Mapping sea-level change in time, space, and probability

Robert Kopp

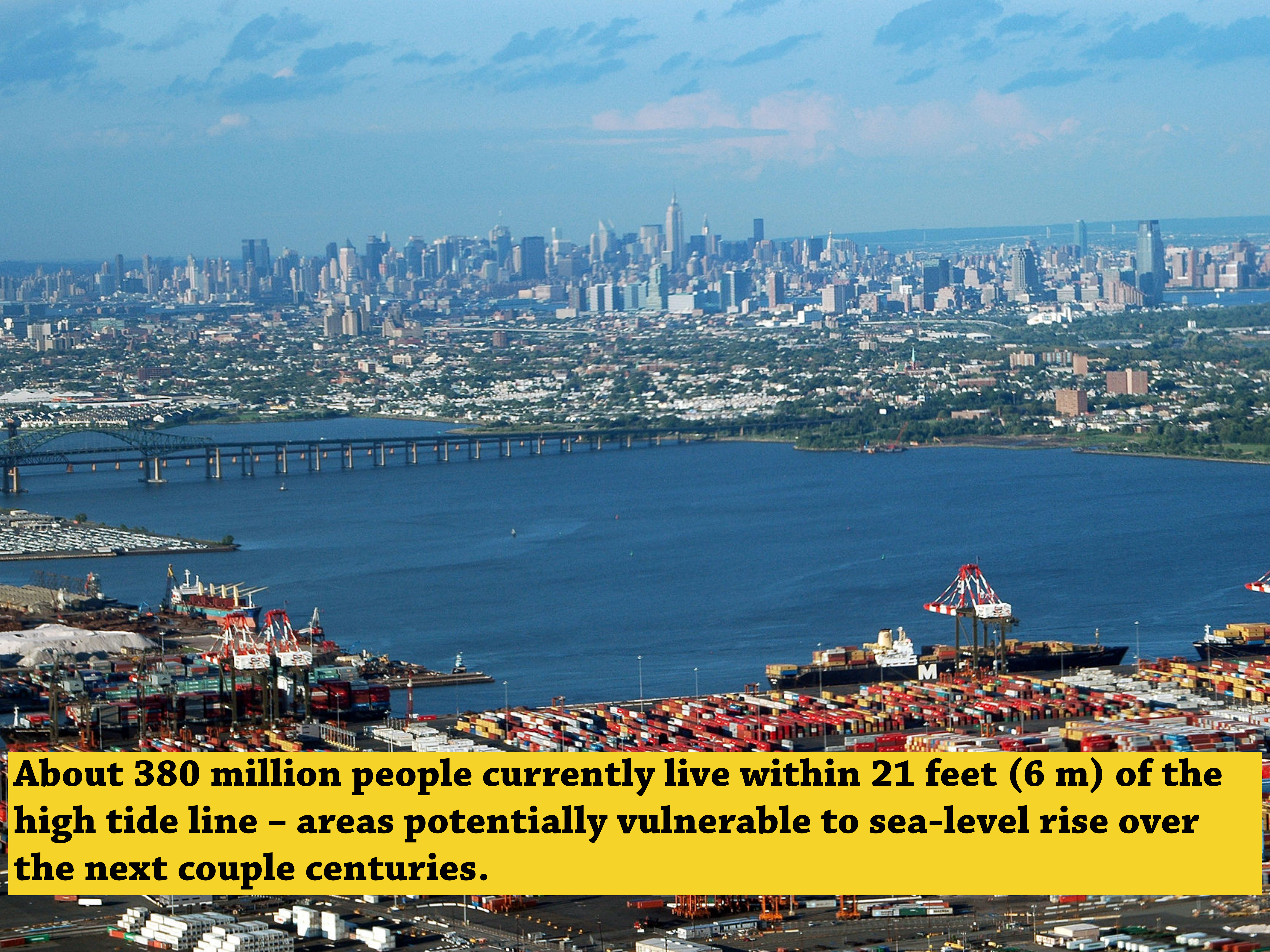
Department of Earth & Planetary Sciences
Institute of Earth, Ocean and Atmospheric Sciences
Rutgers University–New Brunswick

RUTGERS
Institute of Earth, Ocean, and Atmospheric Sciences

Climate Impact Lab

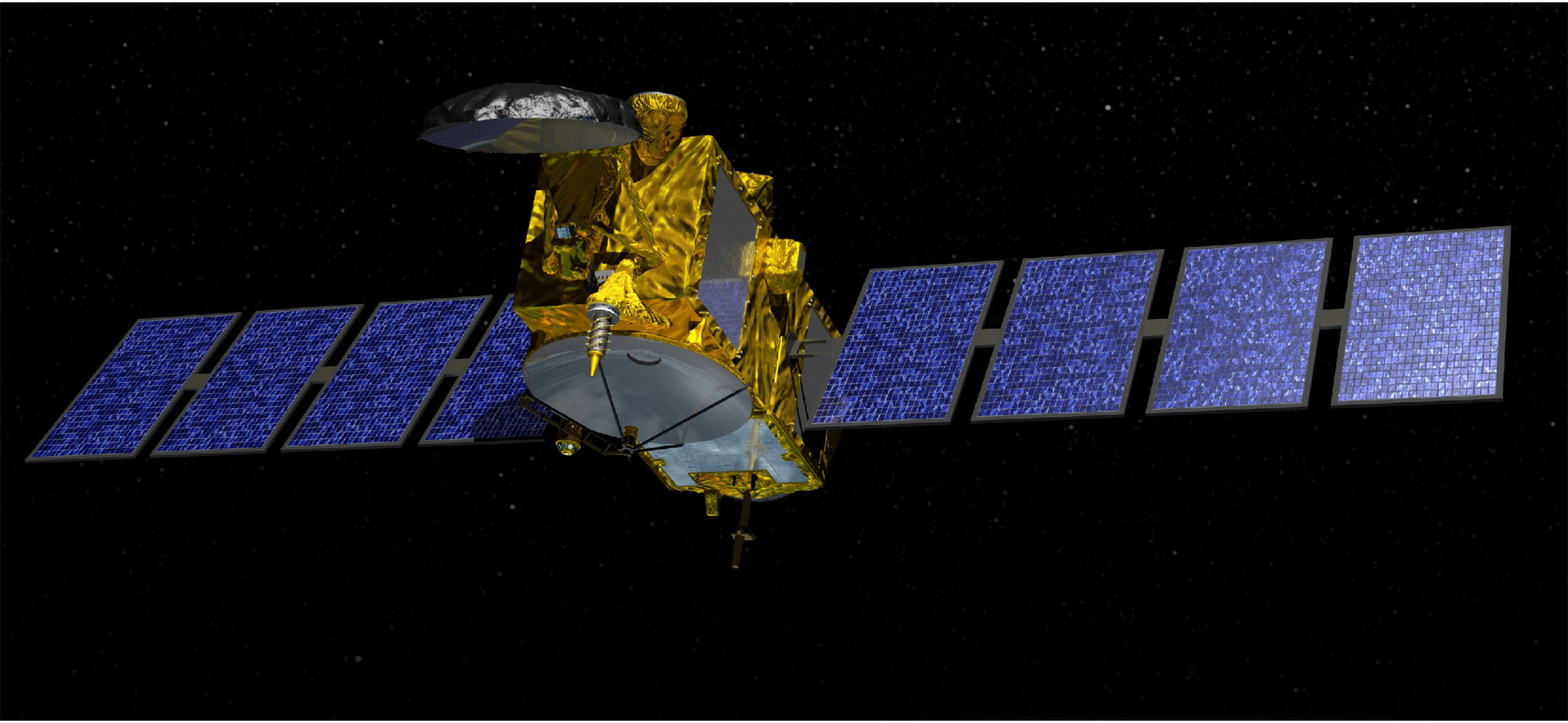
NSF NASA

New York Scientific Data Summit
June 12, 2019



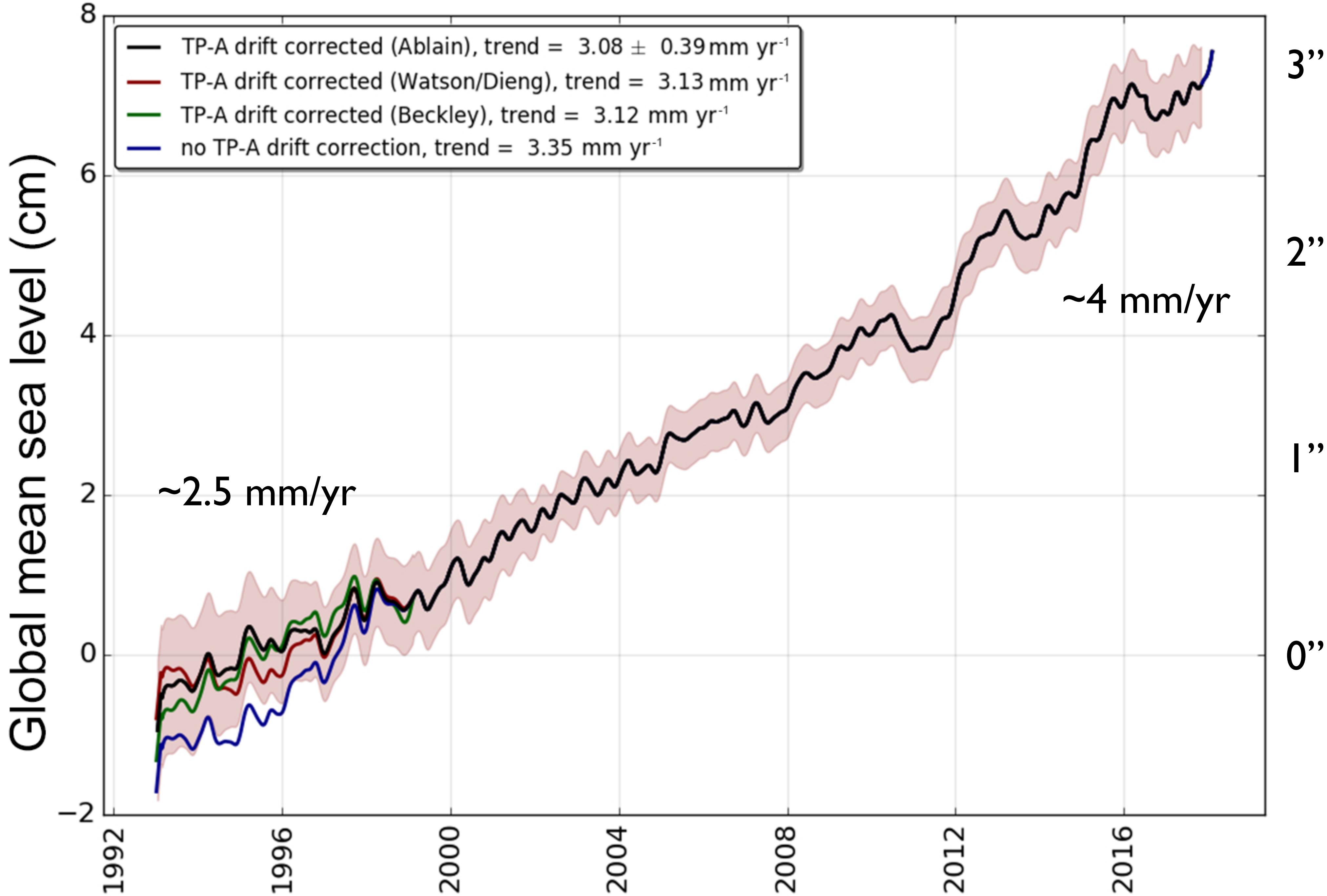
About 380 million people currently live within 21 feet (6 m) of the high tide line – areas potentially vulnerable to sea-level rise over the next couple centuries.

Since the early 1990s, scientists have measured changes in the height of the sea surface using satellite-borne radars.



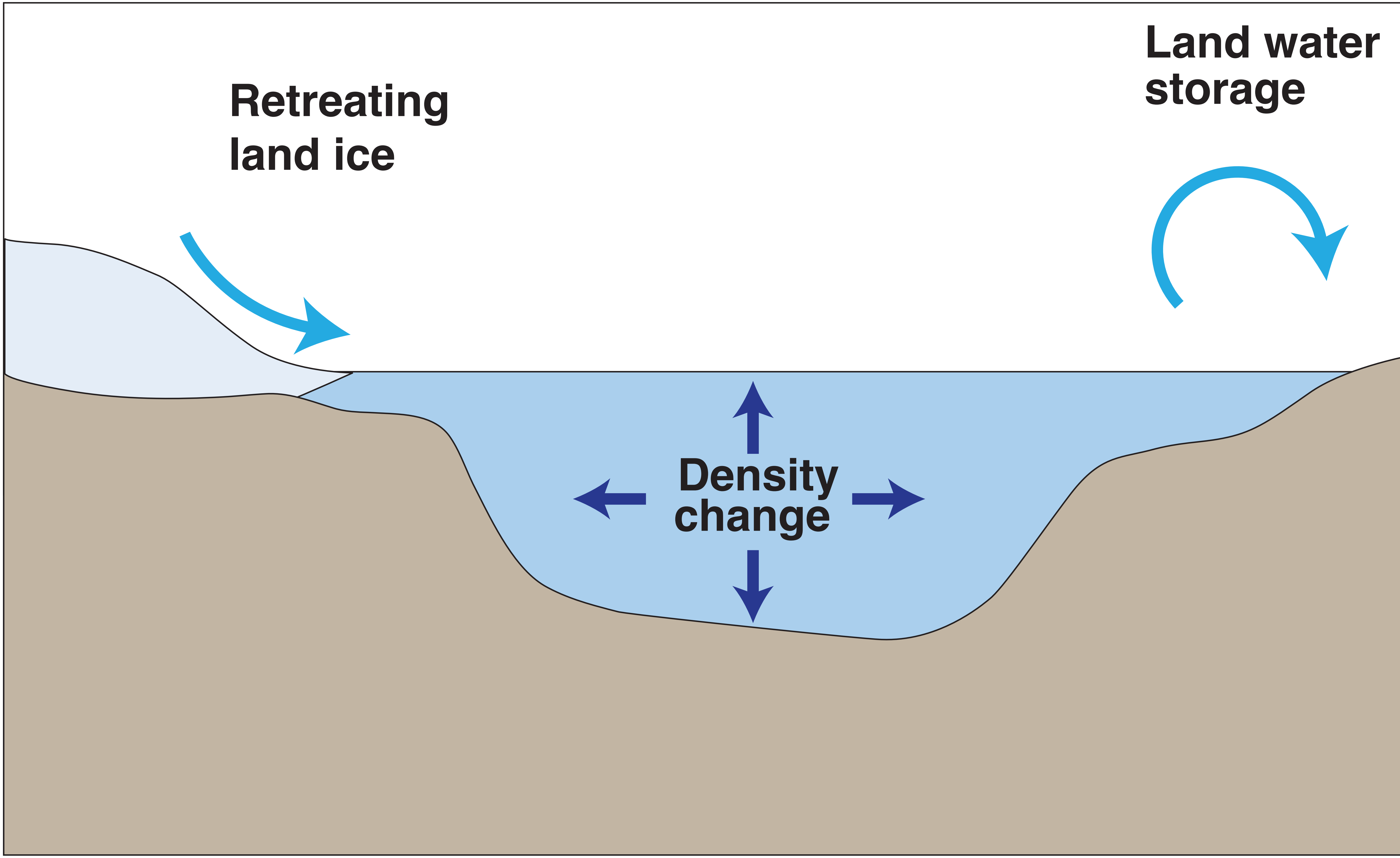
Artists rendition of Jason-3:: NASA/JPL

Satellite altimetry shows us that global average sea level is rising at an accelerating rate.



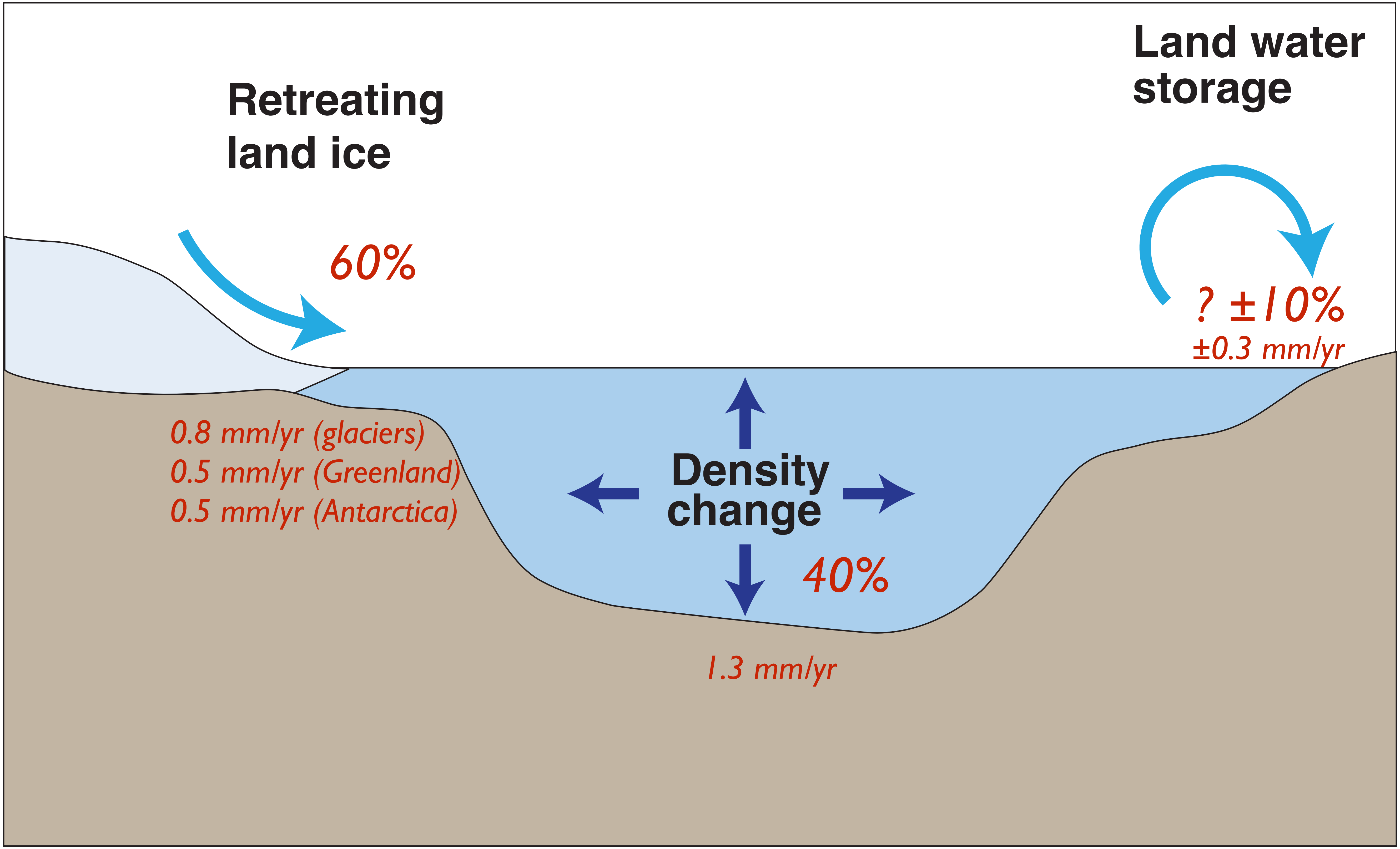
WCRP Global Sea Level Budget Group (2018)

Sources of global mean sea-level change



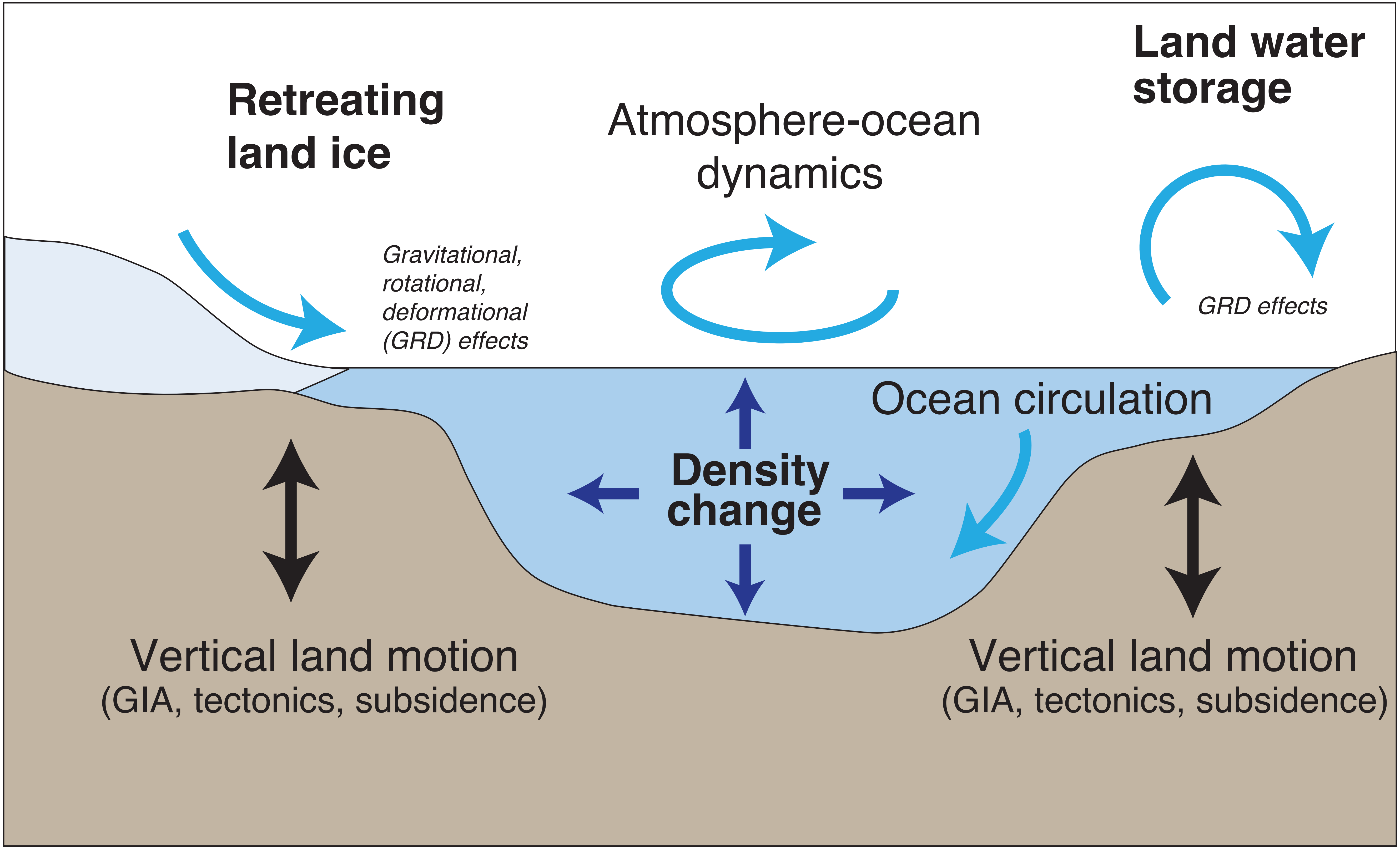
Sources of global mean sea-level change

Contributions over 1993–2017 out of 3.1 ± 0.4 mm/yr (1.2"/decade) total

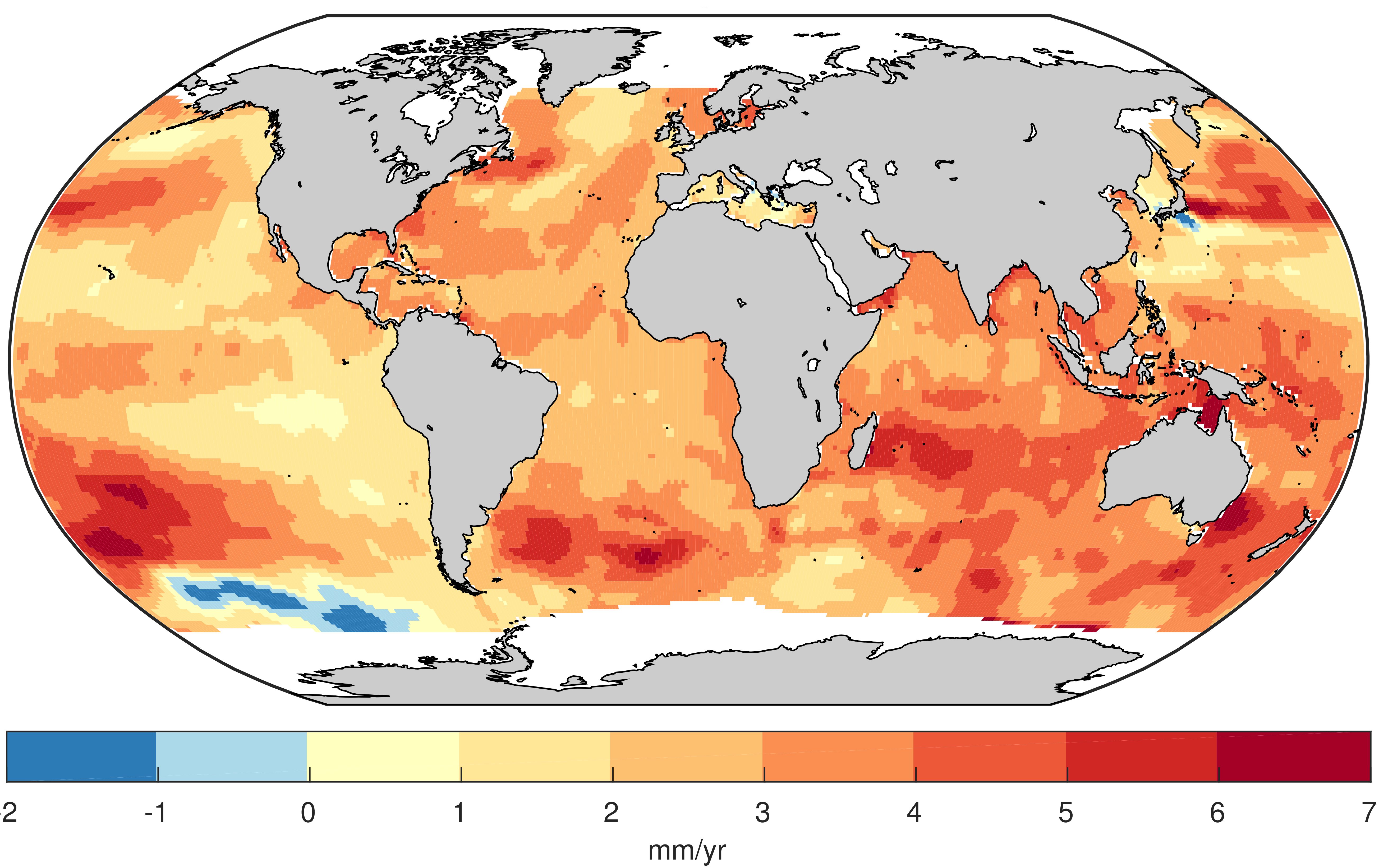


budget based on WCRP Global Sea Level Budget Group (2018)), Rignot et al. (2019), Zemp et al. (2019)

The story becomes more complex when you look at specific places!



Change in sea-surface height, 1993-2018



CSIRO (2019)

In short:

- Sea-level rise is a complex, spatiotemporally varying process of considerable societal importance.

- Reconstructions of past sea-level change provide a crucial baseline for understanding current changes, and producing these reconstructions requires fusing data from multiple different sources with different error structures, sparsity, and process-sensitivity.

- Local sea-level rise projections are a key input to coastal risk management, and require synthesizing many different lines of evidence. In some cases, alternative approaches to estimating different processes highlight areas of deep uncertainty.

- We are working to produce flexible, scalable, open-source tools to facilitate both these tasks.

1. Reconstructing past sea-level changes before the satellite era

Reconstructions of past sea-level change provide a crucial baseline for understanding current changes, and producing these reconstructions requires fusing data from multiple different sources with different error structures, sparsity, and process-sensitivity.

For further reading: review by Erica Ashe

Quaternary Science Reviews 204 (2019) 58–77

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Statistical modeling of rates and trends in Holocene relative sea level

Erica L. Ashe [a, b, c, *], Niamh Cahill [d], Carling Hay [e], Nicole S. Khan [f], Andrew Kemp [g], Simon E. Engelhart [h], Benjamin P. Horton [f, i, j], Andrew C. Parnell [d, k], Robert E. Kopp [b, c]

[a] Department of Statistics and Biostatistics, Rutgers University, New Brunswick, NJ, United States
[b] Department of Earth & Planetary Sciences, Rutgers University, New Brunswick, NJ, United States
[c] Institute of Earth, Ocean & Atmospheric Sciences, Rutgers University, New Brunswick, NJ, United States
[d] School of Mathematics and Statistics, Maynooth University, Kildare, Ireland
[e] Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, United States
[f] Asian School of the Environment, Nanyang Technological University, Singapore
[g] Department of Earth and Ocean Sciences, Tufts University, Medford, MA, United States
[h] Department of Geosciences, University of Rhode Island, Kingston, RI, United States
[i] Earth Observatory of Singapore, Nanyang Technological University, Singapore
[j] Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, United States
[k] Hamilton Institute, Insight Centre for Data Analytics, Maynooth University, Kildare, Ireland

Basic concepts: Hierarchical modeling

A hierarchical statistical model separates into different levels, distinguishing (for example) between uncertainty arising at the observation level and uncertainty arising at the process level.

Basic concepts: Hierarchical modeling

A hierarchical statistical model separates into different levels, distinguishing (for example) between uncertainty arising at the observation level and uncertainty arising at the process level.

For example, at the process level:

$$\mathbf{f}(\mathbf{x},t) = g(t) + \mathbf{f}_{\mathrm{GRD}}(\mathbf{x},t) + \mathbf{f}_{\mathrm{DSL}}(\mathbf{x},t) + \mathbf{f}_{\mathrm{VLM}}(\mathbf{x},t)$$

And at the data level:

$$y_i = f(\mathbf{x}_i, \widehat{t_i} + \delta) + \epsilon$$

1.1. Sea-level change over the instrumental period

Tide gauges

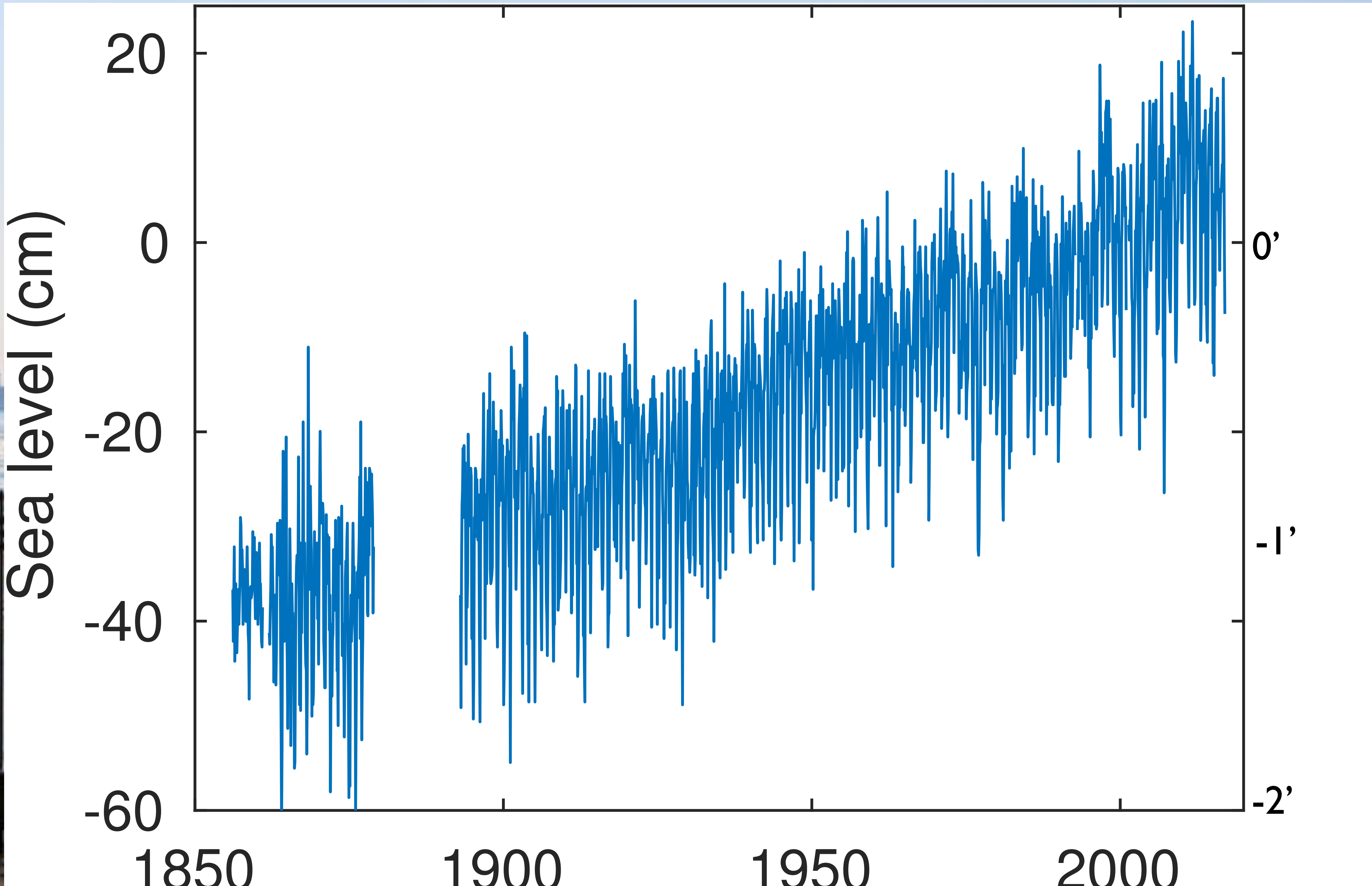
Battery Tide Gauge, New York City

Photo: New York Times (January 14, 2014)

Tide gauges

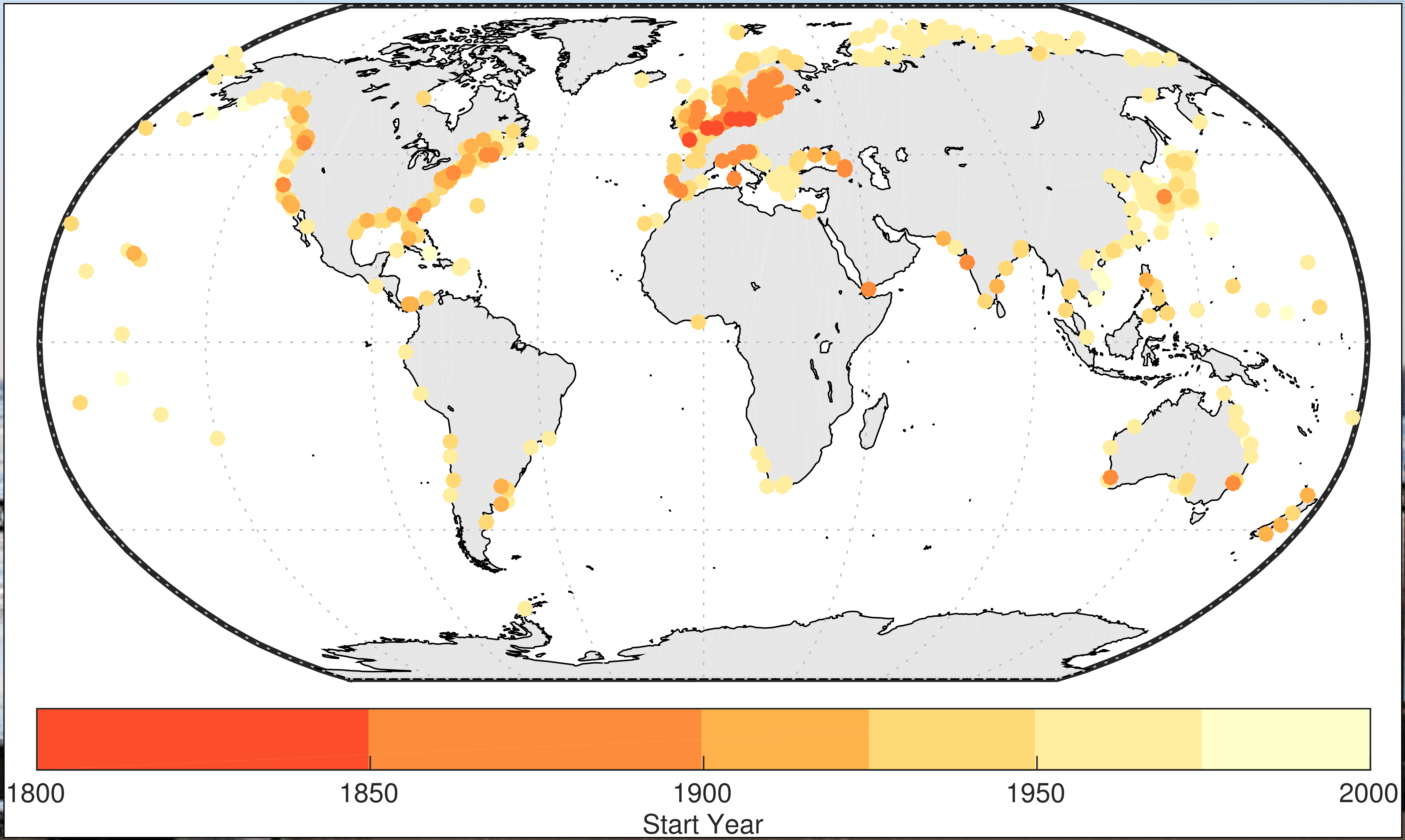
Battery Tide Gauge, New York City

(monthly mean sea-level relative to 1991-2009)



Tide gauges

Start year of tide-gauge records



Tide gauges

Global statistical model

LETTER

doi:10.1038/nature14093

Probabilistic reanalysis of twentieth-century sea-level rise

Carling C. Hay[1,2], Eric Morrow[1,2], Robert E. Kopp[2,3] & Jerry X. Mitrovica[1]

Hay et al. (2015)

Tide gauges

Global statistical model

LETTER

doi:10.1038/nature14093

Probabilistic reanalysis of twentieth-century sea-level rise

Carling C. Hay[1,2], Eric Morrow[1,2], Robert E. Kopp[2,3] & Jerry X. Mitrovica[1]

$$\mathrm{RSL}(\mathbf{x},t) = \mathrm{Uniform}(t) + \sum_j \mathrm{fingerprint}_j(\mathbf{x})\mathrm{Ice}_j(t) + DSL(\mathbf{x},t) + GIA(\mathbf{x},t)$$

$$\mathrm{TG}_i(t) = \mathrm{RSL}(\mathbf{x}_i,t) + Noise(\mathbf{x},t)$$

Hay et al. (2015)

Tide gauges

Global statistical model

LETTER

doi:10.1038/nature14093

Probabilistic reanalysis of twentieth-century sea-level rise

Carling C. Hay[1,2], Eric Morrow[1,2], Robert E. Kopp[2,3] & Jerry X. Mitrovica[1]

$$\mathrm{RSL}(\mathbf{x},t) = \mathrm{Uniform}(t) + \sum_j \mathrm{fingerprint}_j(\mathbf{x})\mathrm{Ice}_j(t) + DSL(\mathbf{x},t) + GIA(\mathbf{x},t)$$

$$\mathrm{TG}_i(t) = \mathrm{RSL}(\mathbf{x}_i,t) + Noise(\mathbf{x},t)$$

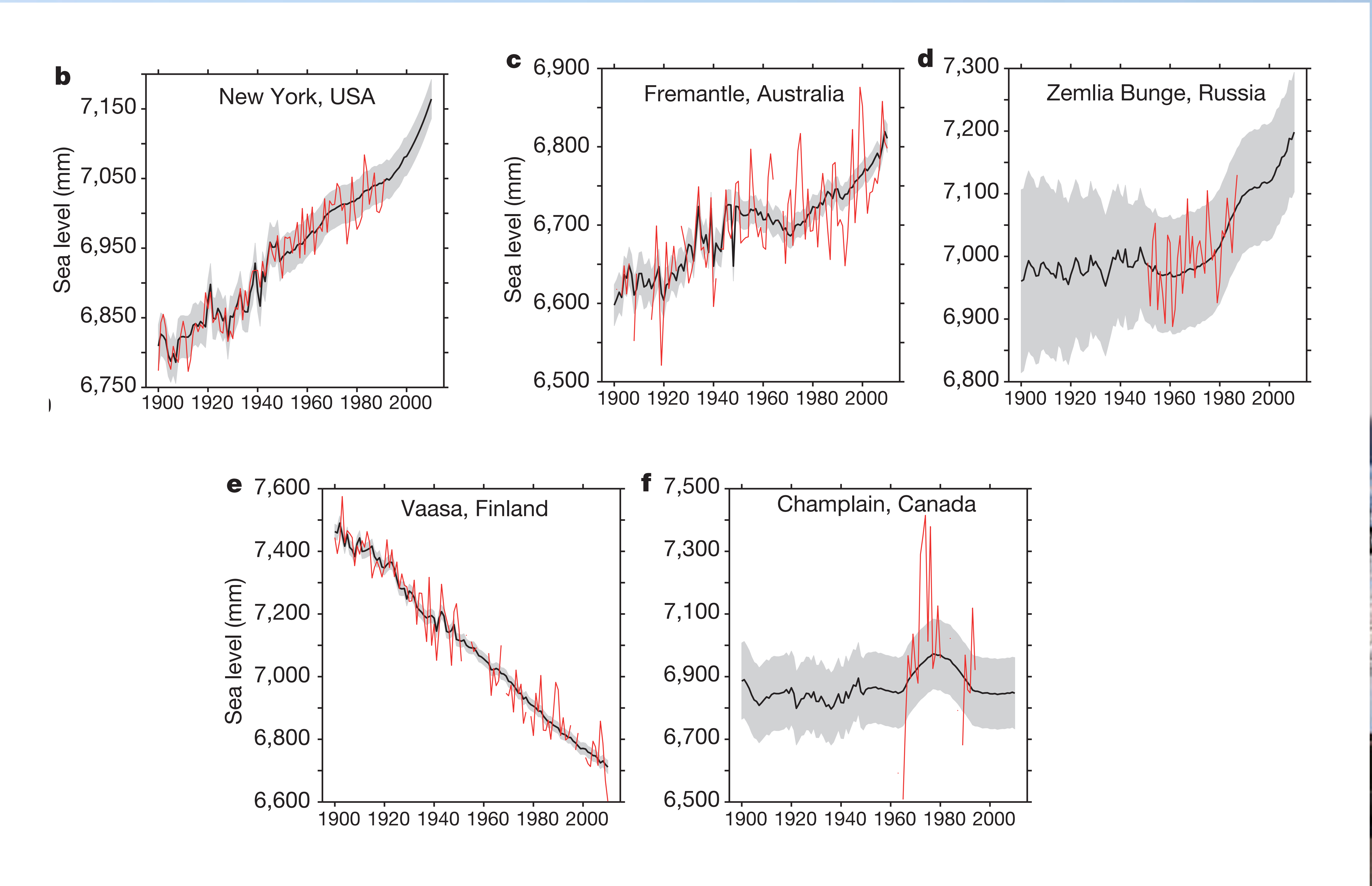
Two computational approaches:

1. State-space model (Kalman smoother)
2. Gaussian process regression

Hay et al. (2015)

Tide gauges

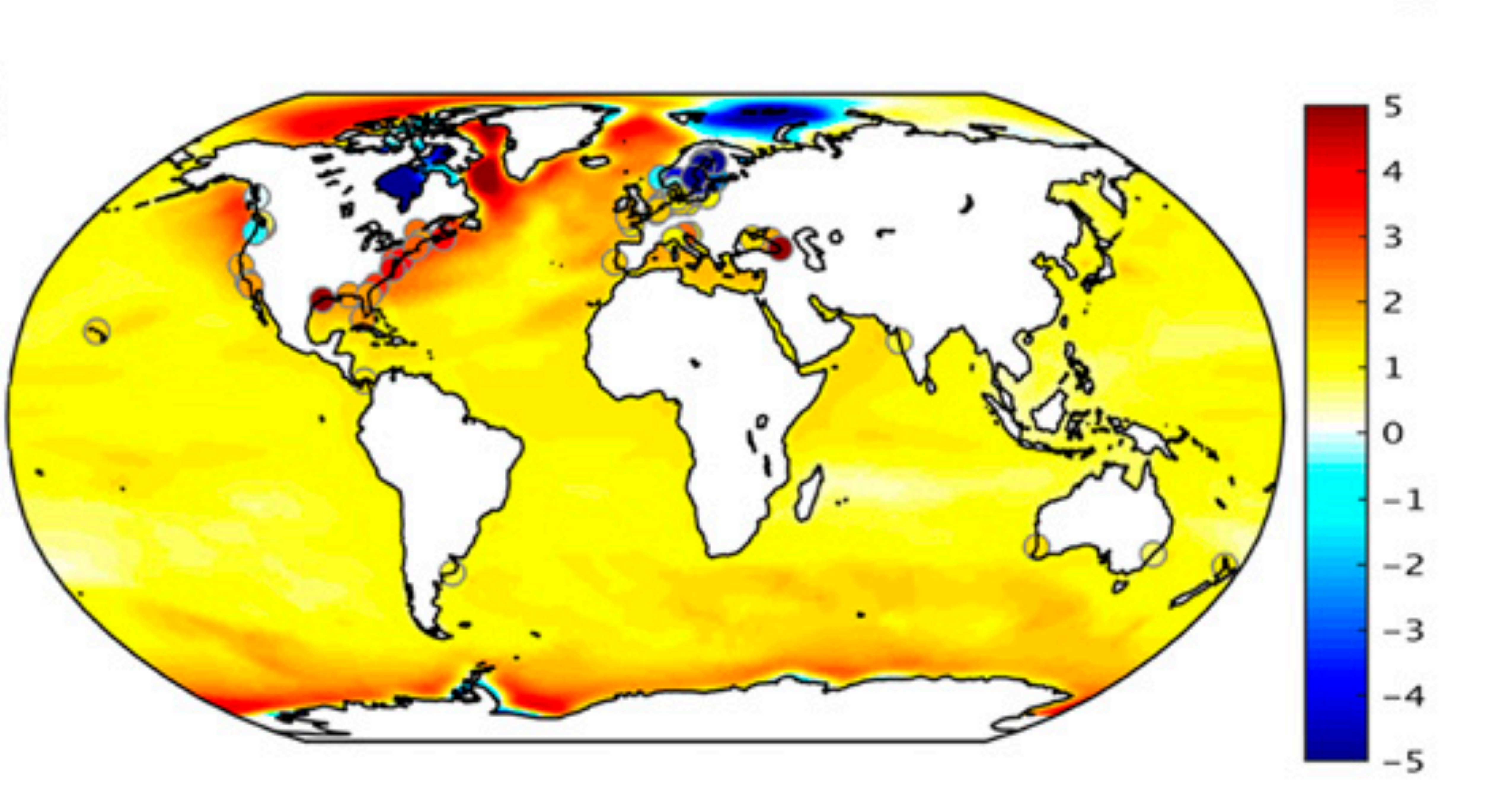
Model fits the data!



Hay et al. (2015)

Tide gauges

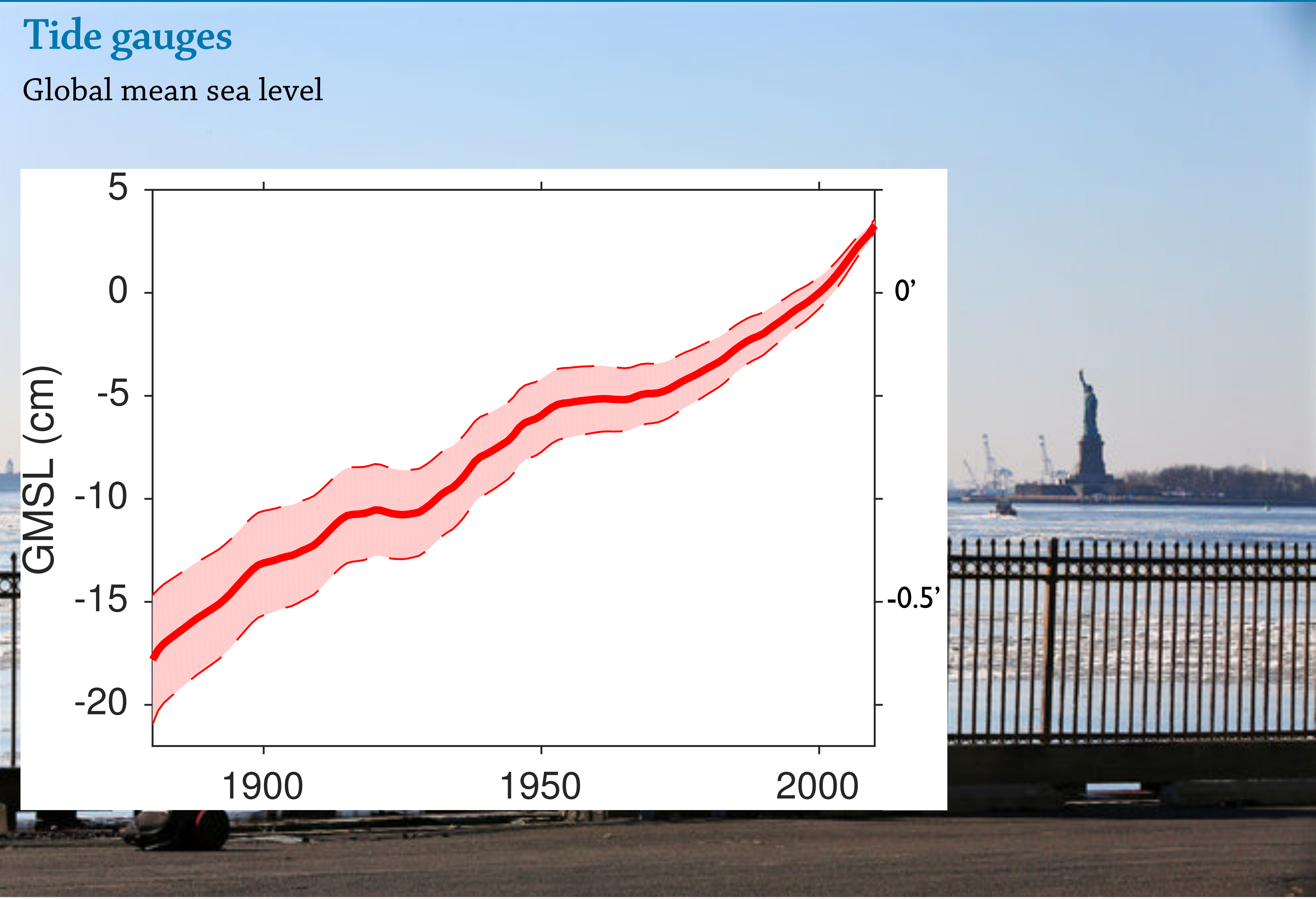
Rate of relative sea-level rise, 1901-1990 (mm/yr)



Hay et al. (2017)

Tide gauges

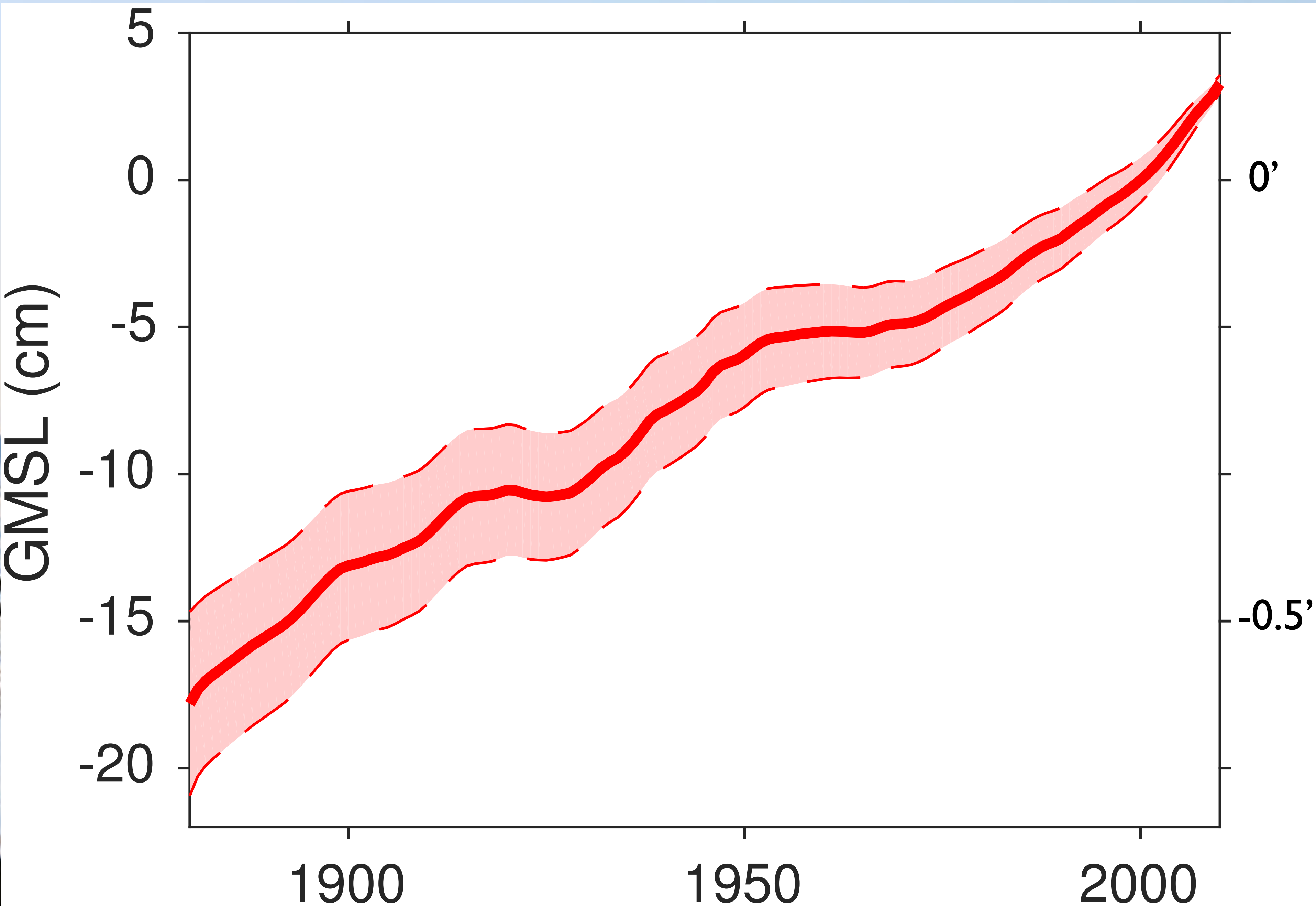
Global mean sea level



Hay et al. (2015)

Tide gauges

Global mean sea level



From 1901-1990, global mean sea level rose at ~1.2 ± 0.2 mm/yr (~0.5"/ decade). From 1993-2010, it rose ~2.5x faster.

Hay et al. (2015)

1.2. Sea-level change over the last three thousand years

Extending the record back with geology

Photo courtesy Ben Horton

Common Era sea-level database

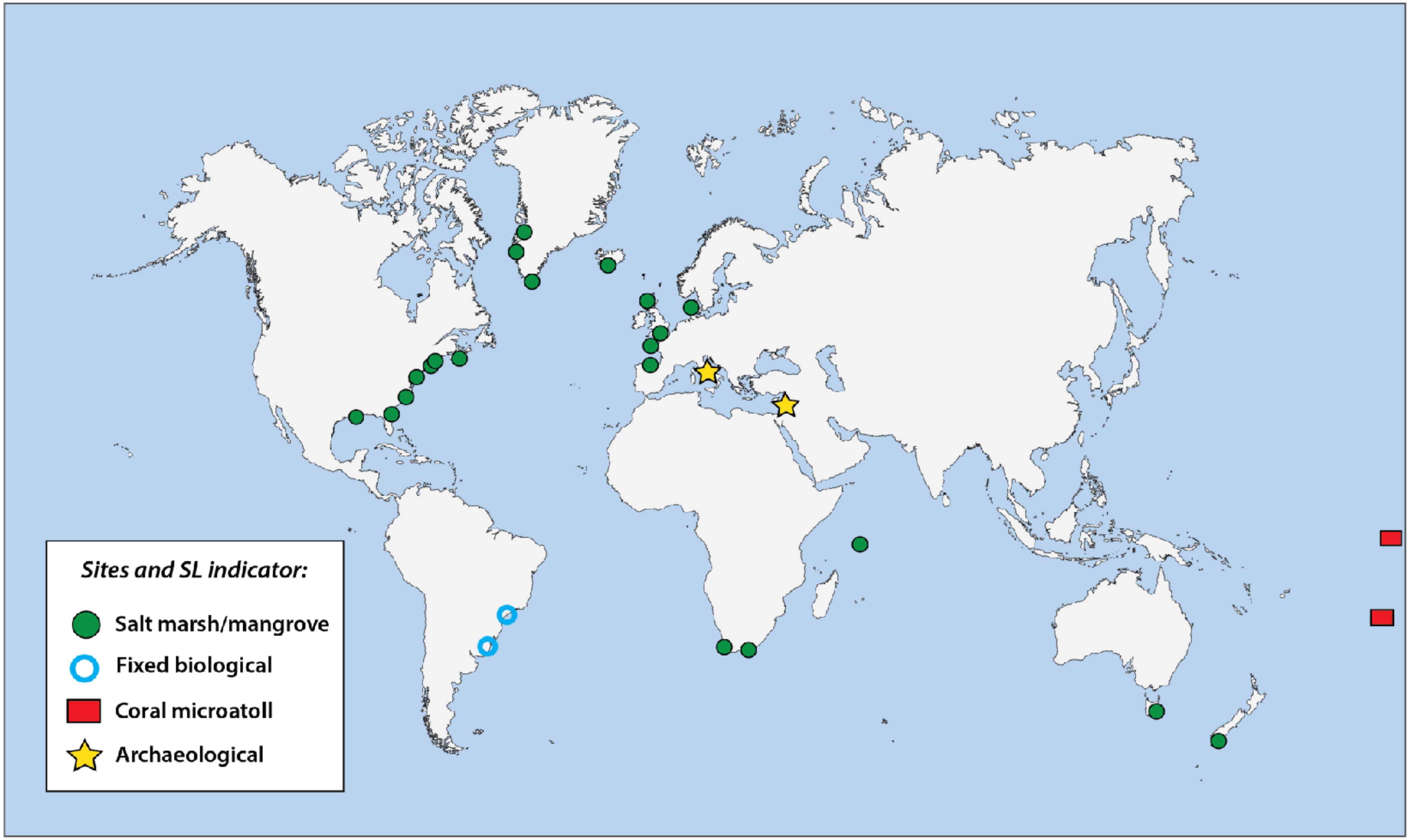
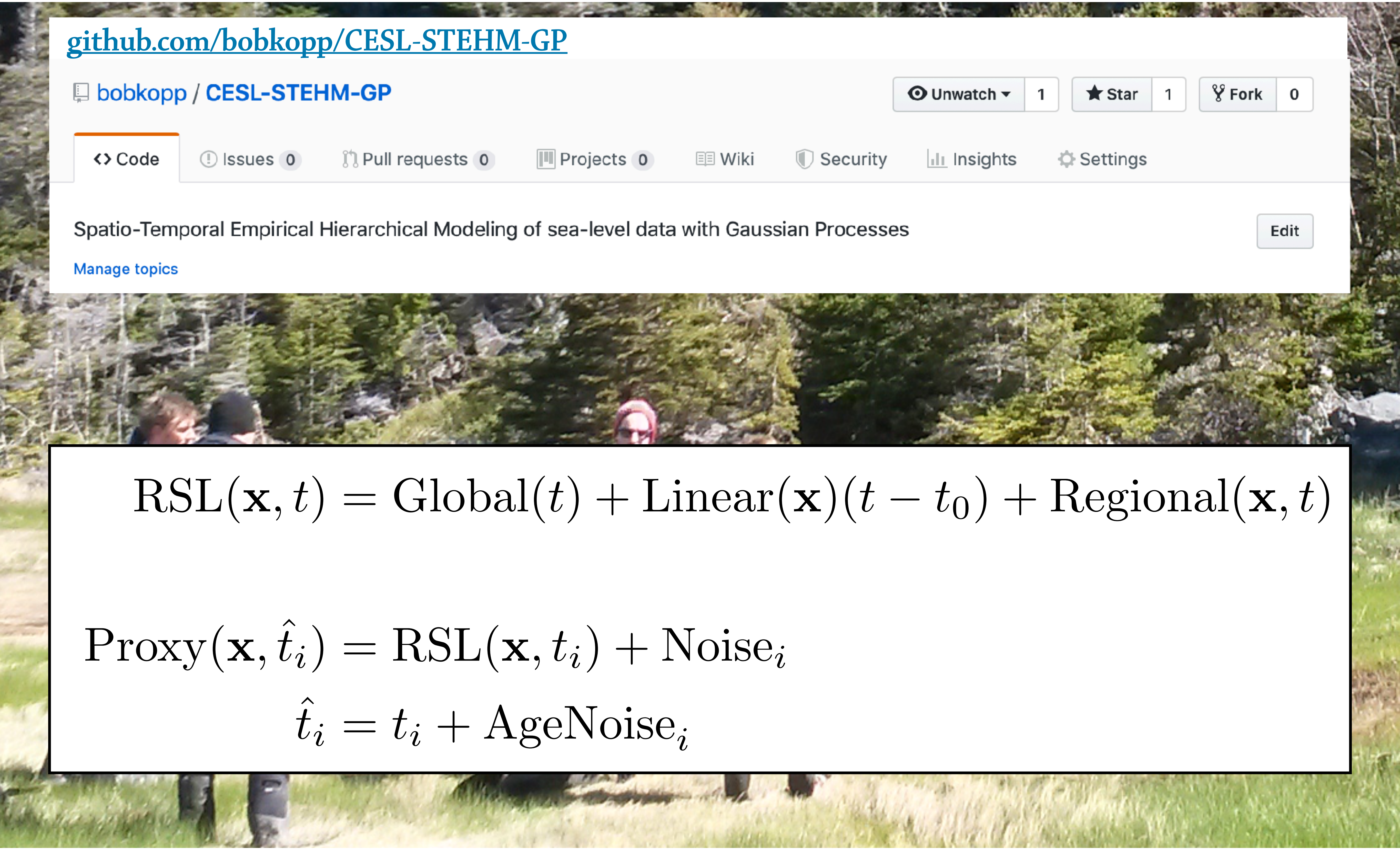


Figure courtesy Ben Horton

Common Era sea-level model



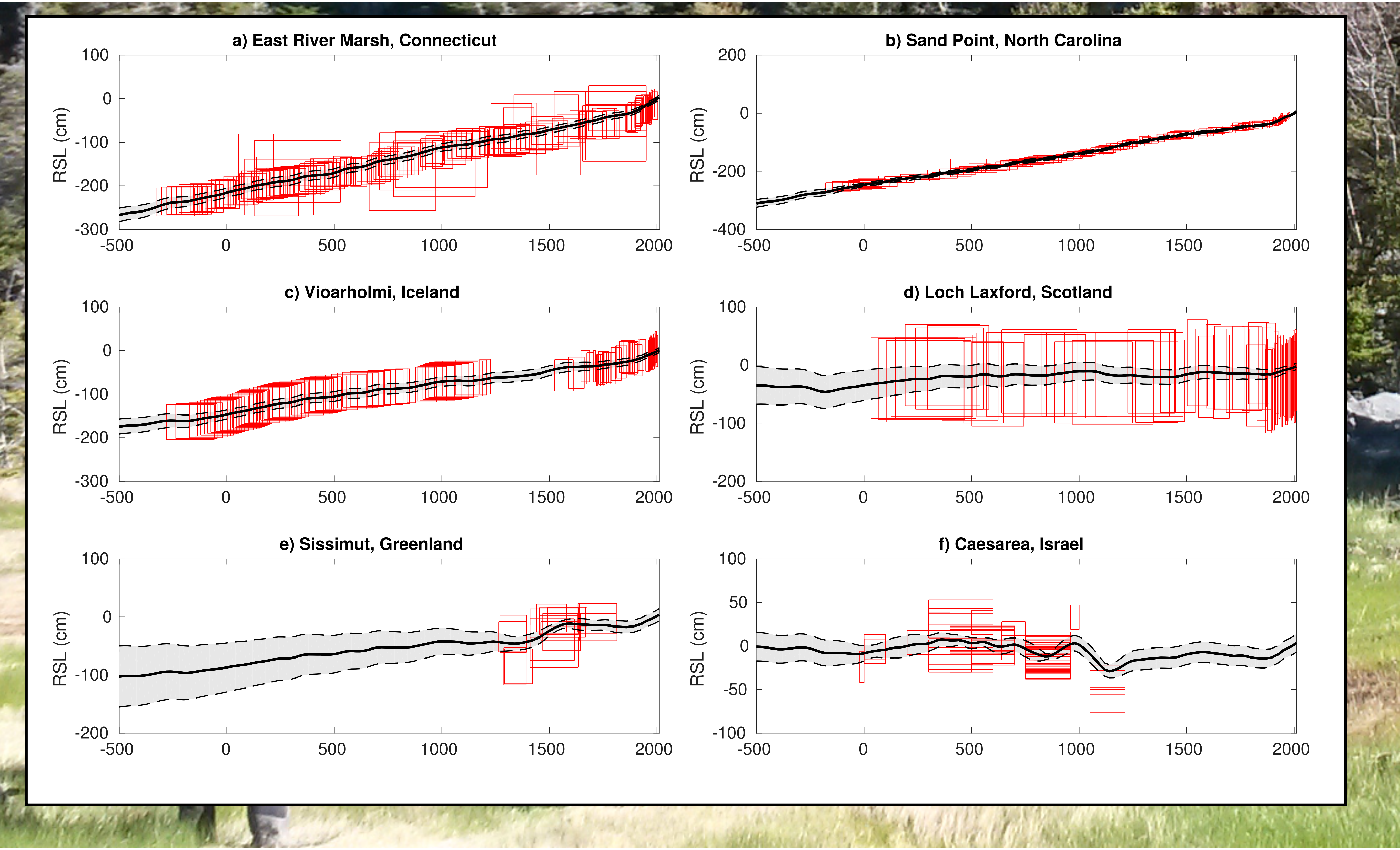
$$\mathrm{RSL}(\mathbf{x}, t) = \mathrm{Global}(t) + \mathrm{Linear}(\mathbf{x})(t - t_0) + \mathrm{Regional}(\mathbf{x}, t)$$

$$\mathrm{Proxy}(\mathbf{x}, \hat{t}_i) = \mathrm{RSL}(\mathbf{x}, t_i) + \mathrm{Noise}_i$$

$$\hat{t}_i = t_i + \mathrm{AgeNoise}_i$$

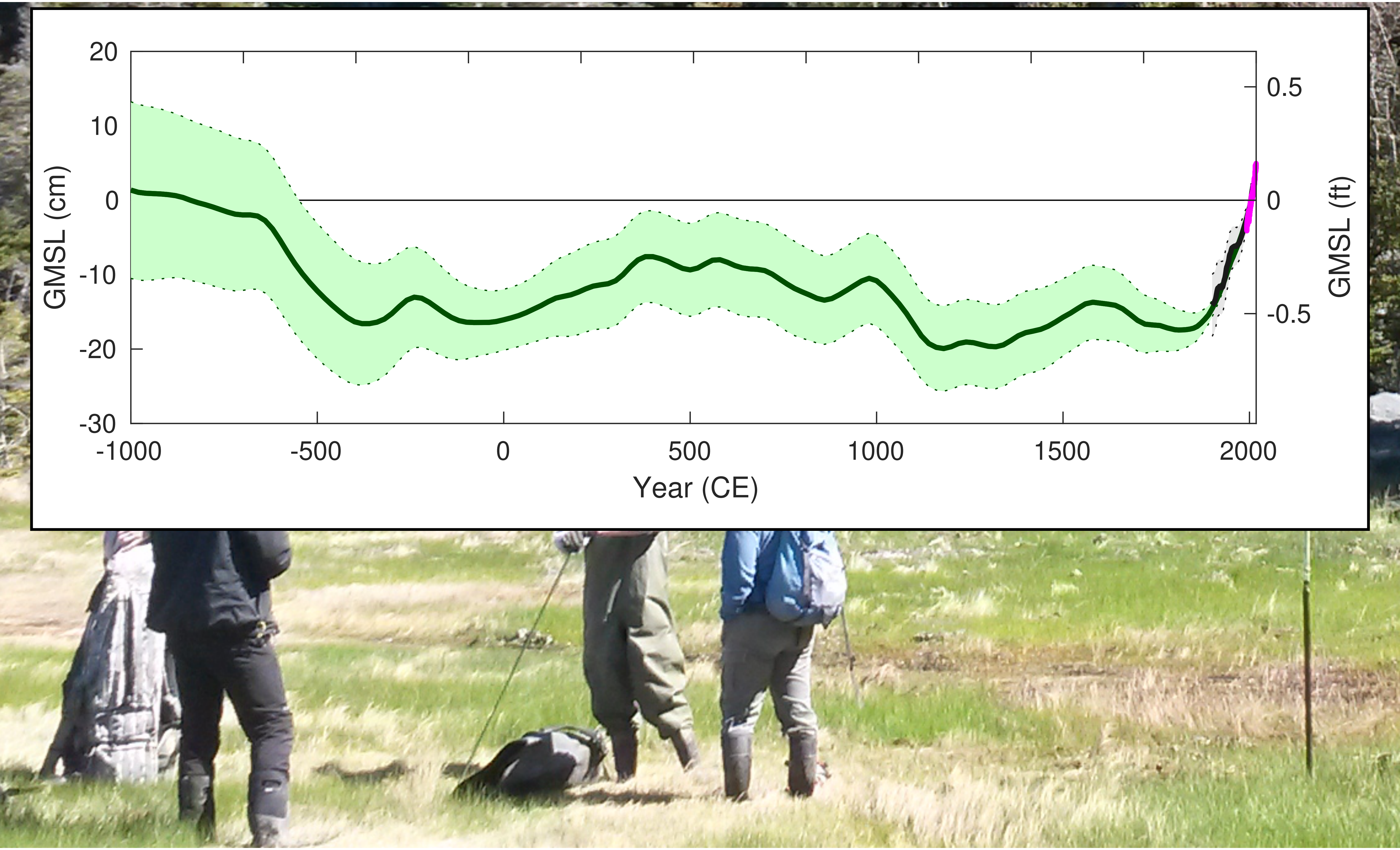
Figure courtesy Ben Horton

Common Era sea-level model fits the data!



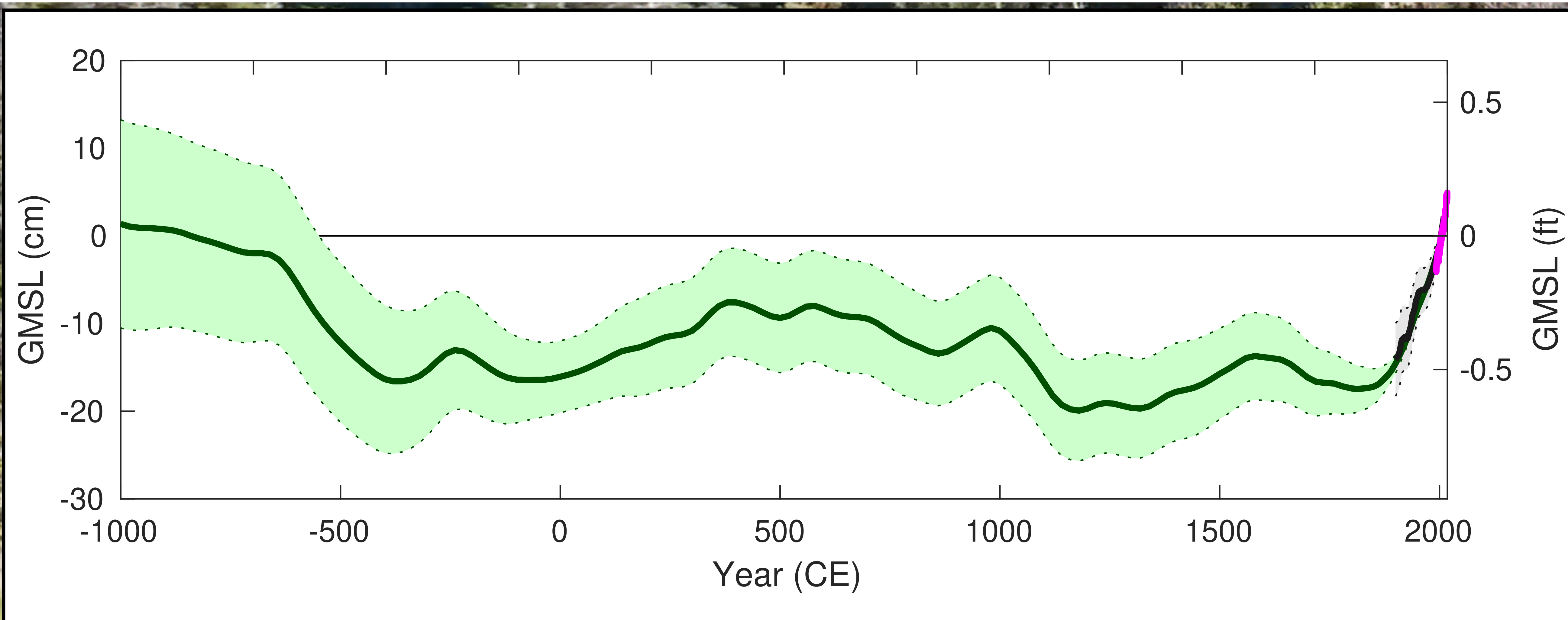
Kopp et al. (2016)

Common Era global sea level



Kopp et al. (2016); Kemp et al. (2018); instrumental data from Hay et al. (2015) and Nerem et al. (2018)

Common Era global sea level

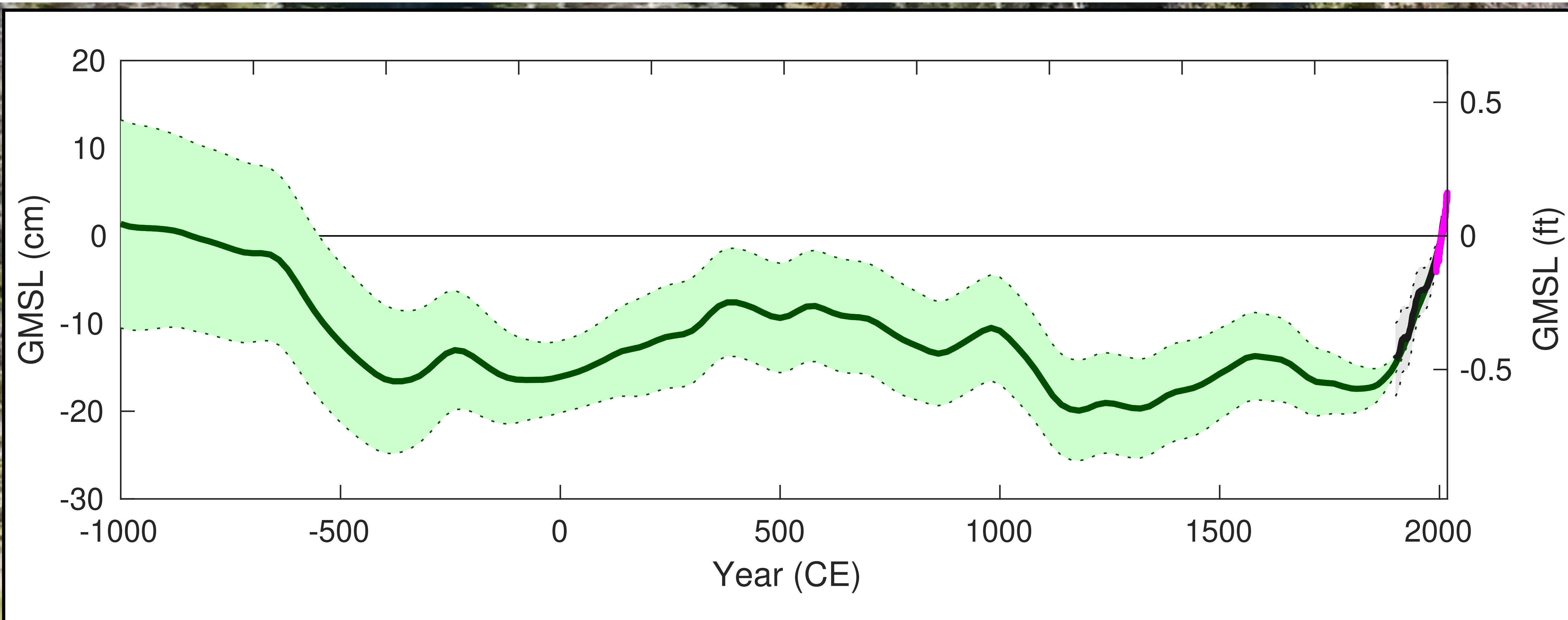


Barack Obama
@BarackObama

We're seeing the fastest rise in sea-levels in nearly 3,000 years: ofa.bo/j9qS #ActOnClimate

Kopp et al. (2016); Kemp et al. (2018); instrumental data from Hay et al. (2015) and Nerem et al. (2018)

Common Era global sea level



Barack Obama
@BarackObama

We're seeing the fastest rise in sea-levels in nearly 3,000 years: ofa.bo/j9qS #ActOnClimate

20th century global mean sea-level rise of 1.4 ± 0.2 mm/yr (6"/century) was *virtually certain* (*P* > 99%) faster than any century since at least 1000 BCE

Kopp et al. (2016); Kemp et al. (2018); instrumental data from Hay et al. (2015) and Nerem et al. (2018)

2. Projections of future changes

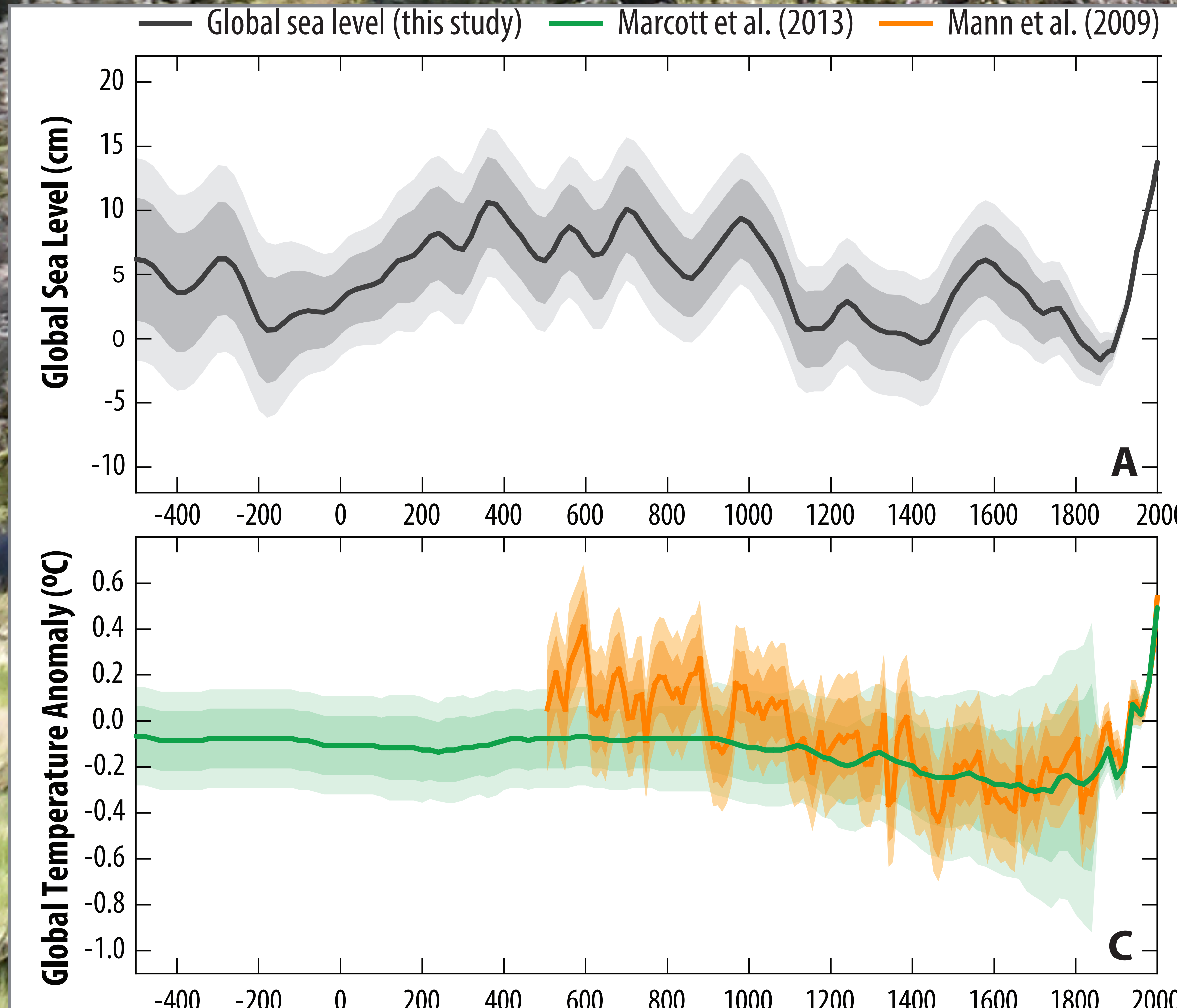
Local sea-level rise projections are a key input to coastal risk management, and require synthesizing many different lines of evidence. In some cases, alternative approaches to estimating different processes highlight areas of deep uncertainty.

Consider the past relationship between temperature and sea level

$$dh/dt = a(T(t) - T_0(t)) + c(t)$$
$$dT_0(t)/dt = (T(t) - T_0(t))/\tau_1$$
$$dc(t)/dt = -c/\tau_2$$

$\tau_1 \approx$ 100 to 200 years

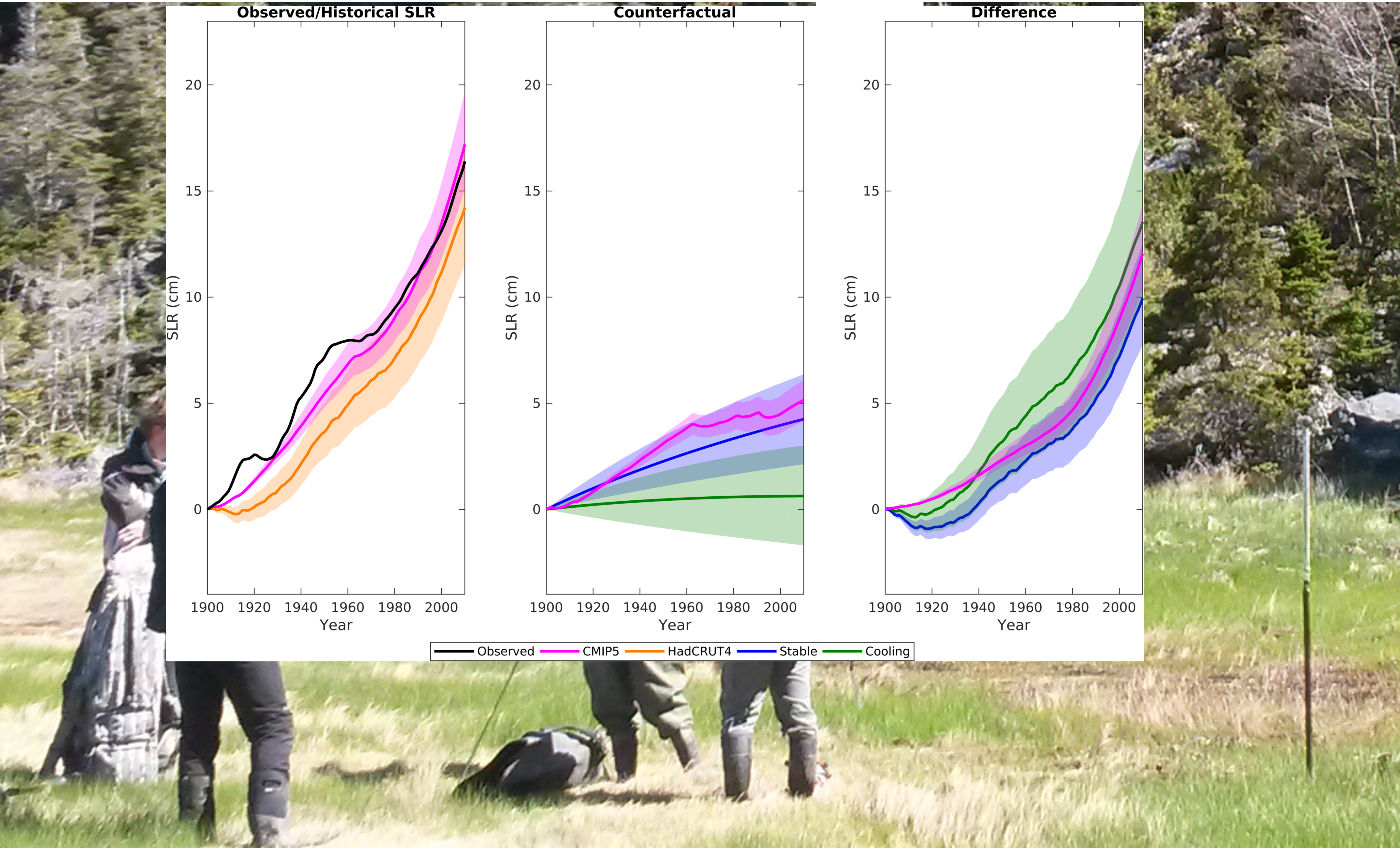
$\tau_2 \approx$ 3000 to 4000 years



Kopp et al. (2016)

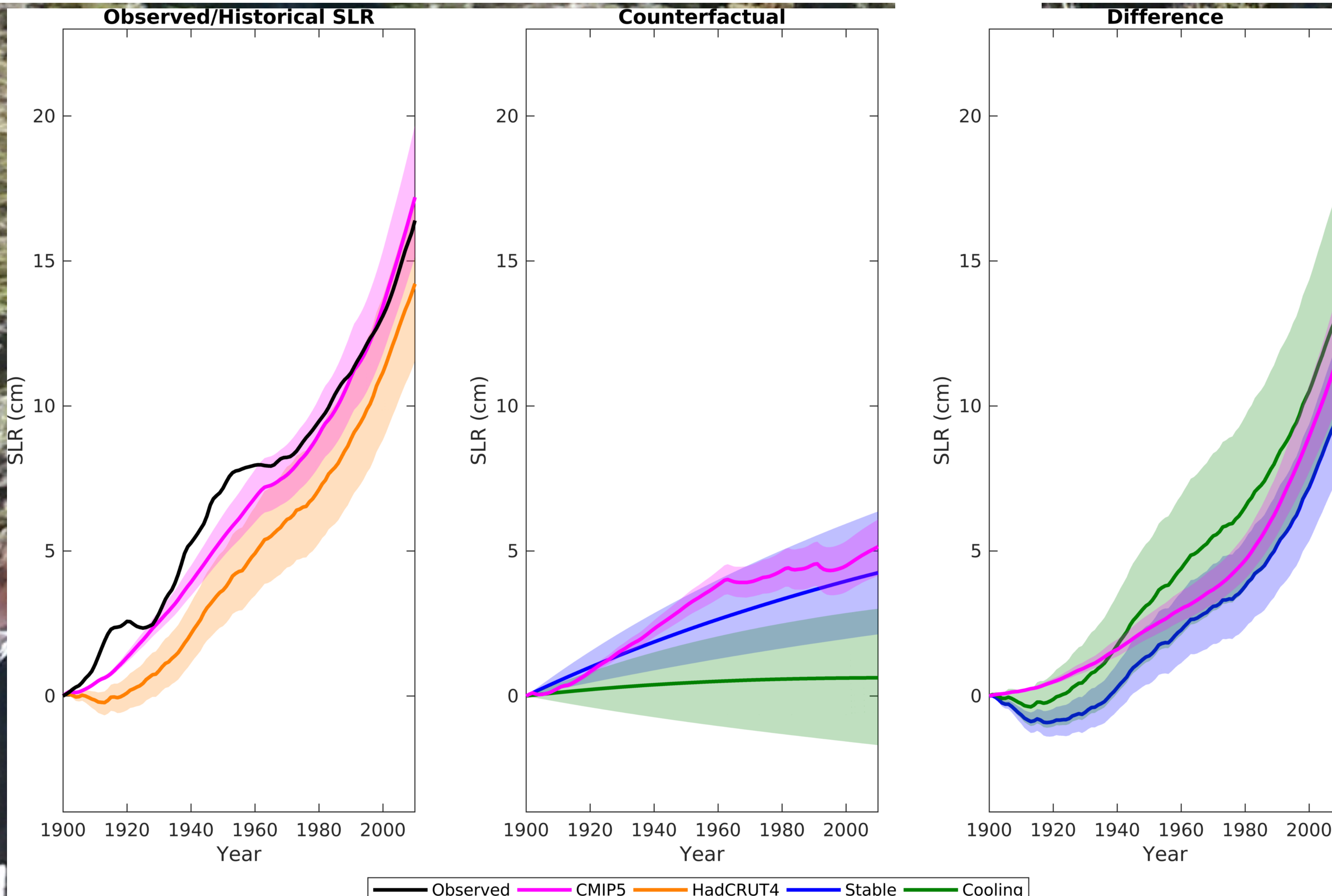
What does this imply for the historical sea-level change?

Counterfactual scenarios for 1900–2012



What does this imply for the historical sea-level change?

Counterfactual scenarios for 1900–2012

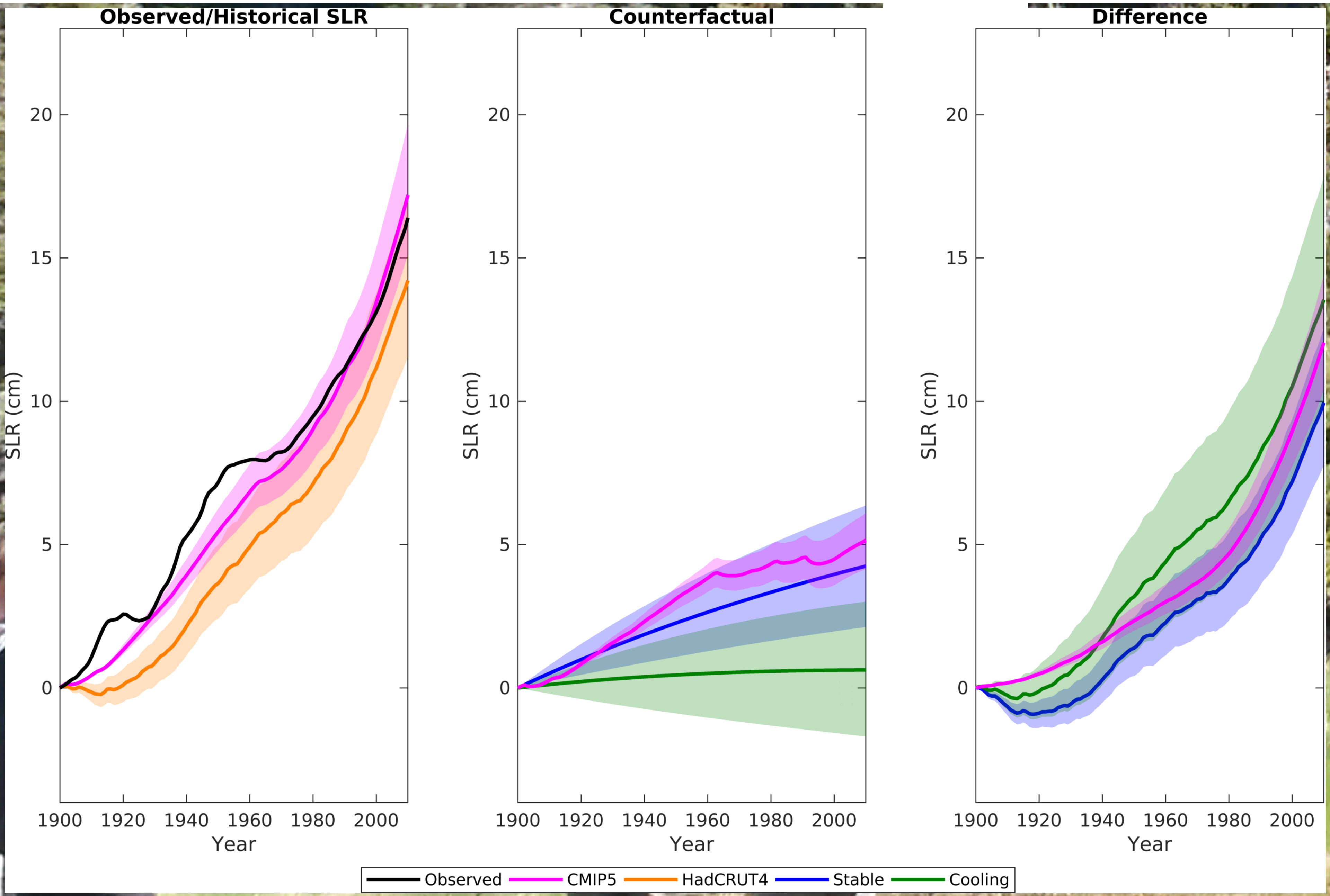


Depending on assumptions, very likely (90% credible) that between 8 and 18 cm of observed 16 cm of GMSL rise over 1900-2012 is due to human-caused climate change.

Strauss et al. (in rev.)

What does this imply for the historical sea-level change?

Counterfactual scenarios for 1900–2012



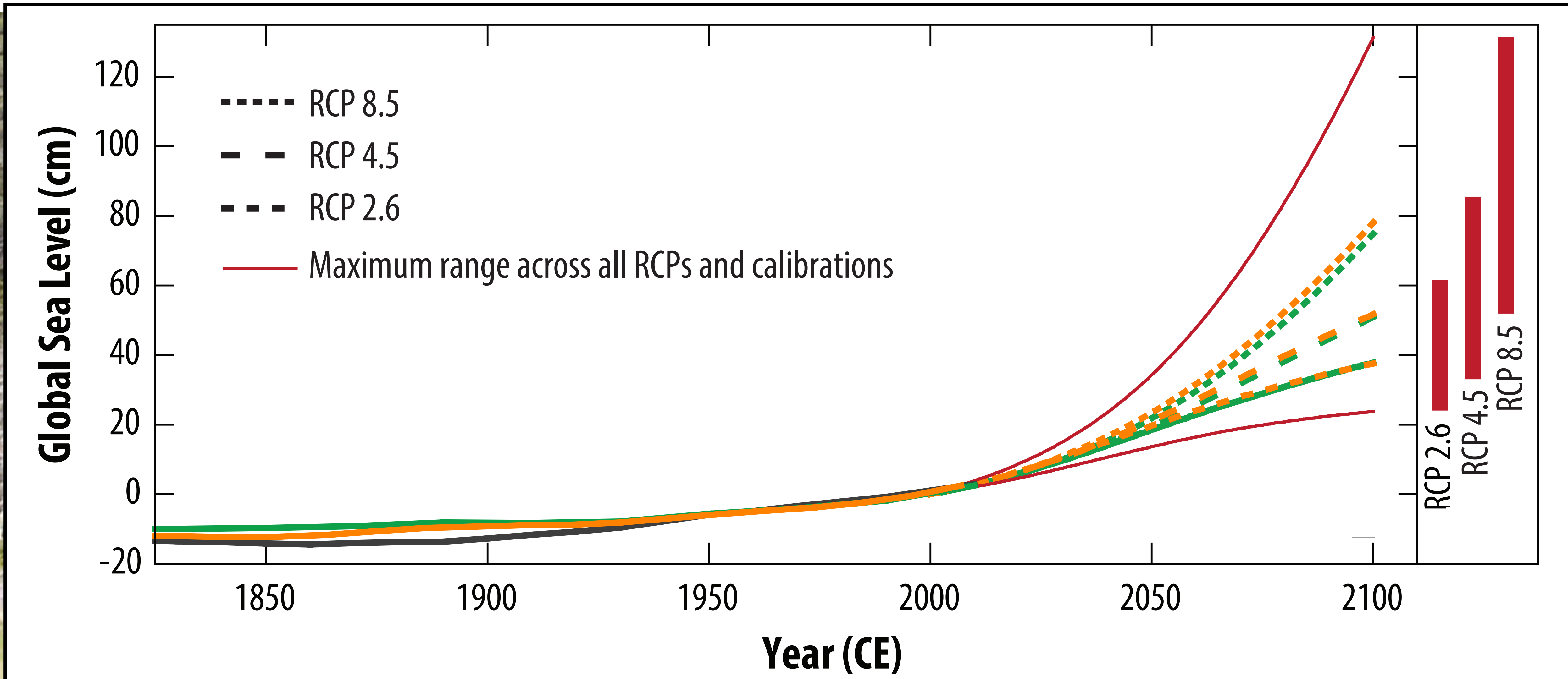
Depending on assumptions, very likely (90% credible) that between 8 and 18 cm of observed 16 cm of GMSL rise over 1900-2012 is due to human-caused climate change.

Implying human-caused SLR is responsible for ~1/6 of Sandy damages…

Strauss et al. (in rev.)

Project forward using the past sea level/temperature relationship

Global mean sea-level rise above year 2000 levels



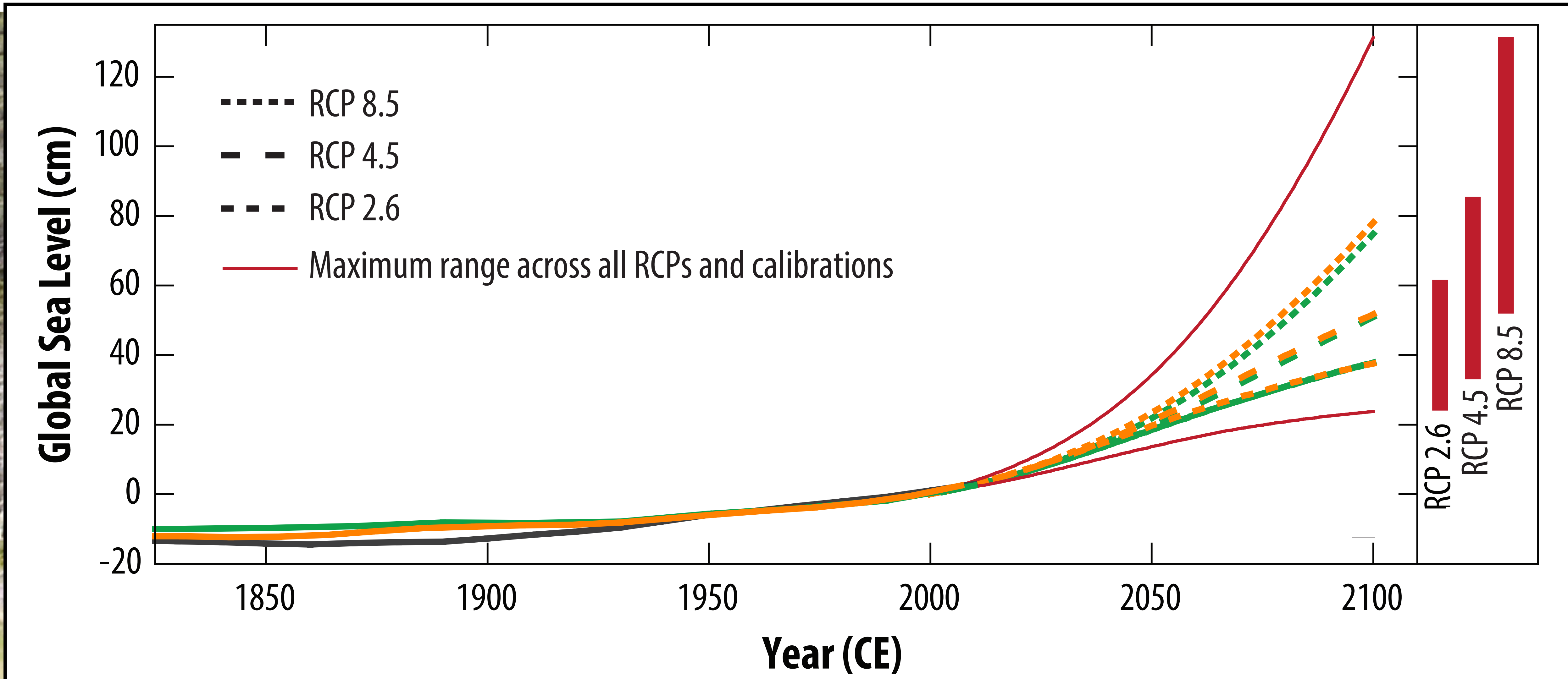
Projected SLR by 2100 (90% probability range):

0.5–1.3 m (1.7-4.3 ft) under high emissions (RCP 8.5)
0.2–0.6 m (0.8-2.0 ft) under low emissions (RCP 2.6)

Kopp et al. (2016)

Project forward using the past sea level/temperature relationship

Global mean sea-level rise above year 2000 levels



Projected SLR by 2100 (90% probability range):

0.5–1.3 m (1.7-4.3 ft) under high emissions (RCP 8.5)
0.2–0.6 m (0.8-2.0 ft) under low emissions (RCP 2.6)

But: statistical model projects global (not local) changes and is calibrated from a time period when thermal expansion and mountain glaciers (and, regionally, ocean dynamics) dominated sea-level change.

Kopp et al. (2016)

Kopp et al. 2014 bottom-up probabilistic framework

Earth's Future

RESEARCH ARTICLE
10.1002/2014EF000239

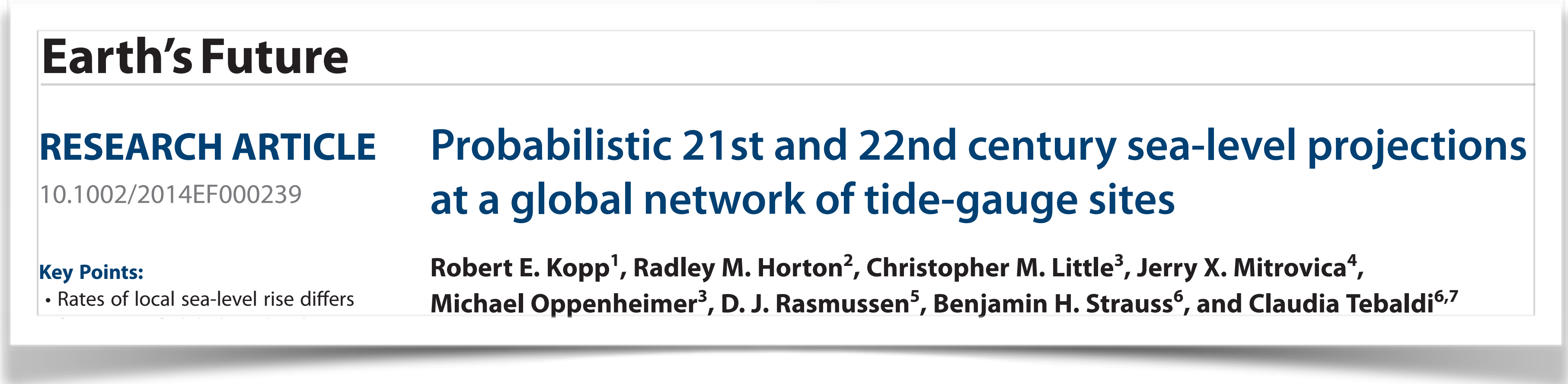
Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites

Robert E. Kopp[1], Radley M. Horton[2], Christopher M. Little[3], Jerry X. Mitrovica[4], Michael Oppenheimer[3], D. J. Rasmussen[5], Benjamin H. Strauss[6], and Claudia Tebaldi[6,7]

Key Points:

- Rates of local sea-level rise differs

Kopp et al. 2014 probabilistic framework

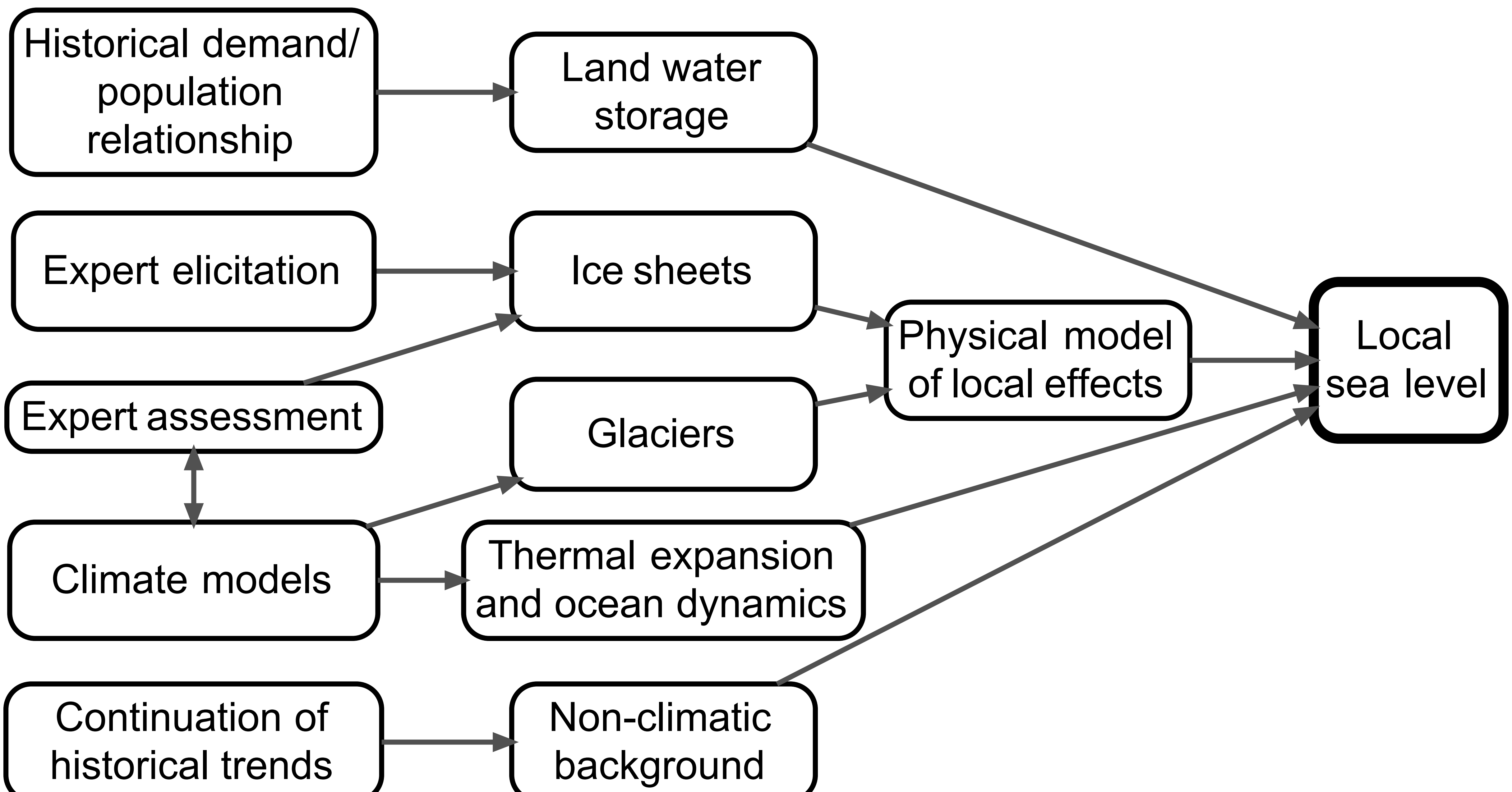

Earth's Future

RESEARCH ARTICLE
10.1002/2014EF000239

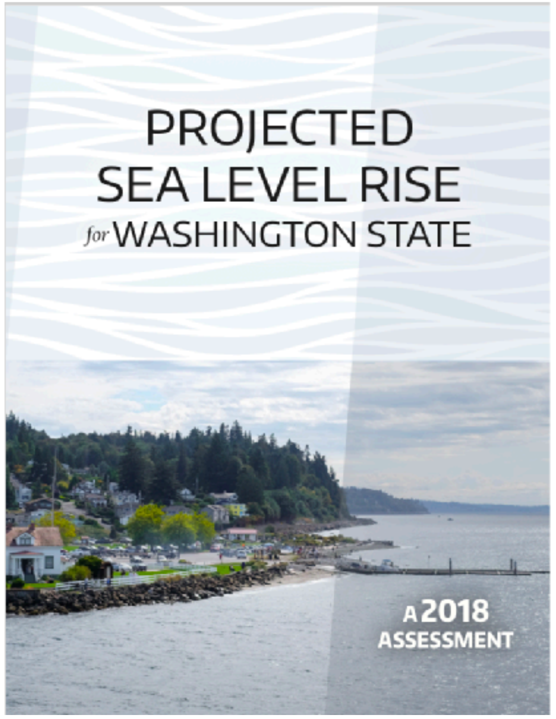
Key Points:
• Rates of local sea-level rise differs

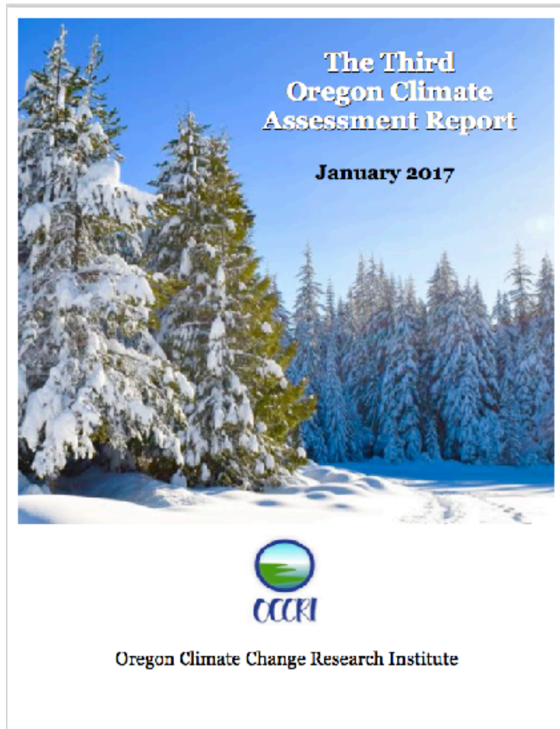
Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites

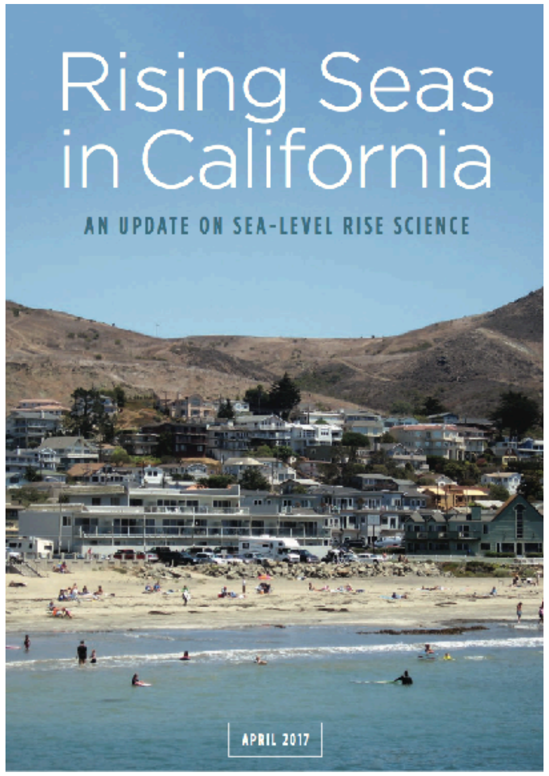
Robert E. Kopp[1], Radley M. Horton[2], Christopher M. Little[3], Jerry X. Mitrovica[4], Michael Oppenheimer[3], D. J. Rasmussen[5], Benjamin H. Strauss[6], and Claudia Tebaldi[6,7]

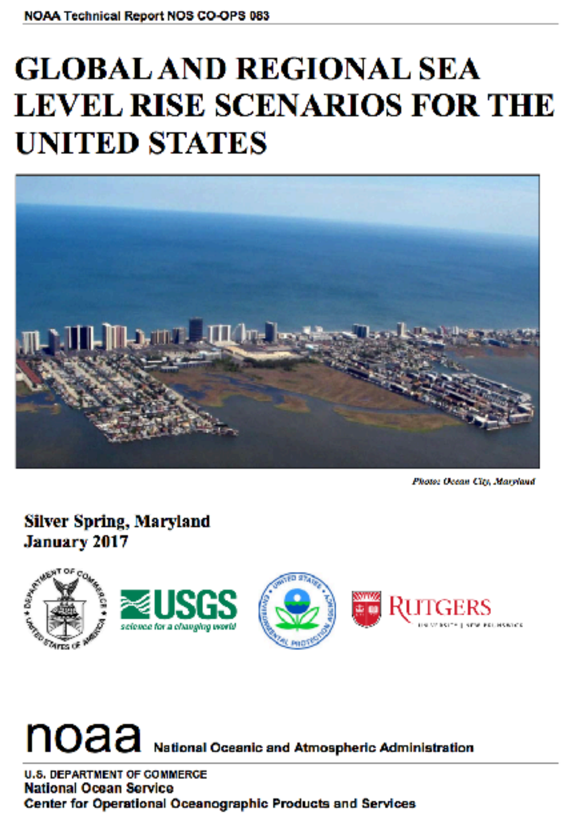


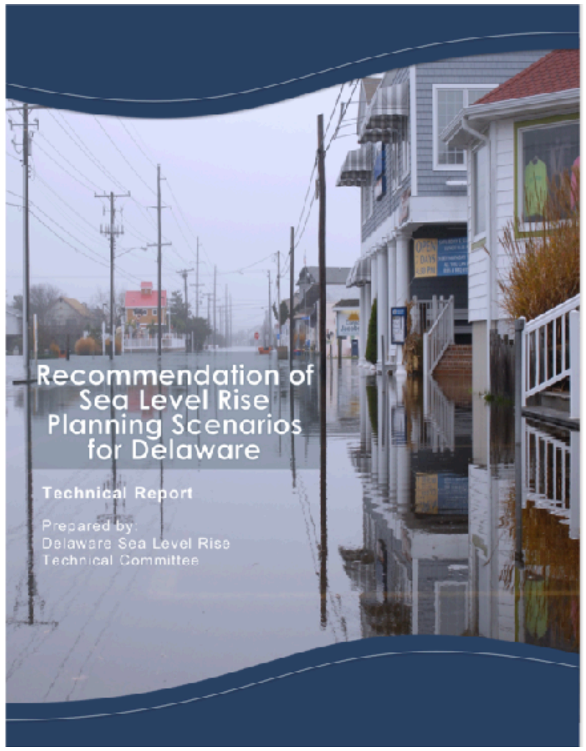
Kopp et al. 2014 framework (± modifications) has been widely used in US

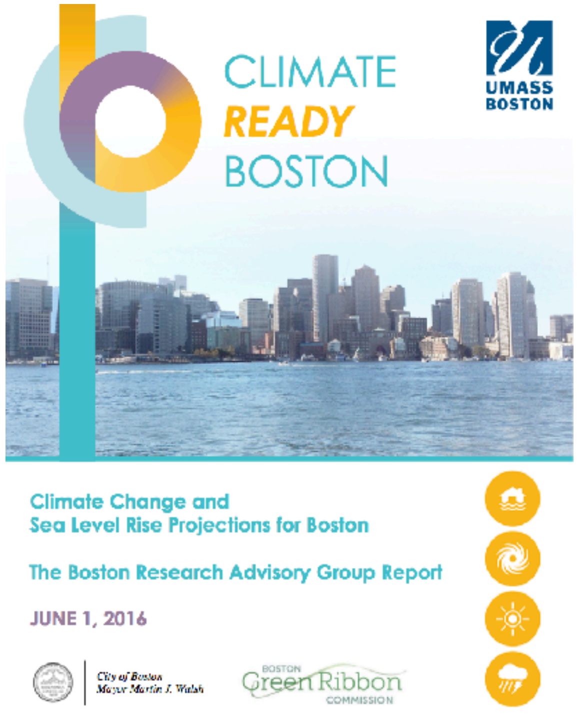


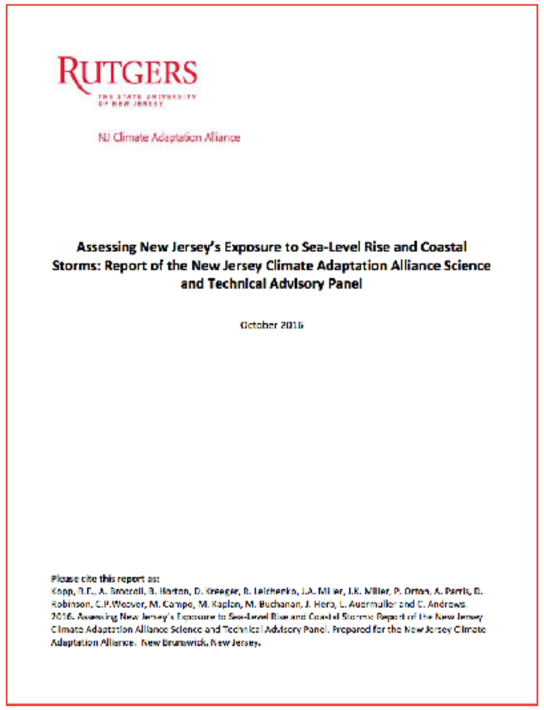






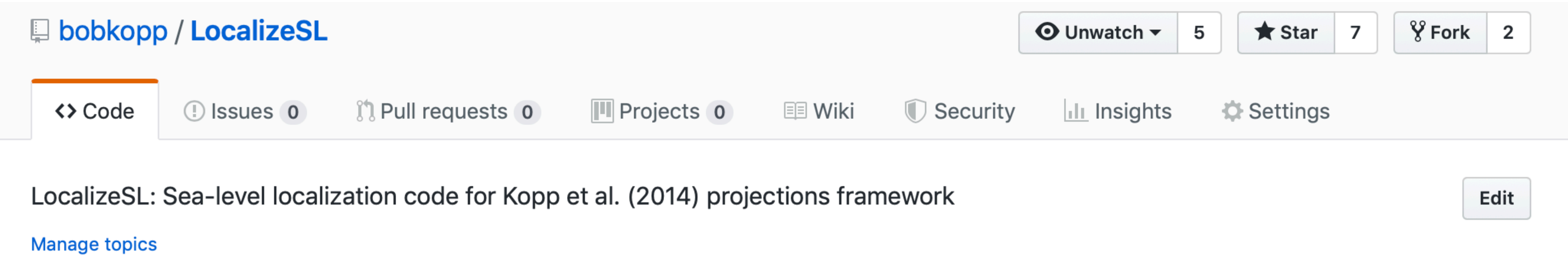




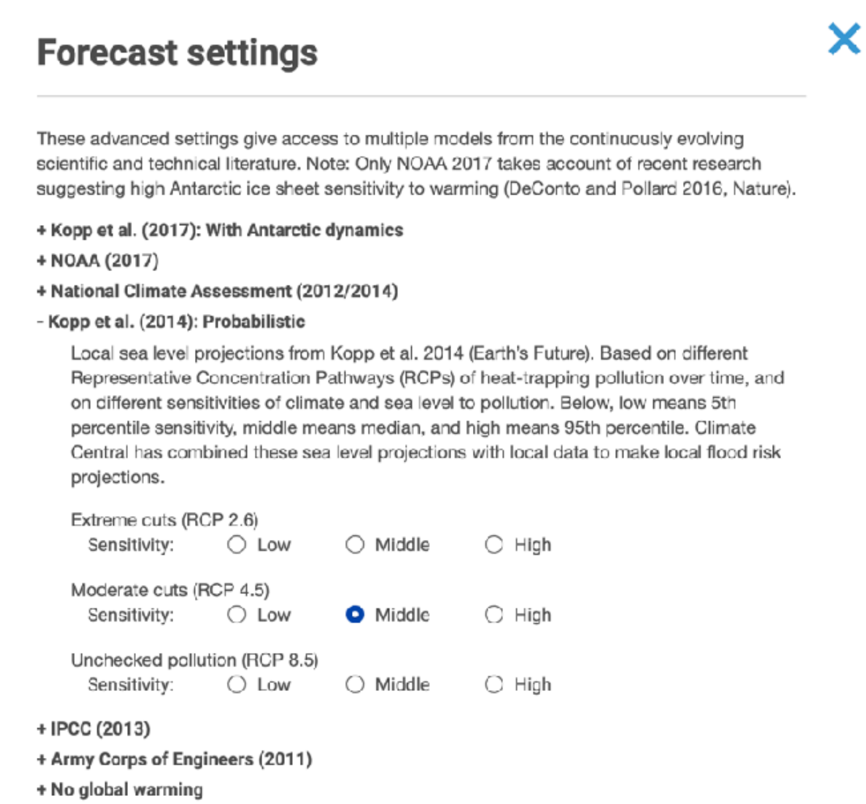


Data and code availability

github.com/bobkopp/LocalizeSL



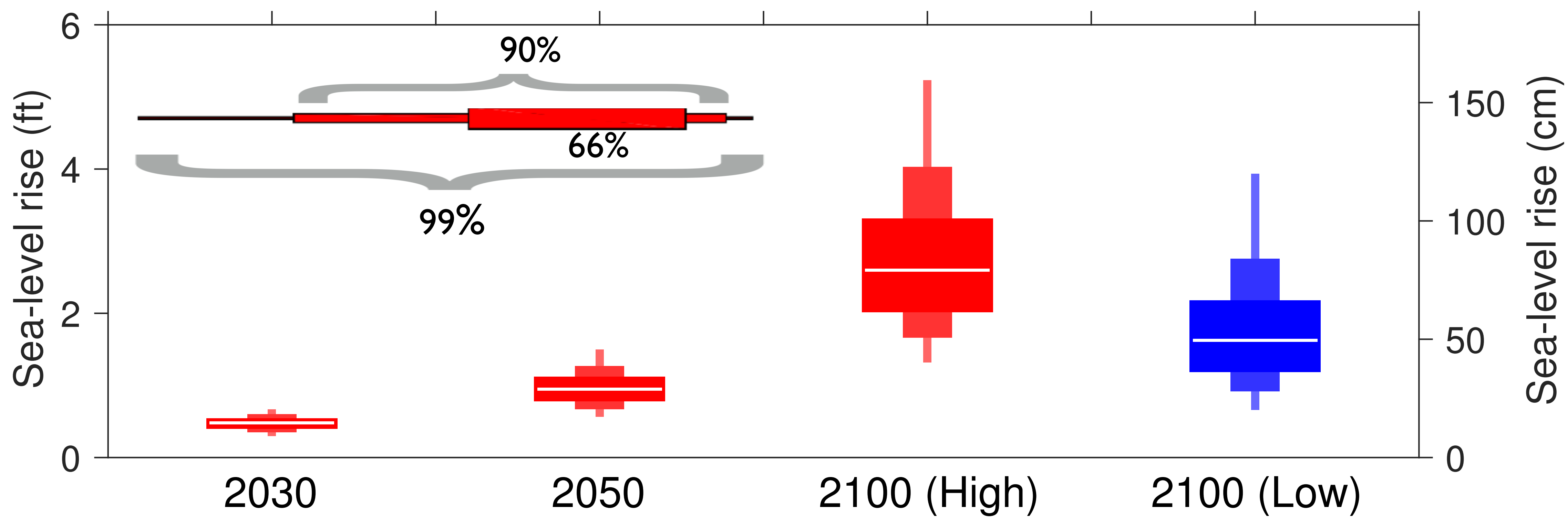
sealevel.climatecentral.org



Projected global mean sea-level rise

Above 1991-2009 average sea level

RUTGERS
Institute of Earth, Ocean, and Atmospheric Sciences



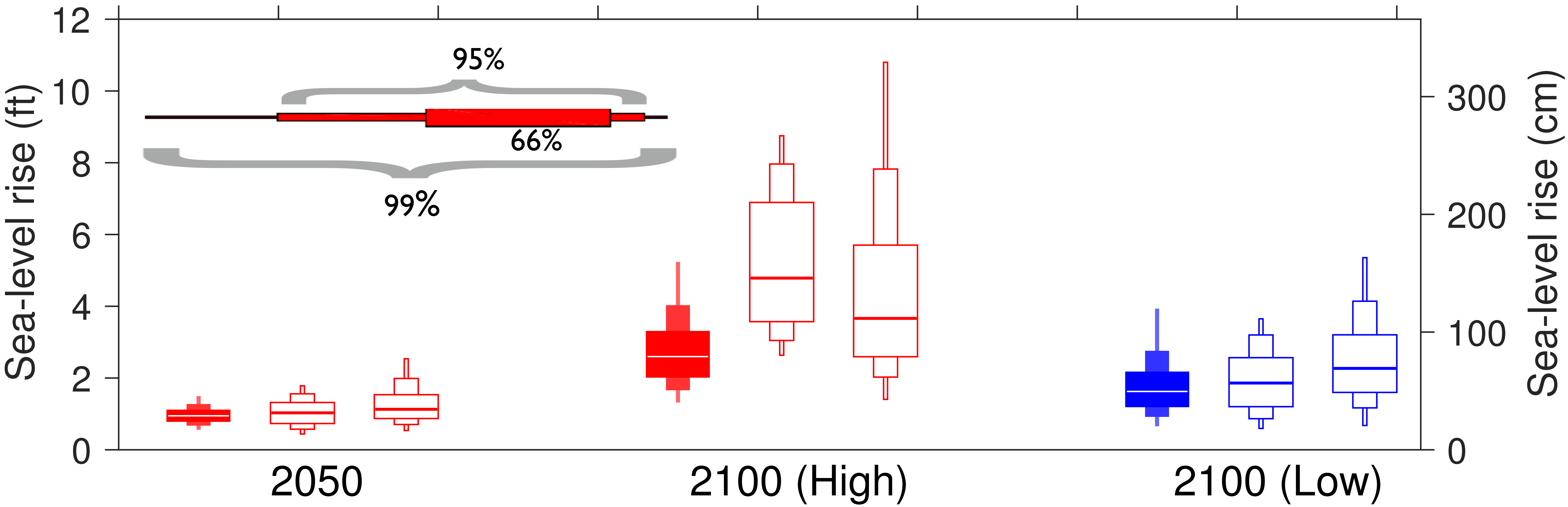
By 2030: very likely 0.1-0.2 m (0.3-0.6 feet), regardless of emissions
By 2050: very likely 0.2-0.4 m (0.6–1.3 feet), almost regardless of emissions

By 2100: very likely 0.5-1.2 m (1.7–4.0 feet) under high emissions
By 2100: very likely 0.3-0.8 m (0.9–2.8 ft) under low emissions

In climate scientist (IPCC) speak,
'very likely' means at least 9 chances in 10.
(But lower probability outcomes also can be important!)

Data from Kopp et al. (2014)

Different treatments of ice sheets give quite different late century global-mean sea-level projections



High emissions

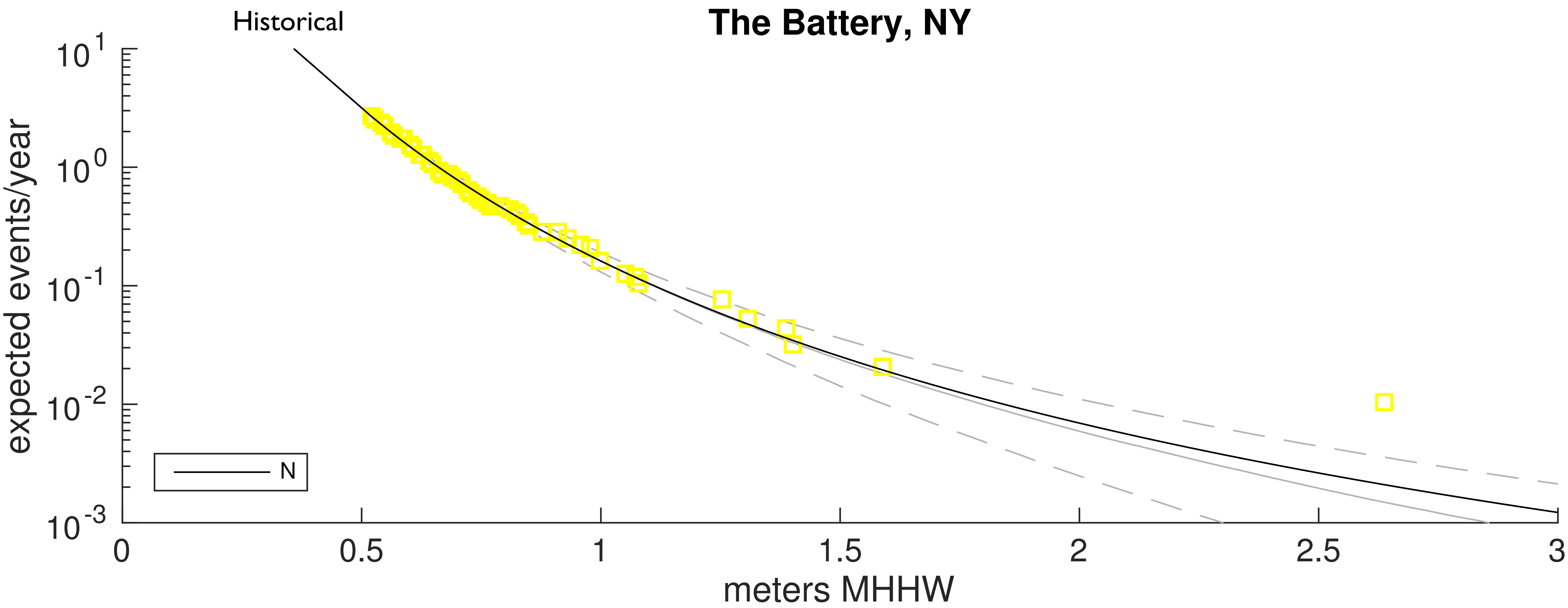
- K14 (sluggish ice): 0.5-1.2 m
- DP16 (fast ice): 0.9-2.4 m
- B19 (structured expert judgement): 0.6-2.4 m

Low emissions

- K14: 0.3-0.8 m
- DP16: 0.3-1.0 m
- B19 0.4-1.3 m

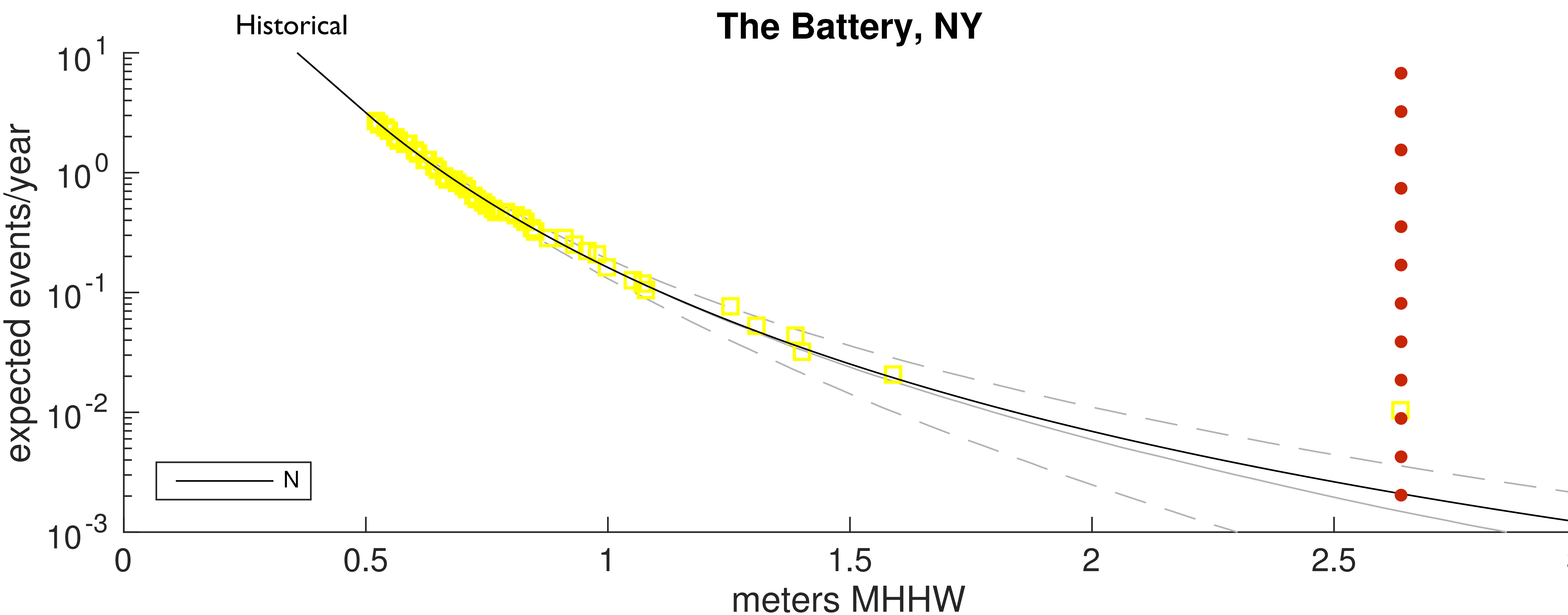
Kopp et al. (in rev.)

Bayesian probabilistic projections can be cautiously combined with frequentist extreme value distributions



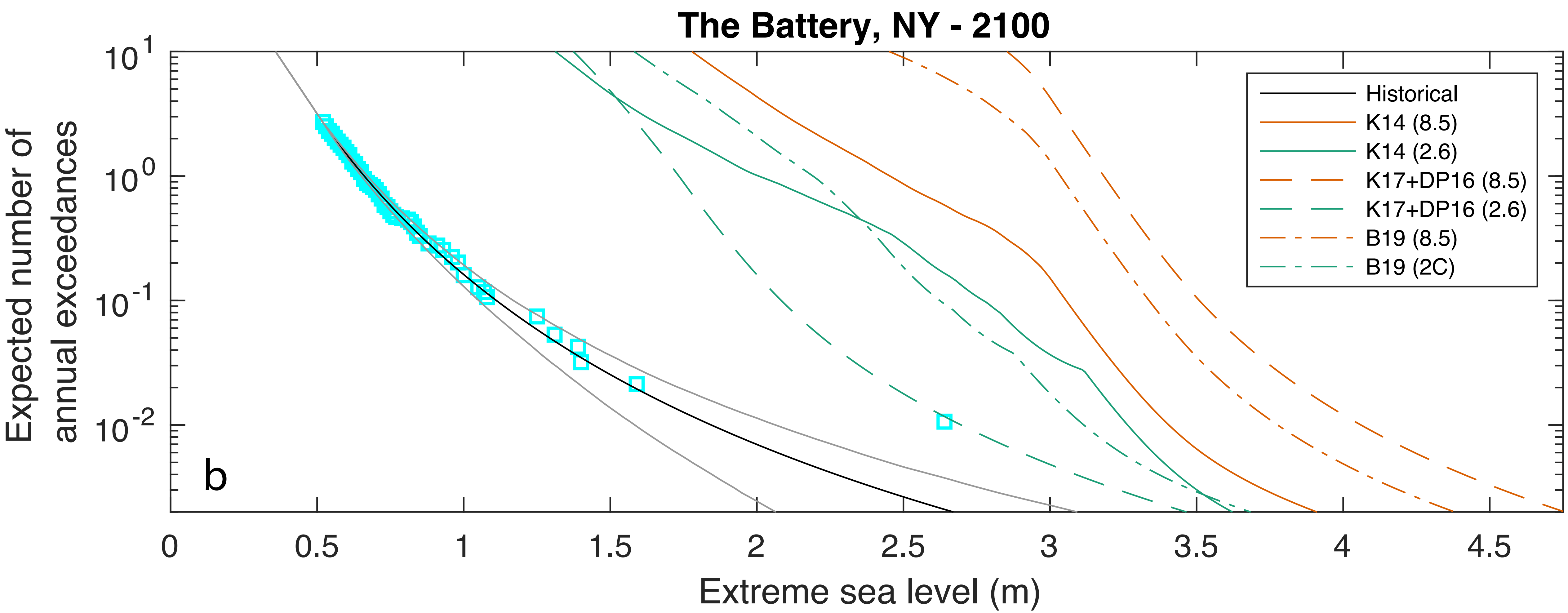
Buchanan et al. 2016

Bayesian probabilistic projections can be cautiously combined with frequentist extreme value distributions



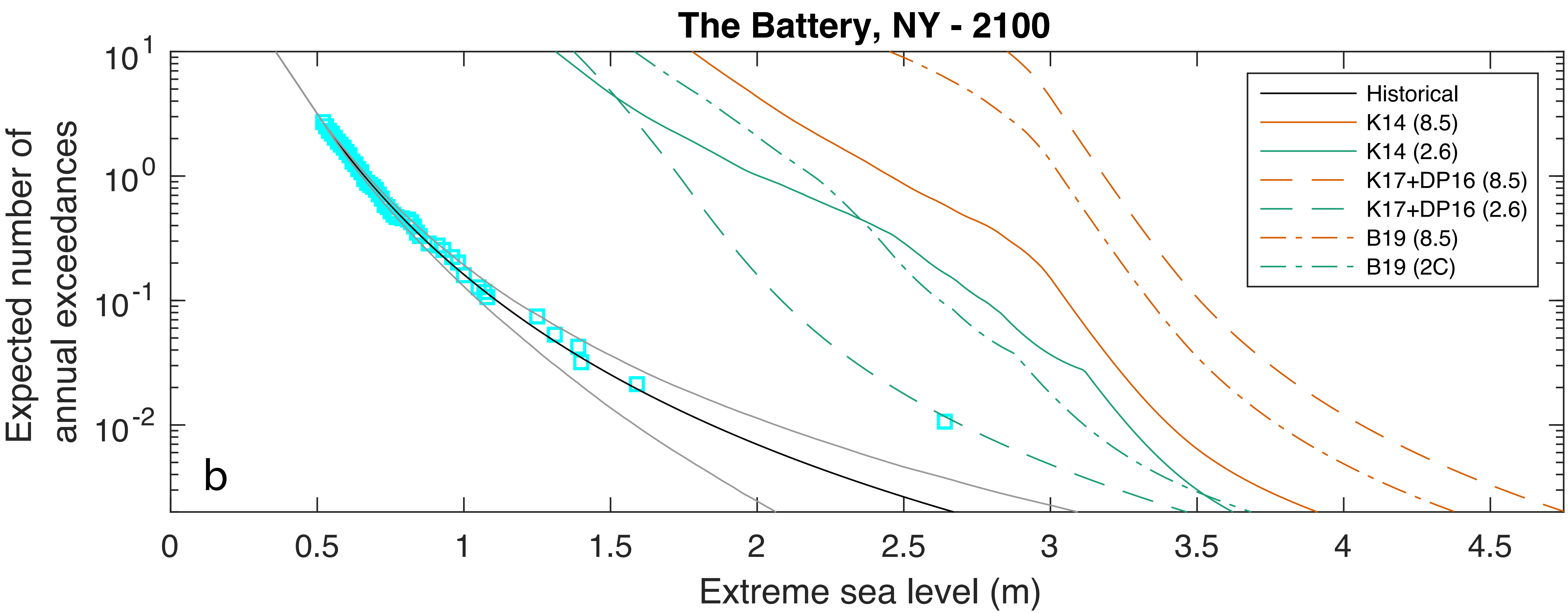
Sandy-scale extreme sea-level (2.6 m above mean higher high water) has an expected return period of about 450 years.

Bayesian probabilistic projections can be cautiously combined with frequentist extreme value distributions



Kopp et al. (in rev.)

Bayesian probabilistic projections can be cautiously combined with frequentist extreme value distributions

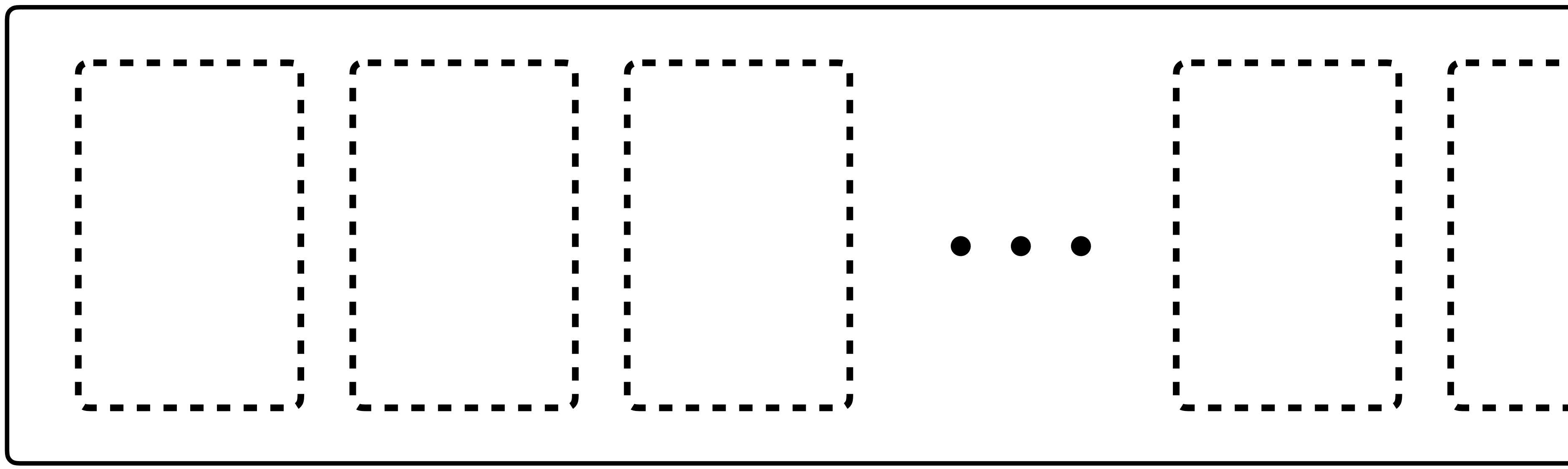


Under low emissions, Sandy-scale extreme sea-level (2.6 m above mean higher high water, ~450 year return period) has an expected return period in 2100 under low emissions of 5–76 years and under high emissions of 2 weeks–1.5 years.

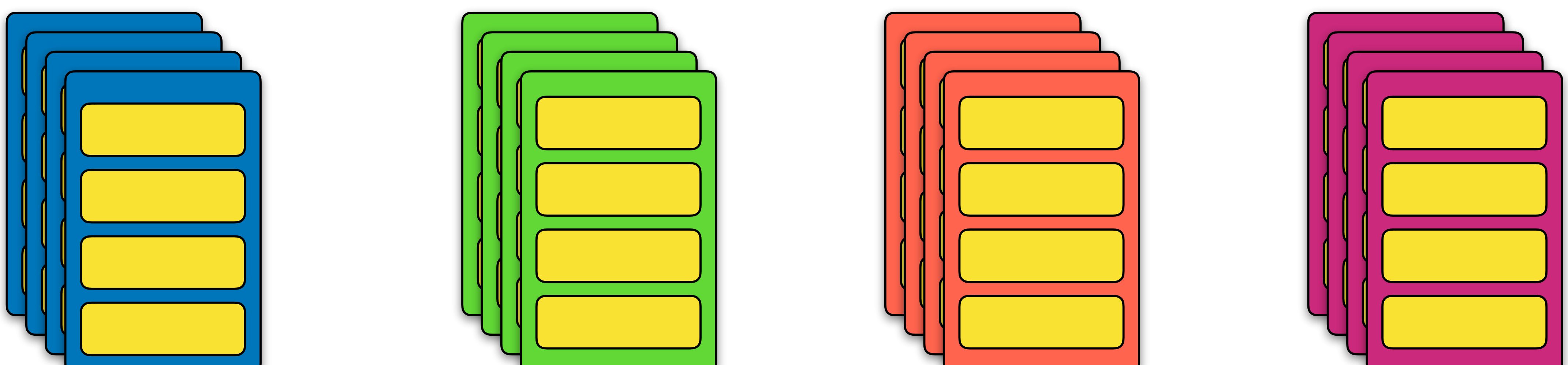
Kopp et al. (in rev.)

Toward a modular, scalable Python-based framework

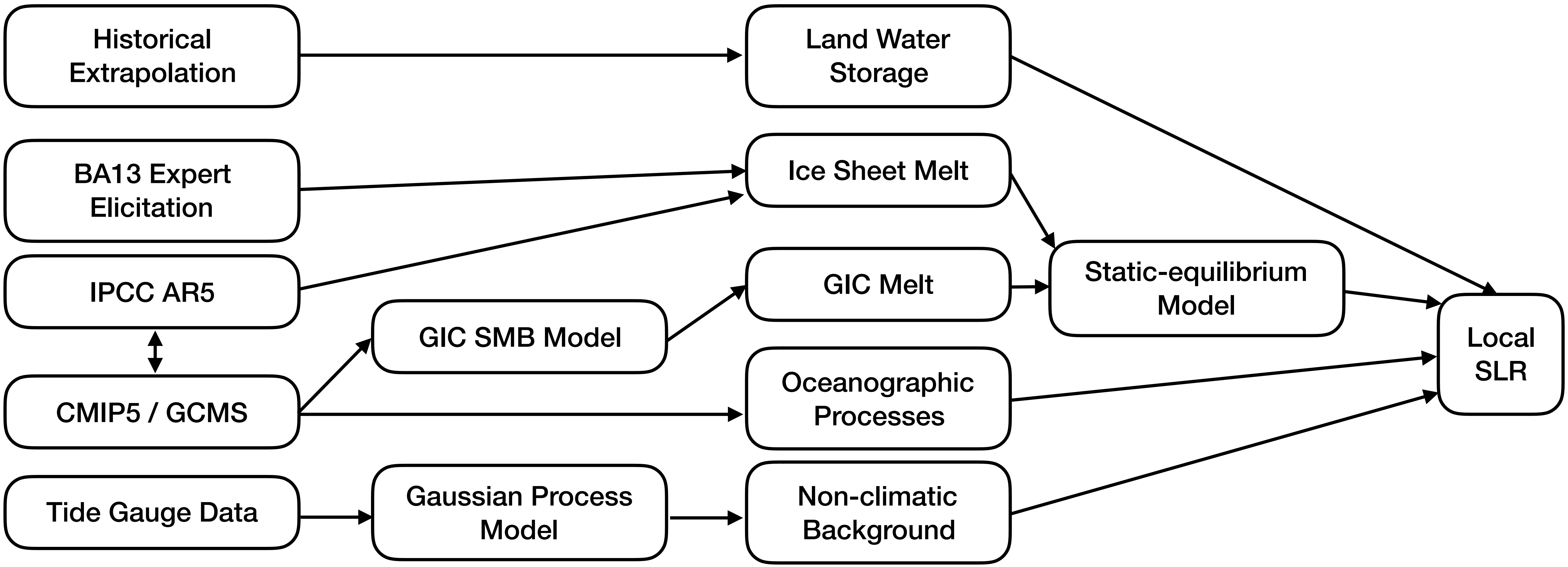
FACTS: Framework for Assessing Changes To Sea-level



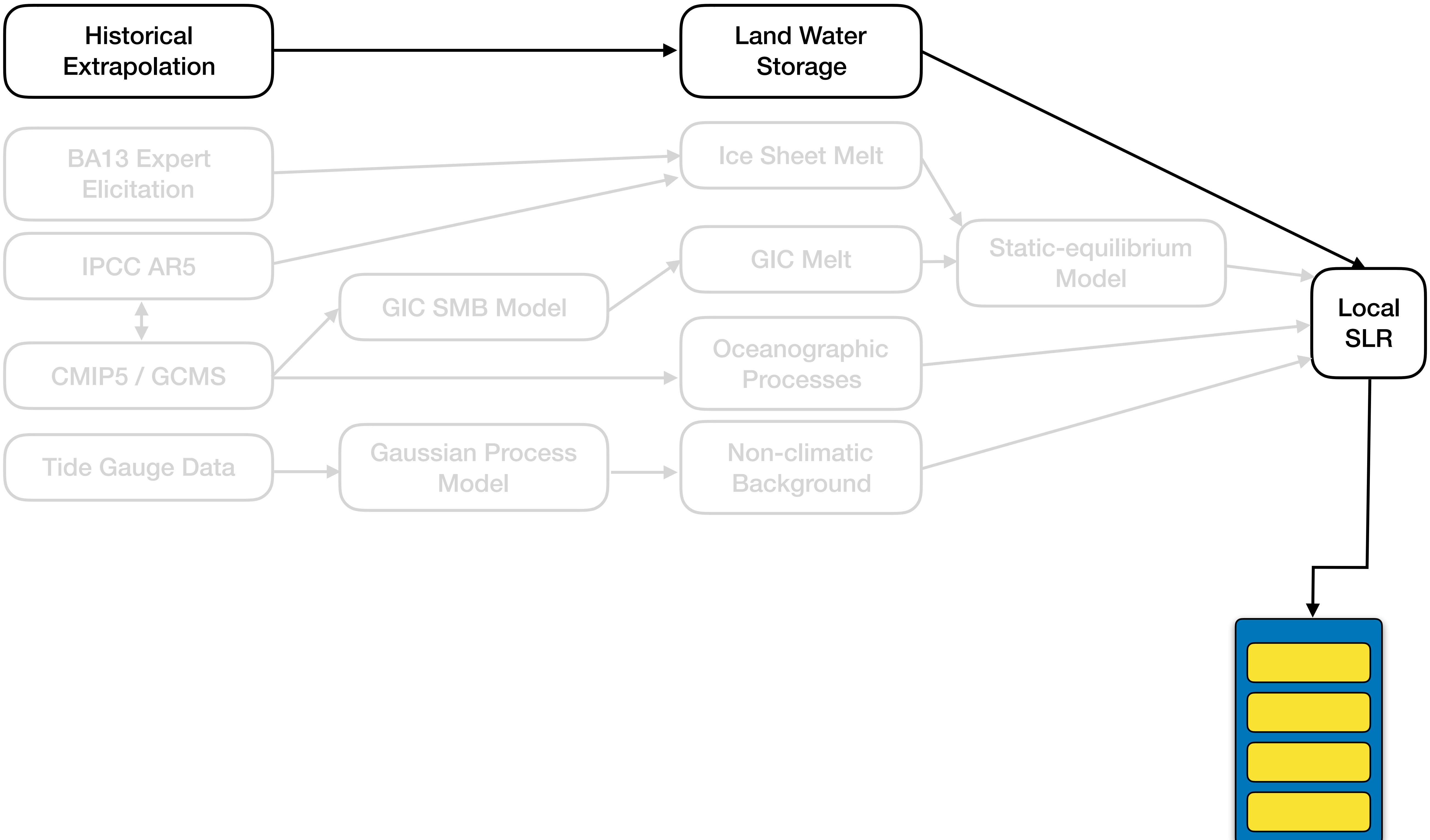

Framework



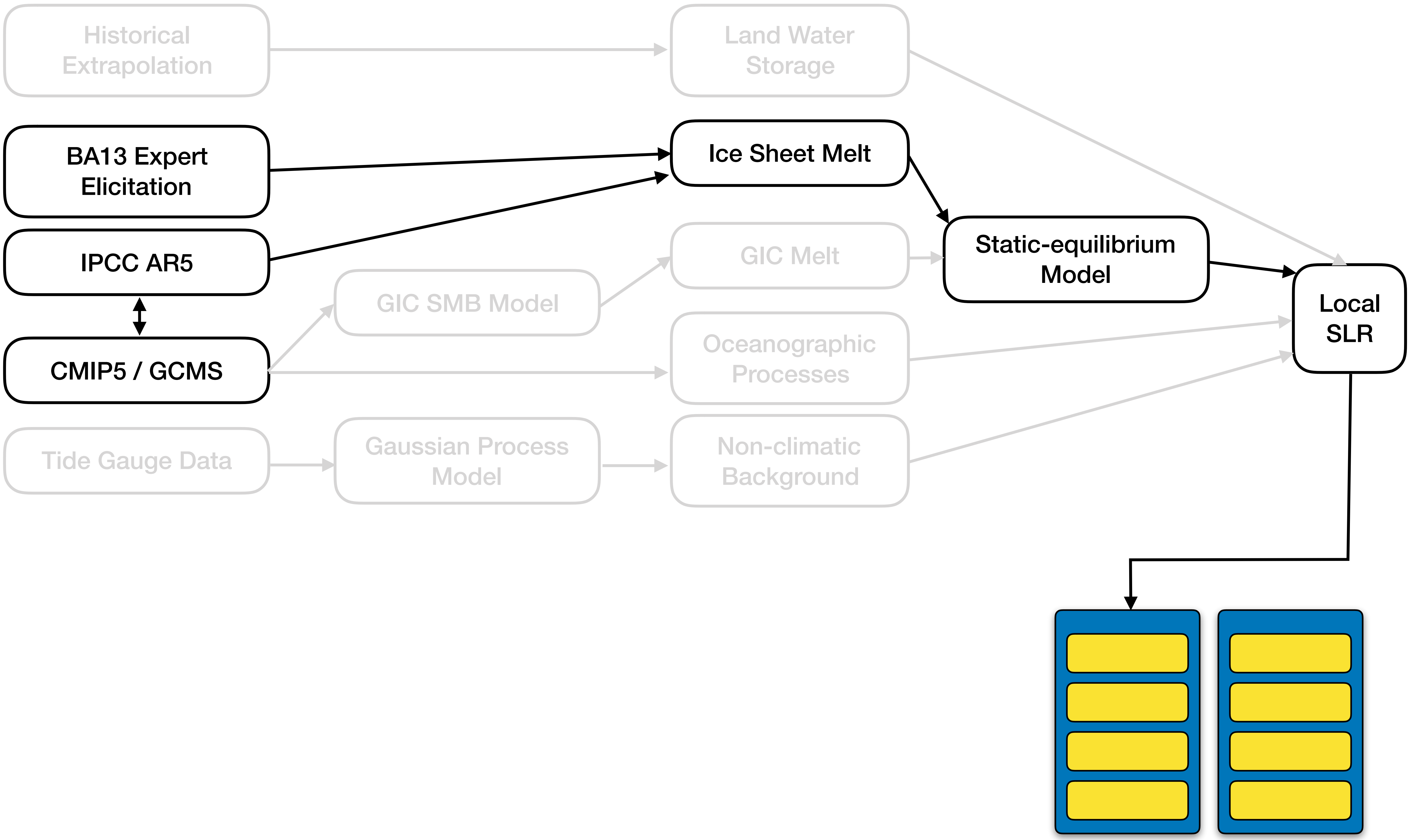
Workflows



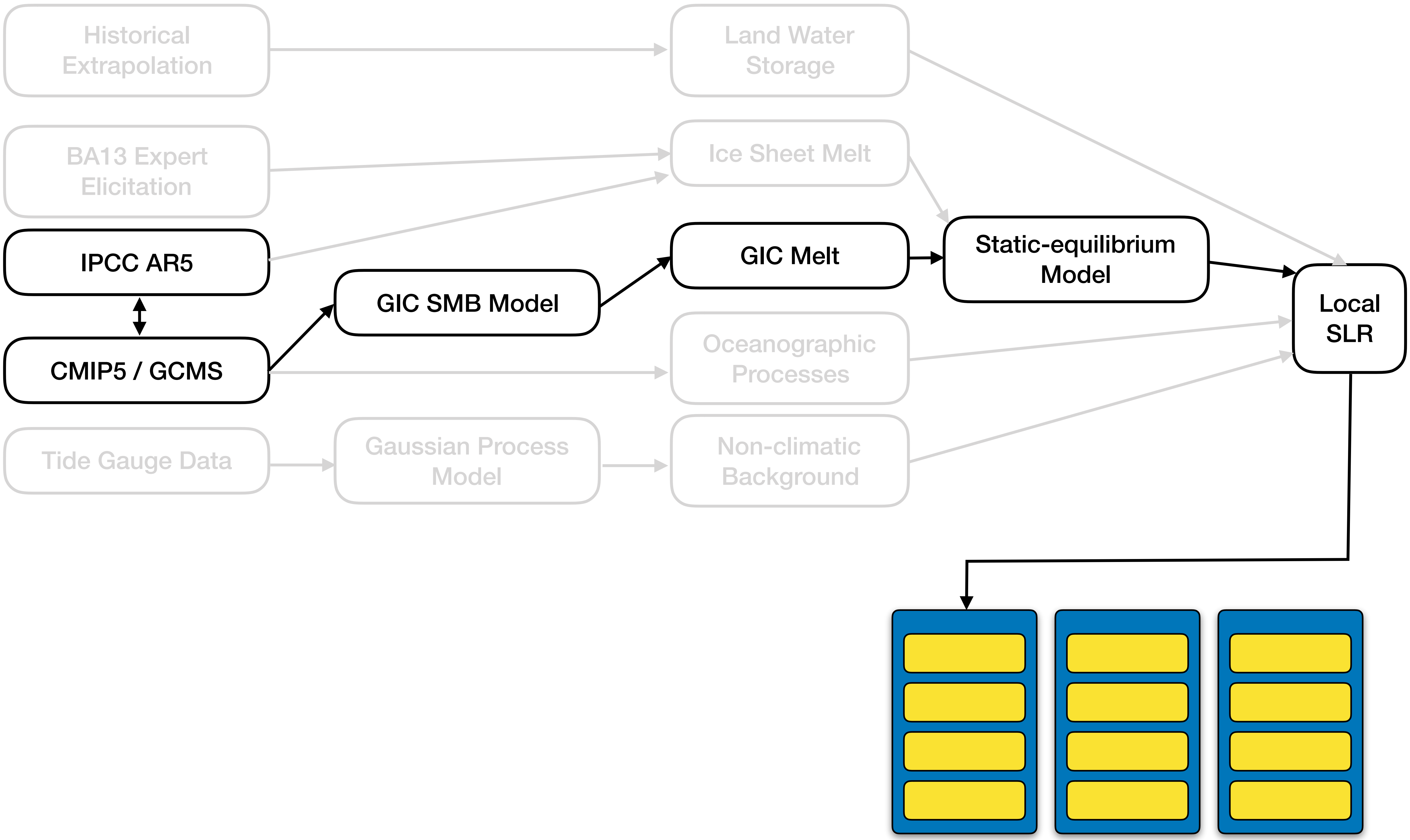
Kopp 2014 Workflow



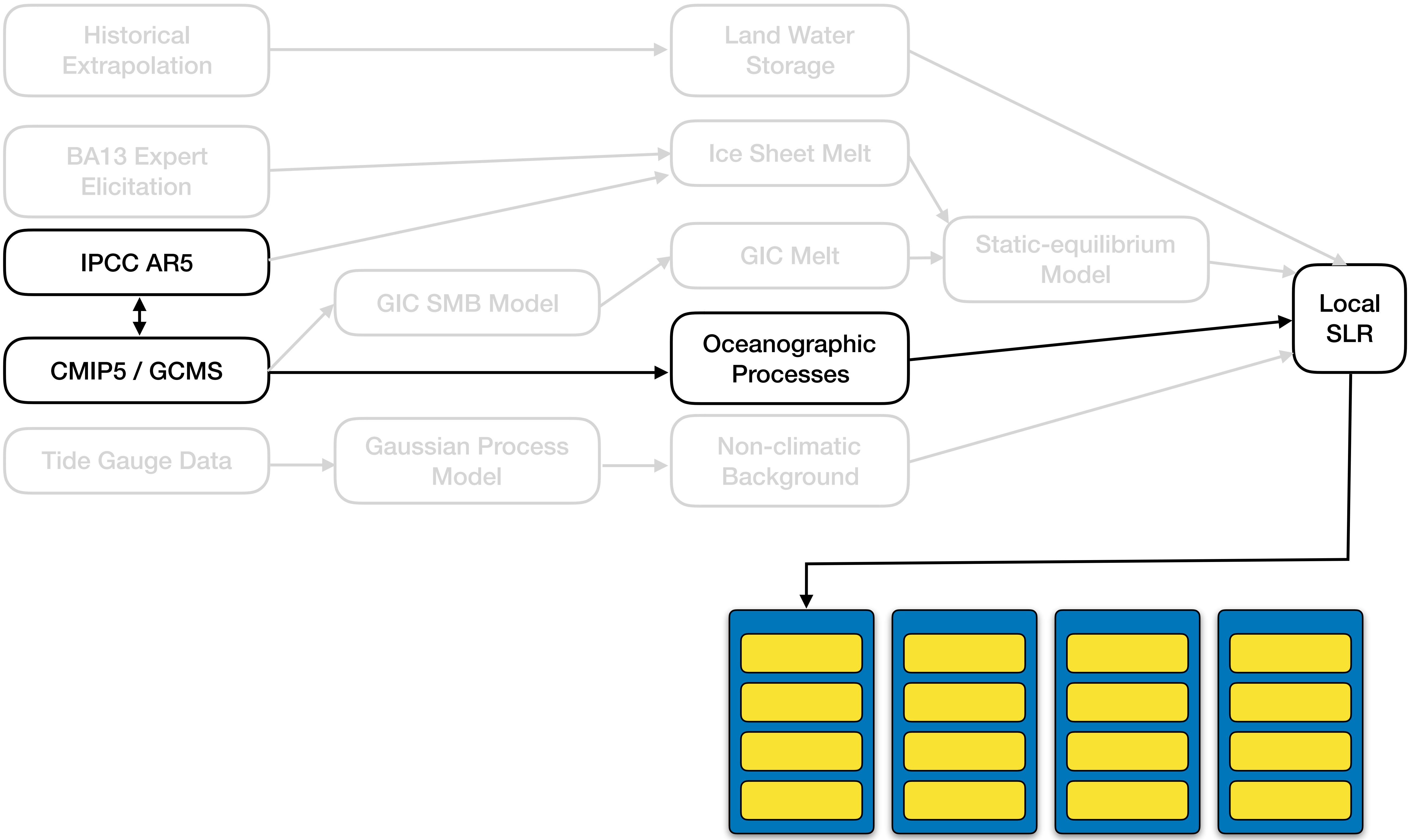
Kopp 2014 Workflow



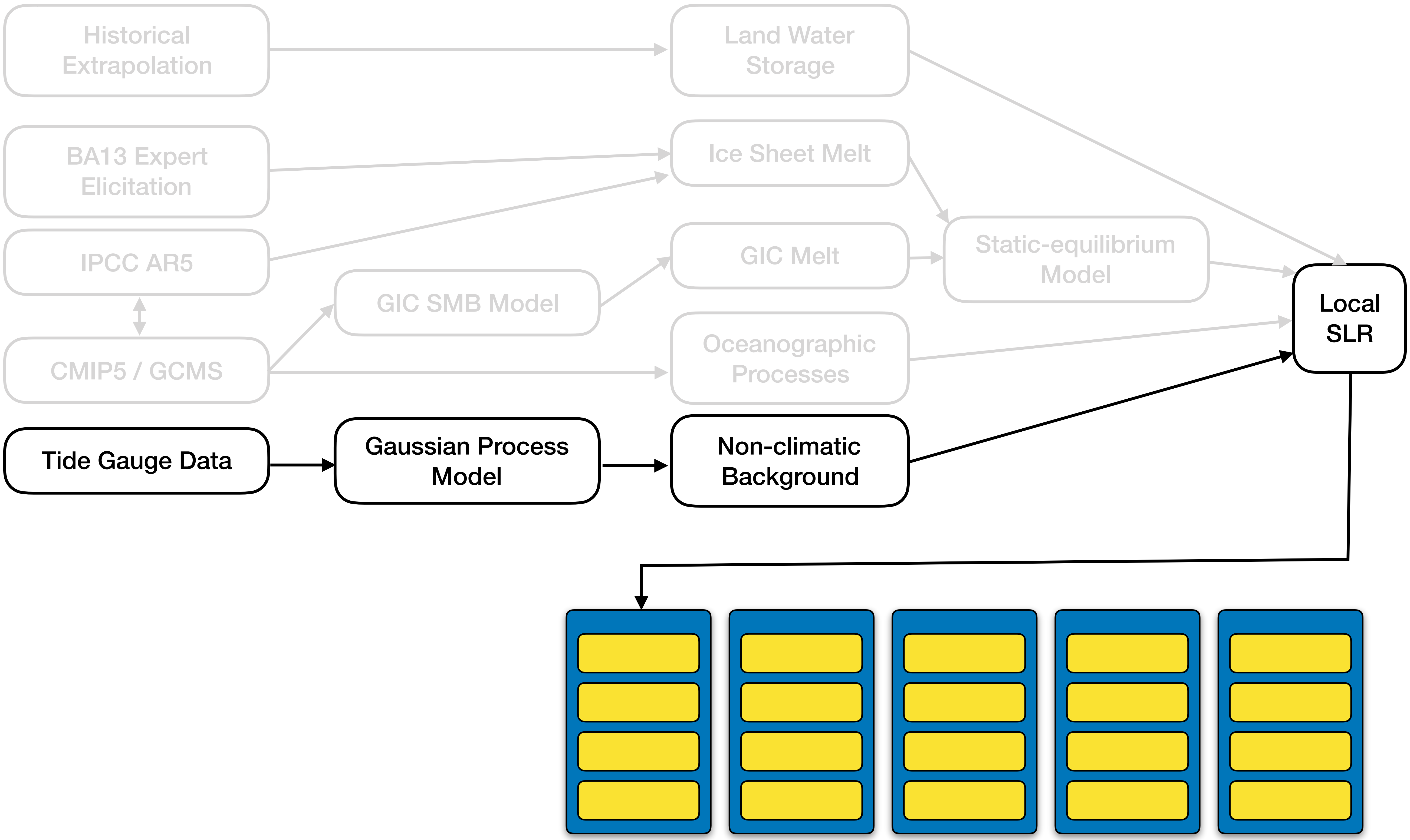
Kopp 2014 Workflow



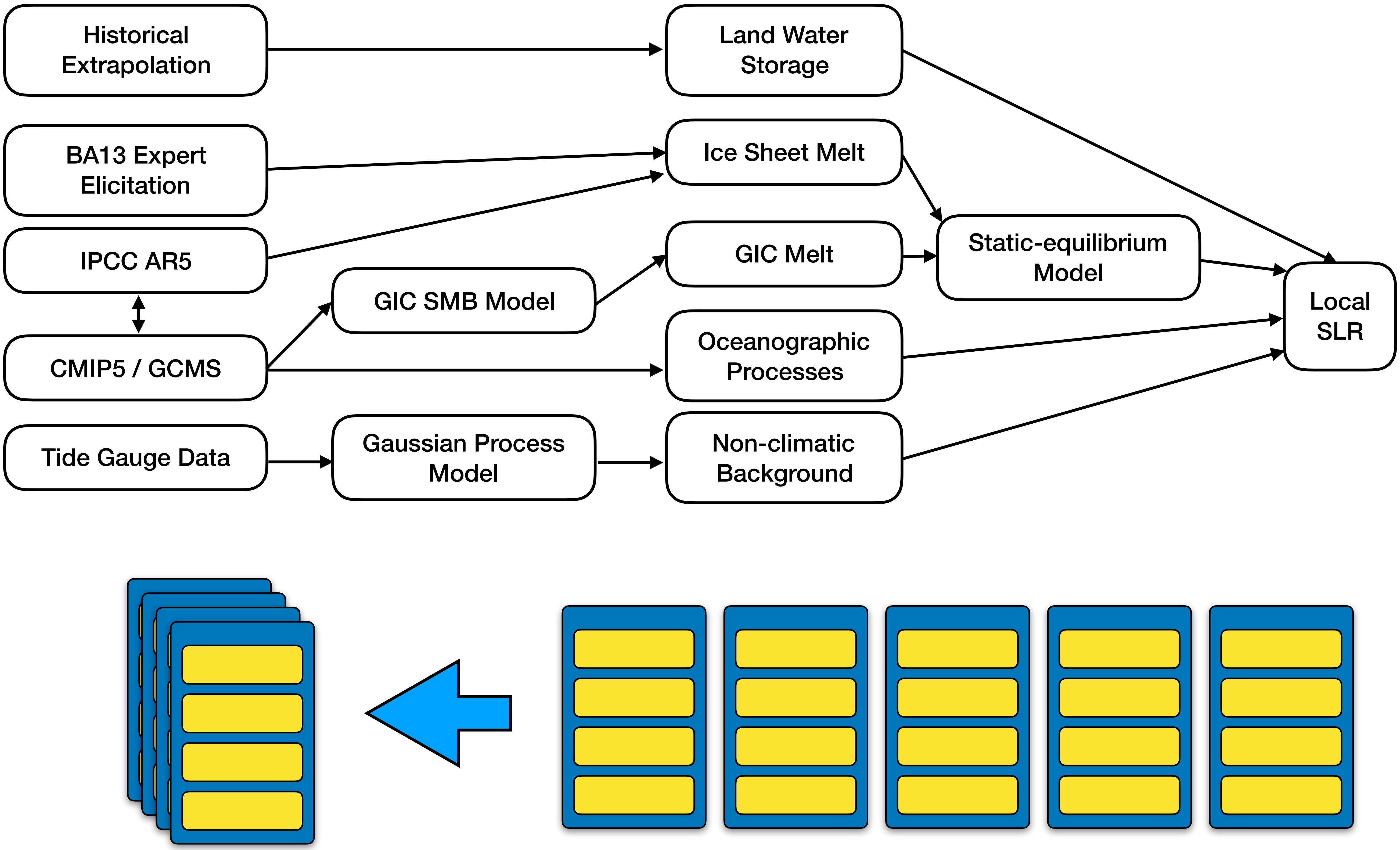
Kopp 2014 Workflow



Kopp 2014 Workflow

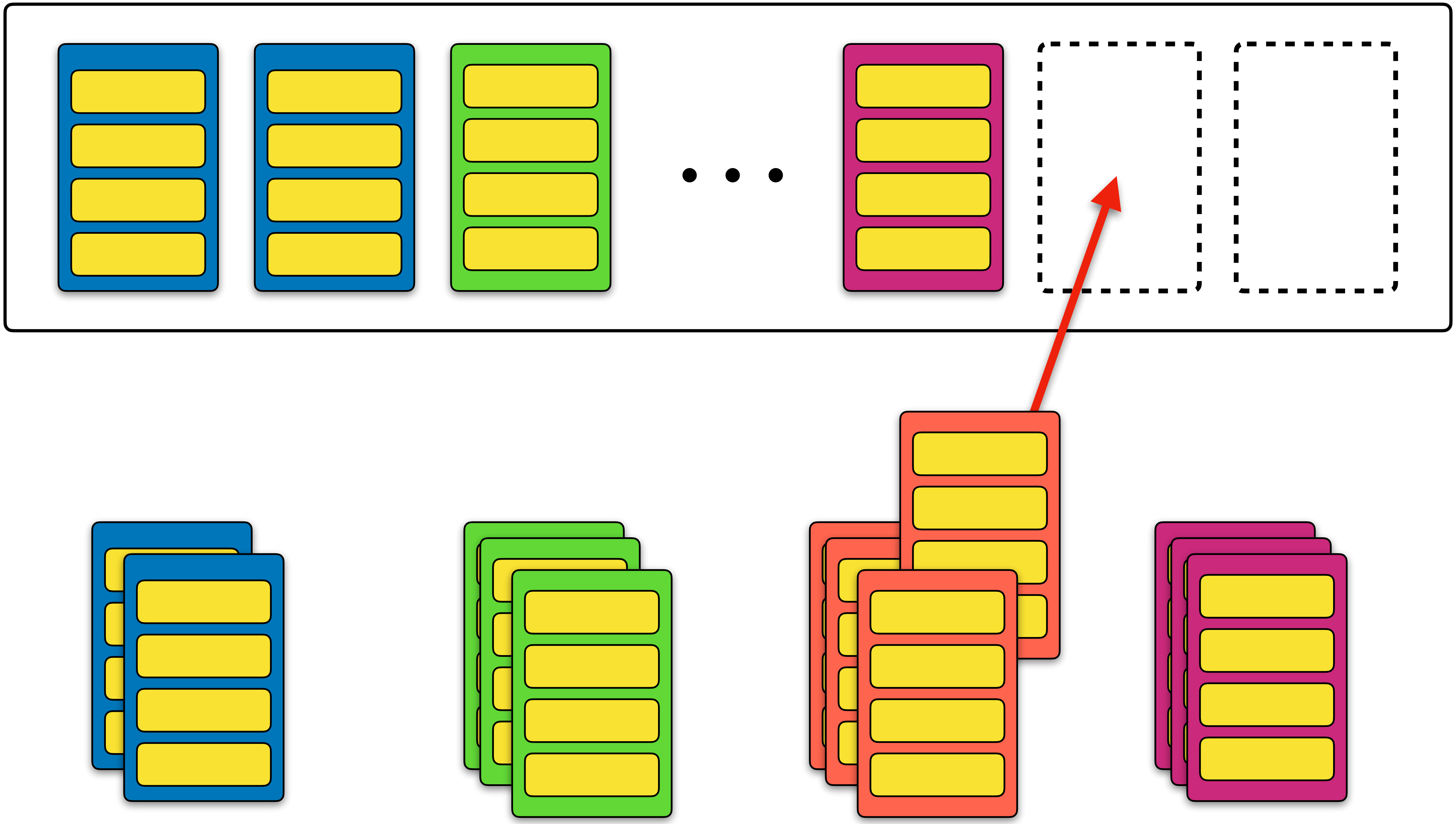


Kopp 2014 Workflow

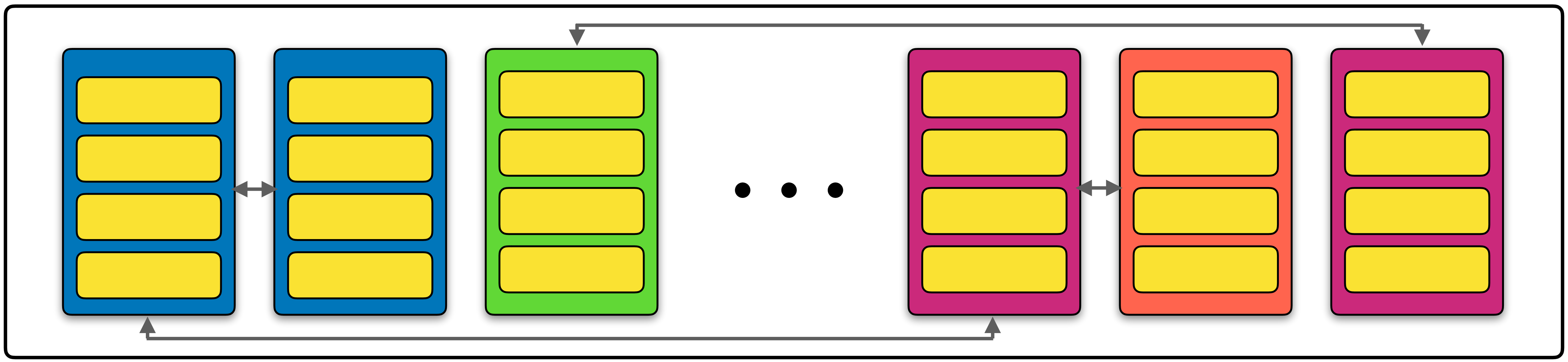


Kopp 2014 Workflow

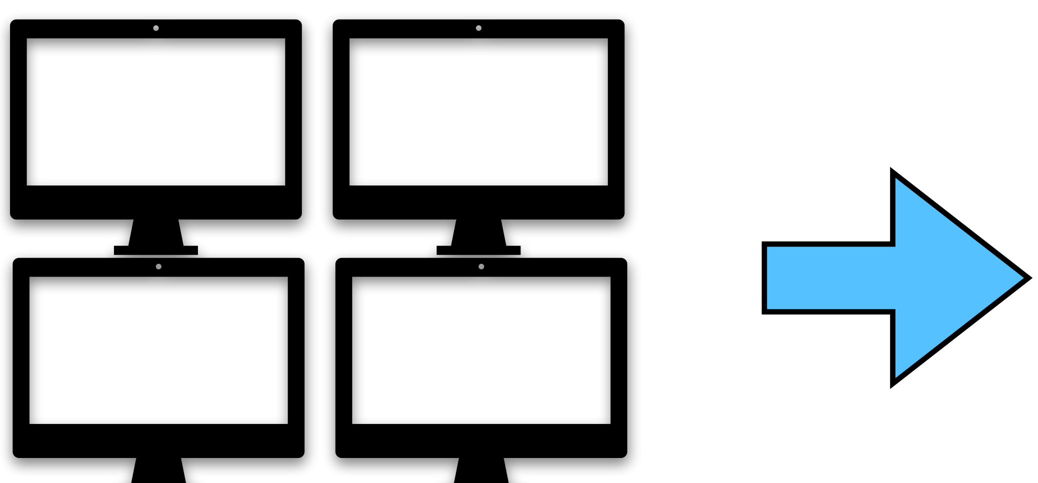
Mix and match sub-models from multiple workflows

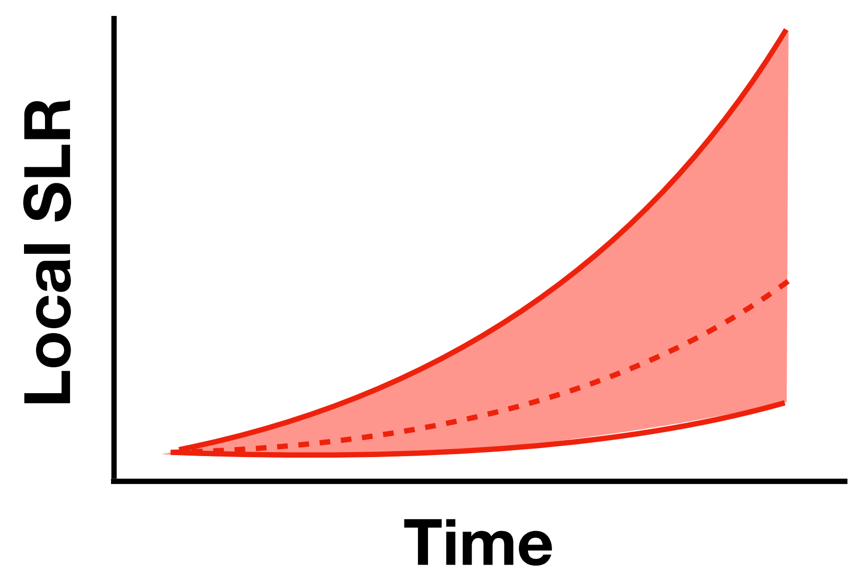


Enable cross-communication among modules



Leverage local or high-performance computing resources





built upon RADICAL Cybertools – Ensemble Toolkit

In short:

- Sea-level rise is a complex, spatiotemporally varying process of considerable societal importance.

- Reconstructions of past sea-level change provide a crucial baseline for understanding current changes, and producing these reconstructions requires fusing data from multiple different sources with different error structures, sparsity, and process-sensitivity.

- Local sea-level rise projections are a key input to coastal risk management, and require synthesizing many different lines of evidence. In some cases, alternative approaches to estimating different processes highlight areas of deep uncertainty.

- We are working to produce flexible, scalable, open-source tools to facilitate both these tasks.

Mapping sea-level change in time, space, and probability

Robert Kopp

Department of Earth & Planetary Sciences
Institute of Earth, Ocean and Atmospheric Sciences
Rutgers University–New Brunswick
Twitter: @bobkopp

RUTGERS
Institute of Earth, Ocean, and Atmospheric Sciences

Climate Impact Lab

NSF

NASA