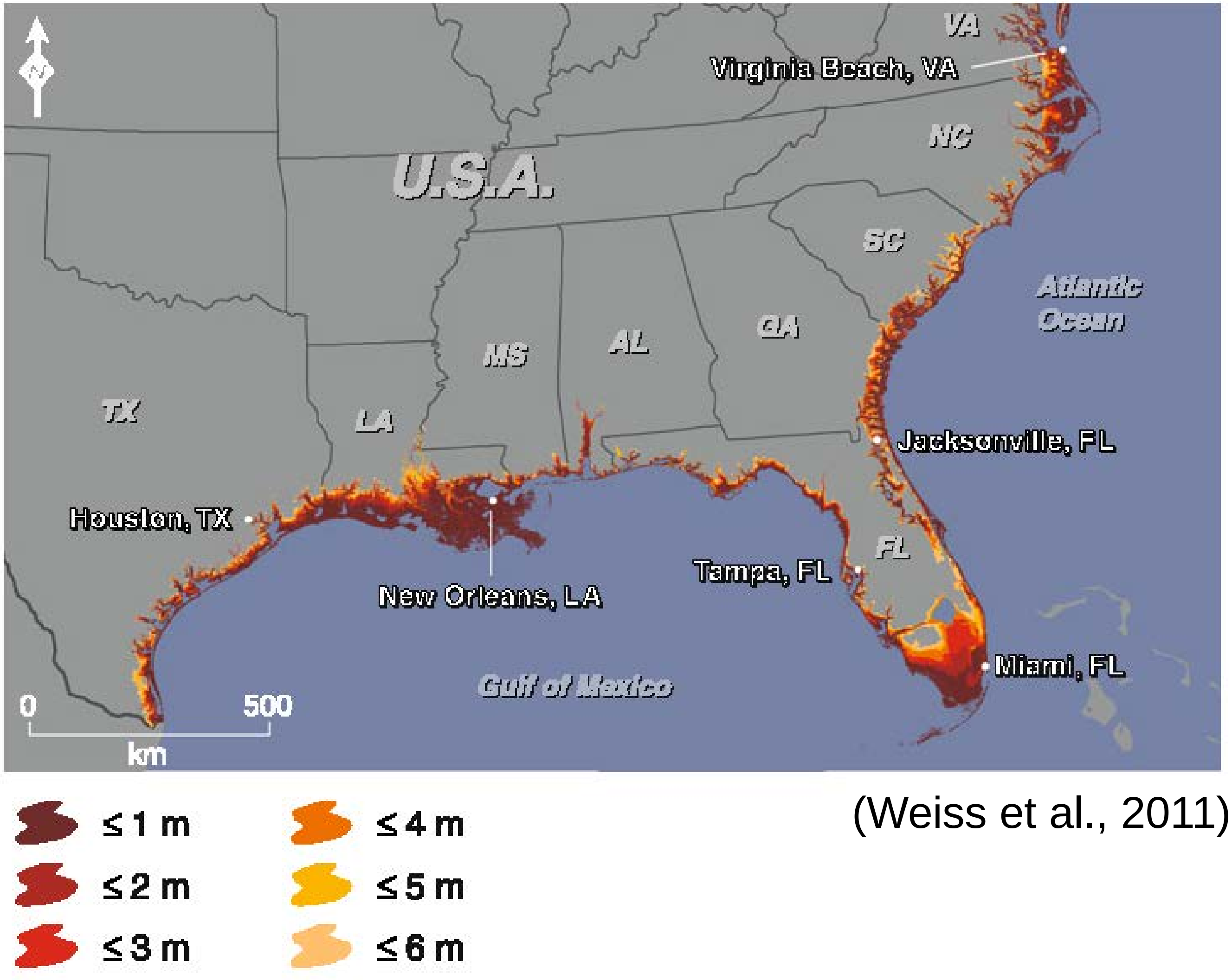
2. Impacts of sea level change

Developing countries

	1 m	5 m
Population	56,000,000	246,000,000
GDP (USD)	219 billion	1 trillion
Agricultural Land	70,000 km^2	378,000 km^2
Wetlands	88,000 km^2	347,000 km^2

(Dasgupta et al., 2009)

2. Impacts of sea level change



(Weiss et al., 2011)

New Orleans

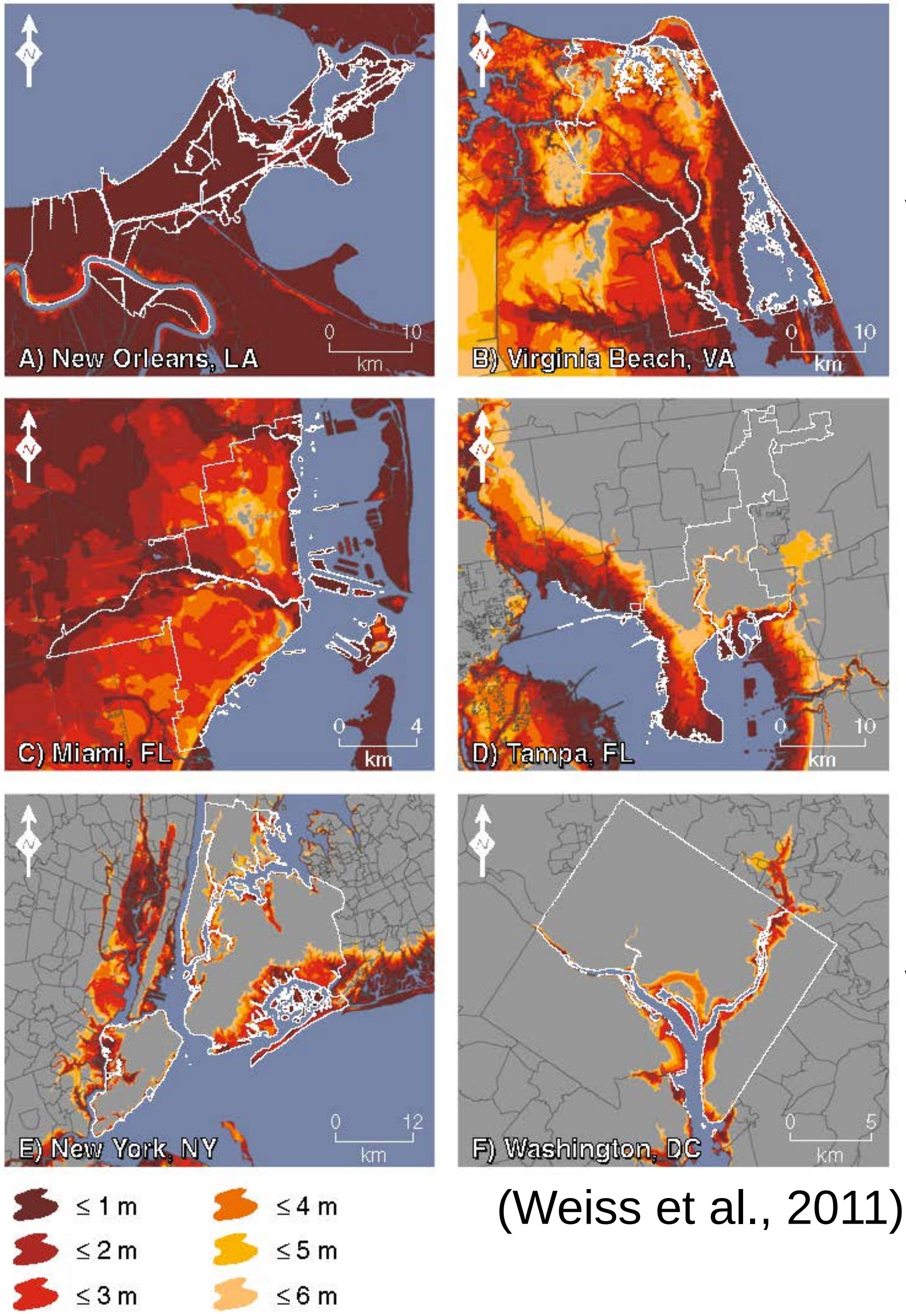
Virginia Beach

Miami

Tampa

New York

Washington, D.C.



(Weiss et al., 2011)

2. Impacts of sea level change

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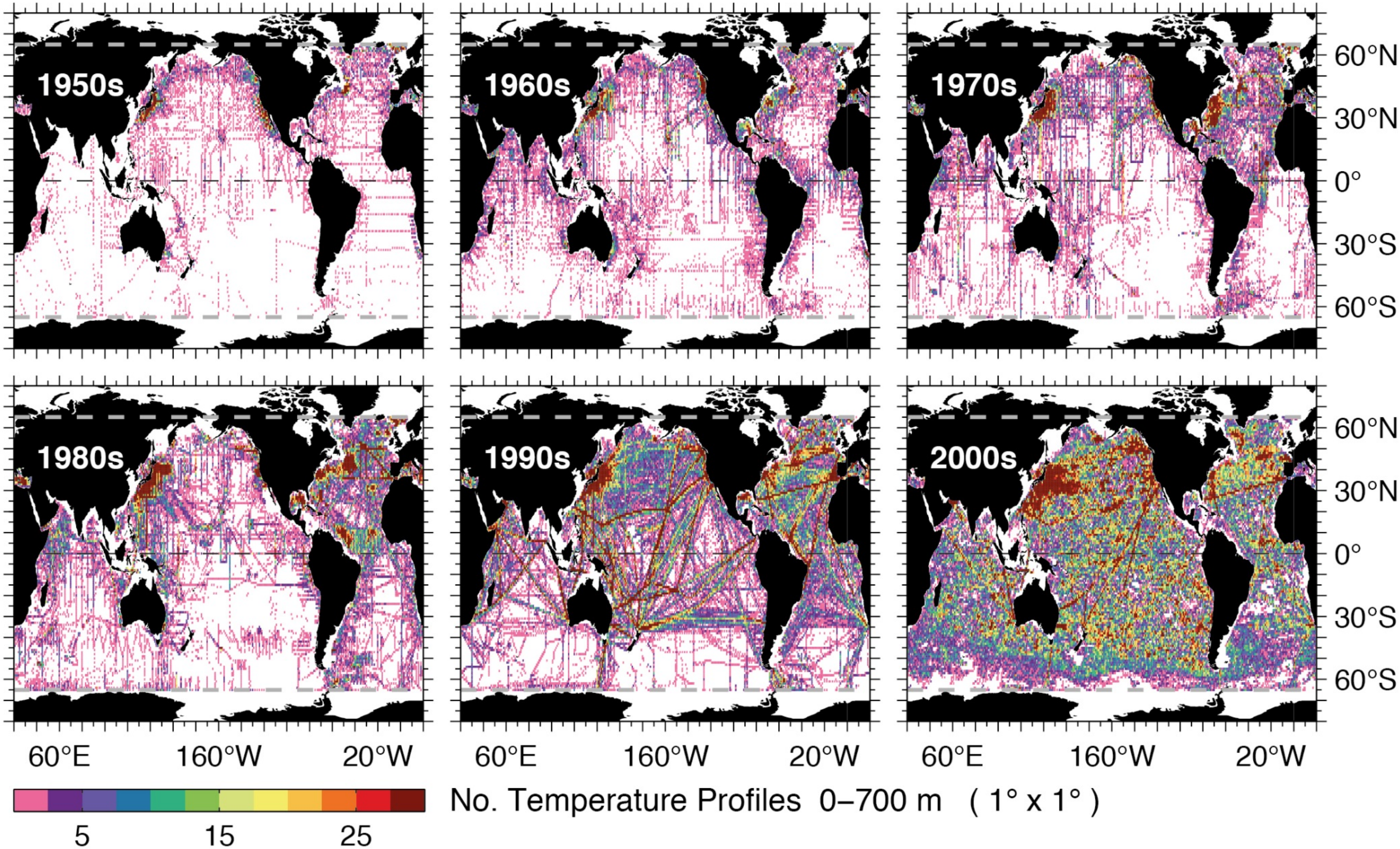
4. Observations



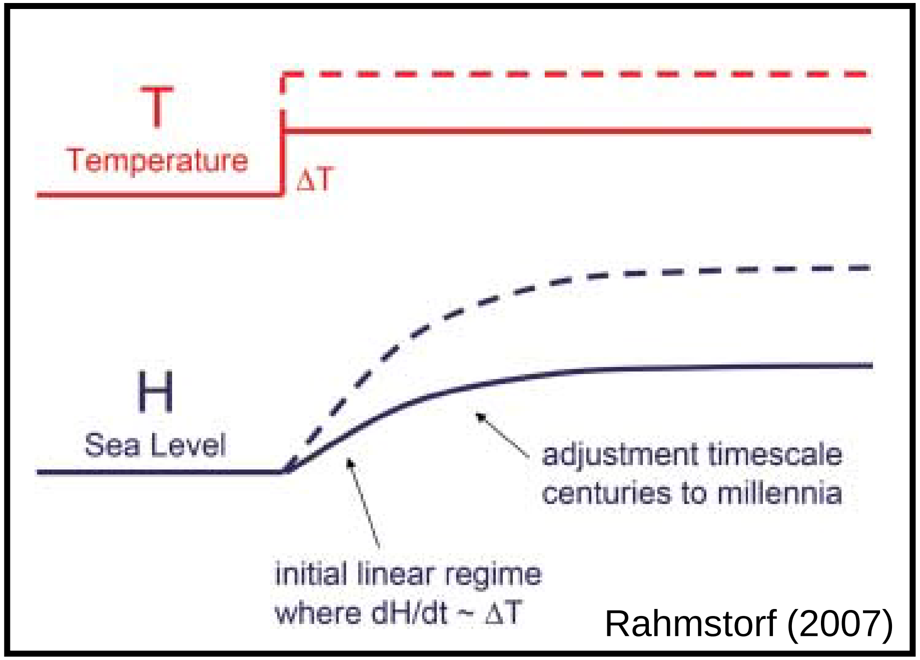
5. Projections

Semi-empirical models (SEMs)

Rate of sea level rise is proportional to global mean temperature (or RF) increase.

$$dH/dt = a(T(t) - T_0)$$

H = sea level change
T = global temperature
T_0 = equilibrium temperature
a = mm yr^{-1} K^{-1}



Rahmstorf (2007)