(scattered thoughts on) Sea Level Rise

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2025 ECCO Summer School

Current rates of sea-level rise are exceptional in a longterm context

Global mean sea level rose faster in the 20th century than in any prior century over the last three millennia

Fox-Kemper et al. (2021)

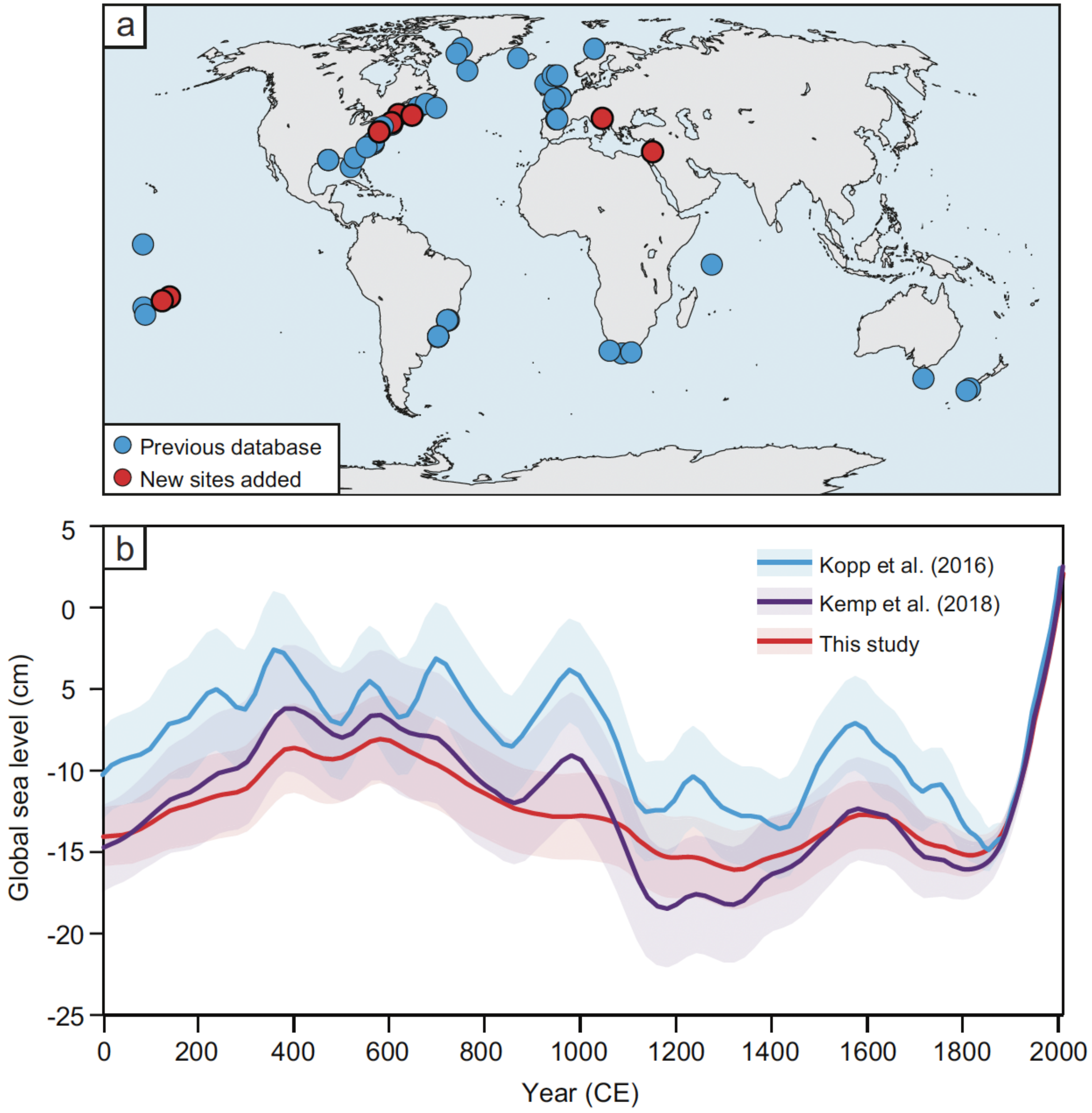


Figure from Walker et al. (2021). See also Kopp et al. (2016), Kemp et al. (2018)

The rate of global sea level rise doubled during the past three decades

Hamlington et al. (2024)

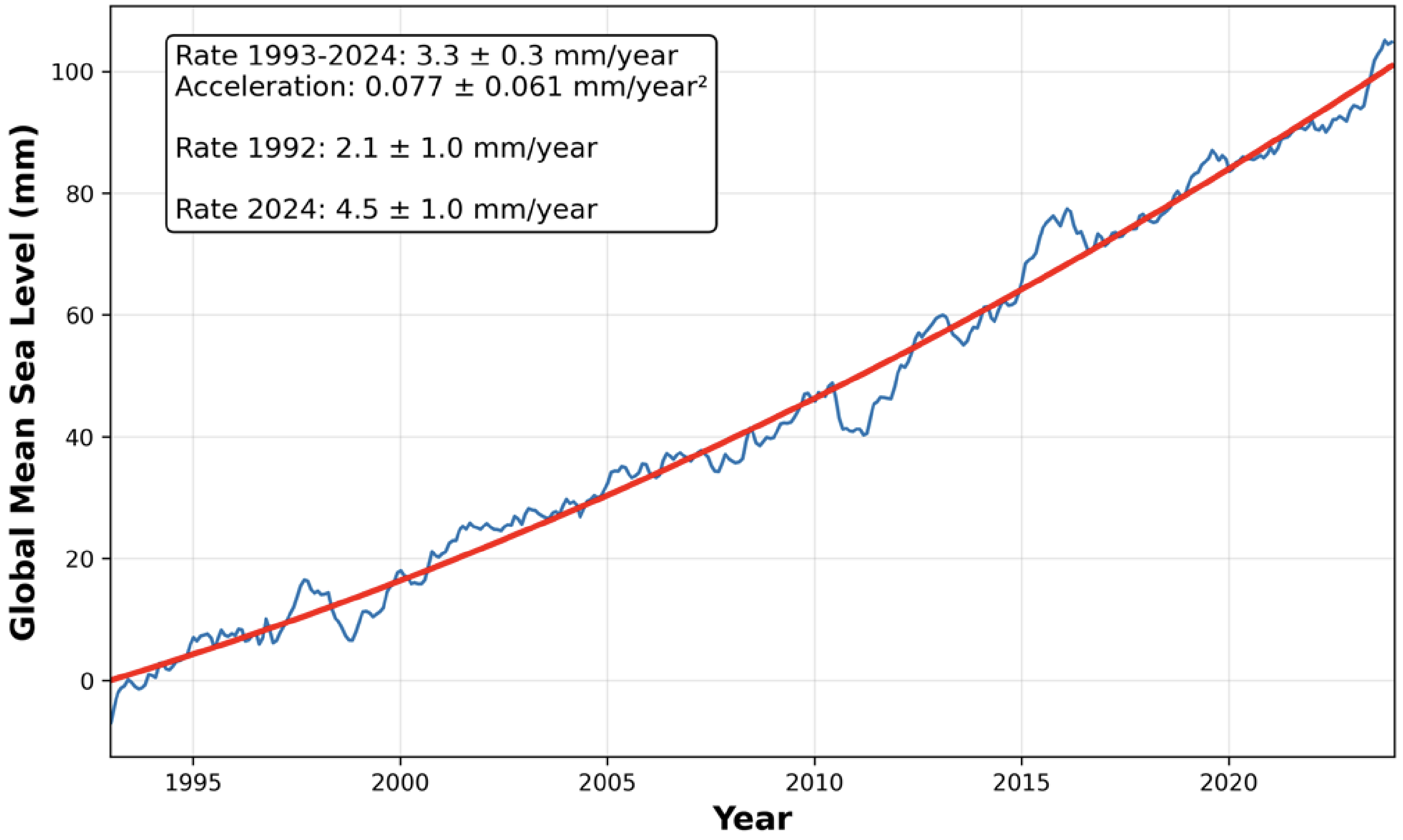


Figure from Hamlington et al. (2024)

Sea-level rise hasn’t occurred at the same rate everywhere

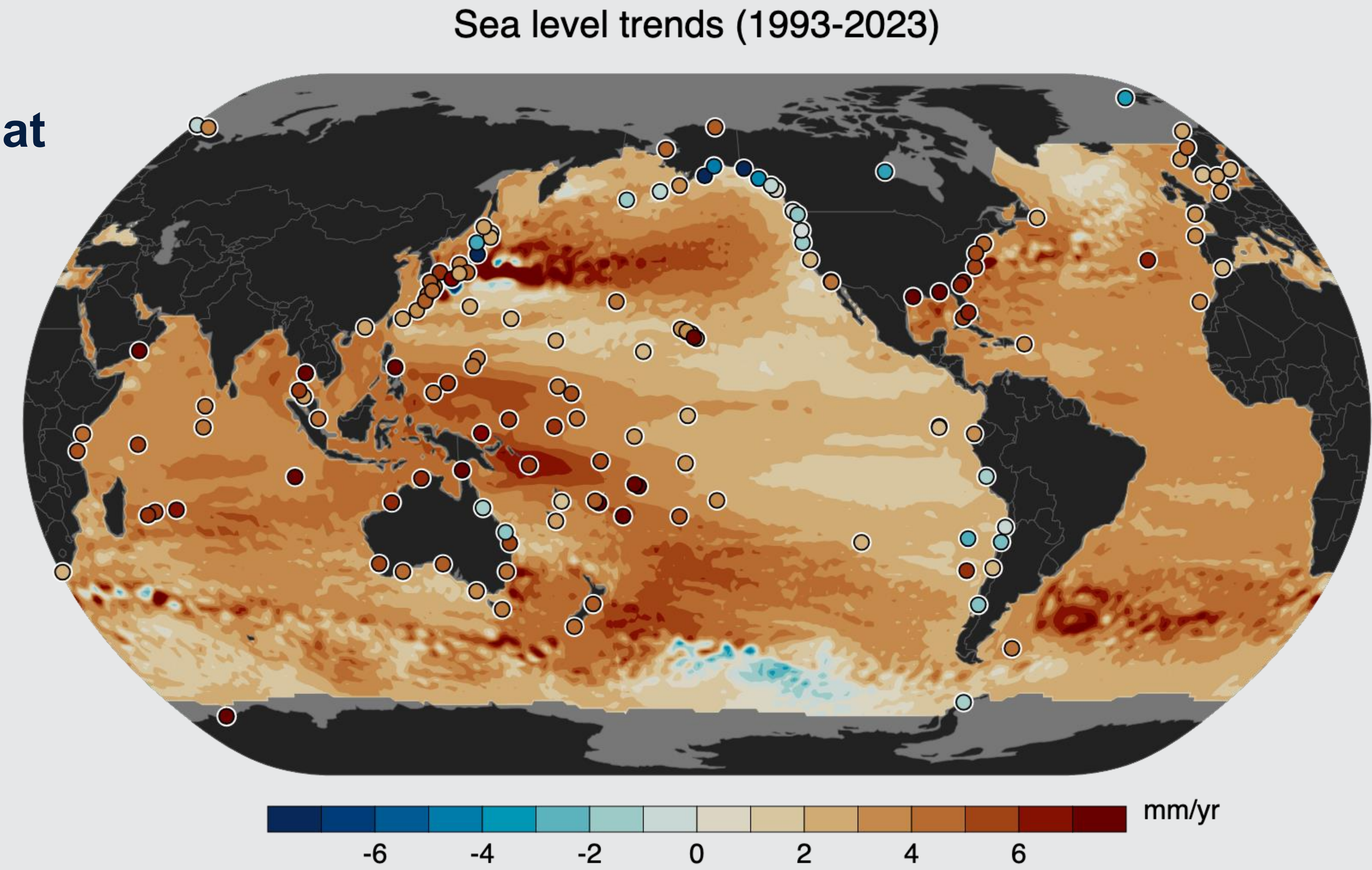


Image courtesy of U. Hawaii

High-tide flooding (HTF) rates are increasing

(AKA nuisance flooding, king-tide flooding, tidal flooding, sea-level-rise flooding …)

NYTIMES

HTF increased by 65% on average globally between 1960-1980 and 1995-2014

Fox-Kemper et al. (2021)

Annual HTF rates in the United States tripled from 1990 to 2020

Sweet et al. (2022)

HTF trends along the United States coastline

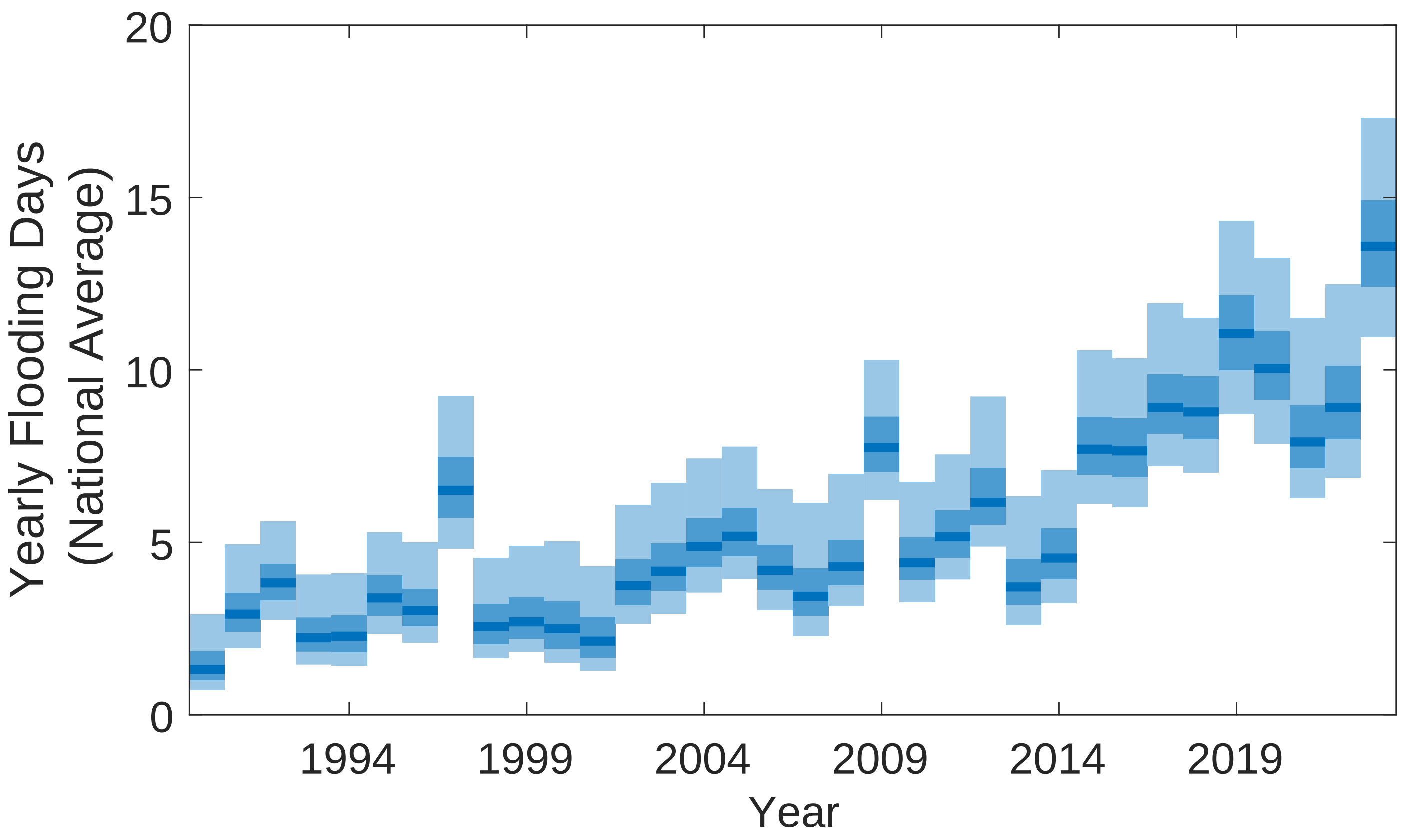


Figure from Piecuch et al. (2025)

How is sea-level changing?

Why is sea-level changing?

And how do we know?

Cautionary note! Terminology …

- 😱 😱 😱 Sea-level science is a highly interdisciplinary field with **LOTS** of terminology (sterodynamic, manometric, barystatic, geocentric, relative sea level …) and acronyms (GIA, GRD, GMSL, IB, SSH, VLM …)

- I won’t always try to give exhaustive, technical definitions (but see, for example, Gregory et al. 2019), but rather introduce things as needed

- Don’t be stressed! Ask Questions!

Global sea-level change

is a whole-Earth process

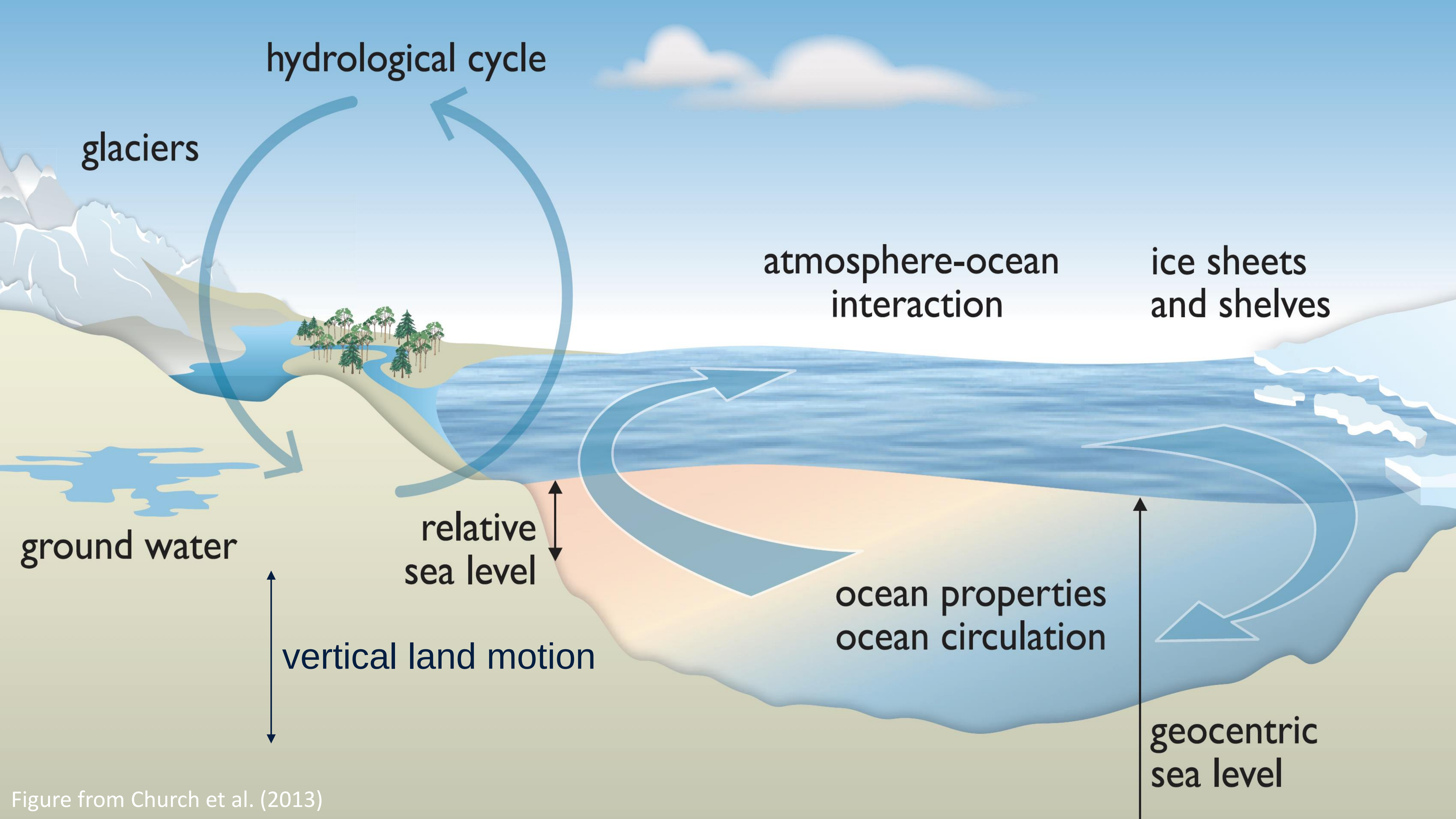


Figure from Church et al. (2013)

Waxing and waning of Pleistocene ice ages

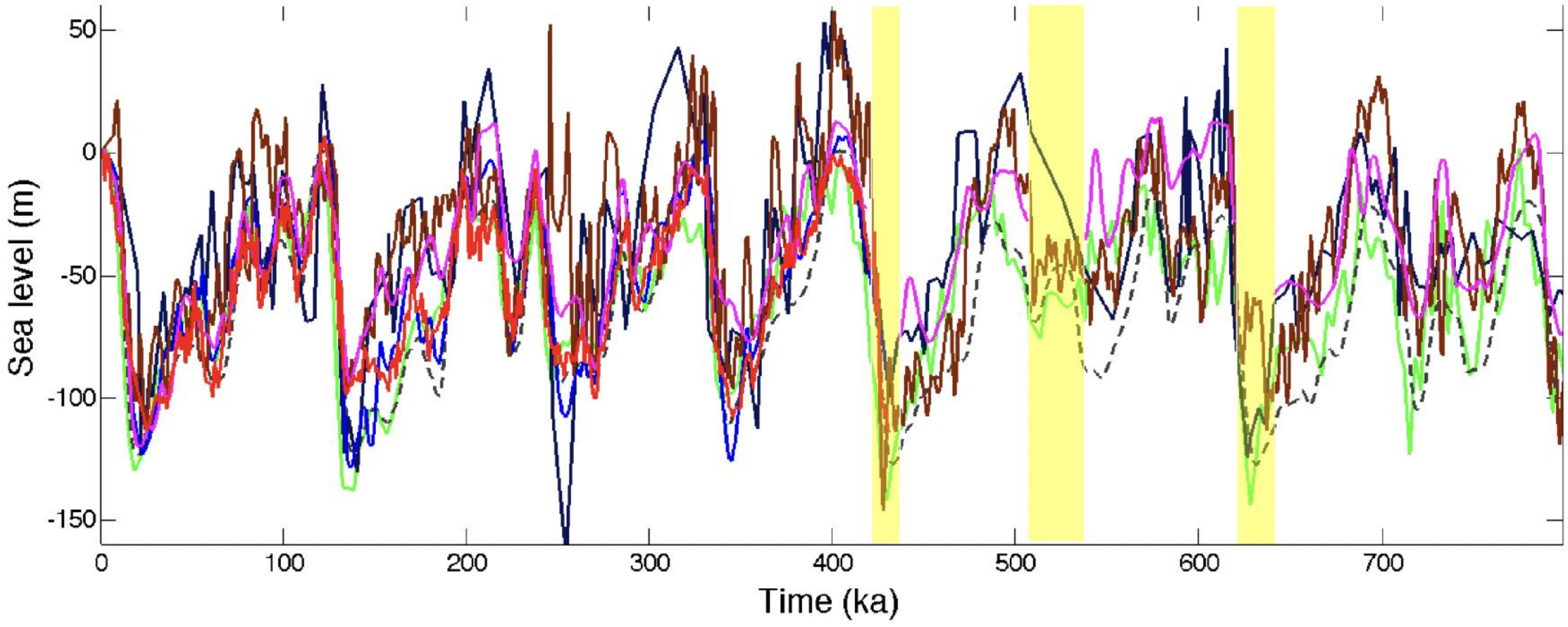


Figure from Spratt and Lisiecki (2017)

Sea-level changes are coupled

to ocean circulation & climate

Sea level strongly constrains Earth's energy imbalance and hydrological cycle

Start with hydrostatic balance

$$\frac{dp}{dz} = -\rho g$$

with hydrostatic pressure p, vertical coordinate z, density ρ, gravity g.

- Integrate from seafloor H to (geocentric) sea level ζ and rearrange

$$\zeta = \frac{p_b - p_s}{\rho_s g} + \left(-\frac{1}{\rho_s g} \int_{-H}^{0} \rho \, dz \right)$$

where p_b / p_s are bottom/surface pressure and ρ_s is surface density.

See Gill and Niiler (1973), Gregory et al. (2019)

Sea level strongly constrains Earth's energy imbalance and hydrological cycle

- Geocentric sea-level changes arise from contributions from changes in ocean mass and ocean density

- **Steric sea-level changes** ζ_ρ arise from changes in ocean density at constant mass

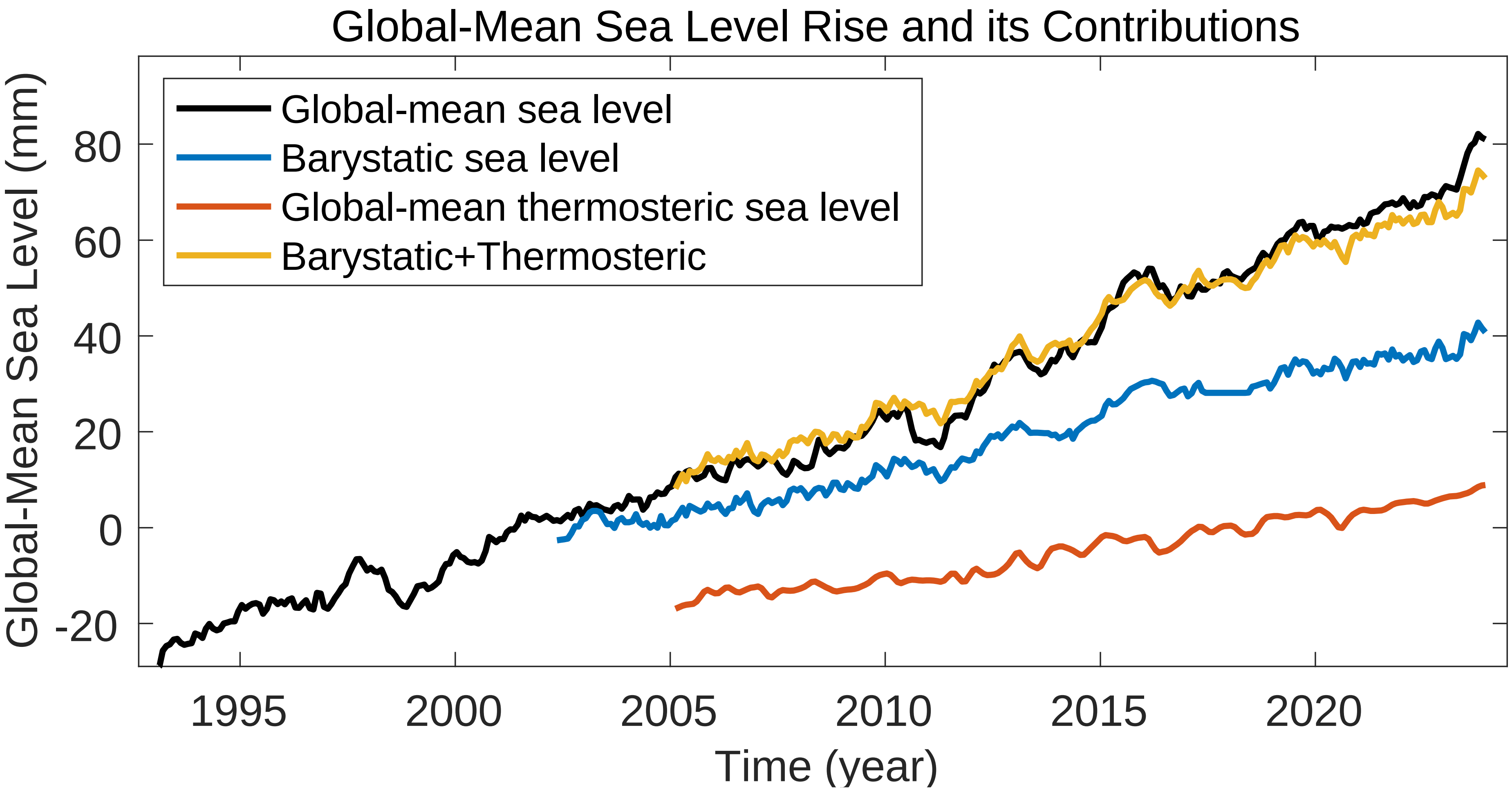
$$\zeta_\rho = -\frac{1}{\rho_s g} \int_{-H}^{0} \rho \, dz$$

- **Manometric sea-level changes** ζ_m come from changes in the local mass of the ocean per unit area at constant density

$$\zeta_m = \frac{p_b - p_s}{\rho_s g}$$

See Gill and Niiler (1973), Gregory et al. (2019)

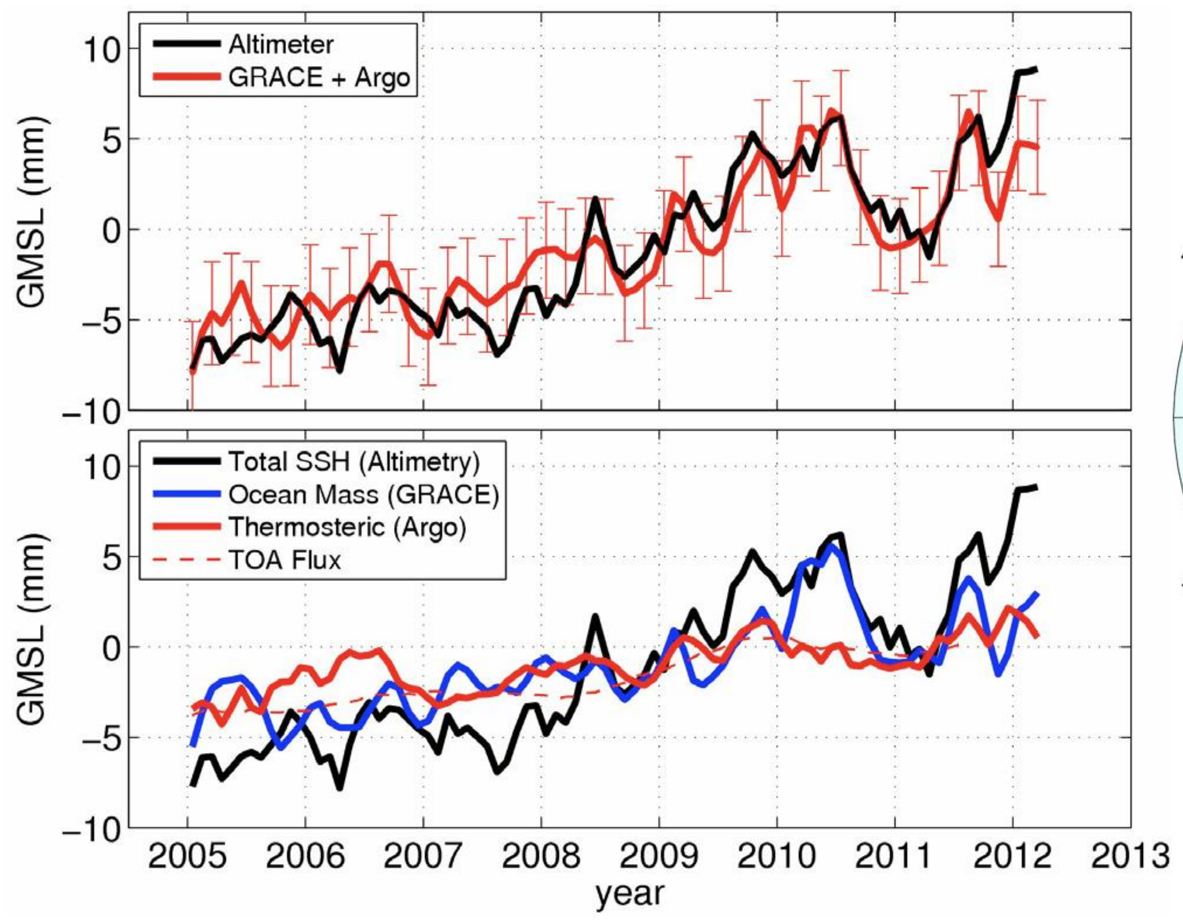
Sea level strongly constrains Earth's energy imbalance and hydrological cycle

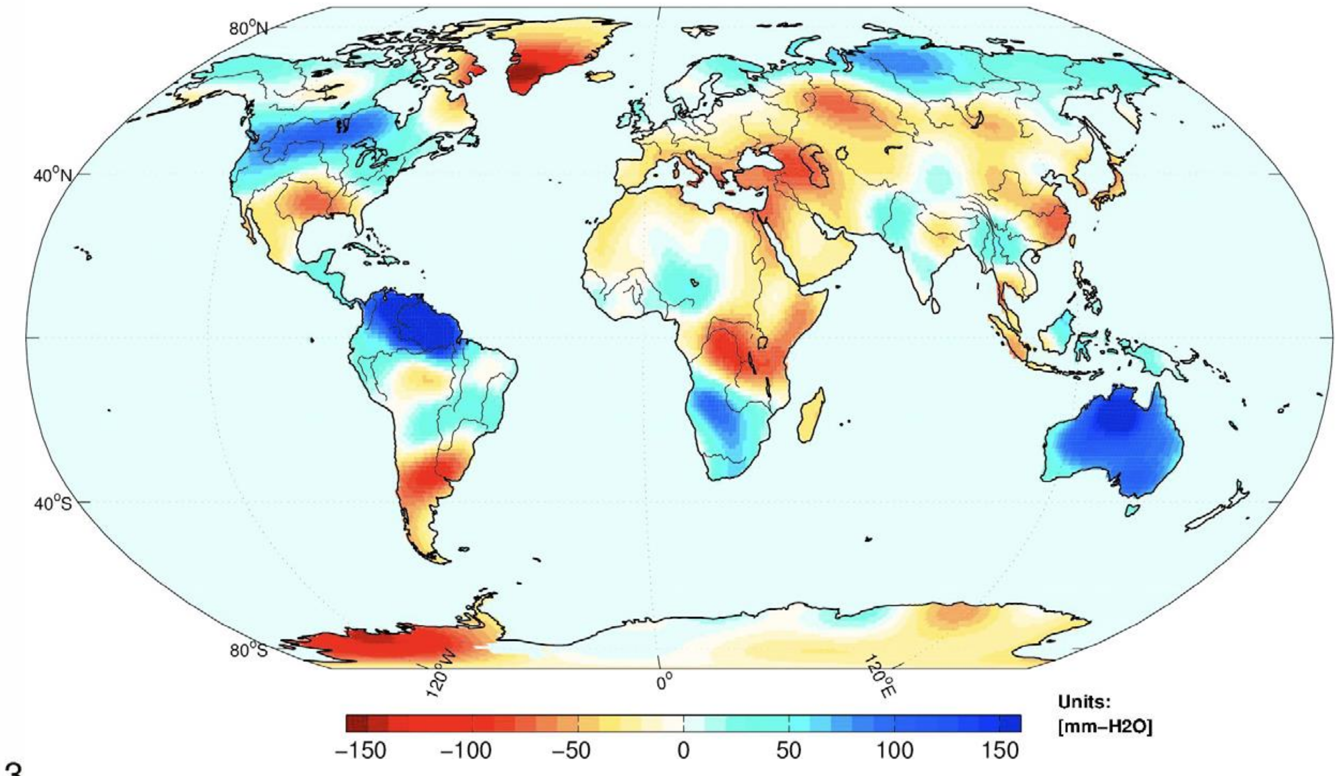


🙊 **Barystatic sea level** is the global average of manometric sea level 🙊

Data from Beckley et al. (2017), Wiese et al. (2022), Roemmich and Gilson (2009)

Sea level strongly constrains Earth's energy imbalance and hydrological cycle





Figures from Boening et al. (2012), Fasullo et al. (2013)

Sea level is coupled to the general circulation

- Consider the forced, linear shallow-water equations (e.g., Gill, 1982)

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = \frac{P - E}{\rho}$$

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial}{\partial x}\left(\zeta + \frac{p_s}{\rho g}\right) + \frac{X_s - X_b}{\rho H}$$

$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial}{\partial y}\left(\zeta + \frac{p_s}{\rho g}\right) + \frac{Y_s - Y_b}{\rho H}$$

u/v horizontal velocities, f Coriolis, P/E precipitation/evaporation, X_s, X_b, Y_s, Y_b horizontal surface and bottom stresses

Simplified physics: geostrophic balance

Time-independent, unforced, frictionless limit of the shallow water equations

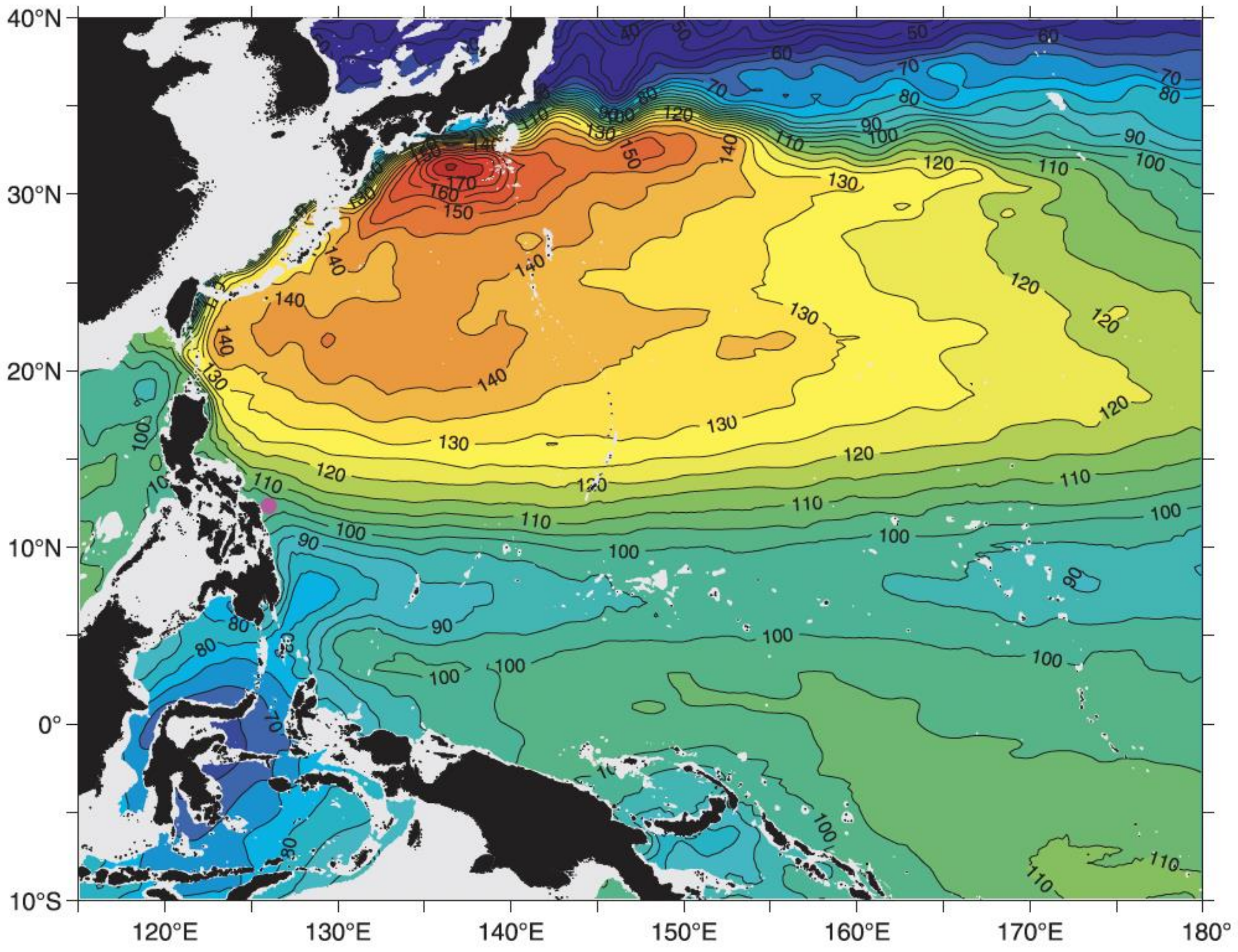


Figure from Qiu and Chen (2010)

Simplified physics: inverted barometer

Time-independent, frictionless, static, pressure-forced limit of the shallow water equations

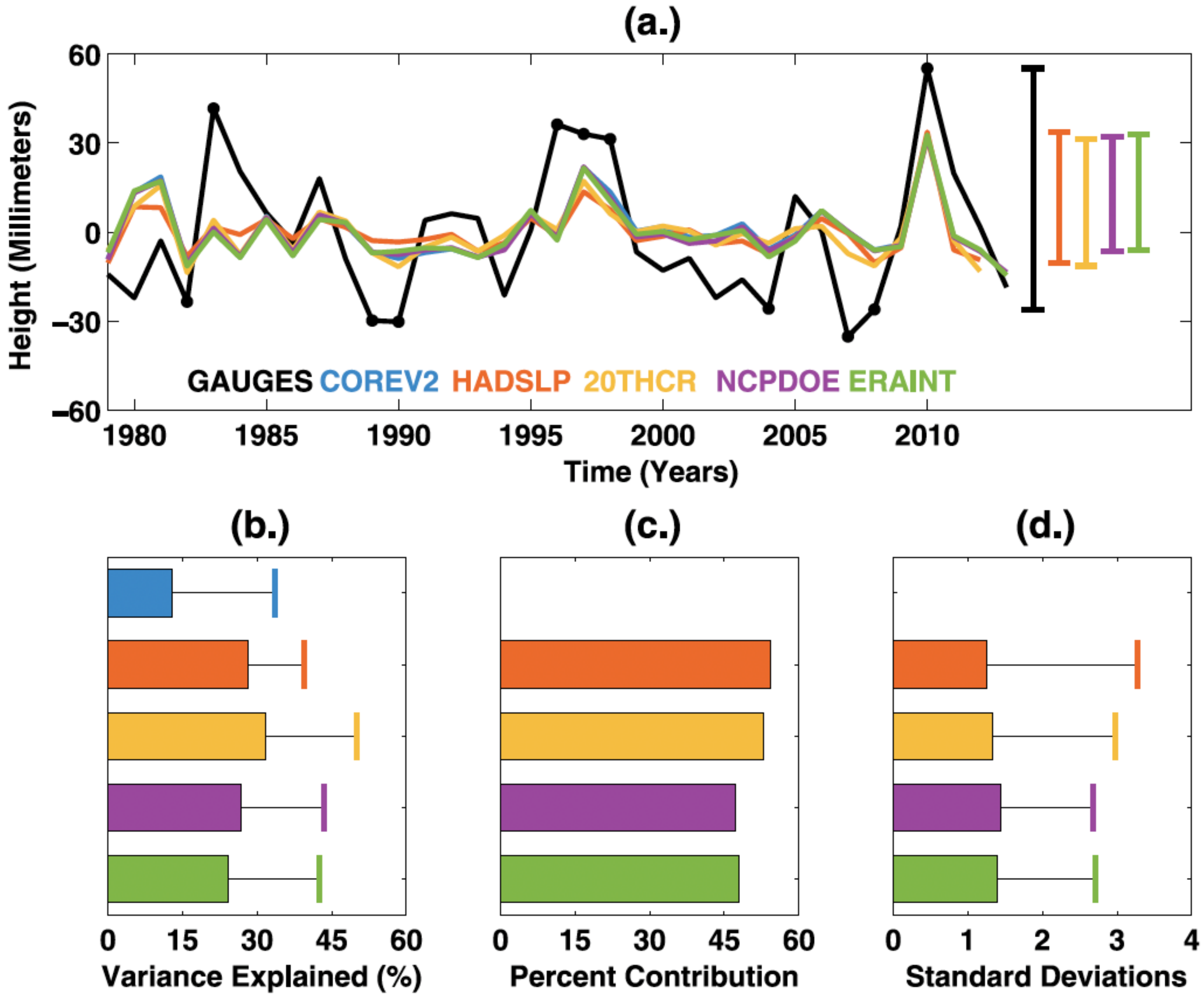


Figure from Piecuch and Ponte (2015)

Simplified physics: damped wind-driven long Rossby waves

Large-scale, sub-inertial limited of the shallow water equations forced by surface wind stress

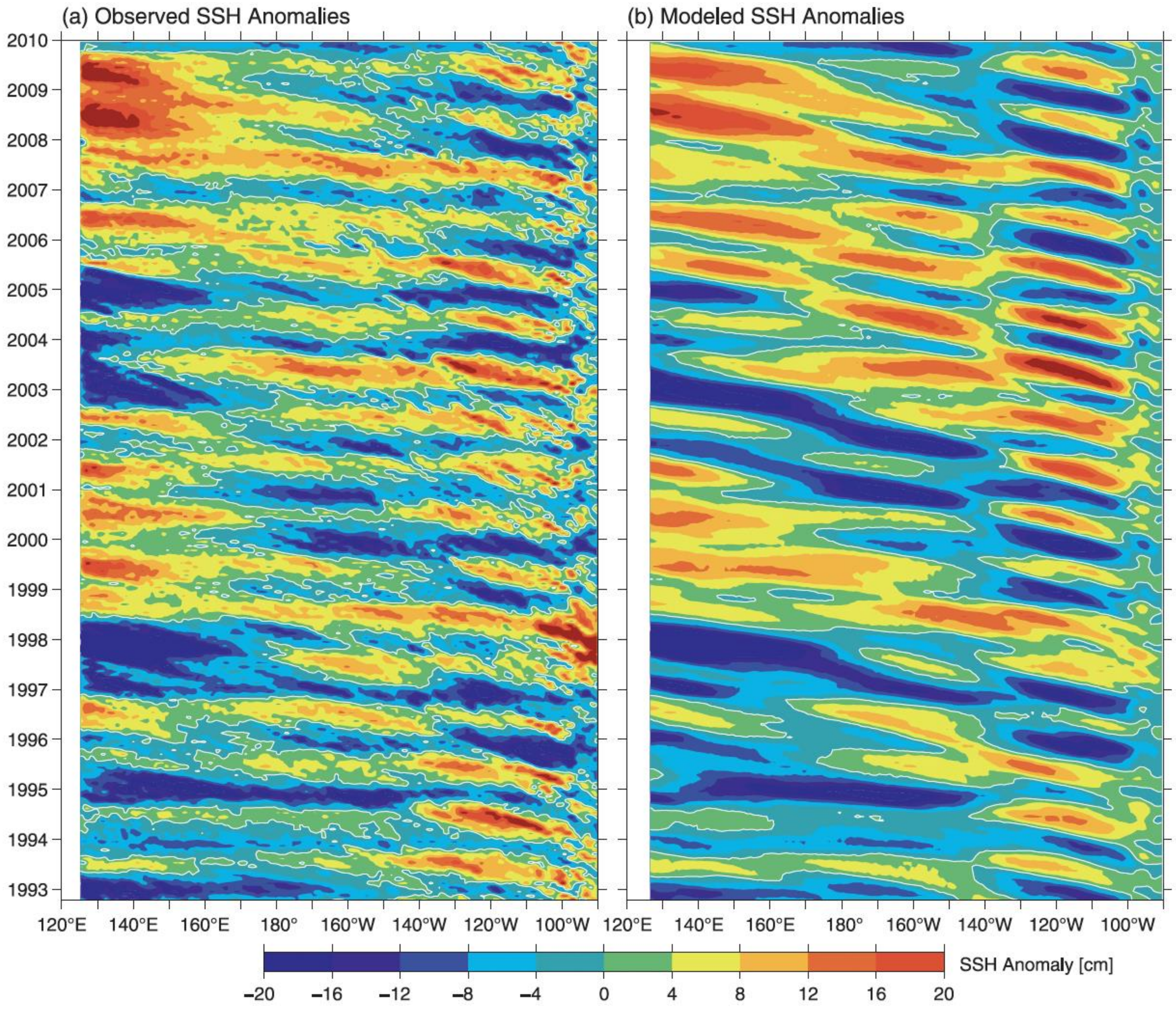


Figure from Qiu and Chen (2010)

Simplified physics: arrested topographic wave (& generalizations)

Time independent with variable bottom bathymetry (different varieties with different forcing)

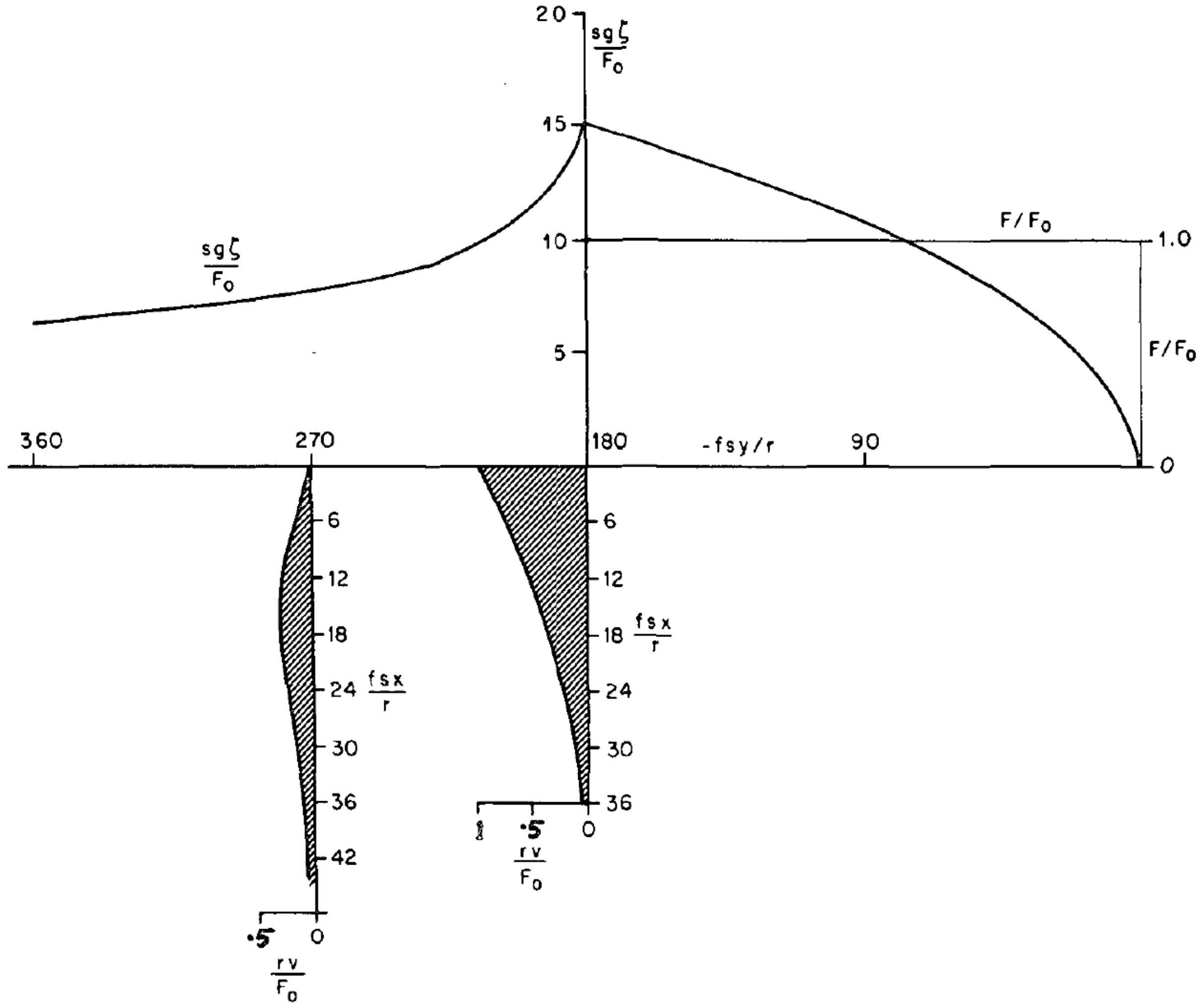


Figure from Csanady (1978)

Sea level is coupled to the general circulation

- This was only the briefest possible overview of the coupling between coastal and open-ocean sea level with circulation!

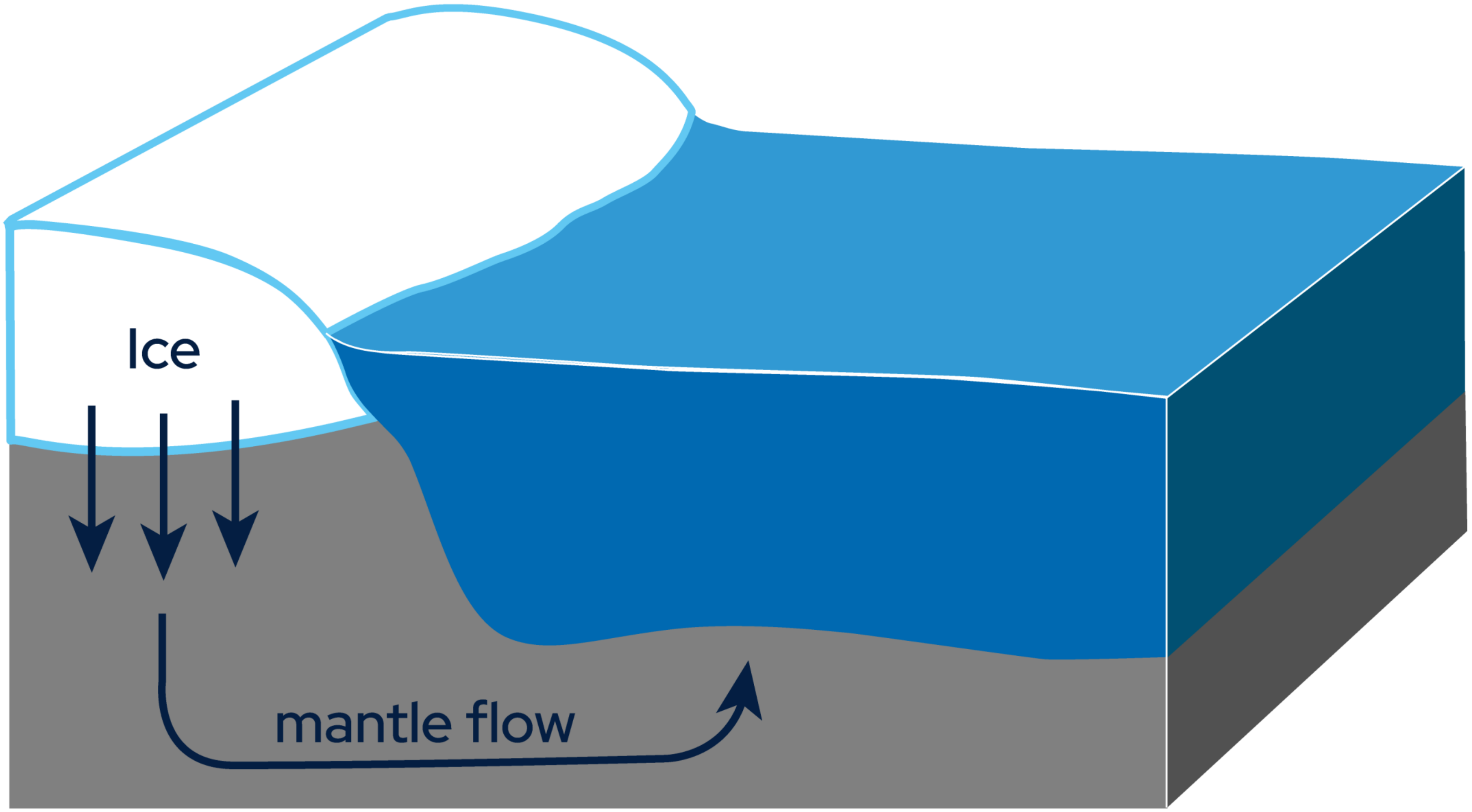
- I passed over many other processes and forcing mechanisms!
  - Other wave motions (coastal and equatorial Kelvin waves, topographic Rossby waves, continental-shelf waves, coastal-trapped waves …)
  - High-frequency phenomena (tsunamis and meteotsunamis, surface gravity waves, tides, storm surge …)
  - Dynamic response to barometric pressure
  - Near-, mid-, and far-field response to river discharge
  - Forcing by large-scale evaporation and precipitation
  - Sea-level changes that arise from changing surface heat flux
  - Relation to large-scale features like gyres and overturning

Gravity, rotation, and deformation (GRD)

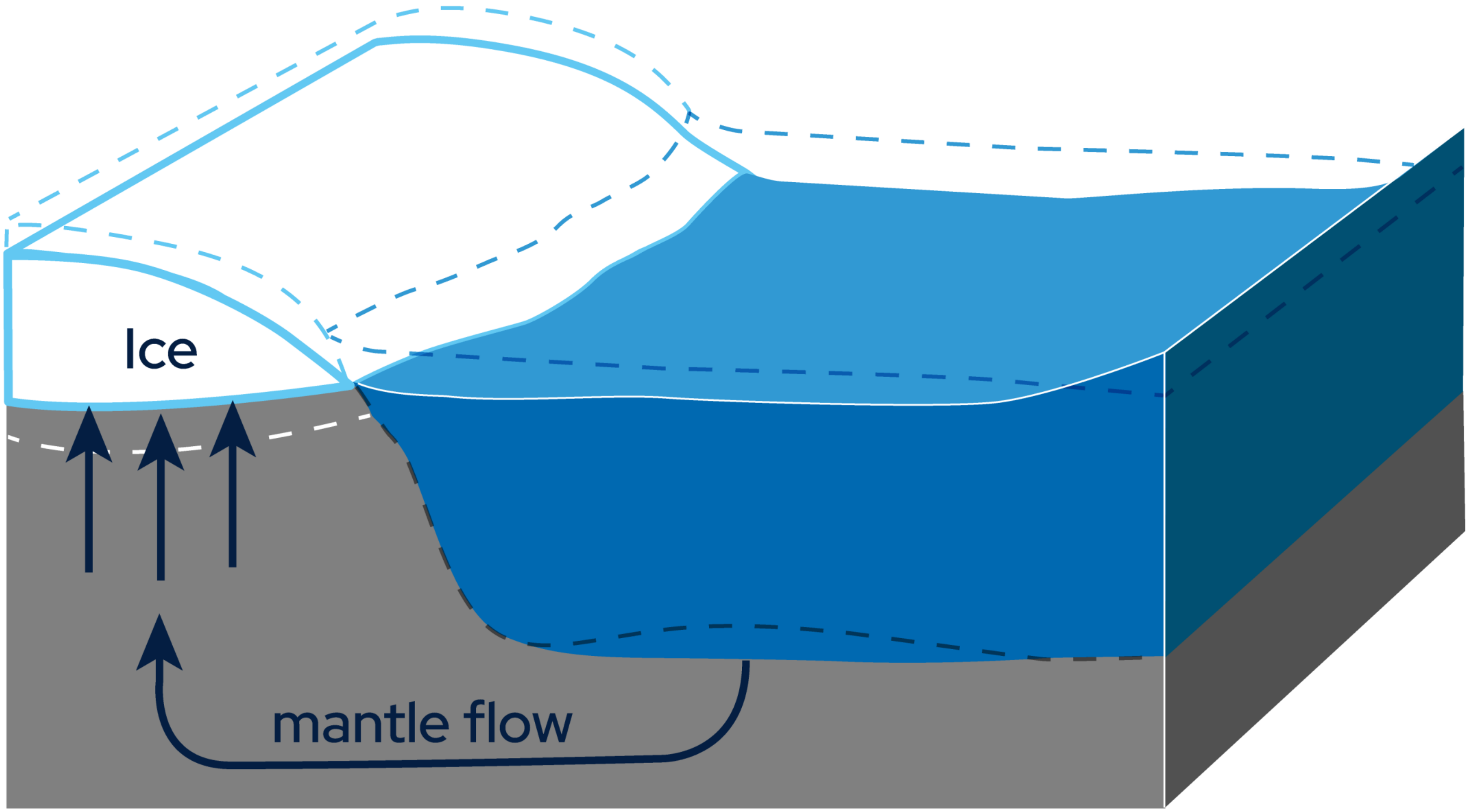
- I've assumed Earth's solid surface, gravity field, and rotation vector are time-invariant … which isn't true!

- These things also matter for sea level (e.g., distinction between *geocentric* sea level and *relative* sea level)

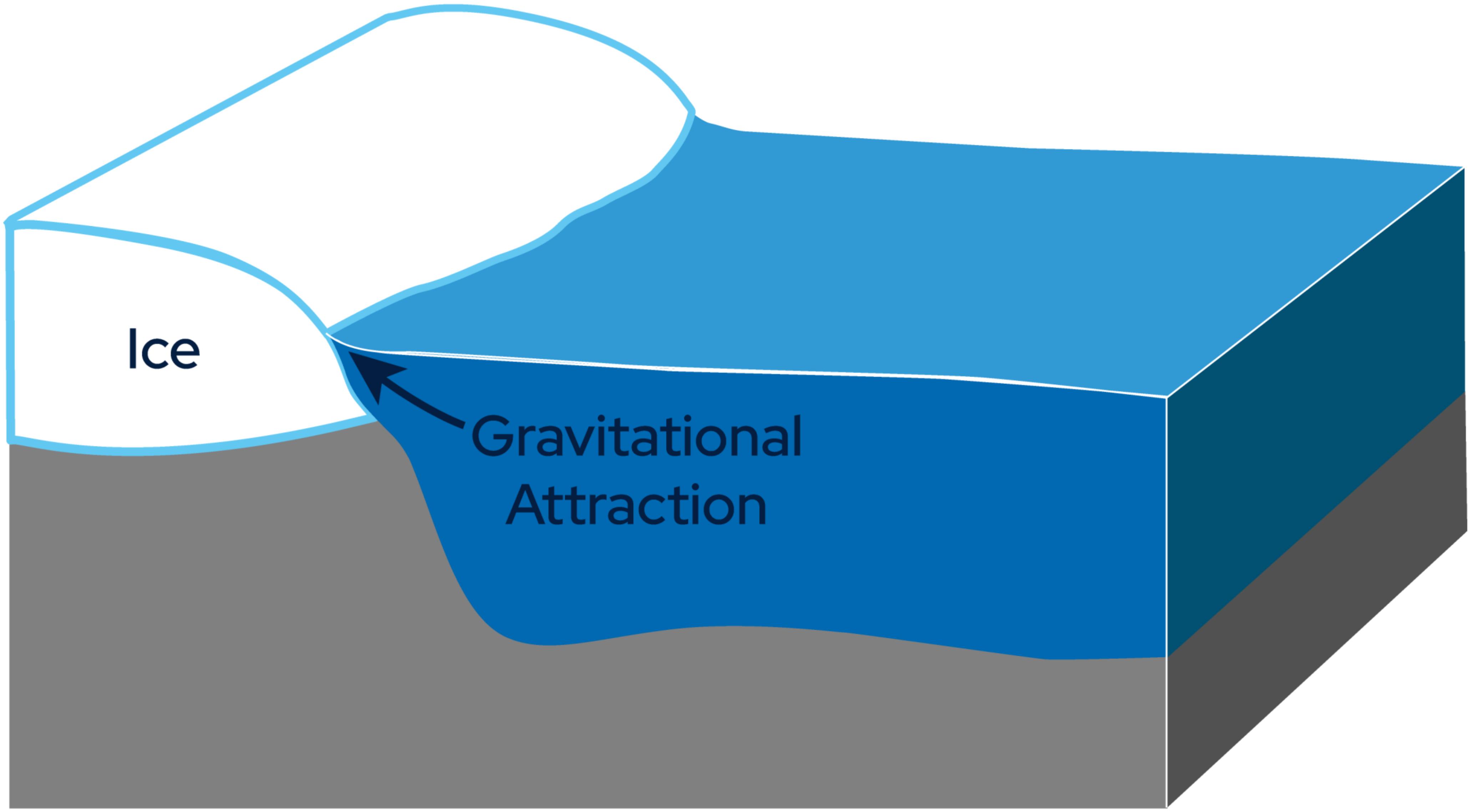
Gravity, rotation, and deformation



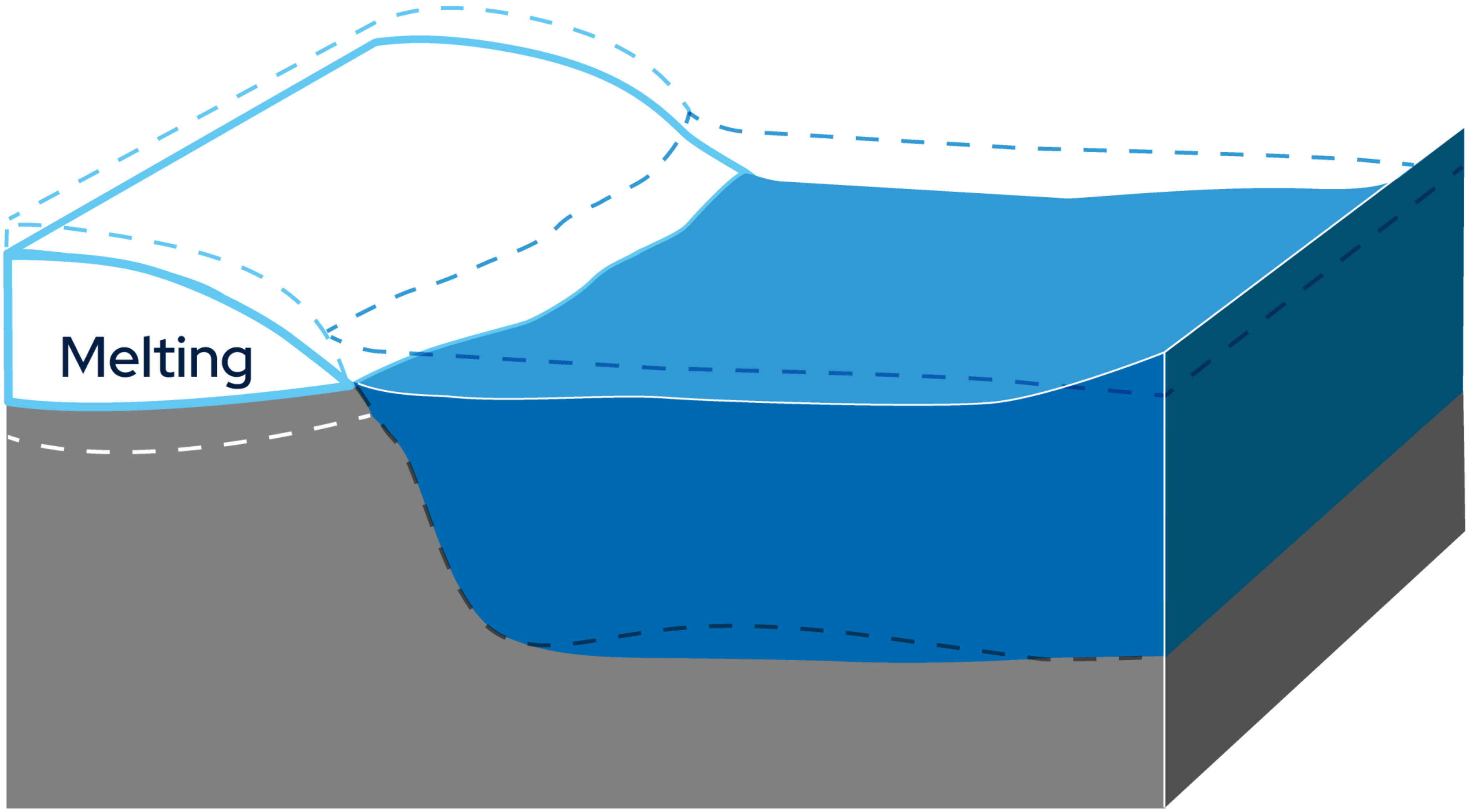
Gravity, rotation, and deformation



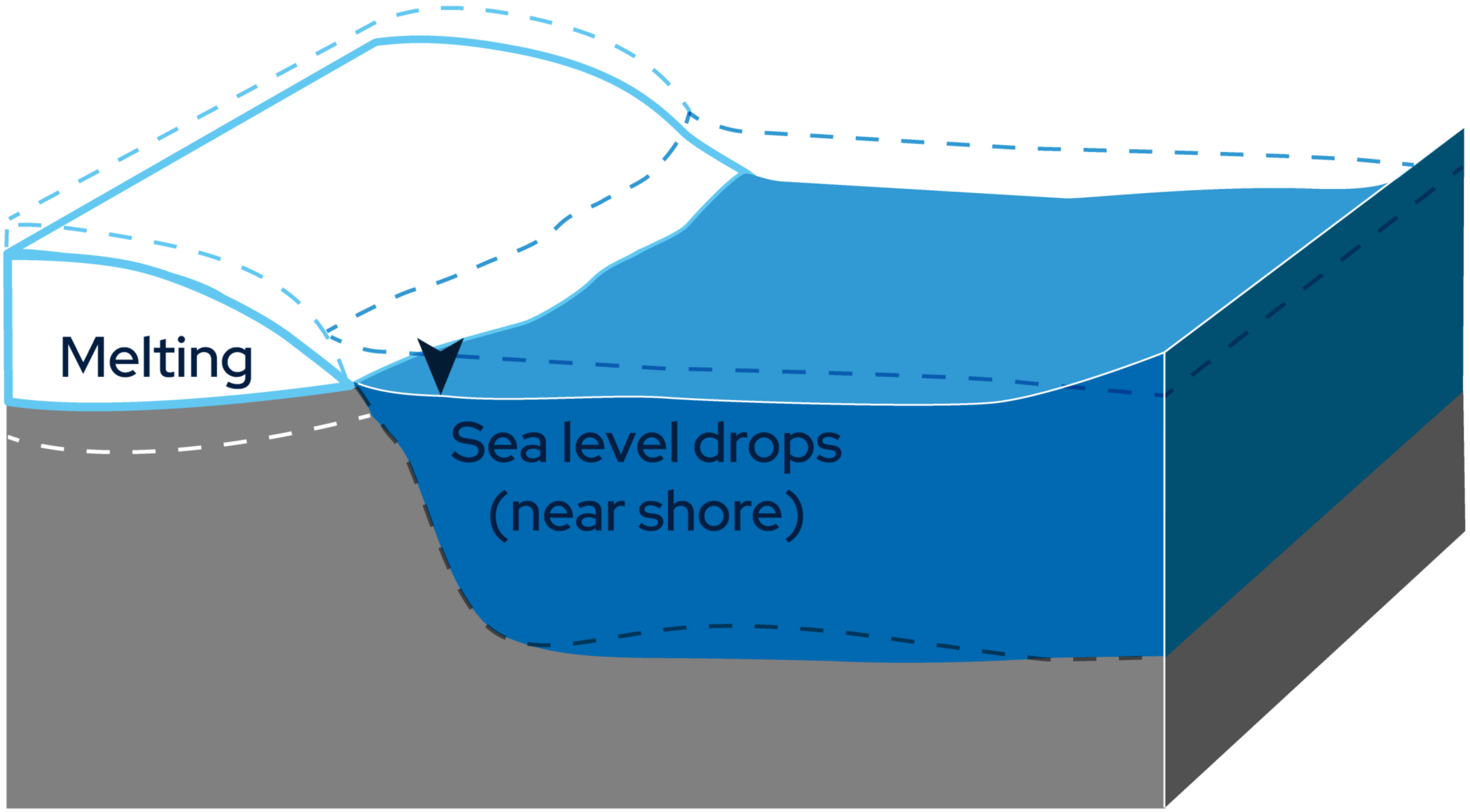
Gravity, rotation, and deformation



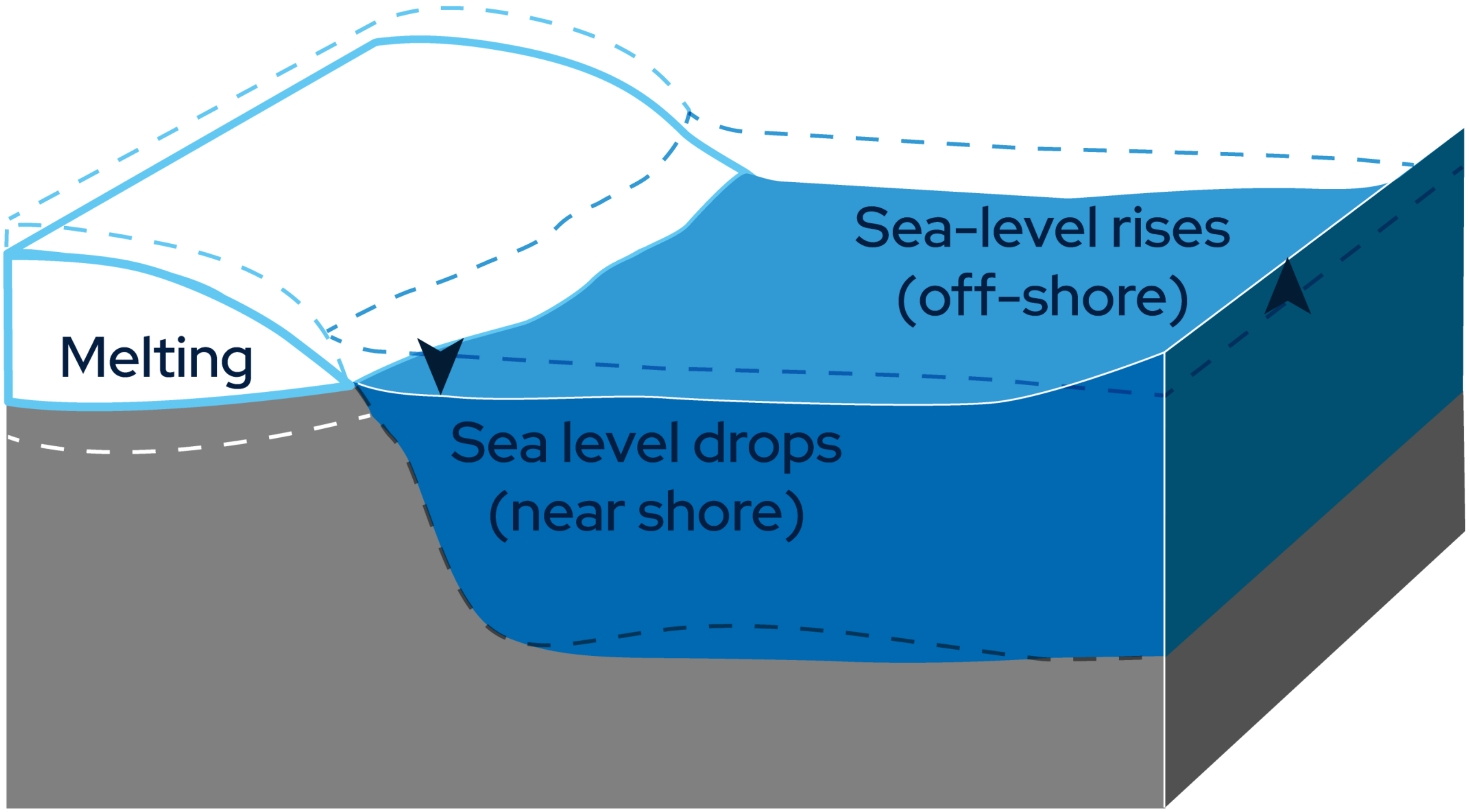
Gravity, rotation, and deformation



Gravity, rotation, and deformation



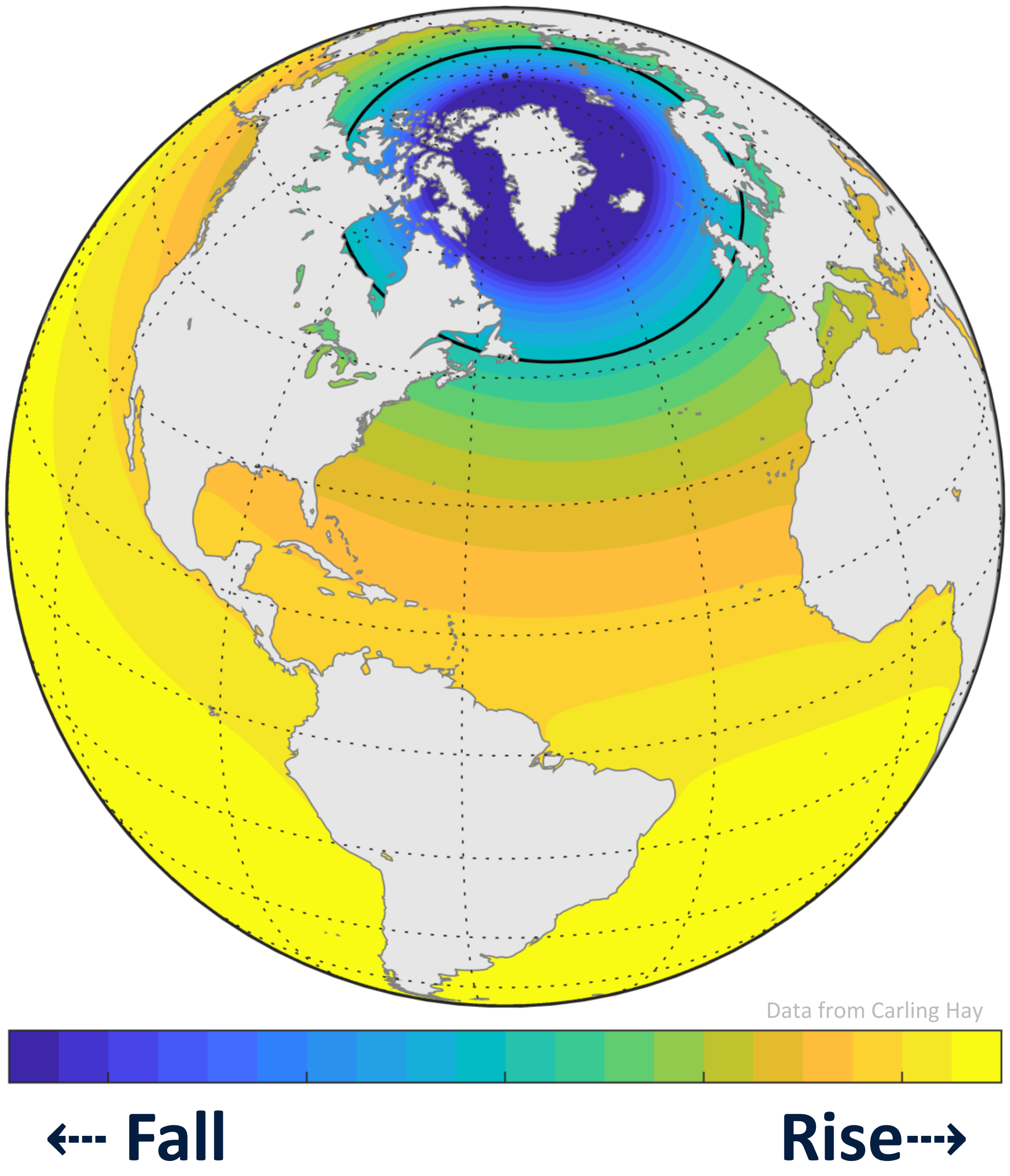
Gravity, rotation, and deformation



Gravity, rotation, and deformation

Elastic sea-level “fingerprint” of Greenland Ice Sheet melt

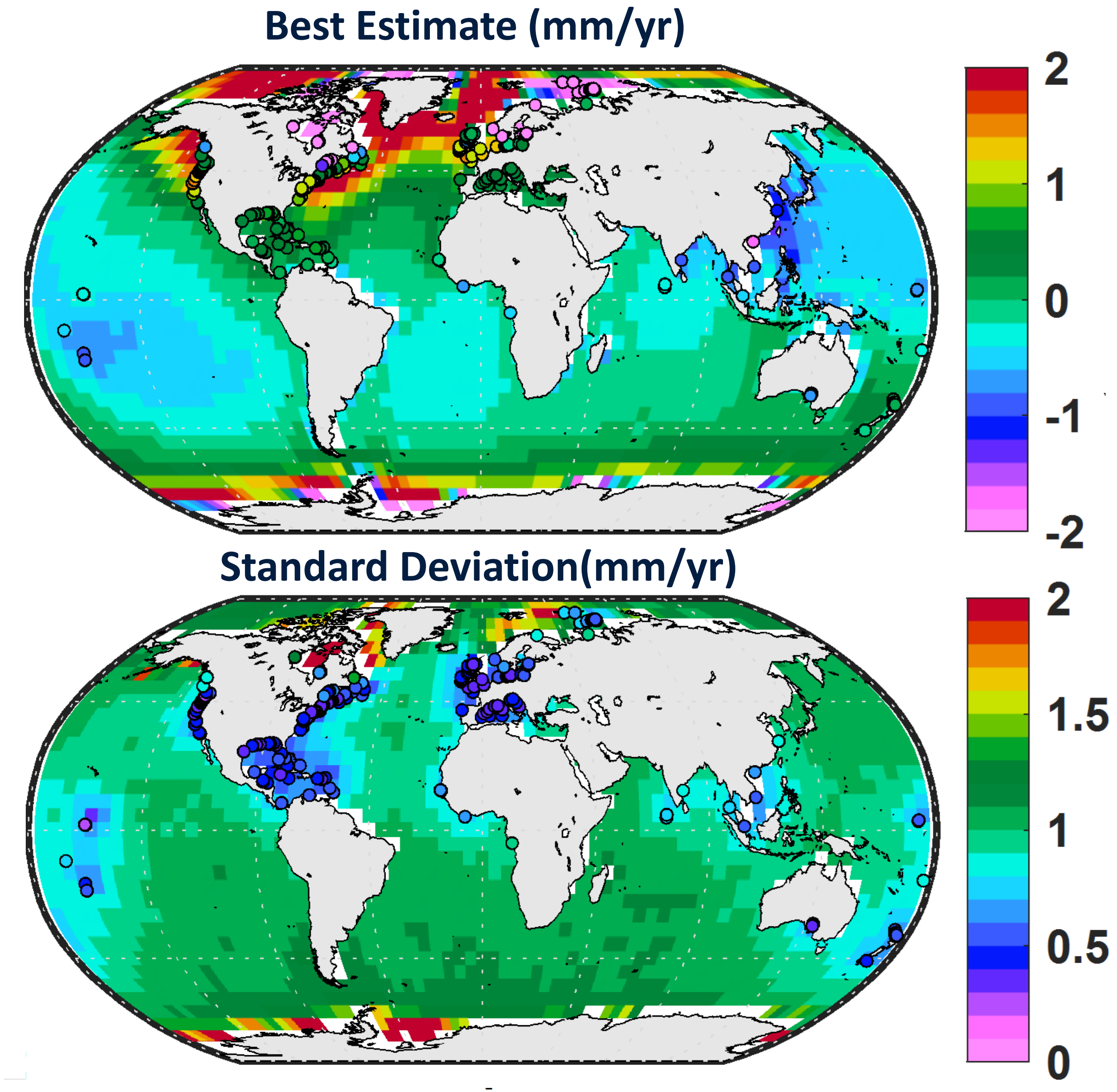
Data courtesy of Carling Hay



Gravity, rotation, and deformation

Probabilistic estimate of relative sea-level trends during the past 2,000 years

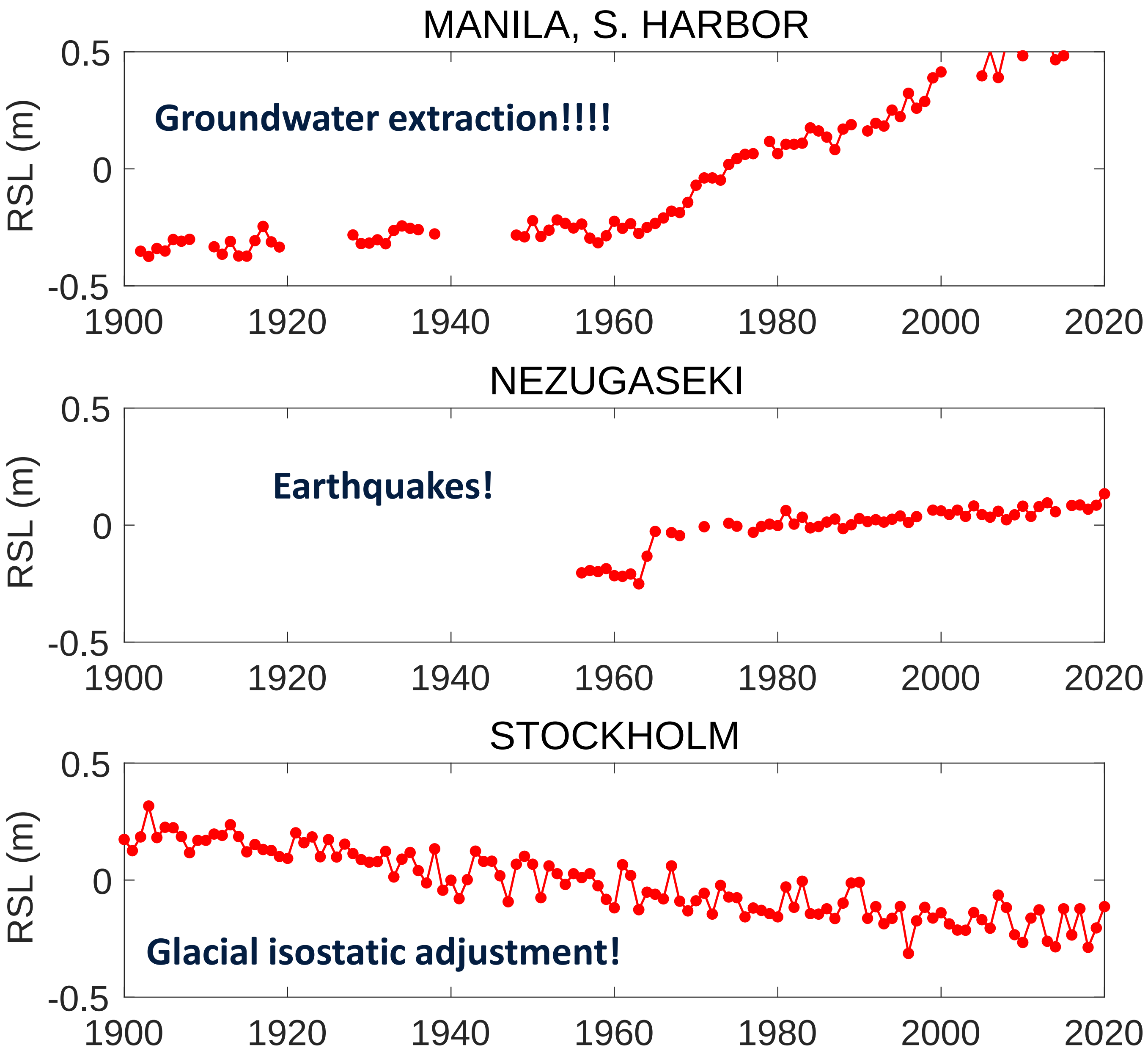
(Piecuch et al., in prep)



Gravity, rotation, and deformation

Example tide-gauge records

(Holgate et al., 2013)

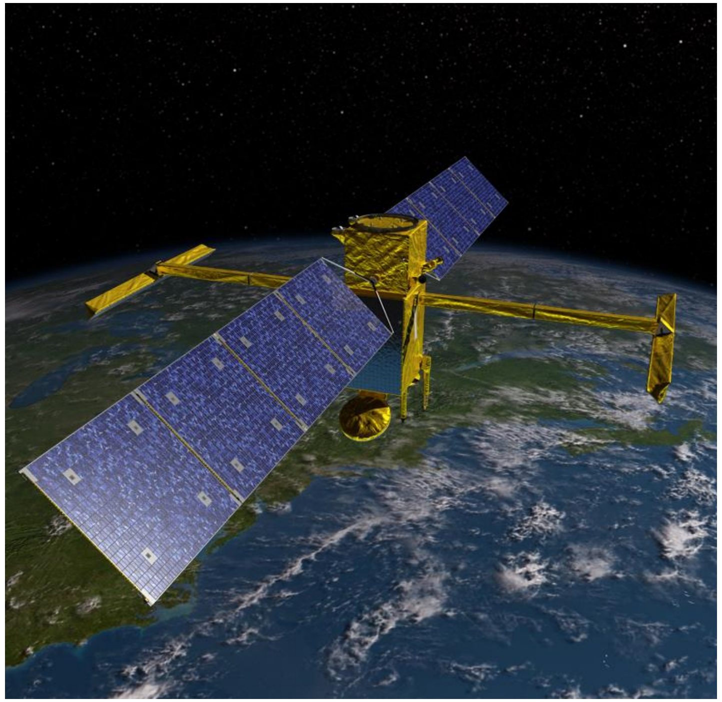


Data from Permanent Service for Mean Sea Level

NASA data and models have greatly advanced understanding of sea level

NASA altimetry observations

TOPEX/Poseidon, Jason series, Sentinel-6/MF, SWOT …



Artists’ renditions courtesy of NASA

NASA altimetry observations

TOPEX/Poseidon, Jason series, Sentinel-6/MF, SWOT …

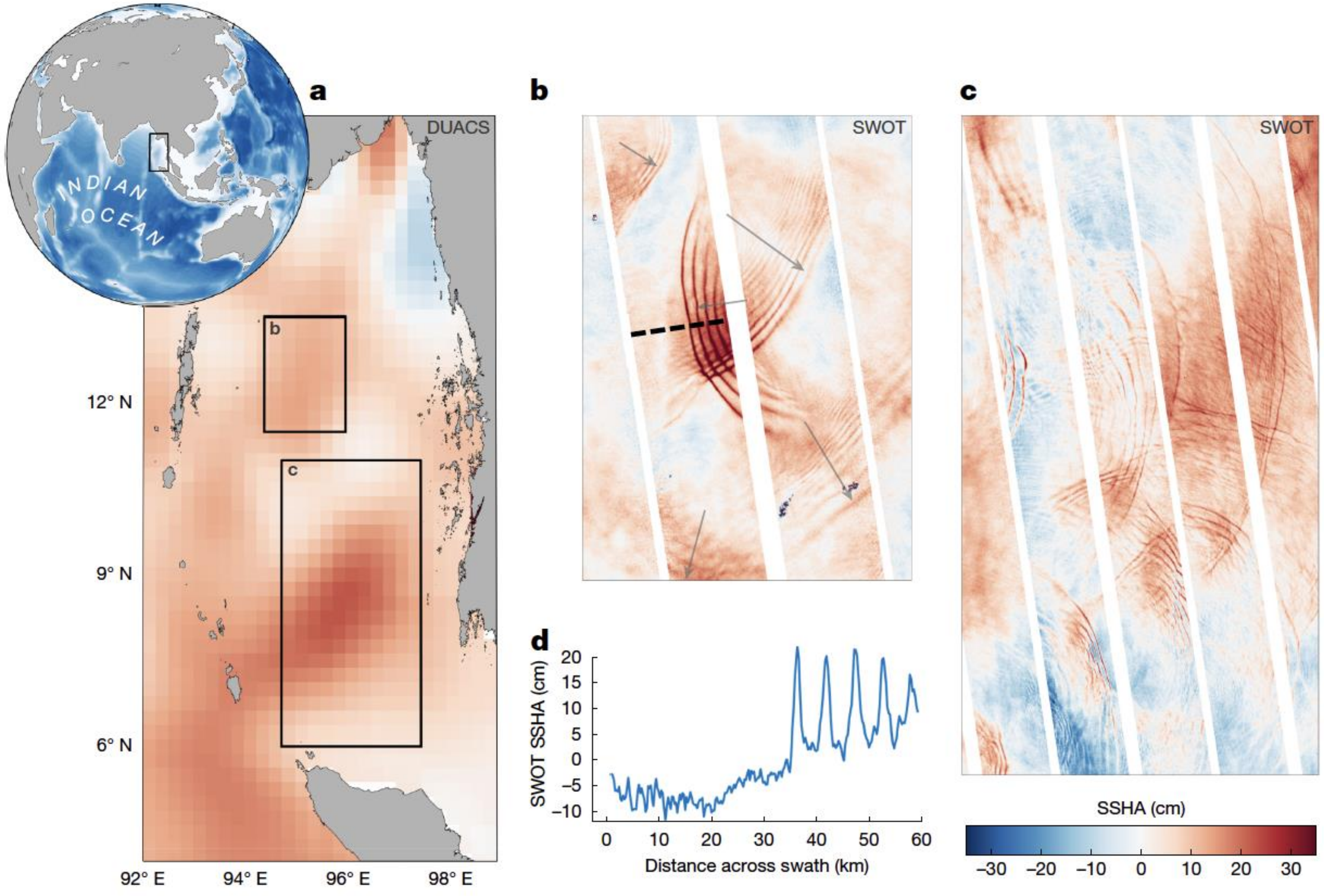


Figure from Archer et al. (2025)

(mostly) NASA observations (and models)

- ICESat-2
- Sentinel-3
- Cryosat-2
- GRACE & GRACE-FO
- InSAR
- GNSS
- 😎🤠🆒 **ECCO** 😎🤠🆒
- GISS ModelE
- ISSM-SLPS
- … and more!

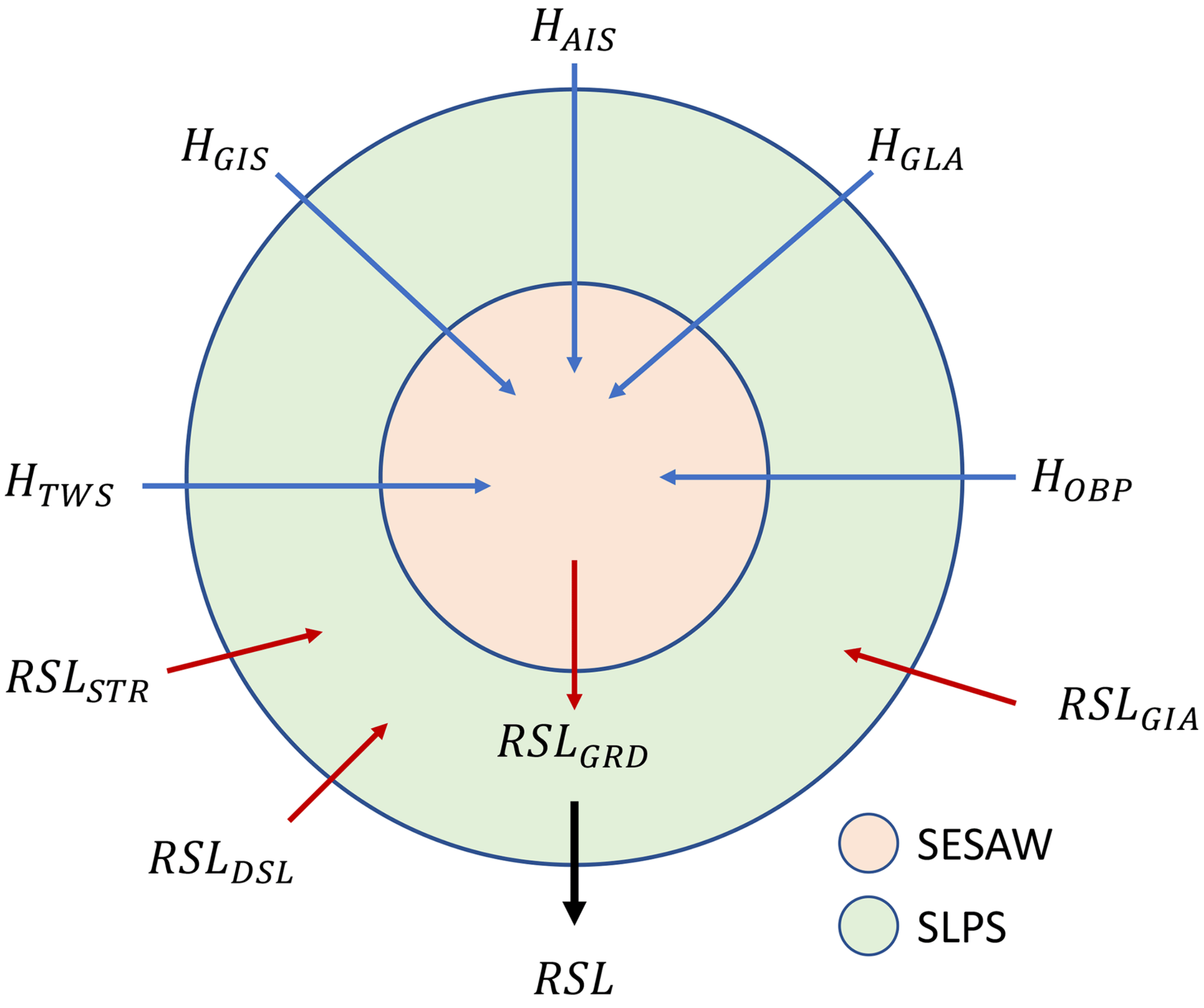
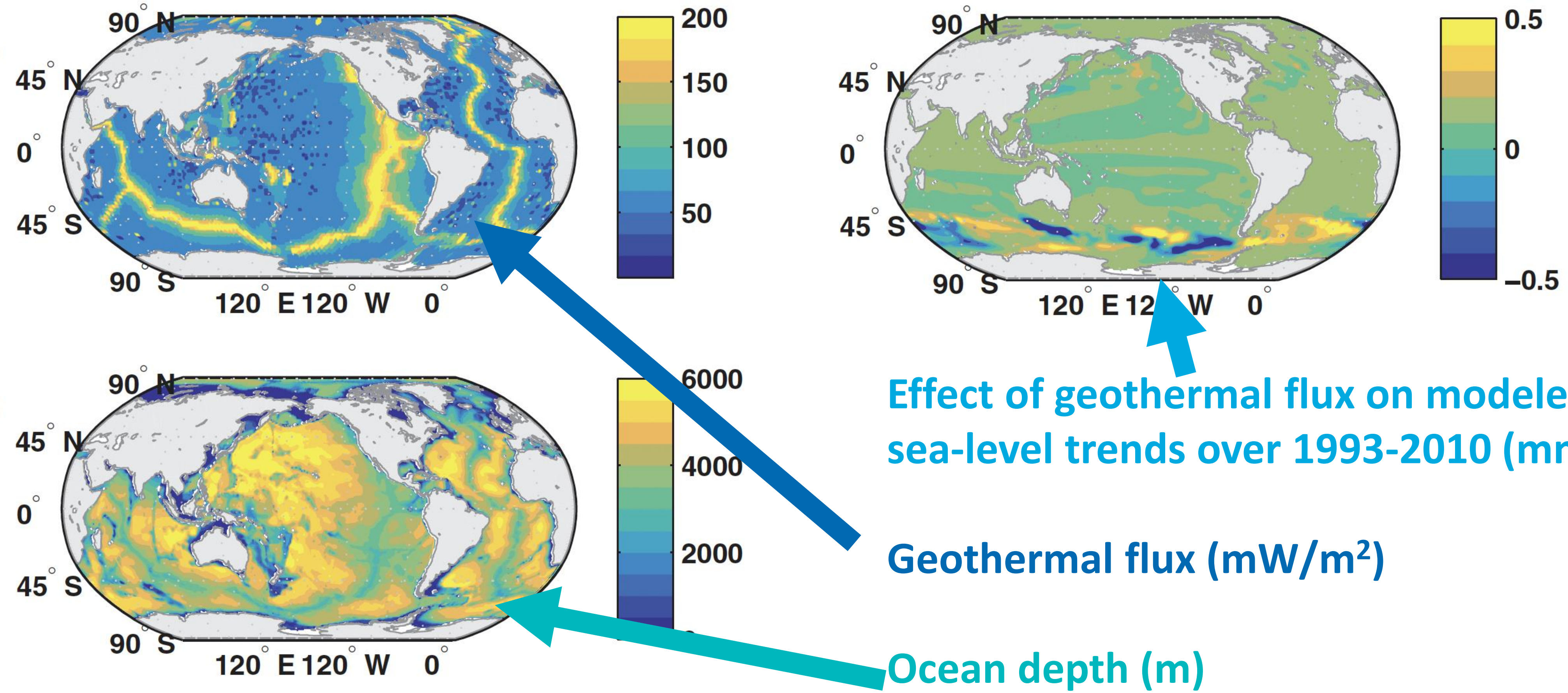


Figure from Larour et al. (2020)

ECCO is a powerful tool for quantifying ocean contributions to sea-level change

ECCO vignettes: forcing perturbation experiments

What influence does a geothermal flux bottom boundary condition have?



Effect of geothermal flux on modeled sea-level trends over 1993-2010 (mm/yr)

Geothermal flux (mW/m^2)

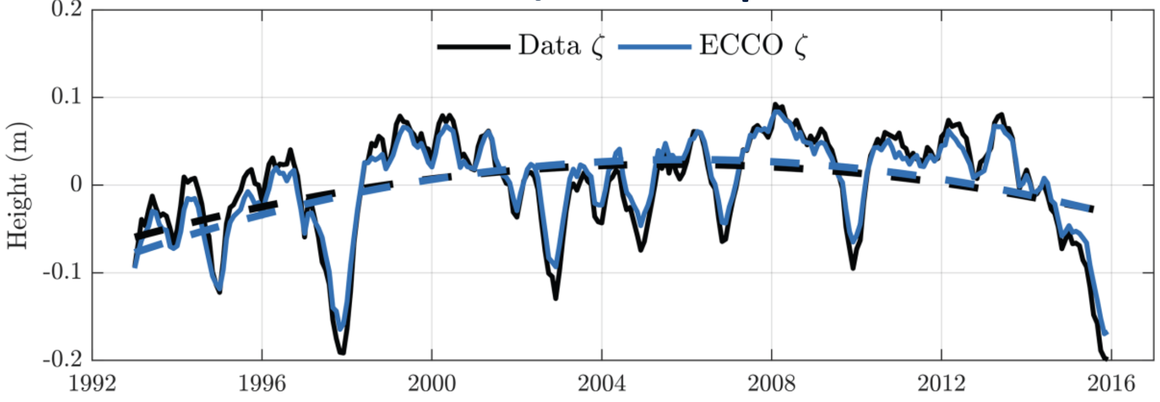
Ocean depth (m)

Figure from Piecuch et al. (2015)

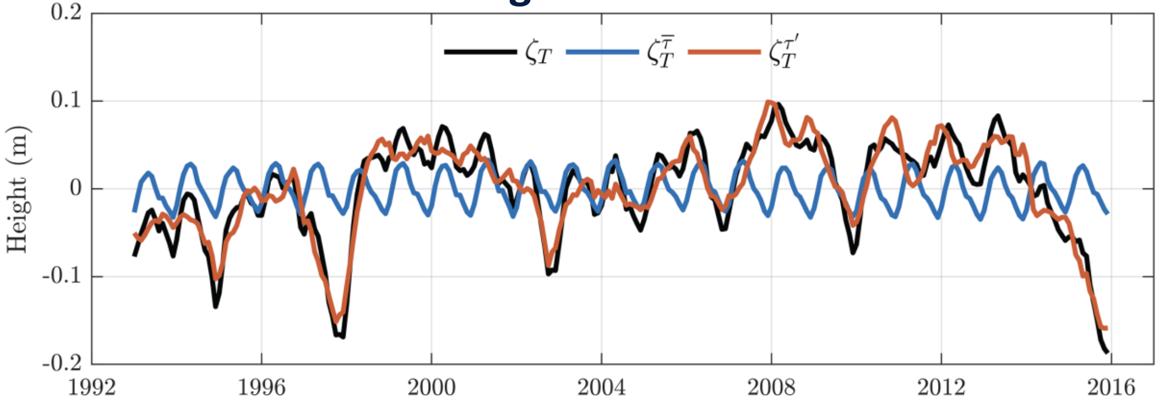
ECCO vignettes: closed budget analyses

What drives decadal variability in western tropical Pacific sea level?

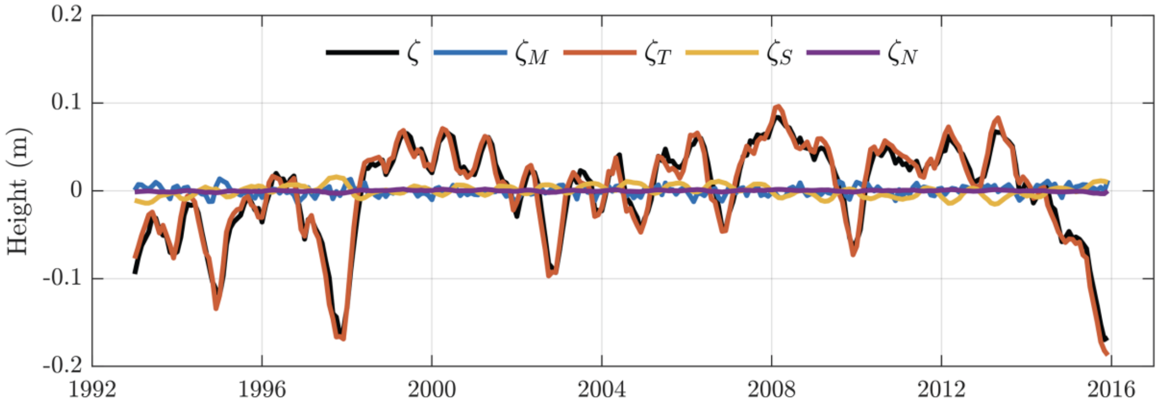
a. model/data comparison



c. forcing contributions



b. hydrostatic decomposition



d. closed budget analysis

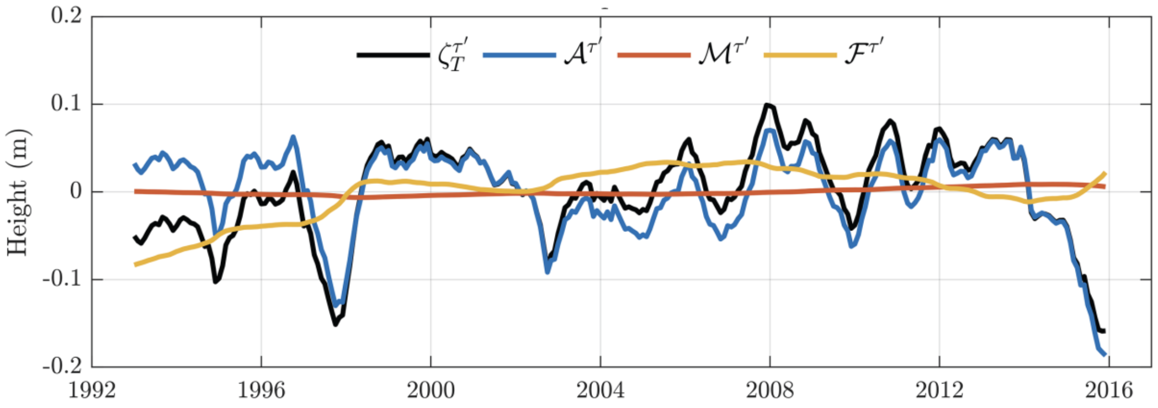


Figure from Piecuch et al. (2019)

ECCO vignettes: adjoint sensitivity analyses

What drives sea-level variability on Nantucket?

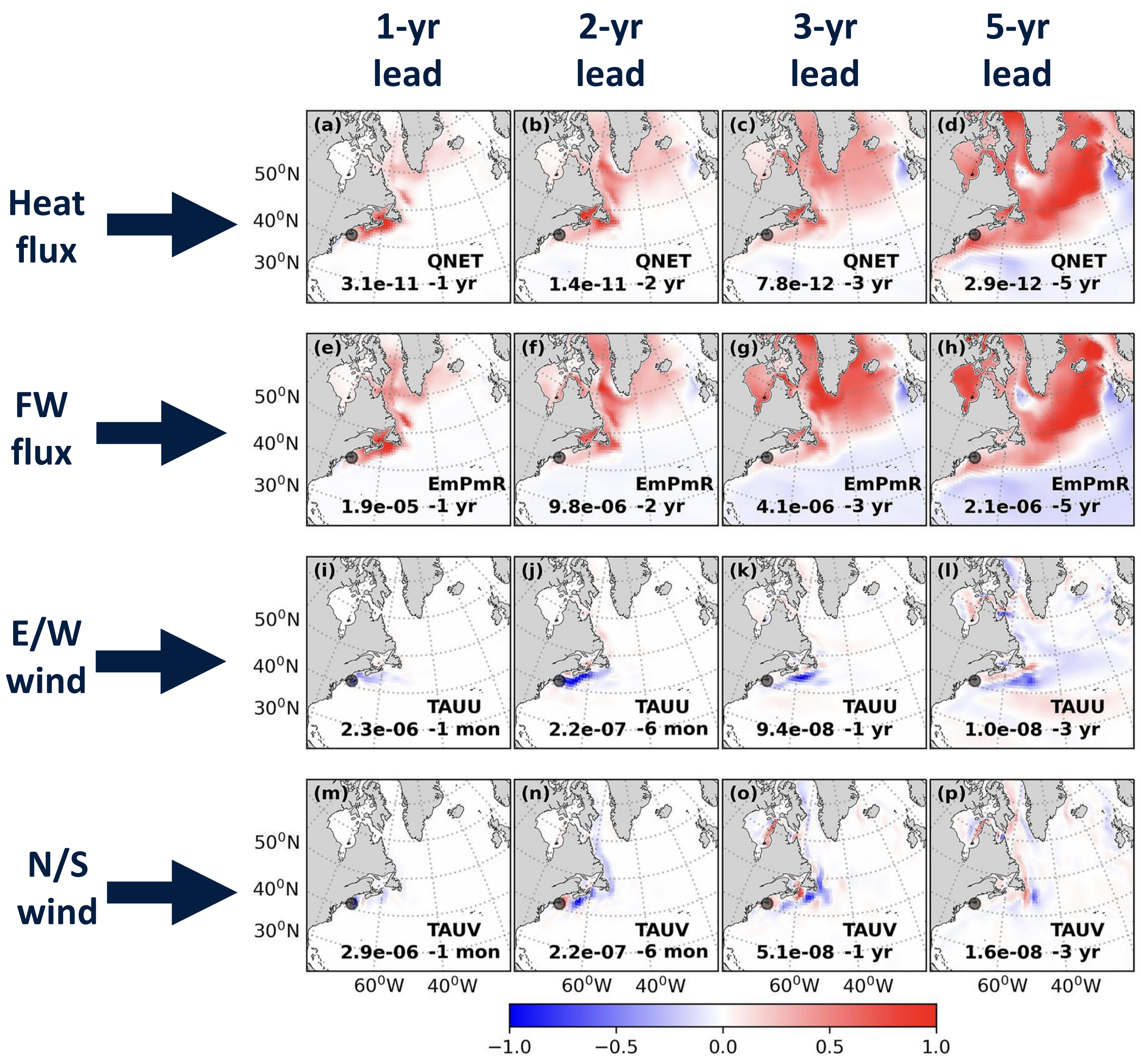


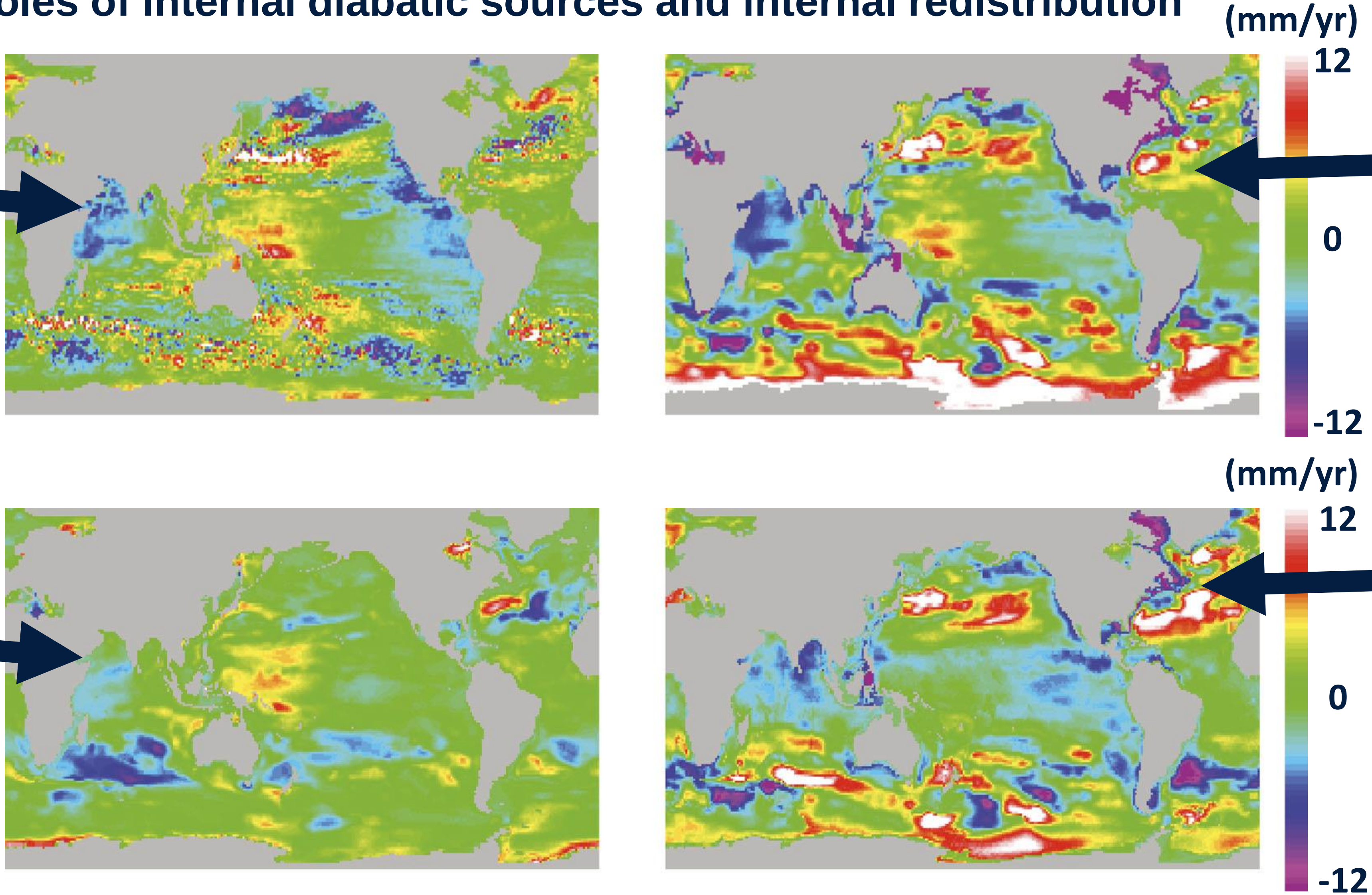
Figure from Wang et al. (2022)

ECCO vignettes: passive tracer experiments

Relative roles of internal diabatic sources and internal redistribution

Observed trends '93-'04

Modeled trends '93-'04 (ECCO v2.216)



Modeled steric trends from external diabatic sources

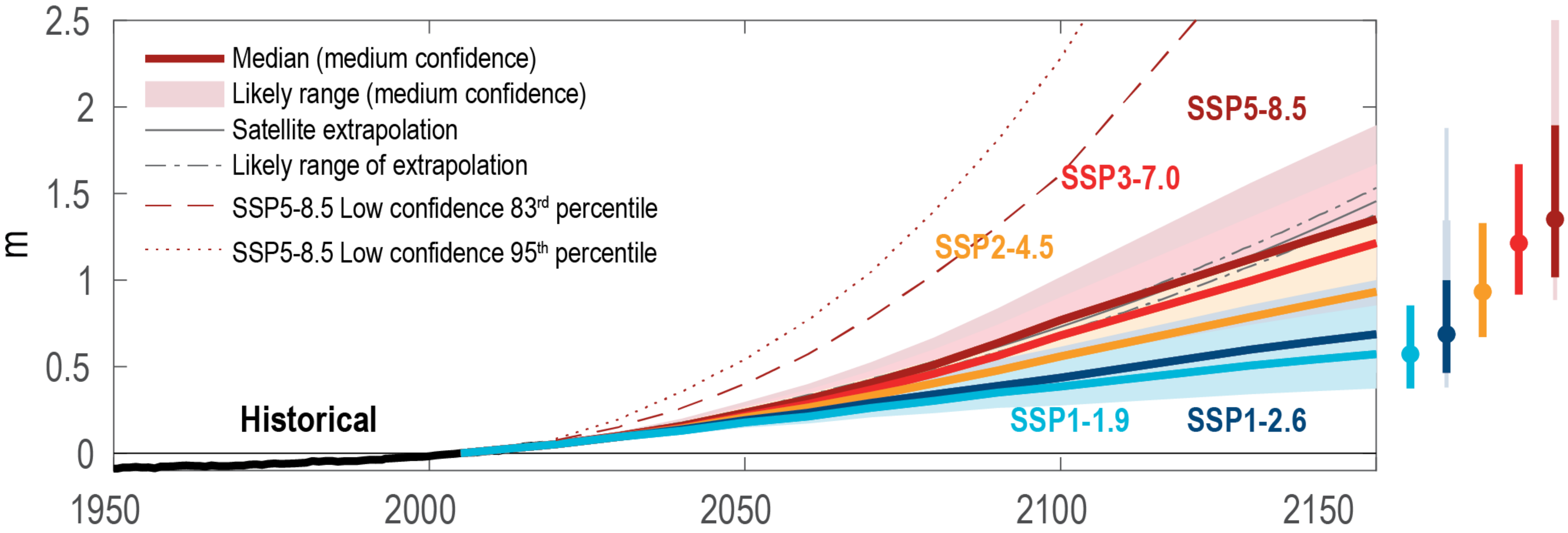
Modeled steric trends from water mass redistribution

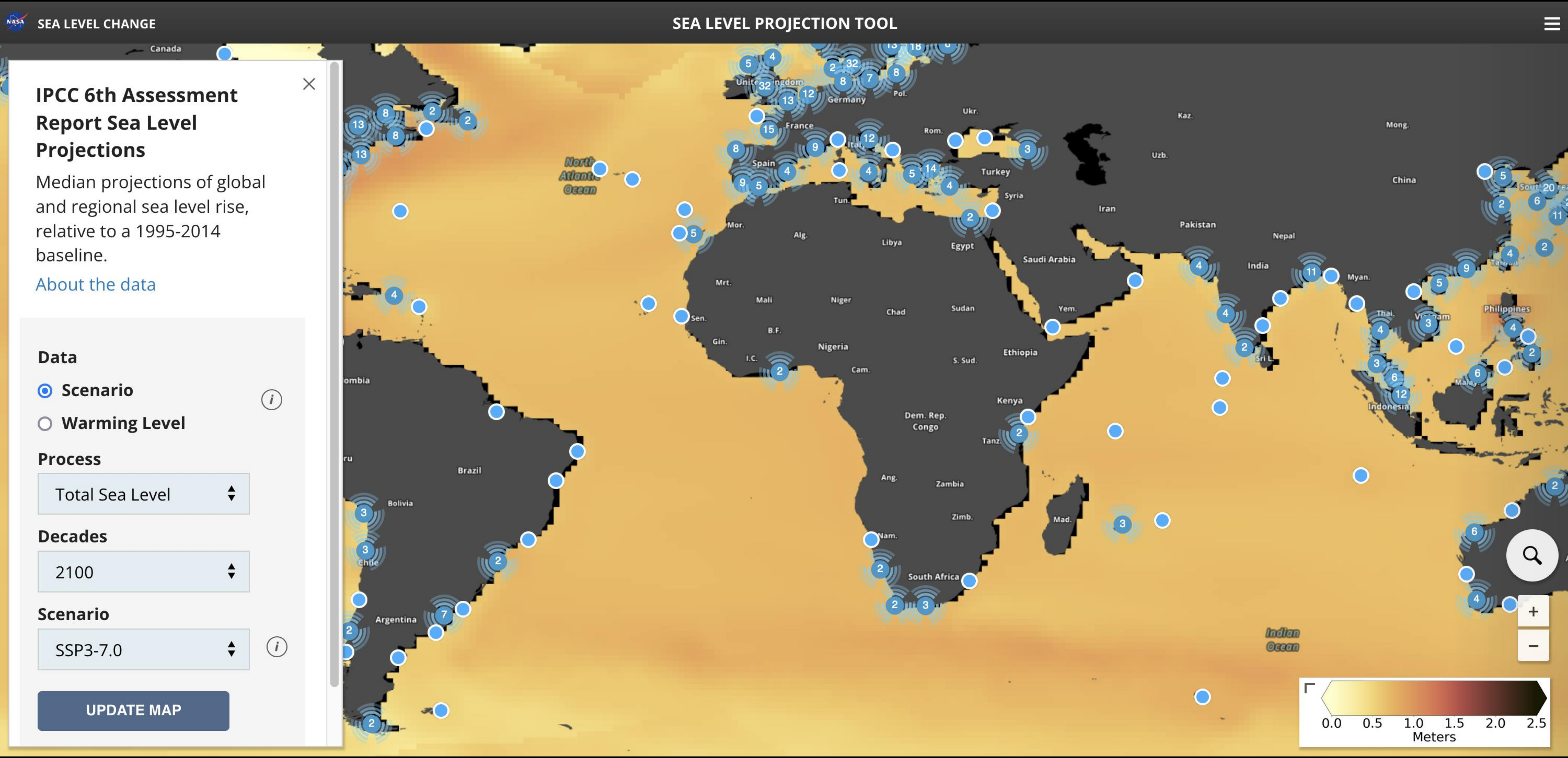
Figure from Fukumori and Wang (2013)

Sea level will continue rising

for centuries and even millennia

Global-mean sea level





https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

300 yr
1-3 m

10,000 yr
6-7 m

LONGTERM COMMITMENT

Future sea-level rise

1.5°C warming by 2100

2,000 yr
2-3 m

IPCC AR6 WG1 Chapter 9 (2021). Ranges represent medium agreement based on limited evidence.

LONGTERM COMMITMENT

Future sea-level rise

5.0°C warming by 2100

300 yr
2-6 m

10,000 yr
28-37 m

2,000 yr
10-24 m

IPCC AR6 WG1 Chapter 9 (2021). Ranges represent medium agreement based on limited evidence.

You should consider contributing

to sea level science!

NASA Sea Level Change Team

- Deepen knowledge of Earth system interactions that influence relative sea level change
- Deliver improved estimates of future sea level effects that integrate across the Earth system processes
- Contribute to National and global science foundations that support sea level and coastal resilience decision-making

NASA Sea Level Change Team

- Planned N-SCLT early-career researcher network
- Planned N-SLCT summer school 2026
- Get in touch! (cpiecuch@whoi.edu)

Summary

Sea-level rise is a whole-Earth process

Current rates of sea-level rise are exceptional

Sea level is coupled to ocean circulation and climate

NASA data and models (including ECCO!) have revolutionized our understanding of sea-level change

You should contribute to sea-level science!