Introduction to Measuring, Modeling, and Interpreting Earth's Changing Sea Level

Jim Davis

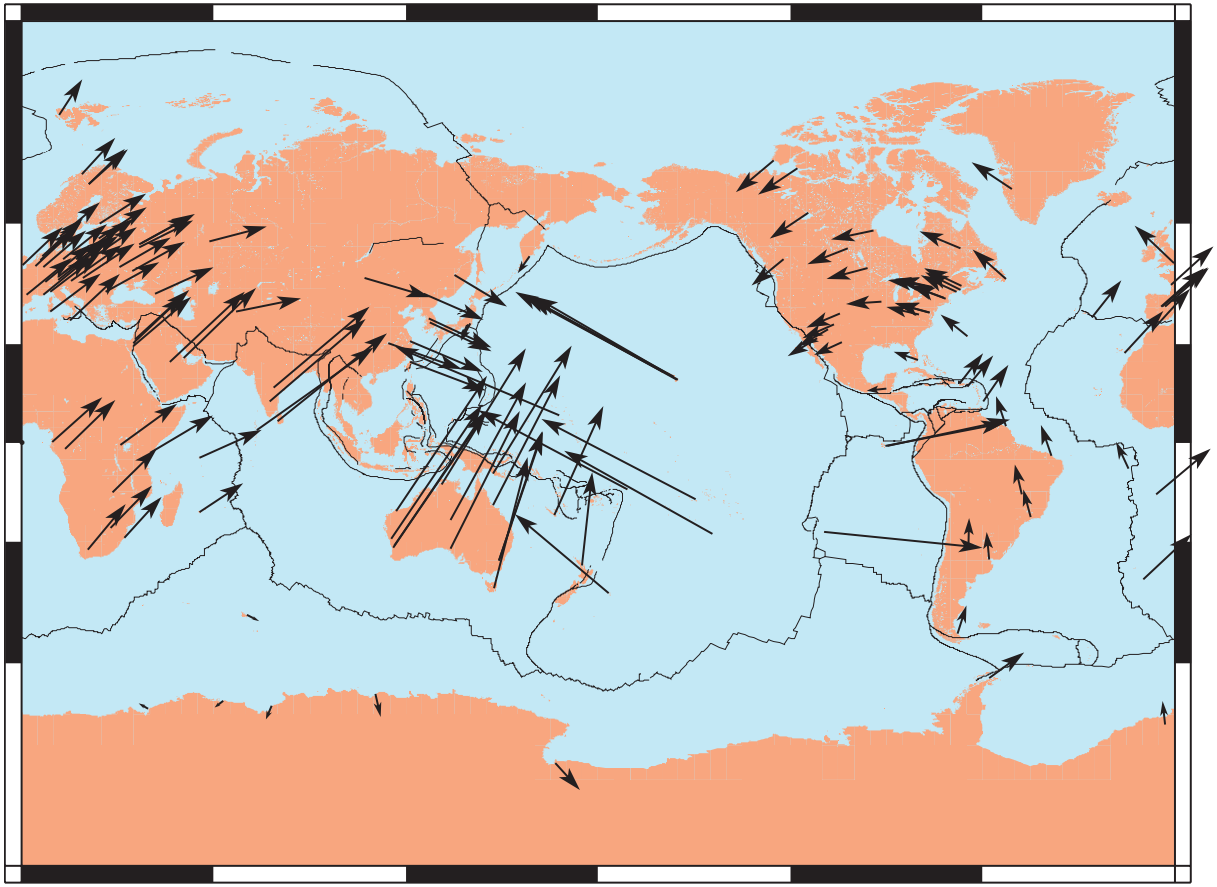
Also see lectures by Mo Raymo, Jeanne Sauber & Wouter van der Wal

CIDER 2015

Geodesy

The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

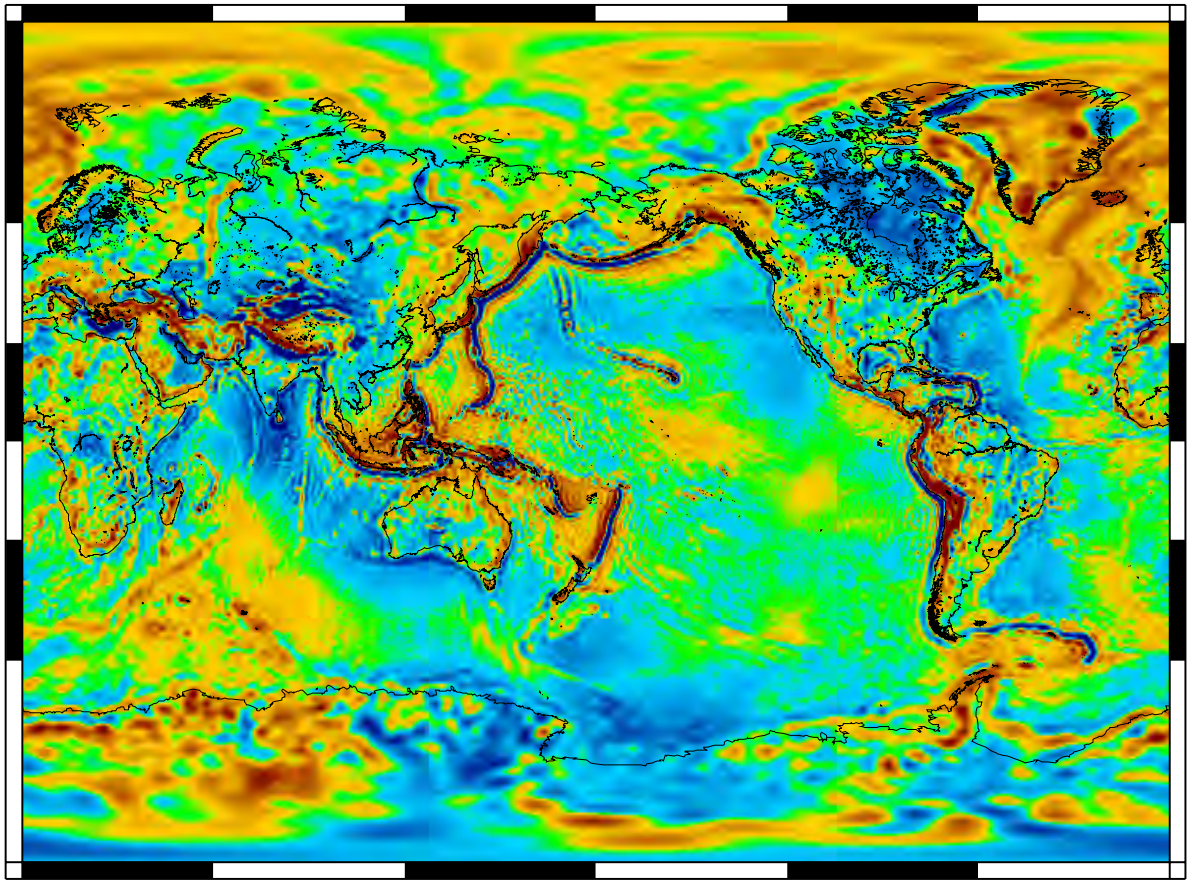
(a) Plate tectonics



Geodesy

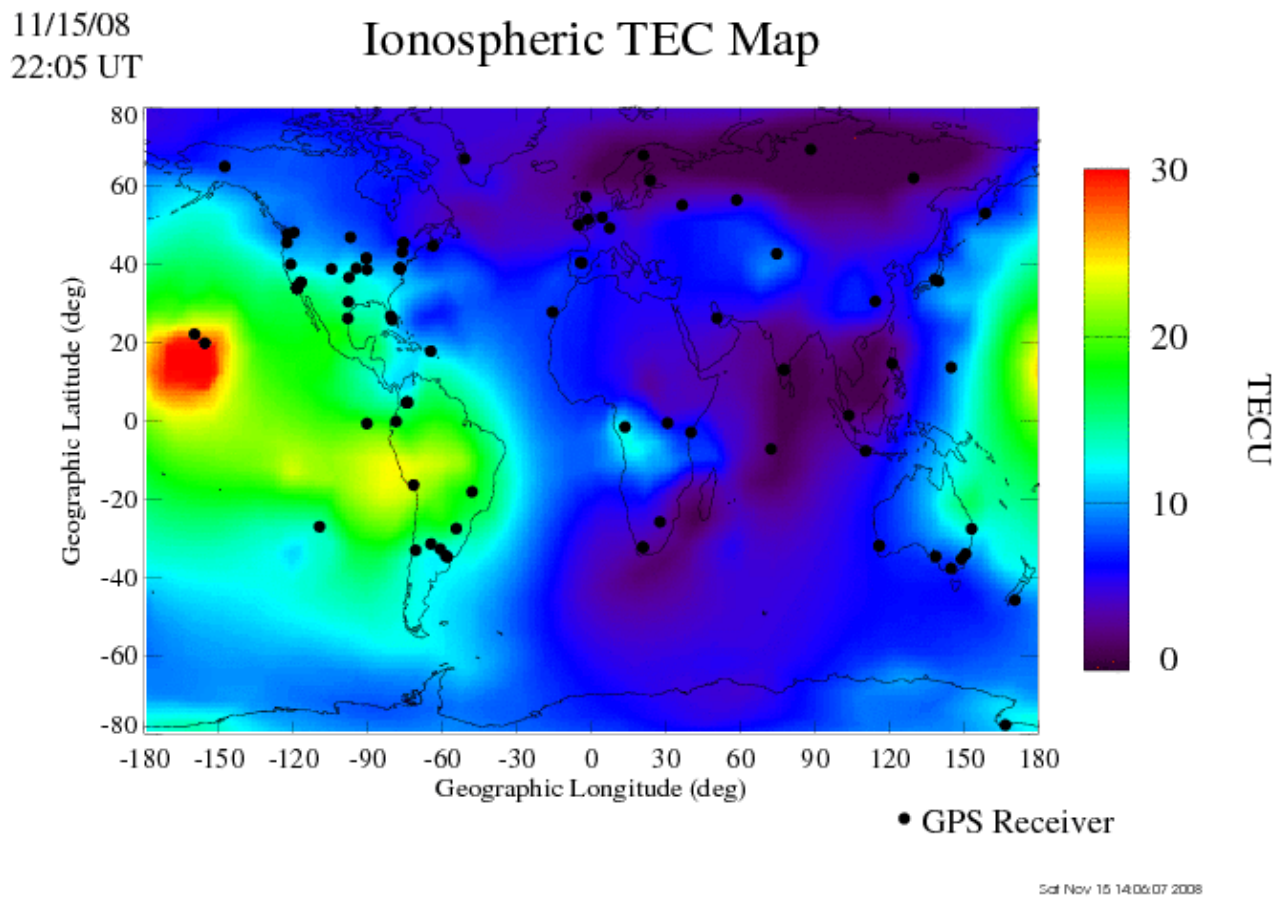
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

(b) Global gravity field



Geodesy

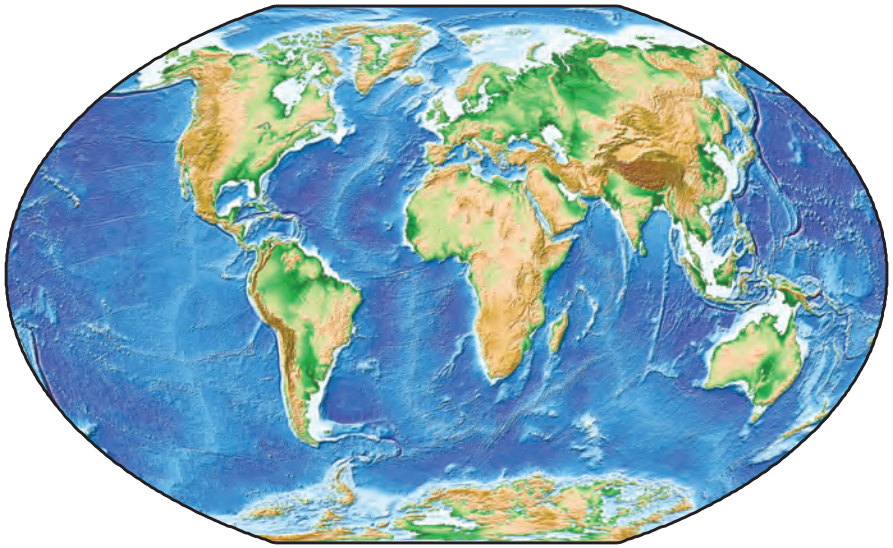
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation



Geodesy

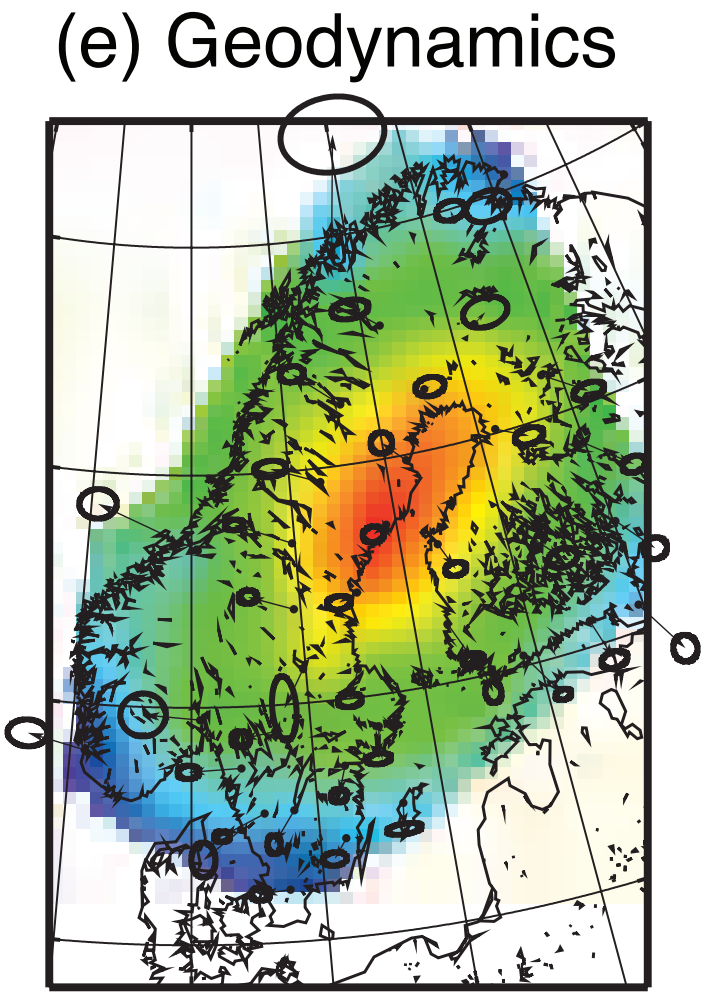
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

(d) Global topography and bathymetry



Geodesy

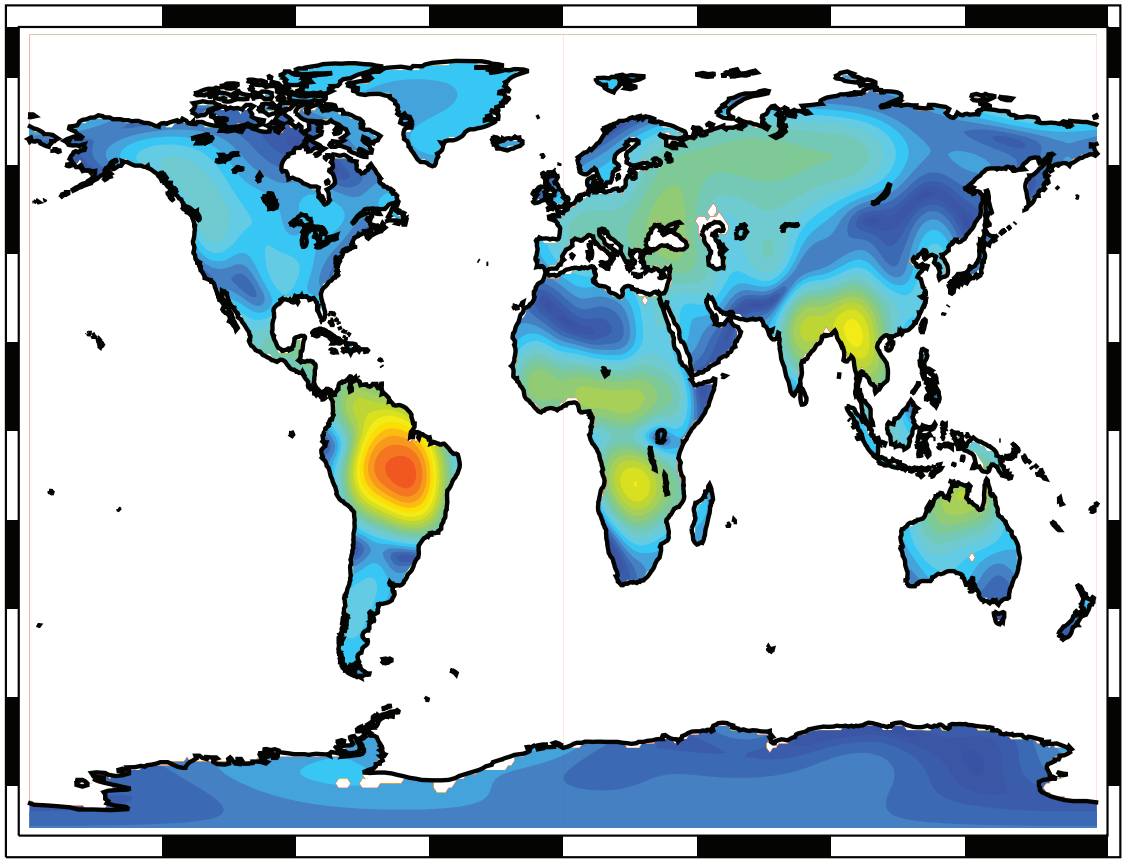
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation



Geodesy

The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

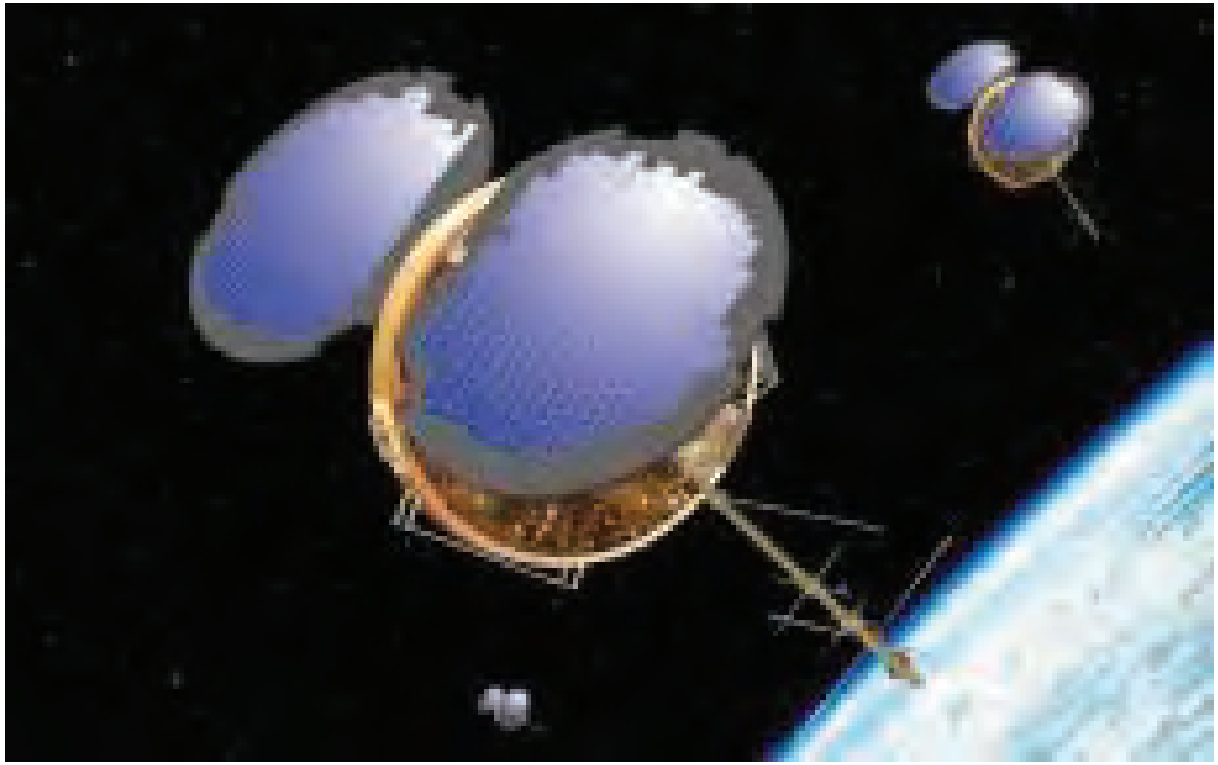
(f) Global water cycle



Geodesy

(g) Weather and atmospheric dynamics

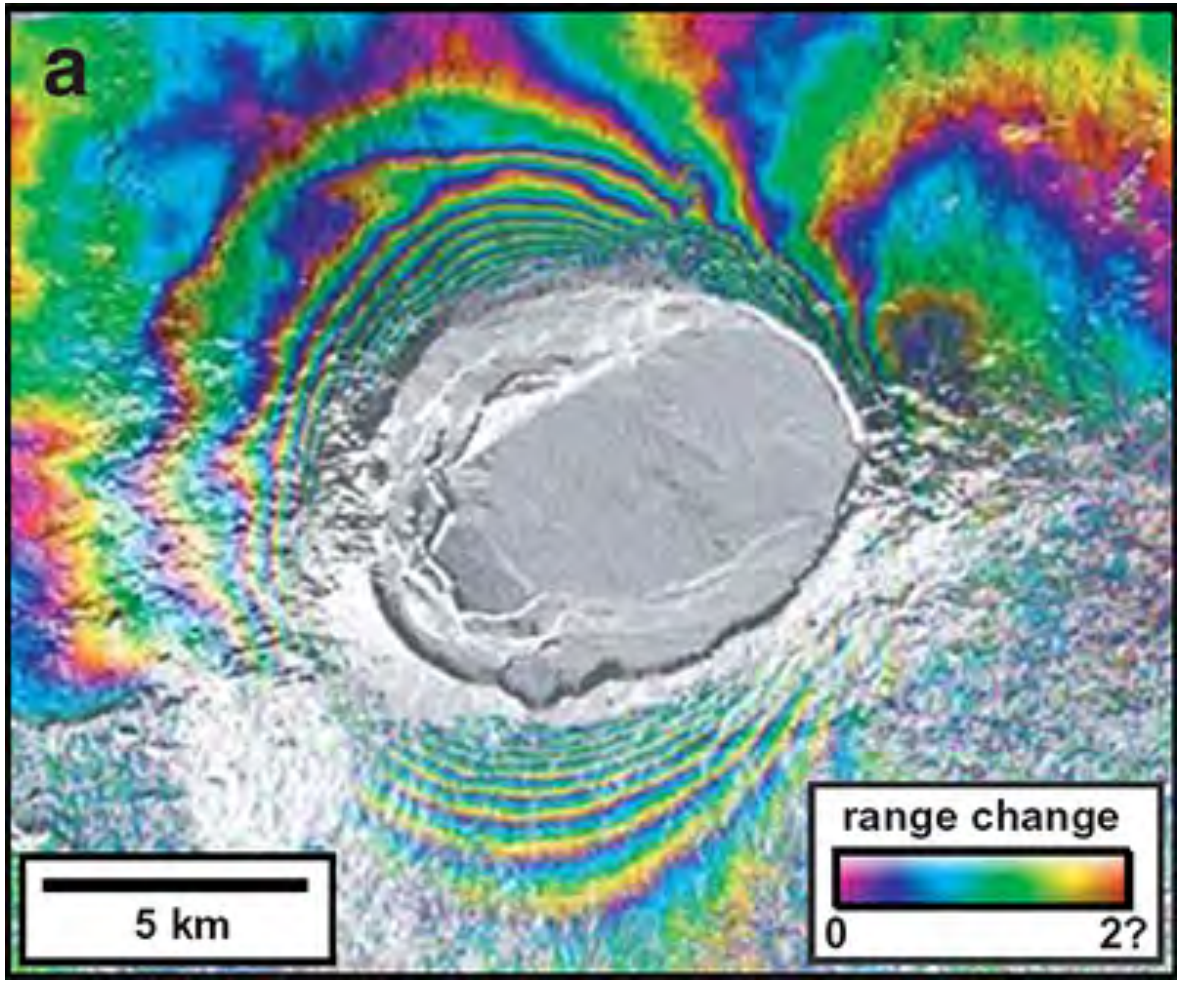
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation



Geodesy

(h) Volcano deformation

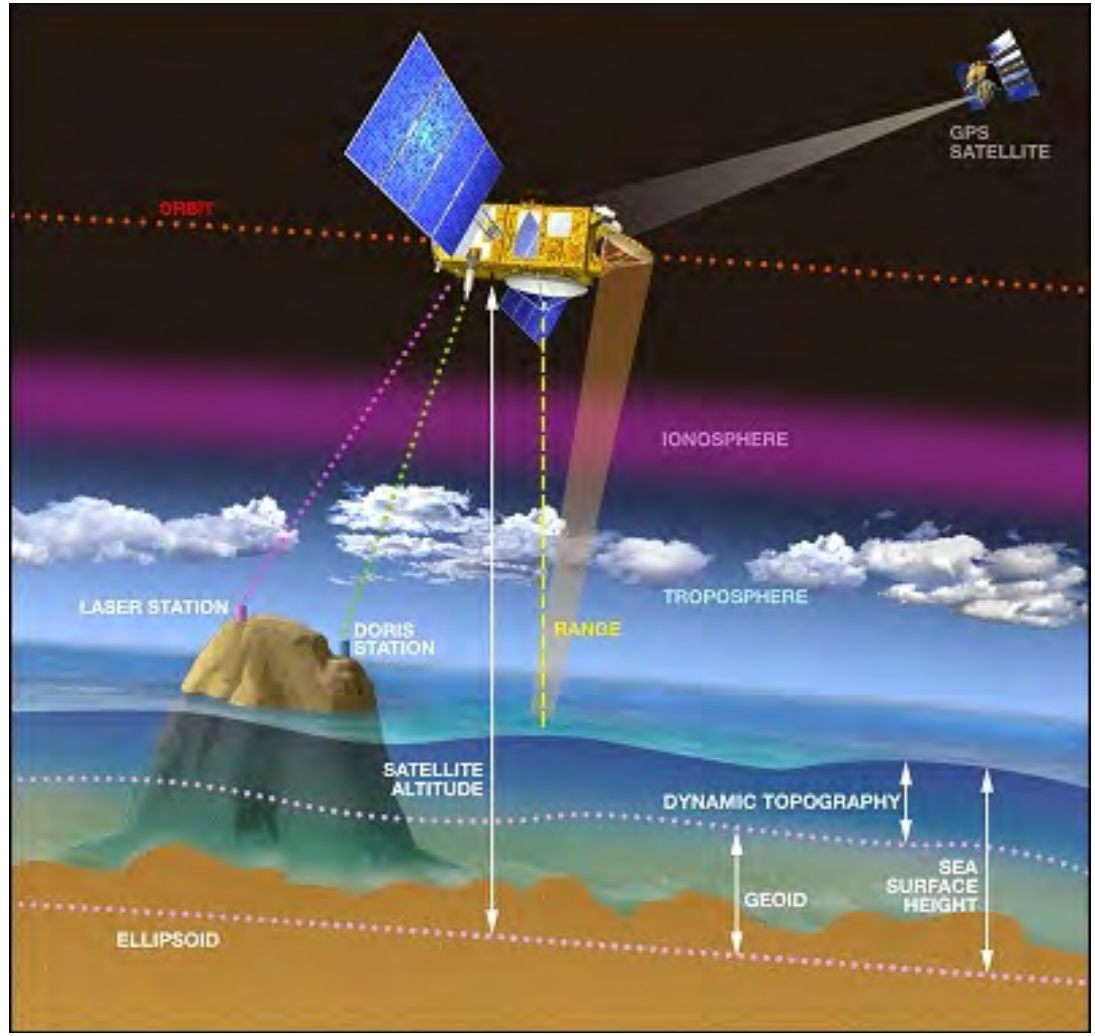
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation



Geodesy

The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

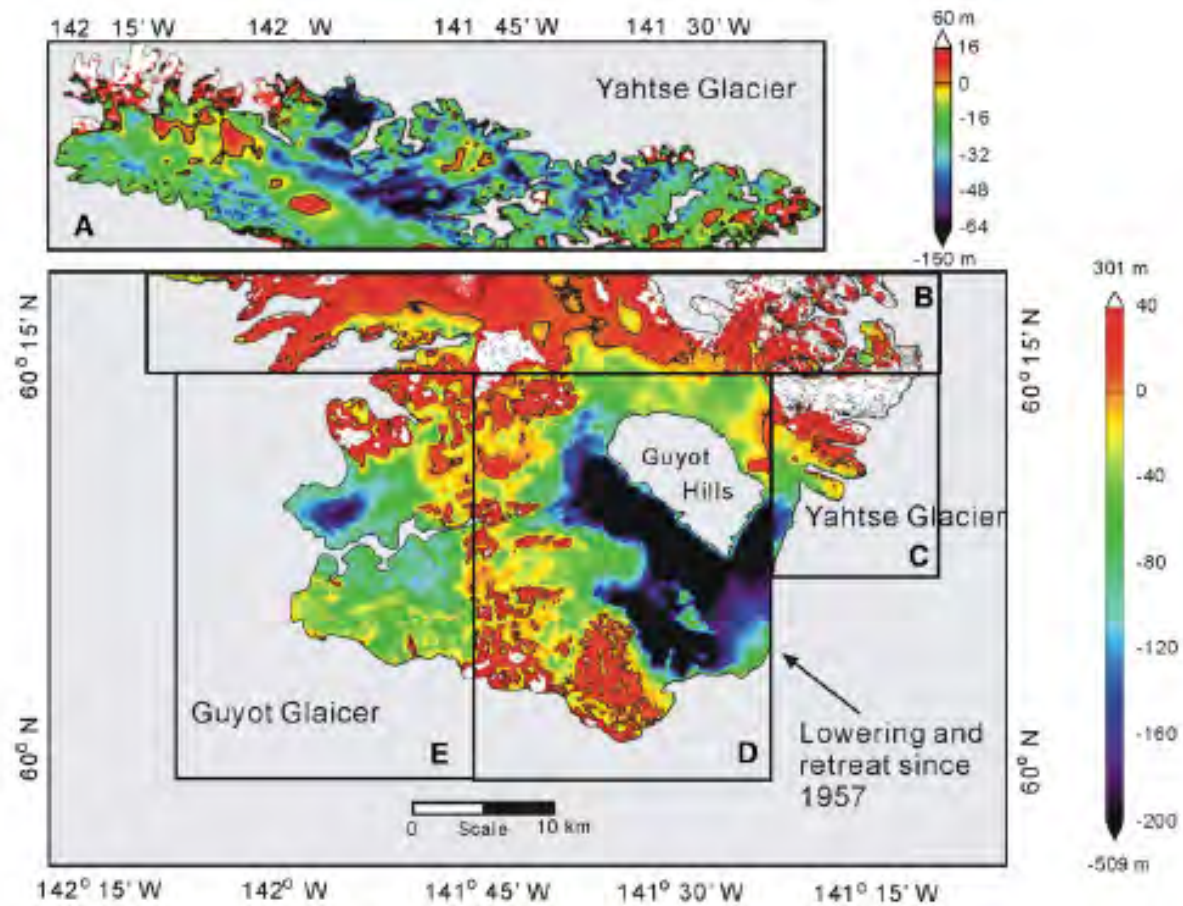
(i) Precise orbit determination



Geodesy

The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

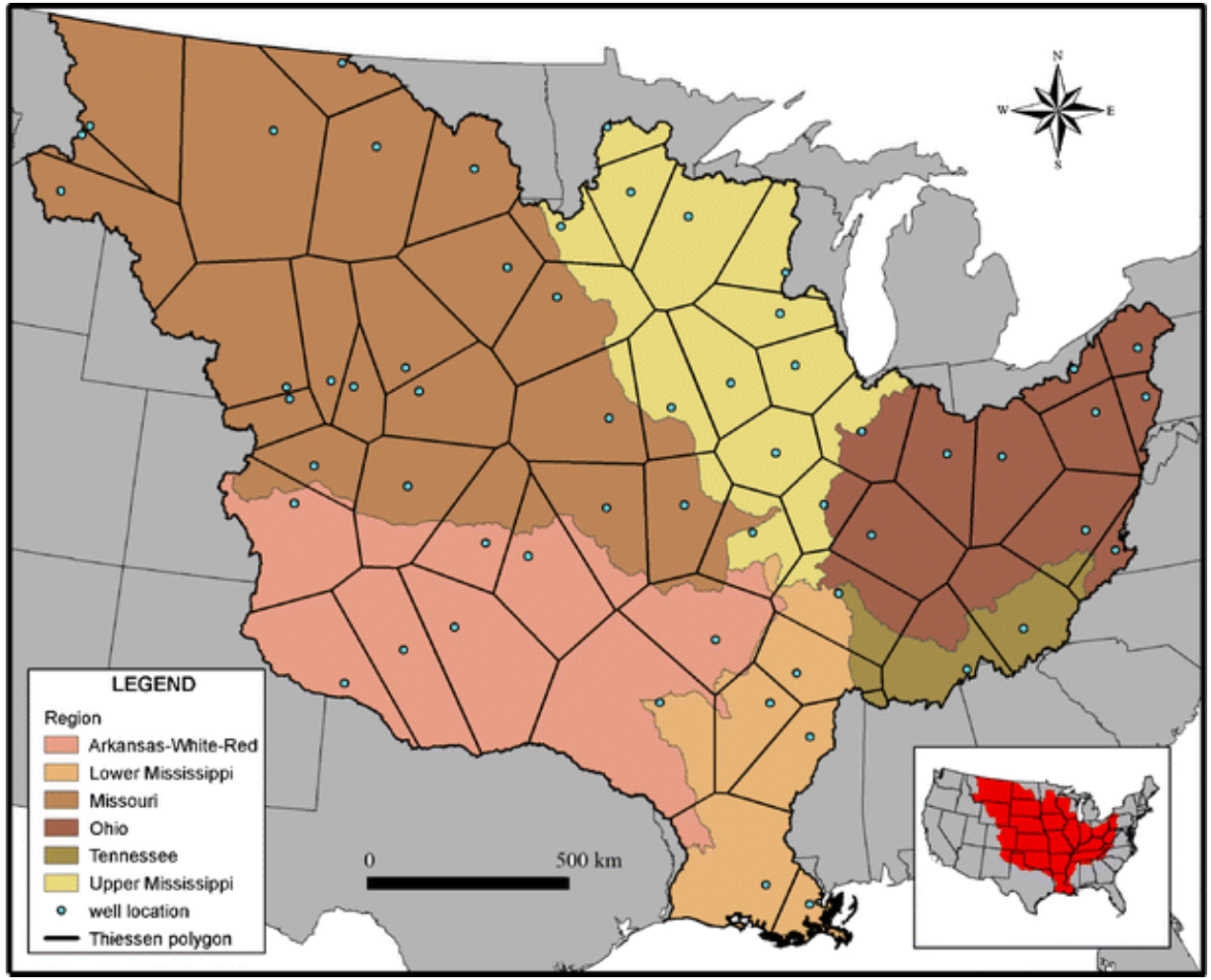
(j) Cryospheric science



Geodesy

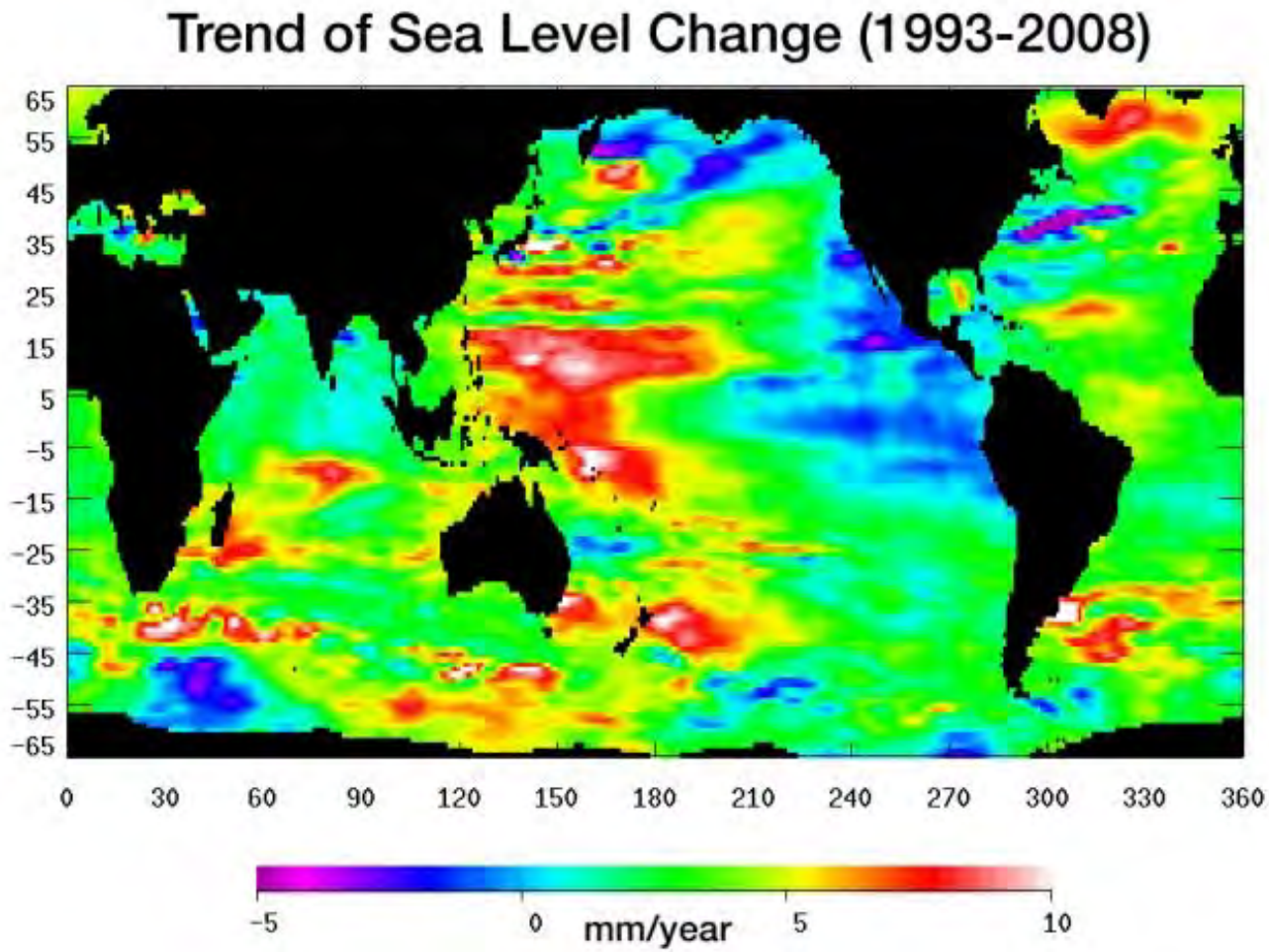
The science of observing and understanding Earth's time-varying shape, gravity field, and rotation

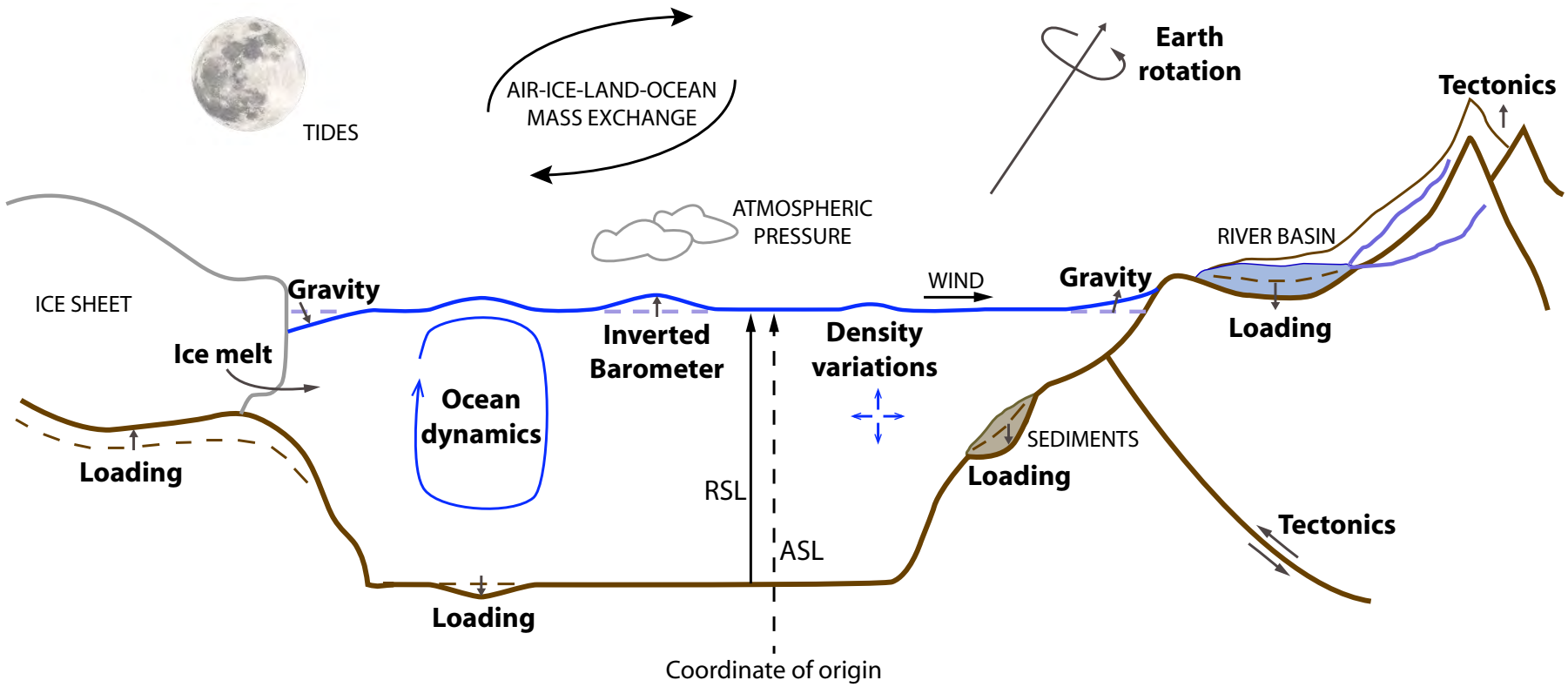
(k) Hydrology



Geodesy

The science of observing and understanding Earth's time-varying shape, gravity field, and rotation





Contributions to Sea-Level Change

Overview

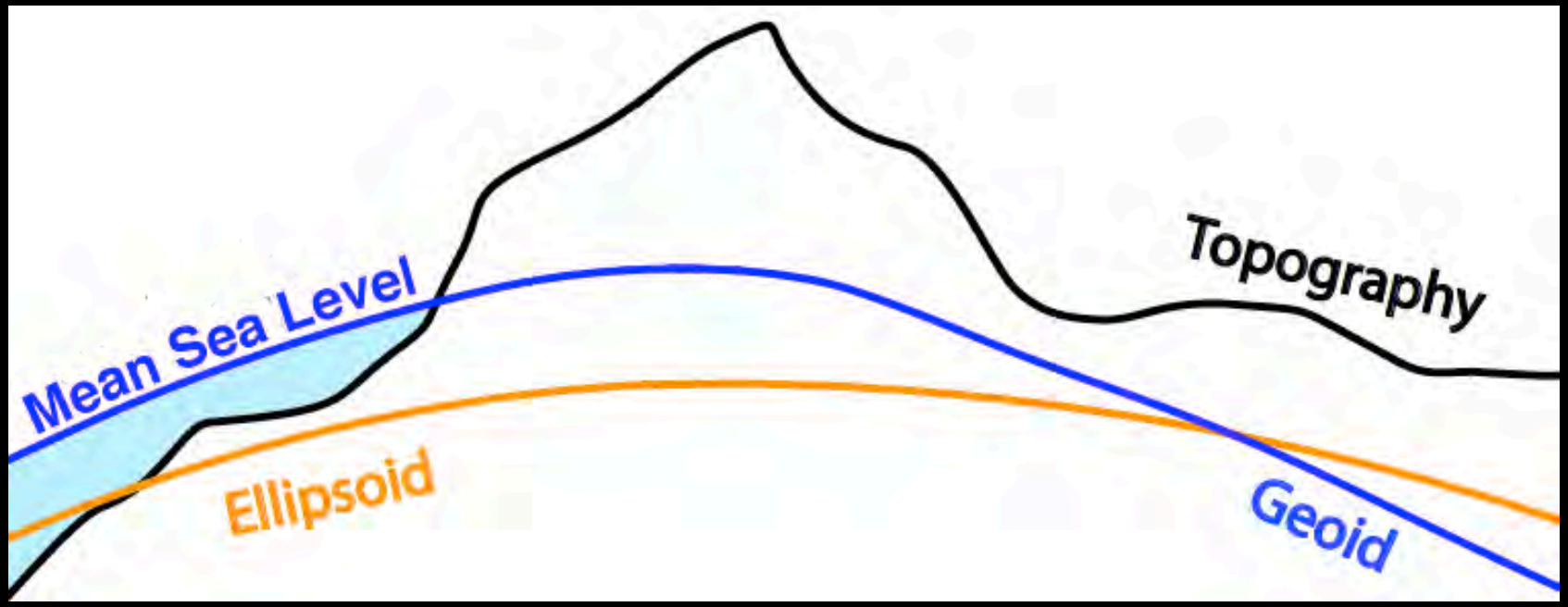
1. Relative vs. absolute sea level
2. Eustasy
3. Glacial isostatic adjustment and sea level change
4. Sea-level change in response to present-day climate forcing

Photo: UNAVCO

Meanings of "Sea Level"

- The instantaneous sea-surface height
- The mean sea-surface height, approximated by the geoid
- The mean *local* sea-surface height (especially in reference to nearby land altitude, e.g., "Lower Manhattan lies less than 2 m above sea level")
- A reference ellipsoid (e.g., interpretation of GPS height coordinates a "above sea level")

Relative vs Absolute Sea Level



ASL: Sea-level relative to reference ellipsoid

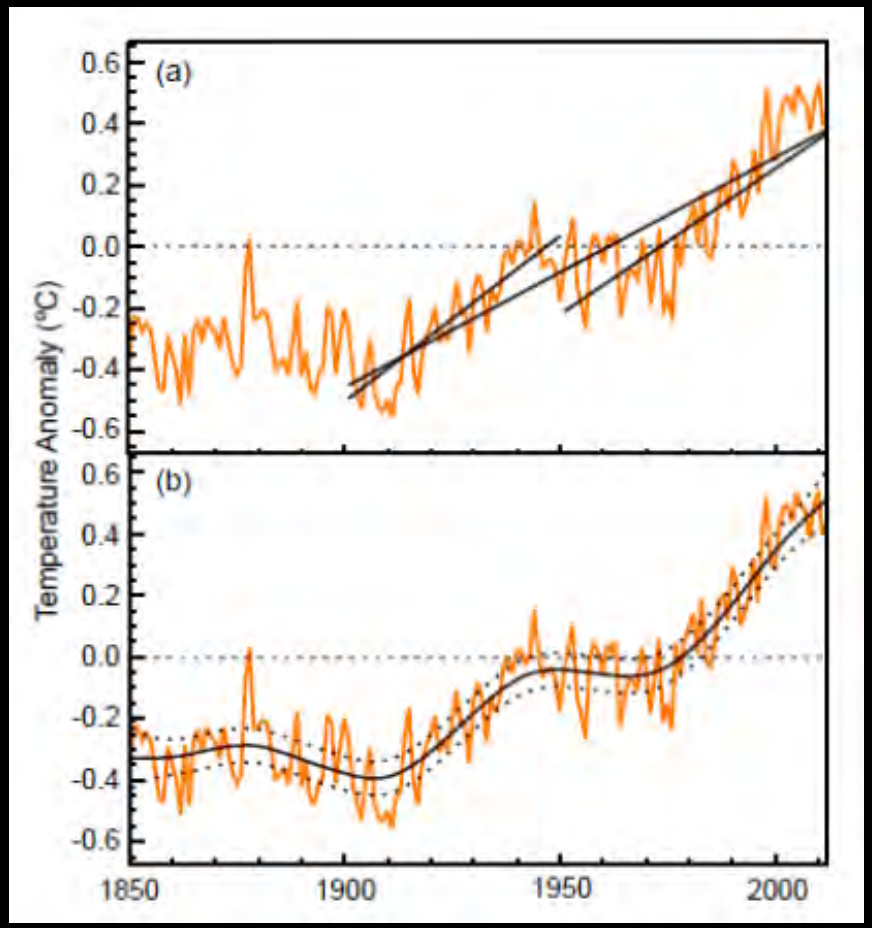
RSL: Sea-level relative to Earth's solid surface

Long-term (mean) SL is *approximated* by the geoid

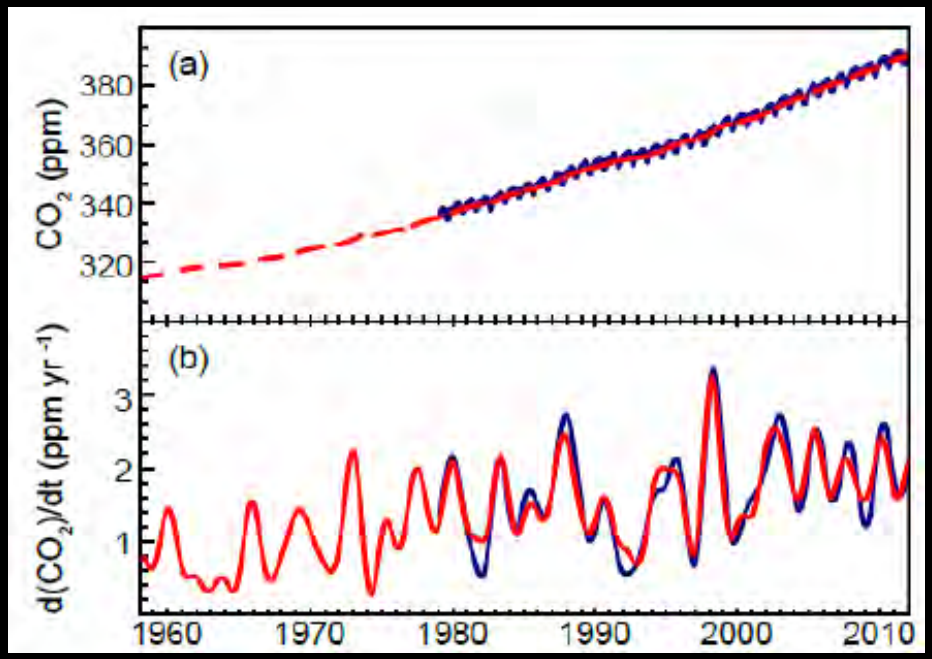
RSL is what generally matters to people!

RSL is what generally matters to people!

Fifth IPCC Assessment



Globally averaged temperature

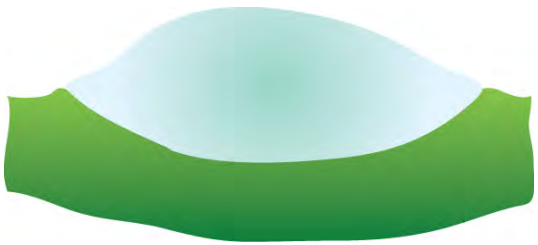


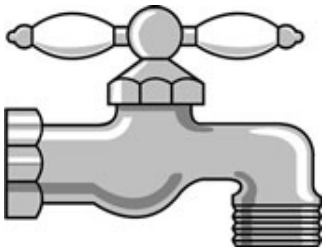
Globally averaged CO_2

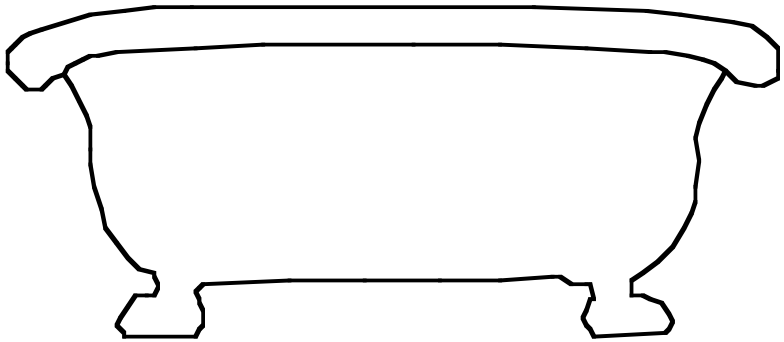
Geodetic focus of sea-level change

- Redistribution of surface mass among air, ocean, ice, and land
  - Deformation of solid Earth
  - Changes to geopotential
- Changes to volume of oceans
  - Mass exchanges
  - Steric changes

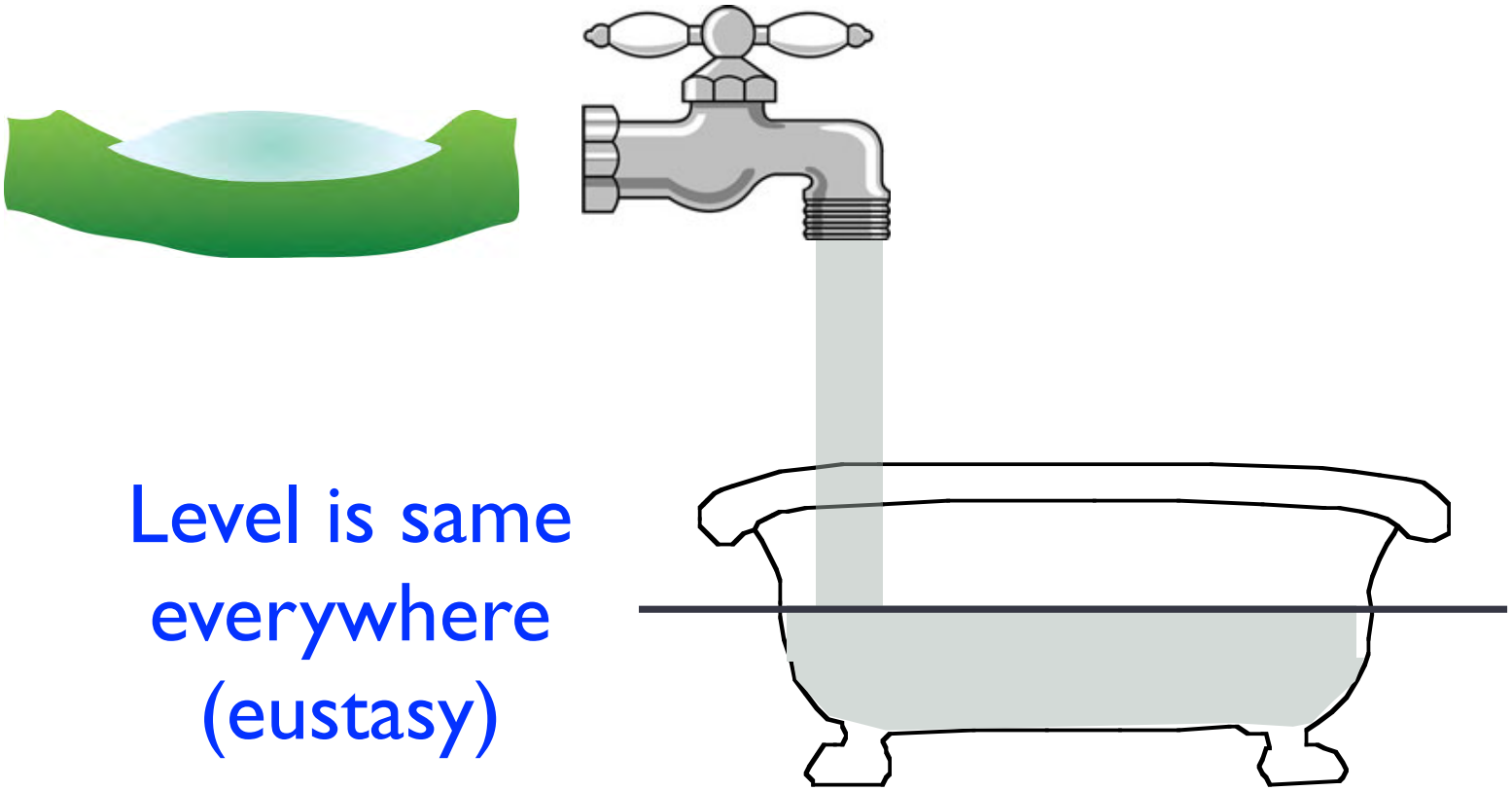
“Bathtub Model” for Sea-Level Change







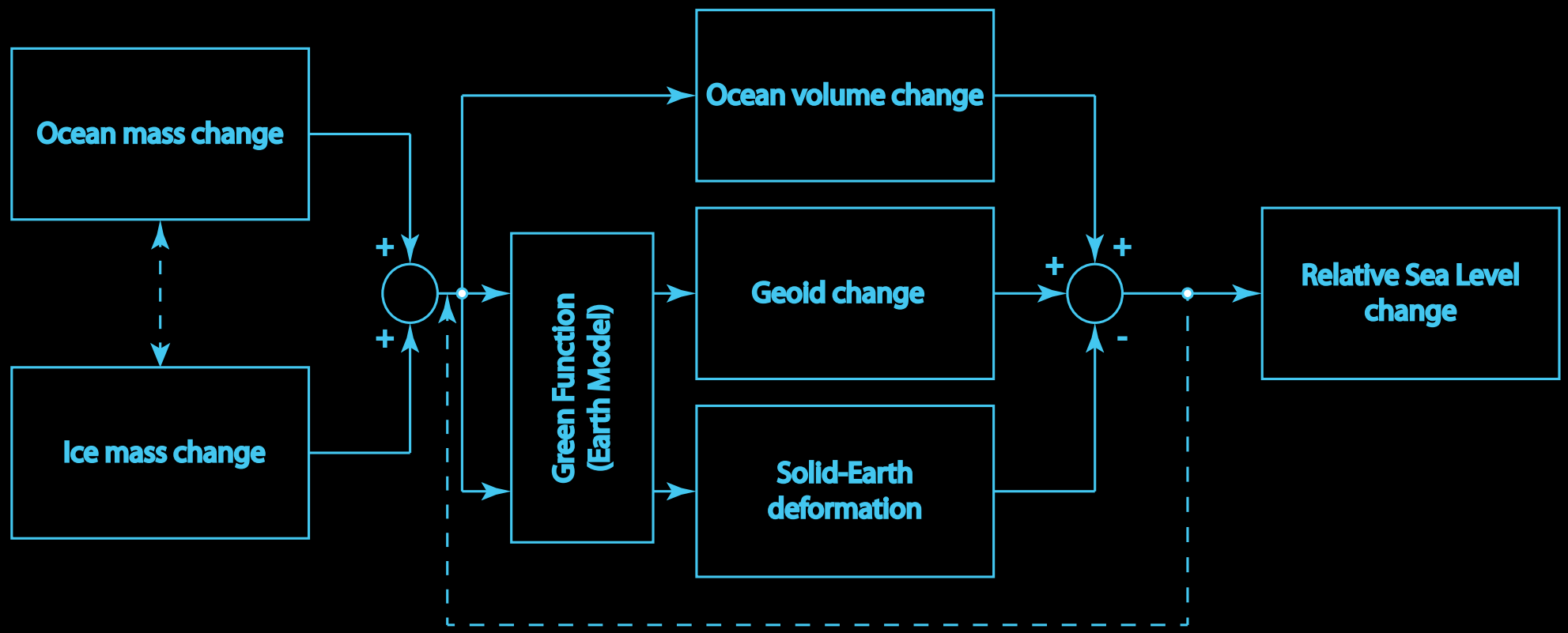
“Bathtub Model” for Sea-Level Change



Level is same everywhere (eustasy)

Eustasy

- Not one clear definition for eustasy
- Term introduced by *Seuss* [1906] to describe the *uniform subsidence of the sea floor that formed the major ocean areas, thereby giving rise to surrounding uniform beach-strand levels*
- More recently:
  - Assumption of "bathtub model"
  - Global spatial average of sea-level rise



RSL change due to cryosphere-ocean mass exchange includes gravitational self-attraction and loading (SAL)

(Steric changes not included in this slide.)

Sea-Level Equation (SLE)

RSL change ΔS written as difference between changes in geoid ΔG and land ΔR plus a term ΔV representing volume changes:

$$\Delta S(\lambda,\phi) = C(\lambda,\phi)\left[\Delta G(\lambda,\phi) - \Delta R(\lambda,\phi) + \Delta V\right]$$

C is 1 when over ocean, 0 when over land.

ΔR and ΔG as response to a gravitational load ΔG on surface of viscoelastic Earth with Green's functions $\Gamma(\gamma)$ and $\Lambda(\gamma)$

$$\Delta R(\lambda,\phi) = \iint d\Omega' \, \Gamma(\gamma) \, \Delta L(\lambda',\phi')$$

$$\Delta G(\lambda,\phi) = \iint d\Omega' \, \Lambda(\gamma) \, \Delta L(\lambda',\phi')$$

γ is angle between (λ,Φ) and (λ',Φ')

Sea-Level Equation (SLE)

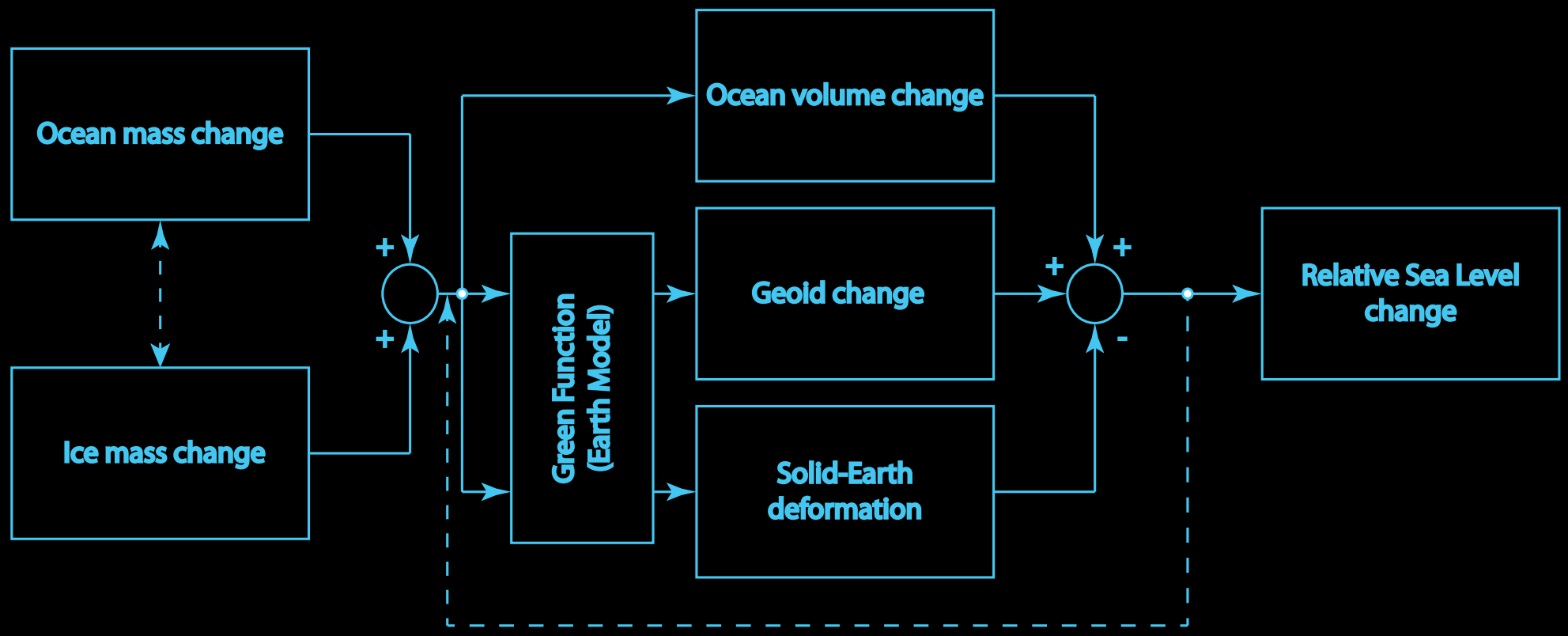
So with K(γ) = Λ(γ) - Γ(γ):

$$\Delta S(\lambda,\phi) = C(\lambda,\phi)\left[\iint d\Omega' \, \mathrm{K}(\gamma)\,\Delta L(\lambda',\phi') + \Delta V\right]$$

But the *total* load change Δ*L* is the sum of ice Δ*I(λ,Φ)* and ocean. The ocean load ***is*** the RSL Δ*S(λ,Φ)* :

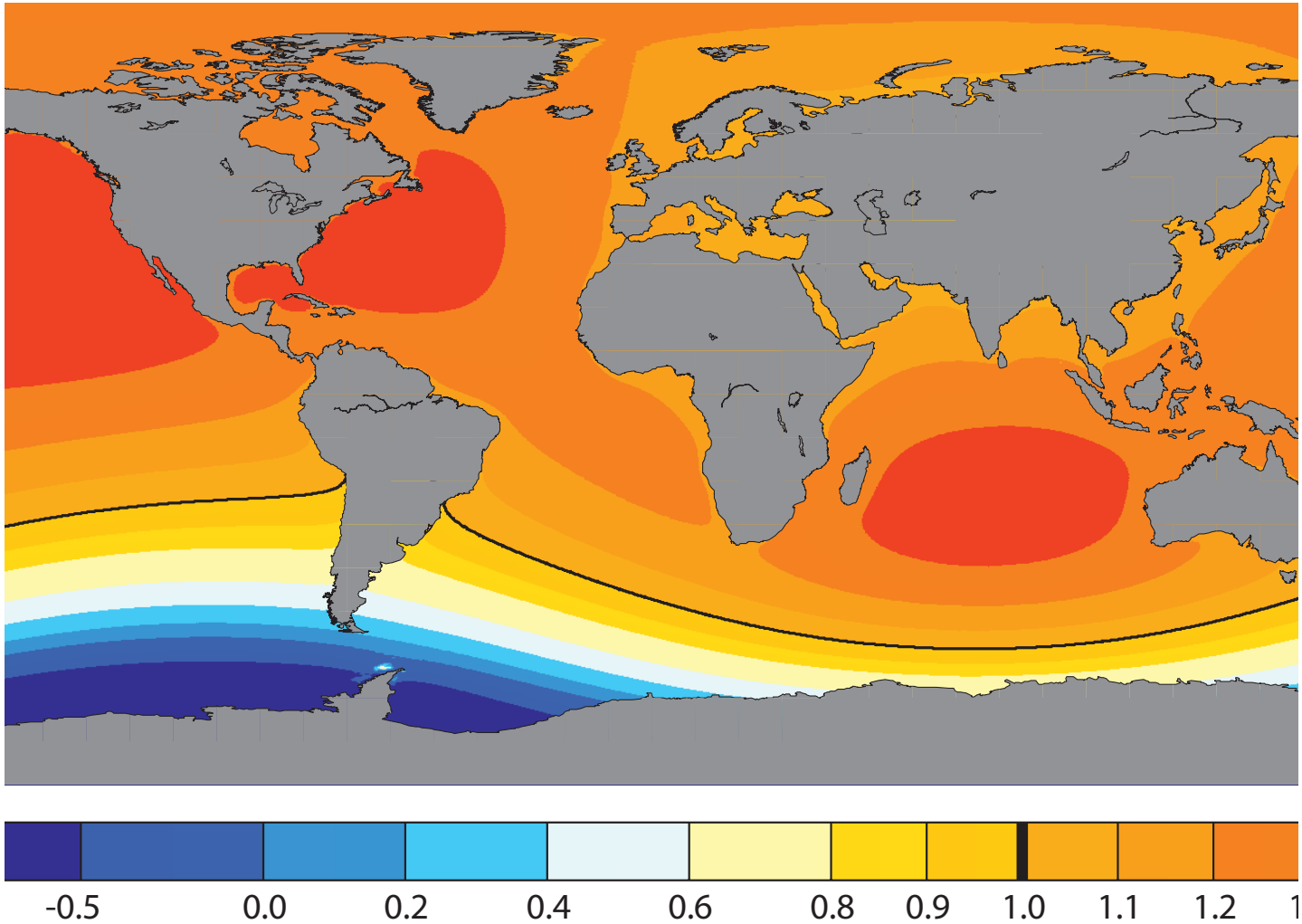
$$\Delta L(\lambda,\phi) = \Delta I(\lambda,\phi) + \Delta S(\lambda,\phi)$$

Thus the change in RSL appears both on the LHS of the SLE and in the integrand on the RHS. This is represented pictorially on the "flow chart" slide by the "feedback loop."



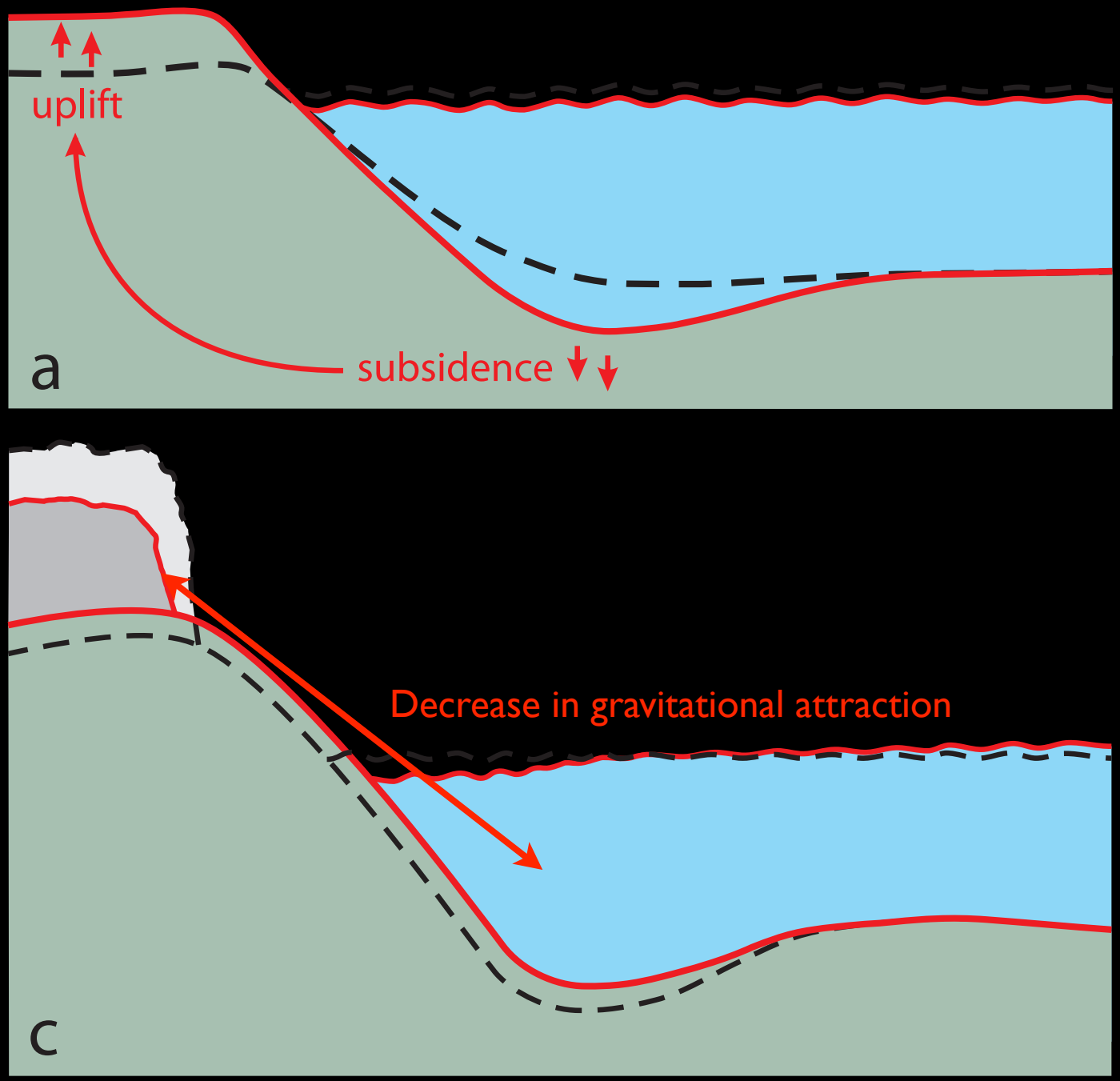
RSL change due to cryosphere-ocean mass exchange includes gravitational self-attraction and loading (SAL)

(Steric changes not included in this slide.)



Tamisiea & Mitrovica [2011]

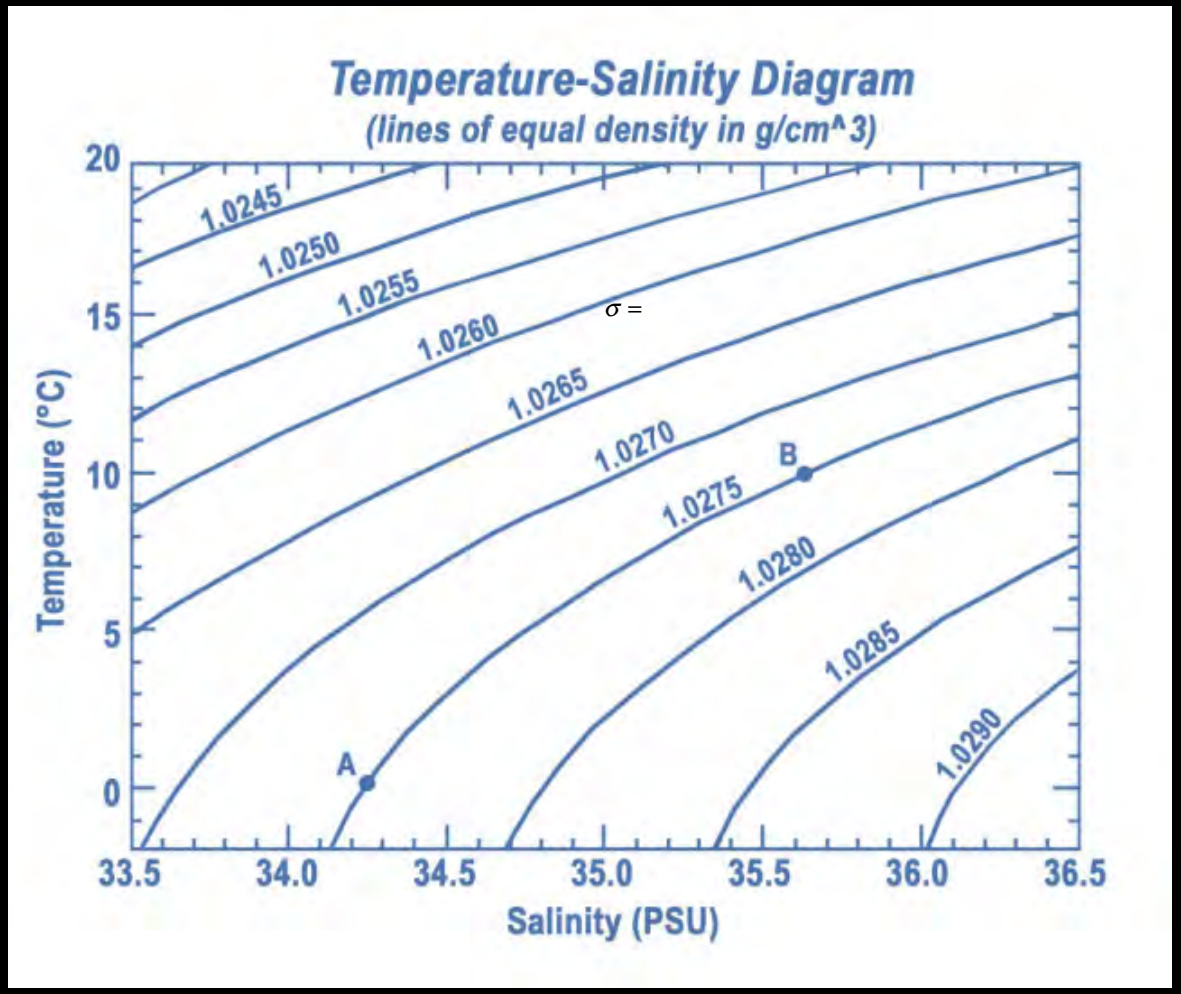
Solution to SLE leads to SL fingerprint
(Above, for collapse of WAIS, normalized by eustatic value)



Tamisiea and Mitrovica [2011]

Steric Changes

$$\Delta H = -\frac{1}{\rho_o}\int_{-H_o}^{0} dz\, \Delta\rho\left(z;\Delta T(z),\Delta S(z)\right)$$



NASA/Aquarius

Glacial Isostatic Adjustment (GIA)

- Viscoelastic adjustment of Earth due to ice-mass variations that occurred in past
- Also called "postglacial rebound"
- Major impact on gravity, solid-Earth deformation, and sea level
- Major source of uncertainty in interpreting RSL change and modeling ice-ocean mass interchange
- Difficult to model accurately
- Requires accurate model for Earth's elastic and rheological properties, as well as computational approach

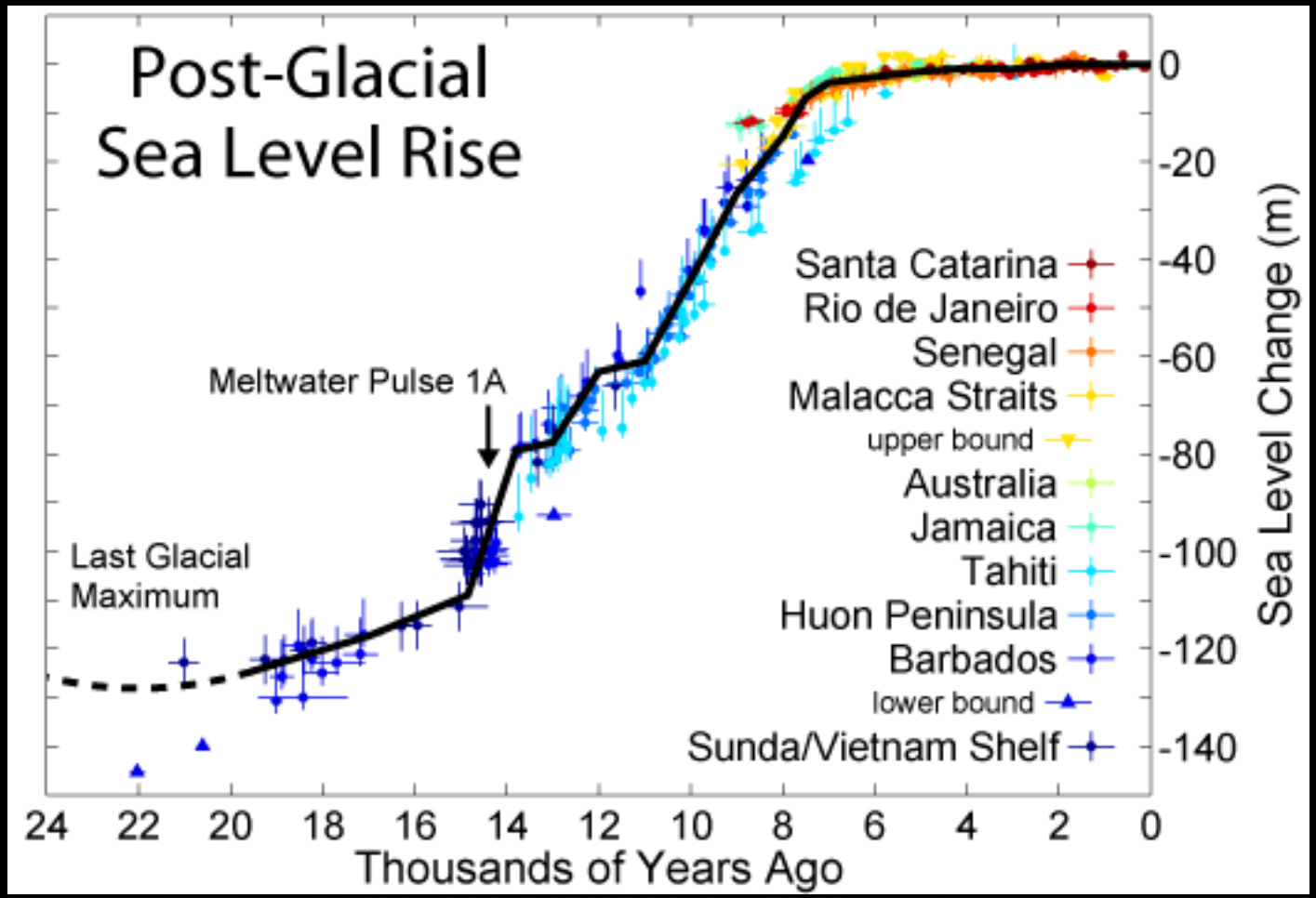
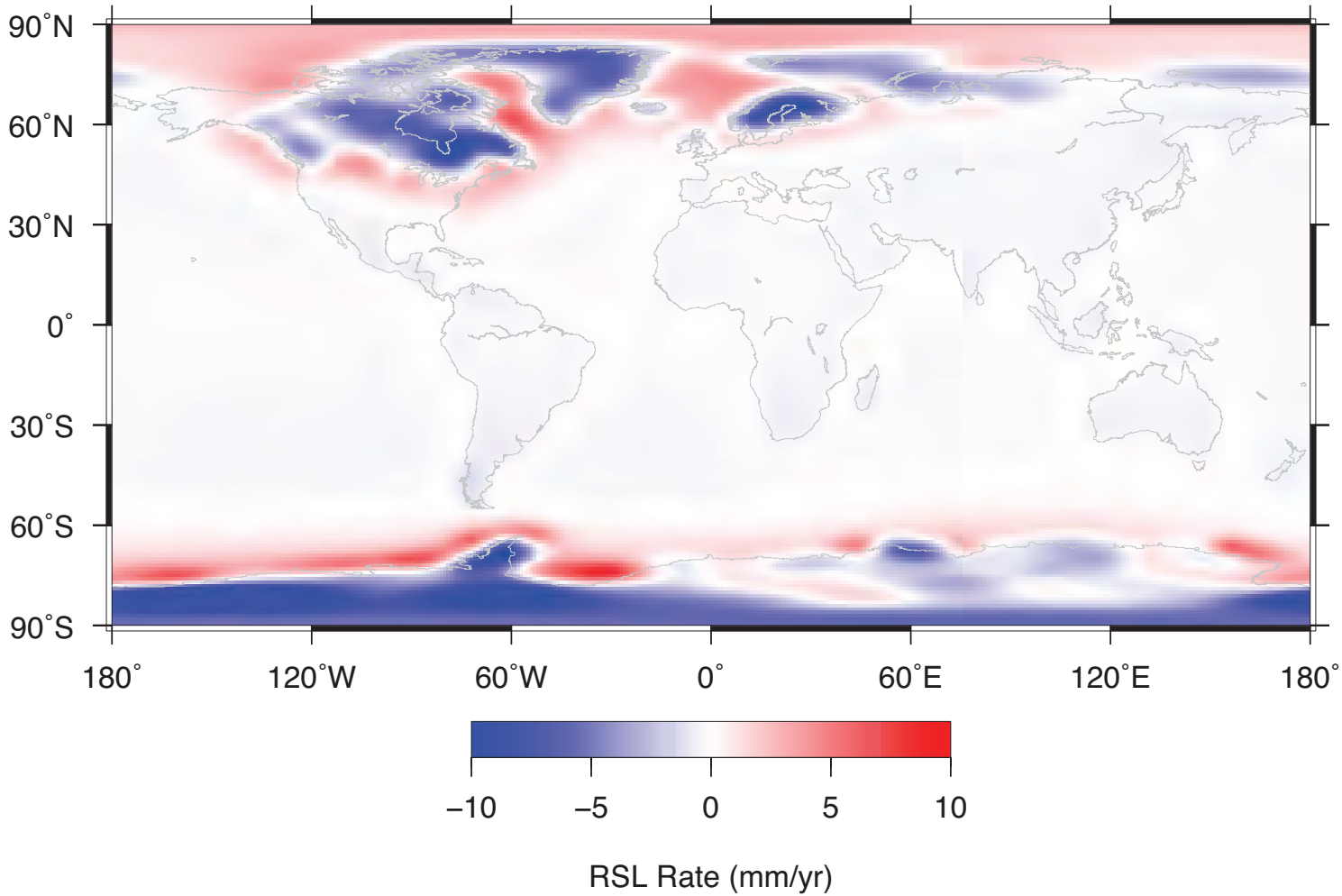
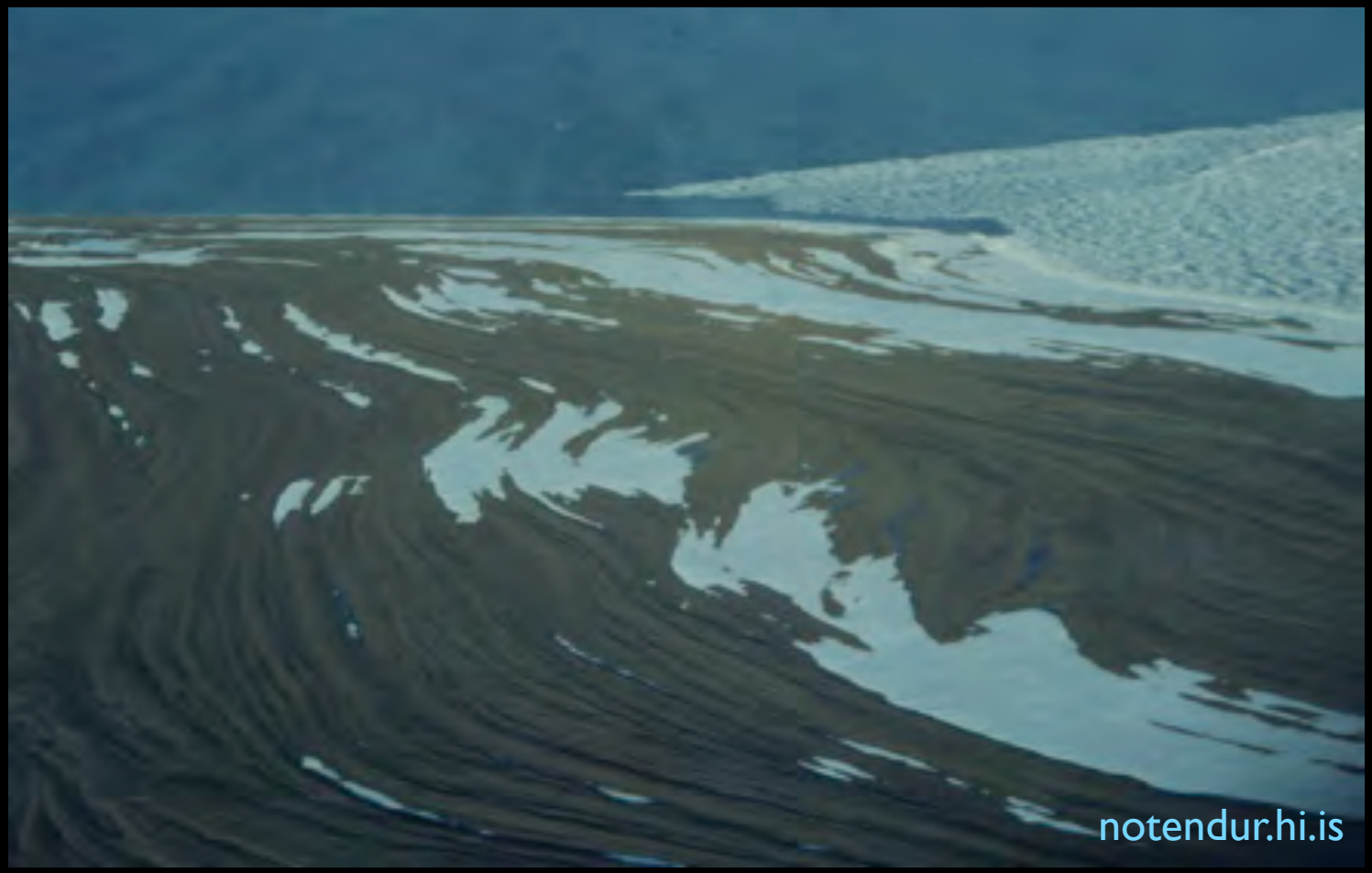


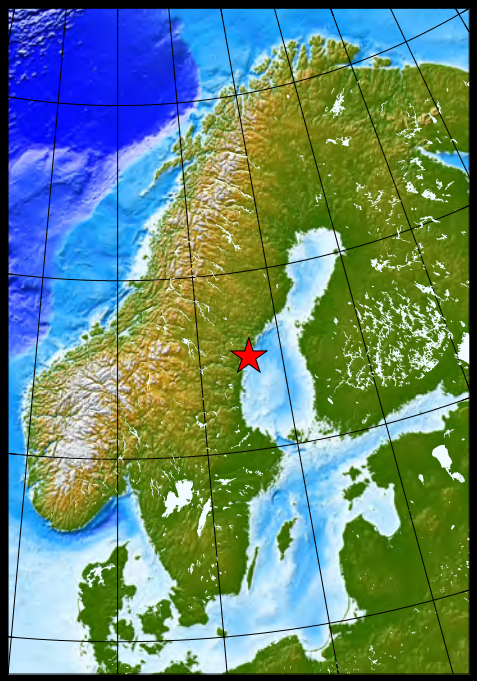
Image created by Robert A. Rohde / Global Warming Art

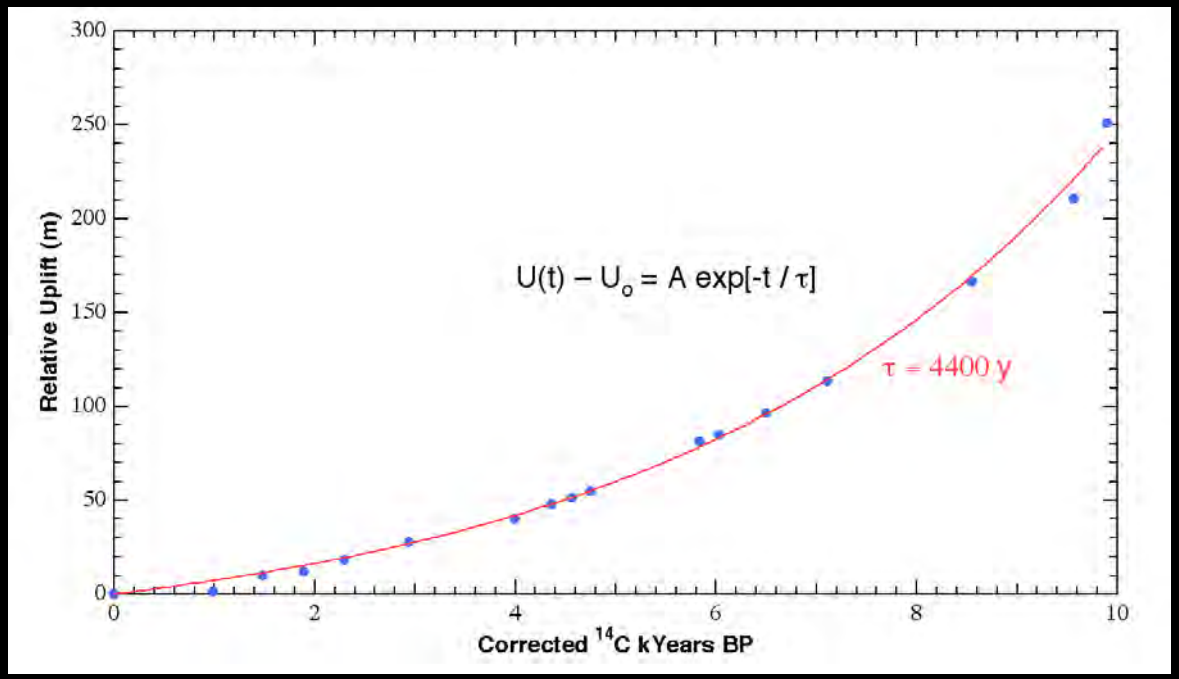


GIA: Present-day RSL

Raised beach terraces from Svalbard Islands







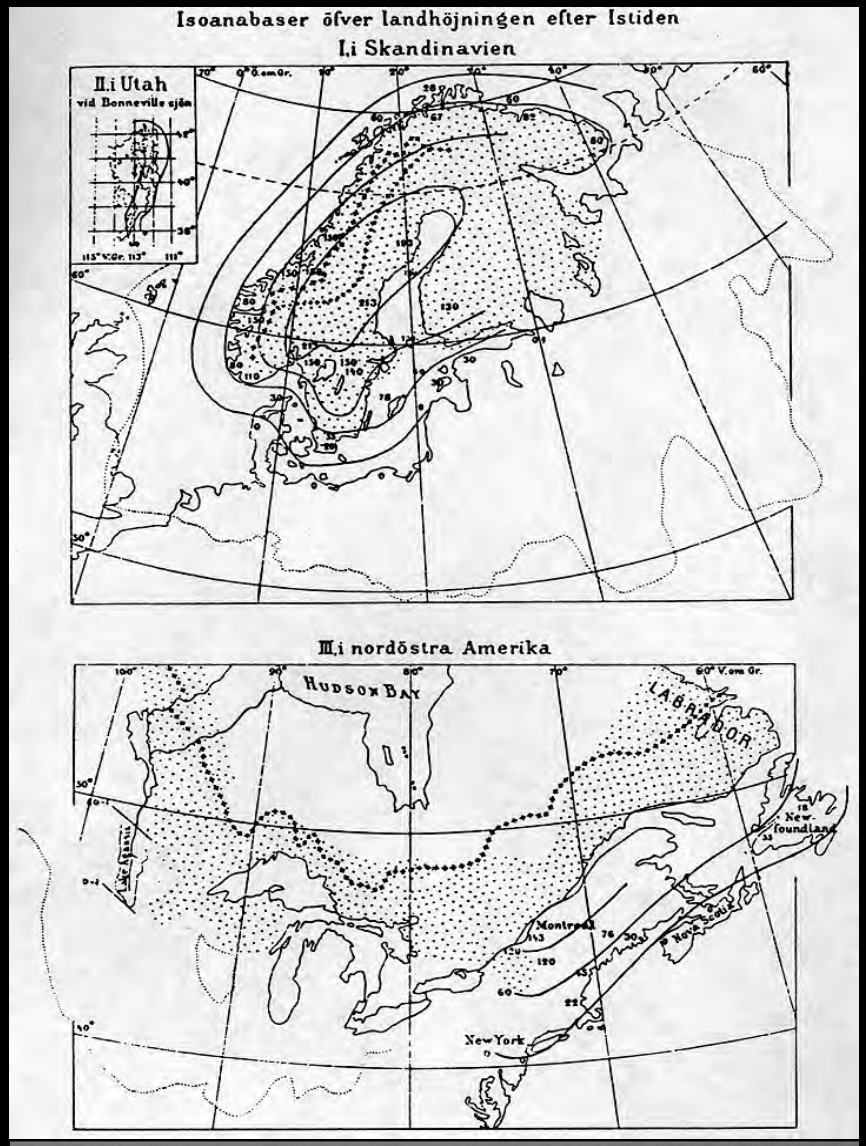
Uplift near Ångermann River

Celsius Rock

Lövgrund, Sweden

Photo: M. Ekman

GIA in Fennoscandia and Laurentia



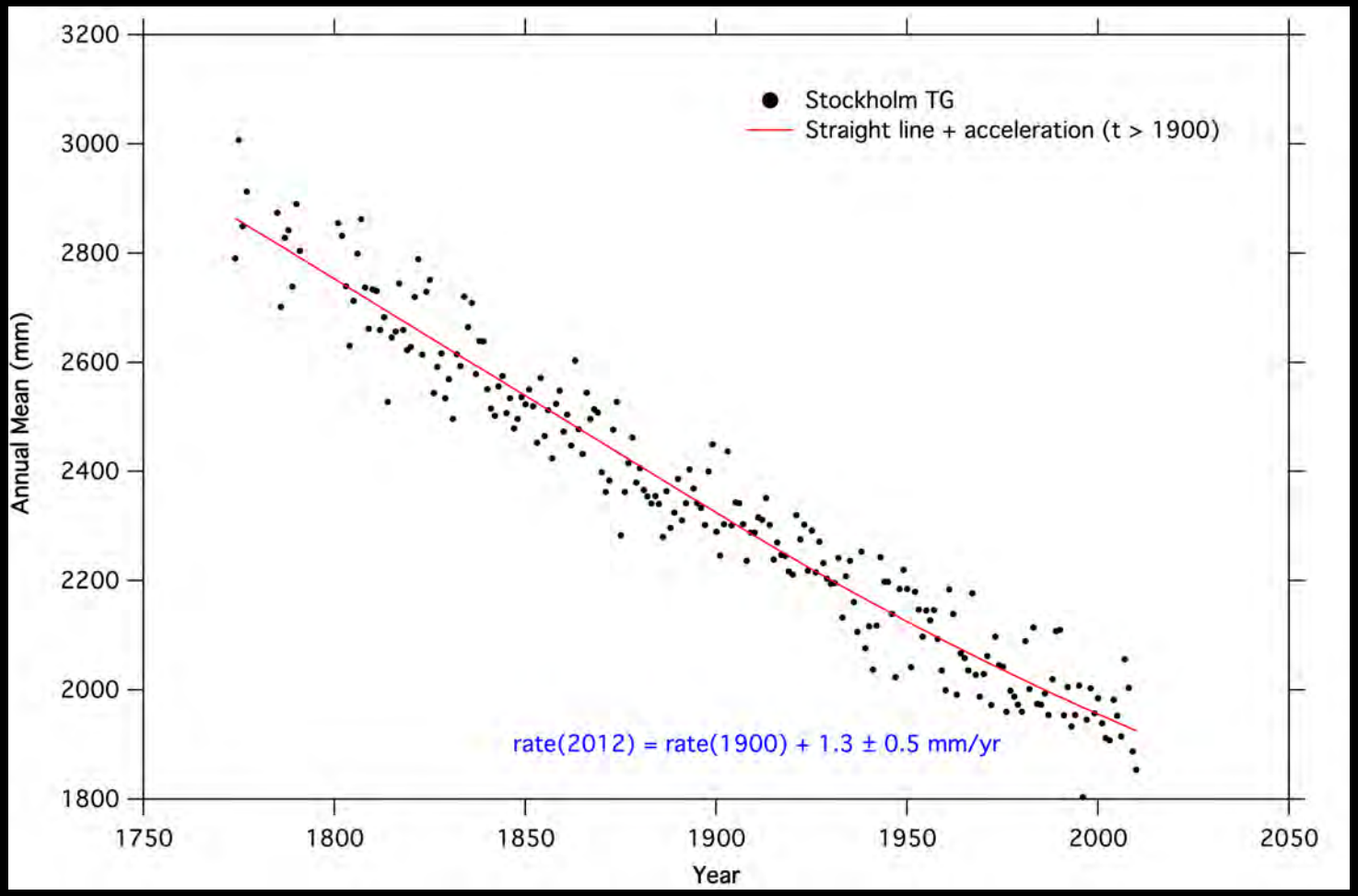
De Geer [1888]


Boathouse, Lövgrund, Sweden
Ekman [2009]

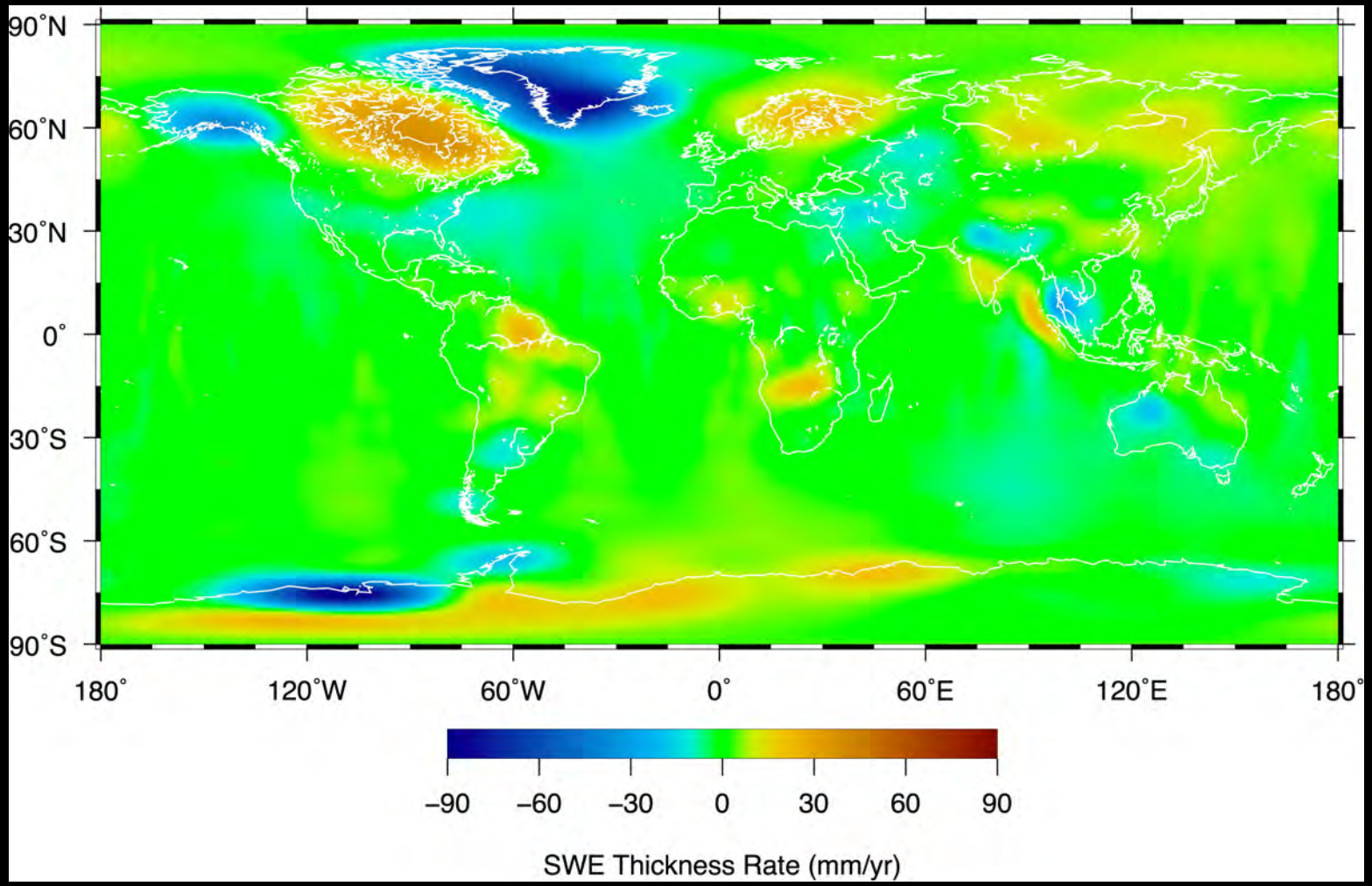
Bomarsund Sea-Level Scale

Åland, Sweden

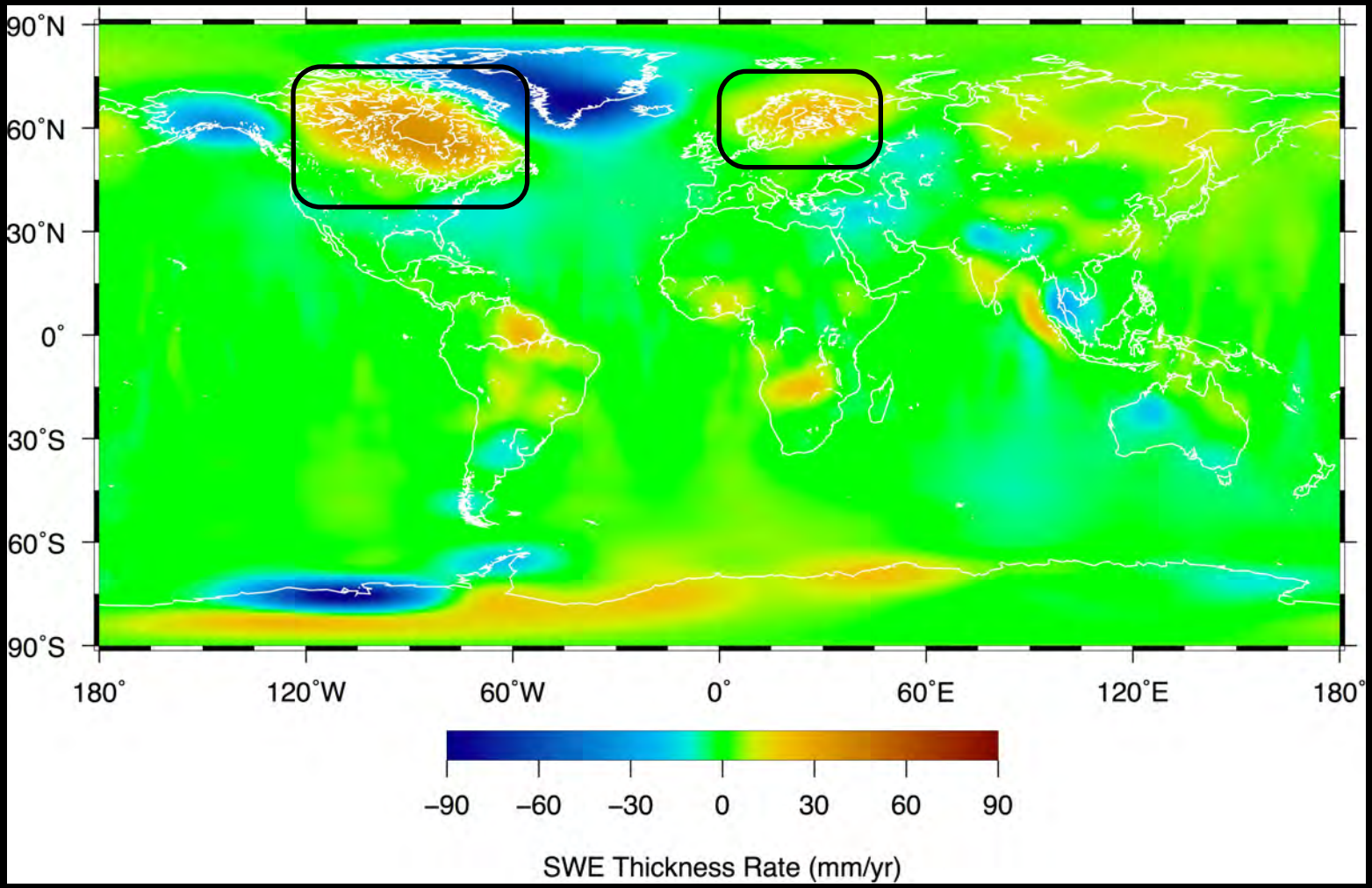
Oldest preserved sea-level gauge



Stockholm tide-gauge record



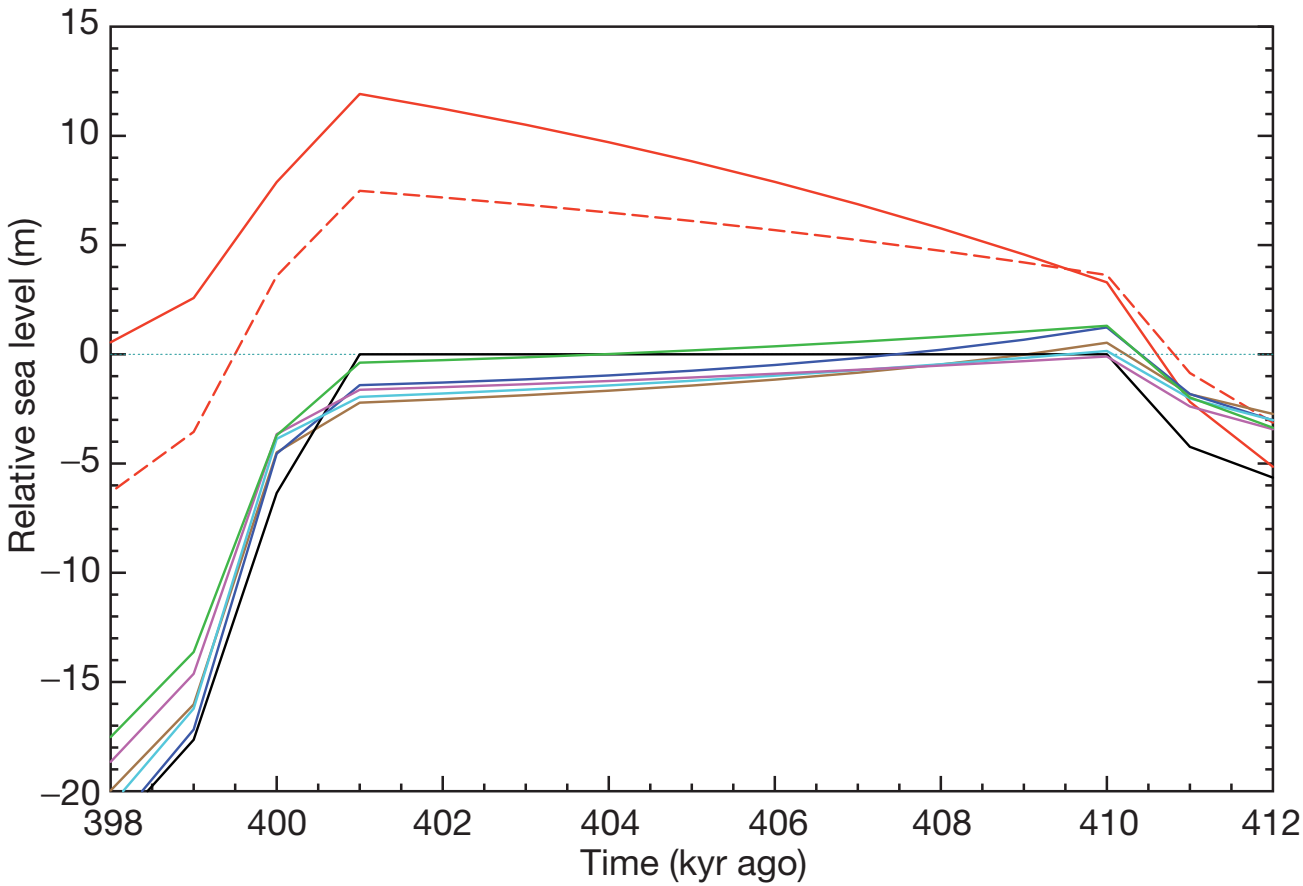
GRACE Gravity Rates



GRACE Gravity Rates

GIA and Sea Level

- Interpretation of long- and short-term sea level record requires accurate GIA models
- This has meant using imperfect models to "correct for" the impact of GIA
- Incorrect interpretation of sea-level record can result from
  - Not accounting for GIA [e.g., *Raymo & Mitrovica*, 2012]
  - Errors in GIA model [e.g., *Davis & Mitrovica*, 2006]
- GIA adds complexity to interpreting sea-level record, leading to…misunderstandings by public



Raymo & Mitrovica [2011]

RSL change during MIS 11

GIA and Sea Level

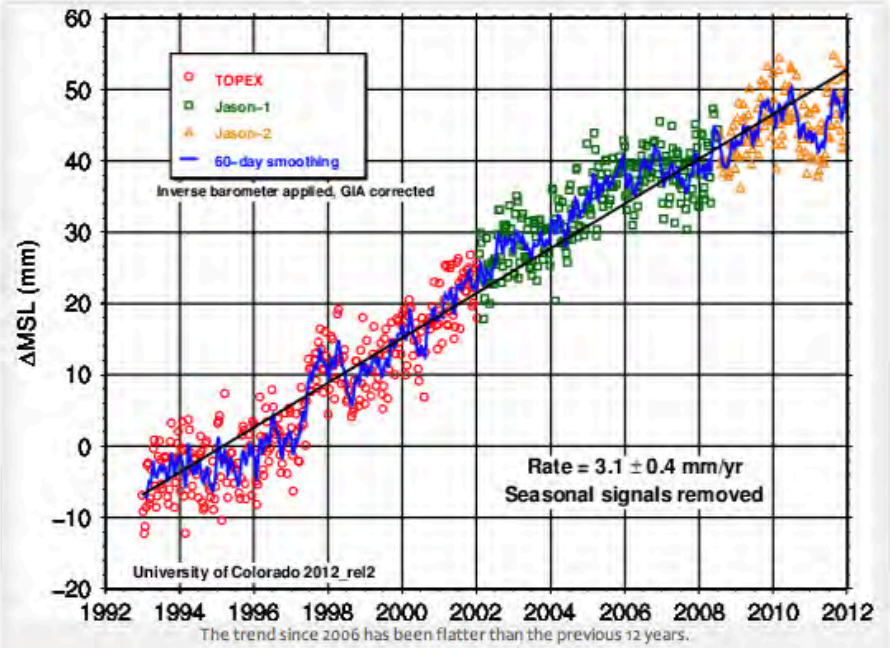
- Interpretation of long- and short-term sea level record requires accurate GIA models
- This has meant using imperfect models to "correct for" the impact of GIA
- Incorrect interpretation of sea-level record can result from
  - Not accounting for GIA [e.g., *Raymo & Mitrovica*, 2012]
  - Errors in GIA model [e.g., *Davis & Mitrovica*, 2006]
- GIA adds complexity to interpreting sea-level record, leading to…misunderstandings by public

10% of sea level rise is due to land rising too. Got that?

Just in case you missed it, there has been yet another example of data manipulation in the endless round of adjustments that bring reality closer to the models. Thanks to James Taylor in *Climate Change Weekly* for drawing our attention to it.

Sea levels are one of the top five most critical measurements to tell us about the planet's "heat". Remember, they say "it's worse than we thought" and that sea level rise is accelerating. Yet the measurements by the best equipment available — satellites — tell of a steady linear rise of just 3mm year after year, except for lately, when it's been lower. (What kind of scientist can't predict where a straight line is headed?)

Sea level is hard to measure — the sea is not flat — the ground also moves, but satellites measure the world's oceans every ten days to an accuracy of several millimeters, and what's more, they measure it compared to the *center of the Earth* (see below). NASA says so. So it is hard to explain why, after delaying the latest (shrinking) results for a couple of months past the usual posting date, they now announce that they've added *"a correction of 0.3 mm/year due to Glacial Isostatic Adjustment (GIA)"*.



The trend since 2006 has been flatter than the previous 12 years.

According to the University of Colorado the GIA is apparently needed to compensate for all the glaciers which have melted — taking the weight of the ice off the continents, and letting that land rise up.

Silly me, I thought the point of worrying about sea level rise was the concern about sea-rising *compared* to the beaches, what's the point of building a levee to keep out the water if the beaches are rising as well?

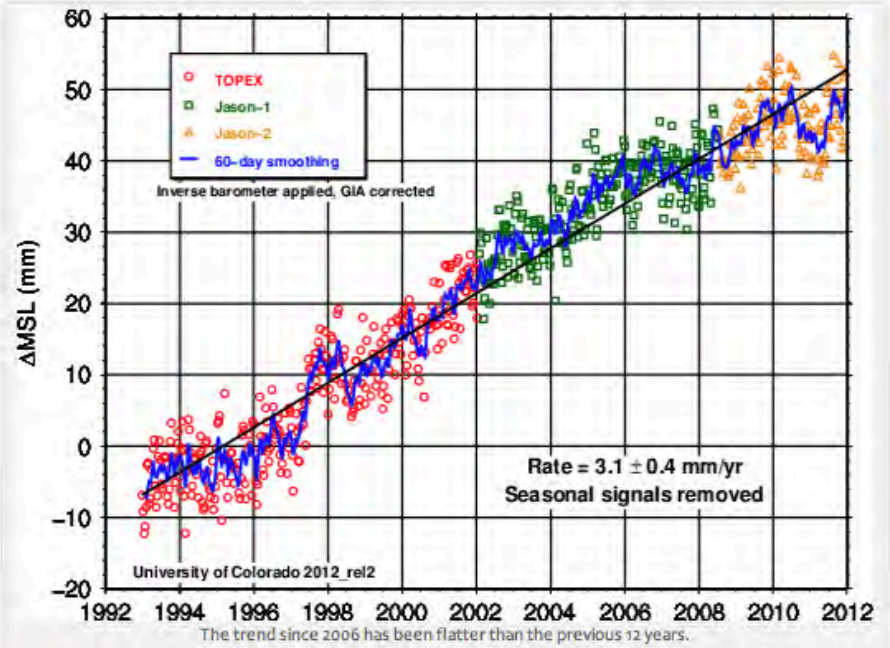
Hidden in the adjustment is the news that (they say) the world's land masses are rising 10% as fast as the oceans. Who knew? The continents are getting 0.3mm higher each year!

10% of sea level rise is due to land rising too. Got that?

Just in case you missed it, there has been yet another example of data manipulation in the endless round of adjustments that bring reality closer to the models. Thanks to James Taylor in *Climate Change Weekly* for drawing our attention to it.

Sea levels are one of the top five most critical measurements to tell us about the planet's "heat". Remember, they say "it's worse than we thought" and that sea level rise is accelerating. Yet the measurements by the best equipment available — satellites — tell of a steady linear rise of just 3mm year after year, except for lately, when it's been lower. (What kind of scientist can't predict where a straight line is headed?)

Sea level is hard to measure — the sea is not flat — the ground also moves, but satellites measure the world's oceans every ten days to an accuracy of several millimeters, and what's more, they measure it compared to the *center of the Earth* (see below). NASA says so. So it is hard to explain why, after delaying the latest (shrinking) results for a couple of months past the usual posting date, they now announce that they've added *"a correction of 0.3 mm/year due to Glacial Isostatic Adjustment (GIA)"*.



The trend since 2006 has been flatter than the previous 12 years.

According to the University of Colorado the GIA is apparently needed to compensate for all the glaciers which have melted — taking the weight of the ice off the continents, and letting that land rise up.

Silly me, I thought the point of worrying about sea level rise was the concern about sea-rising *compared* to the beaches, what's the point of building a levee to keep out the water if the beaches are rising as well?

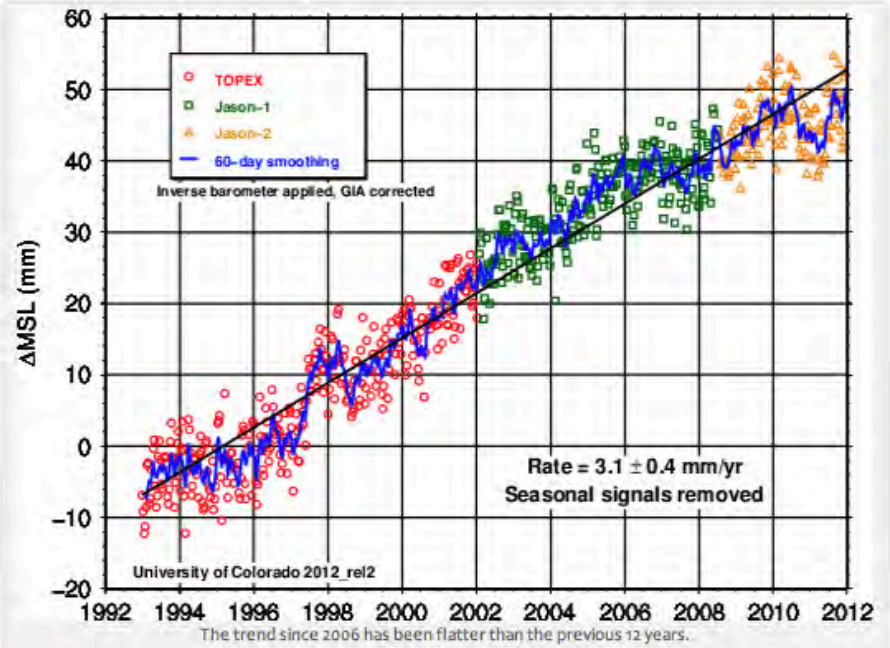
Hidden in the adjustment is the news that (they say) the world's land masses are rising 10% as fast as the oceans. Who knew? The continents are getting 0.3mm higher each year!

10% of sea level rise is due to land rising too. Got that?

Just in case you missed it, there has been yet another example of data manipulation in the endless round of adjustments that bring reality closer to the models. Thanks to James Taylor in *Climate Change Weekly* for drawing our attention to it.

Sea levels are one of the top five most critical measurements to tell us about the planet's "heat". Remember, they say "it's worse than we thought" and that sea level rise is accelerating. Yet the measurements by the best equipment available — satellites — tell of a steady linear rise of just 3mm year after year, except for lately, when it's been lower. (What kind of scientist can't predict where a straight line is headed?)

Sea level is hard to measure — the sea is not flat — the ground also moves, but satellites measure the world's oceans every ten days to an accuracy of several millimeters, and what's more, they measure it compared to the *center of the Earth* (see below). NASA says so. So it is hard to explain why, after delaying the latest (shrinking) results for a couple of months past the usual posting date, they now announce that they've added *"a correction of 0.3 mm/year due to Glacial Isostatic Adjustment (GIA)"*.



The trend since 2006 has been flatter than the previous 12 years.

According to the University of Colorado the GIA is apparently needed to compensate for all the glaciers which have melted — taking the weight of the ice off the continents, and letting that land rise up.

Silly me, I thought the point of worrying about sea level rise was the concern about sea-rising *compared* to the beaches, what's the point of building a levee to keep out the water if the beaches are rising as well?

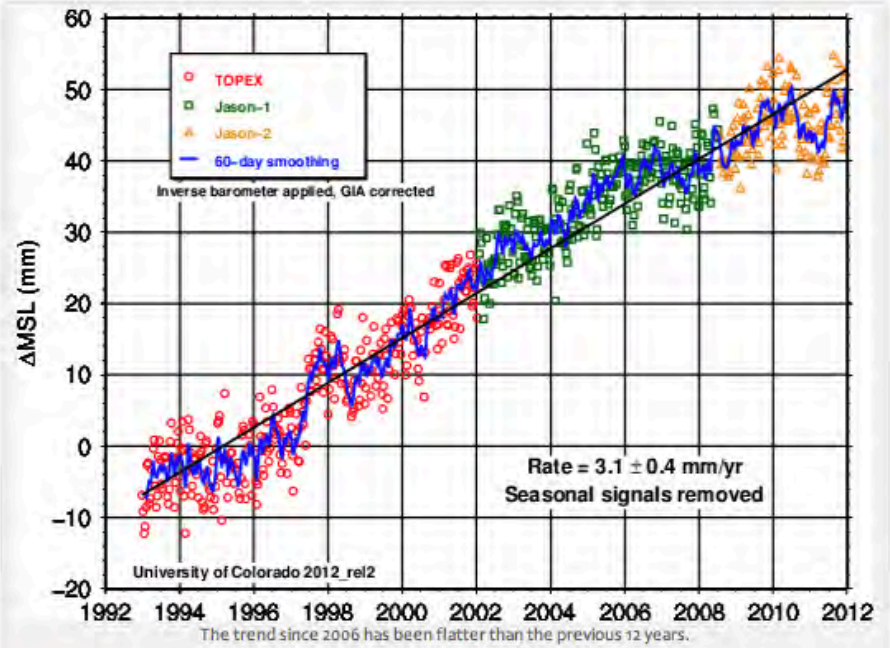
Hidden in the adjustment is the news that (they say) the world's land masses are rising 10% as fast as the oceans. Who knew? The continents are getting 0.3mm higher each year!

10% of sea level rise is due to land rising too. Got that?

Just in case you missed it, there has been yet another example of data manipulation in the endless round of adjustments that bring reality closer to the models. Thanks to James Taylor in *Climate Change Weekly* for drawing our attention to it.

Sea levels are one of the top five most critical measurements to tell us about the planet's "heat". Remember, they say "it's worse than we thought" and that sea level rise is accelerating. Yet the measurements by the best equipment available — satellites — tell of a steady linear rise of just 3mm year after year, except for lately, when it's been lower. (What kind of scientist can't predict where a straight line is headed?)

Sea level is hard to measure — the sea is not flat — the ground also moves, but satellites measure the world's oceans every ten days to an accuracy of several millimeters, and what's more, they measure it compared to the *center of the Earth* (see below). NASA says so. So it is hard to explain why, after delaying the latest (shrinking) results for a couple of months past the usual posting date, they now announce that they've added *"a correction of 0.3 mm/year due to Glacial Isostatic Adjustment (GIA)"*.



The trend since 2006 has been flatter than the previous 12 years.

According to the University of Colorado the GIA is apparently needed to compensate for all the glaciers which have melted — taking the weight of the ice off the continents, and letting that land rise up.

Silly me, I thought the point of worrying about sea level rise was the concern about sea-rising *compared* to the beaches, what's the point of building a levee to keep out the water if the beaches are rising as well?

Hidden in the adjustment is the news that (they say) the world's land masses are rising 10% as fast as the oceans. Who knew? The continents are getting 0.3mm higher each year!

Sea-level change in response to present-day climate forcing

Sea-level change in response to present-day climate forcing

- Observational goal: Make accurate, high resolution measurements of temporal and spatial changes to ice, ocean, land, and gravity

Sea-level change in response to present-day climate forcing

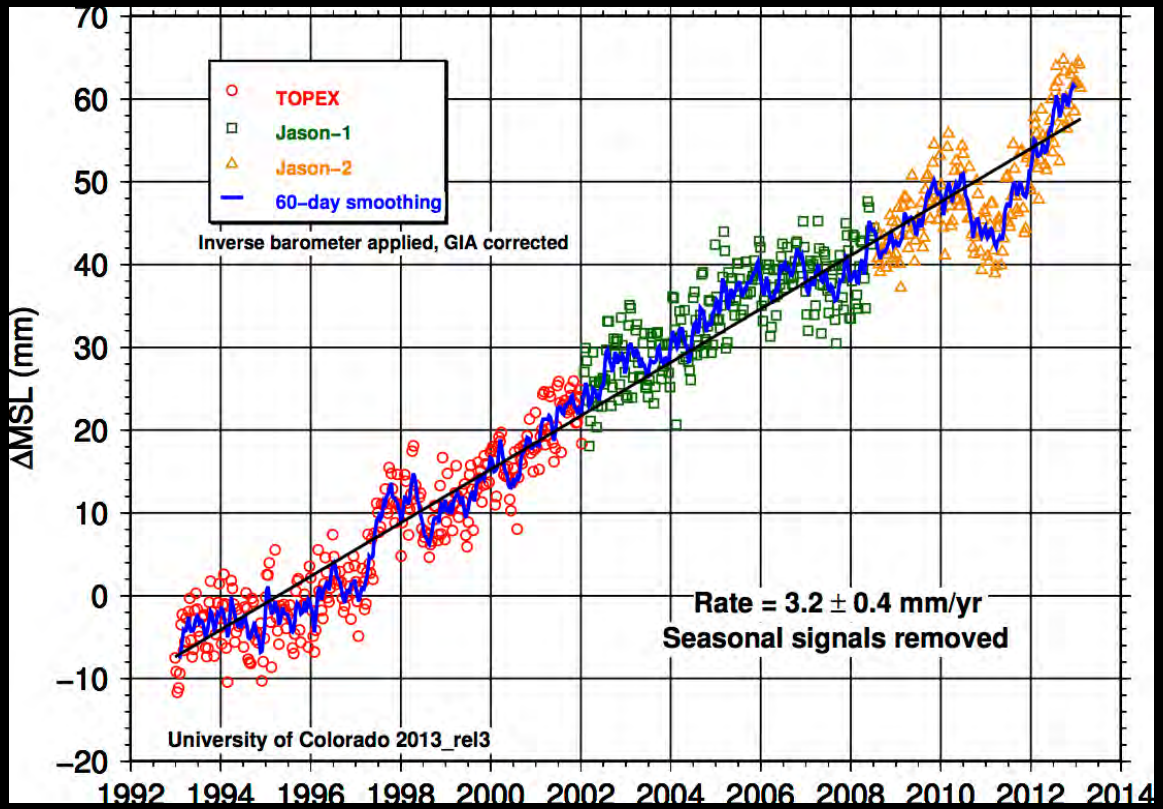
- Observational goal: Make accurate, high resolution measurements of temporal and spatial changes to ice, ocean, land, and gravity
- Science goal: Understand changing mass redistribution (including SL change) and ocean response to climate forcing

Sea-level change in response to present-day climate forcing

- Observational goal: Make accurate, high resolution measurements of temporal and spatial changes to ice, ocean, land, and gravity
- Science goal: Understand changing mass redistribution (including SL change) and ocean response to climate forcing
- Societal need: Make predictions, assess risks, plan (local) mitigation of impacts of SL change

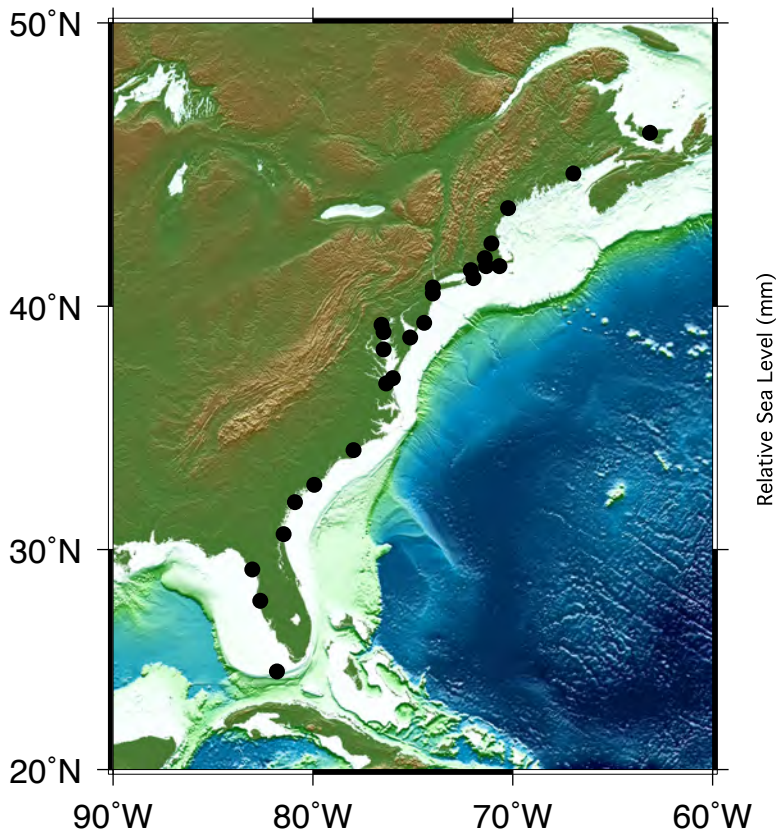
Sea-surface altimetry

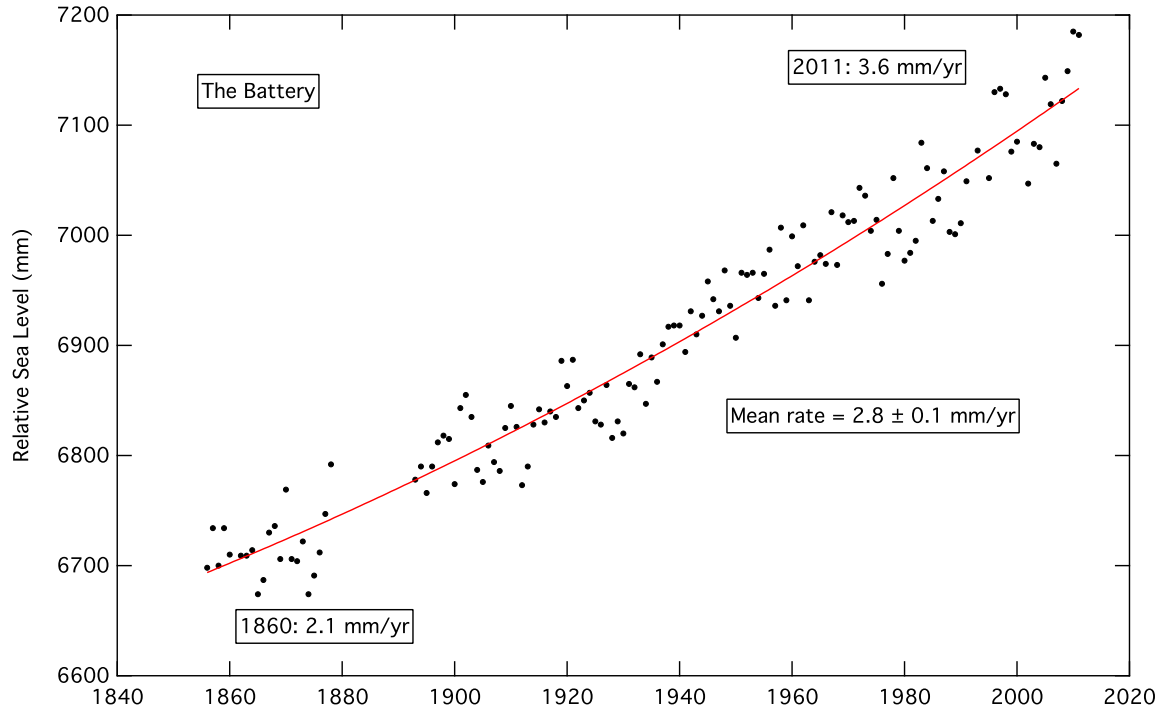
High spatial and temporal resolution of sea-surface height, requires spatial integration for accuracy



sealevel.colorado.edu

Tide-gauge data

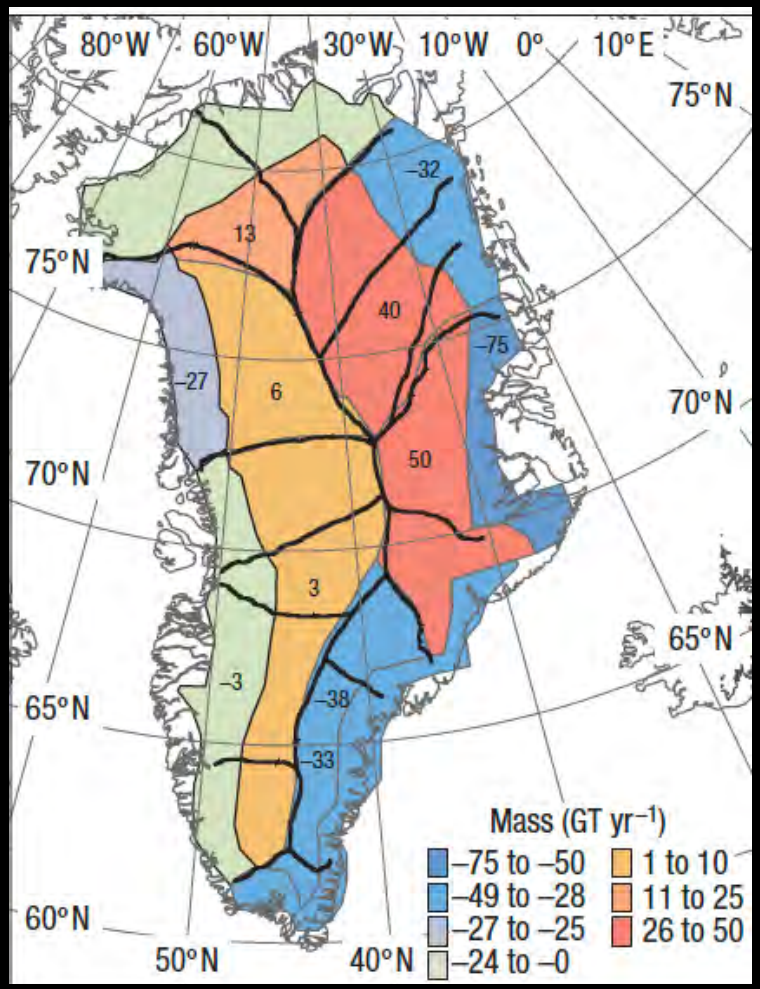




Long record of RSL at TG location

GRACE Gravity

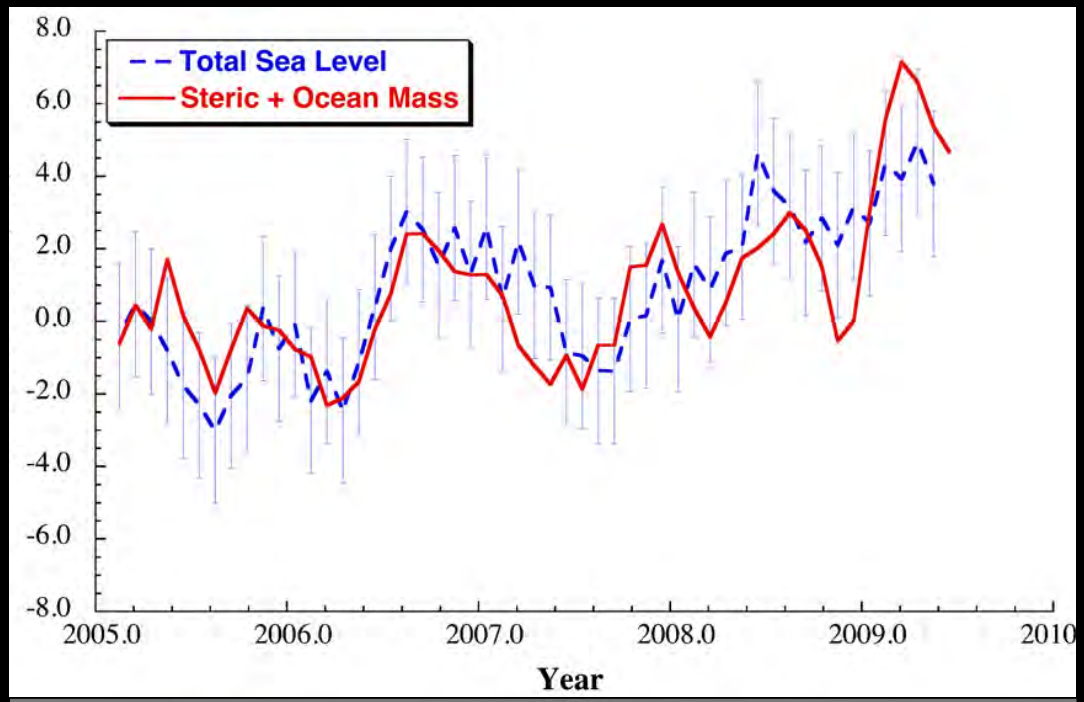
Monthly measurement of ice mass variability (+ GIA) with low spatial resolution



Luthcke et al. [2006]; *Bell et al.* [2008]

GRACE Gravity

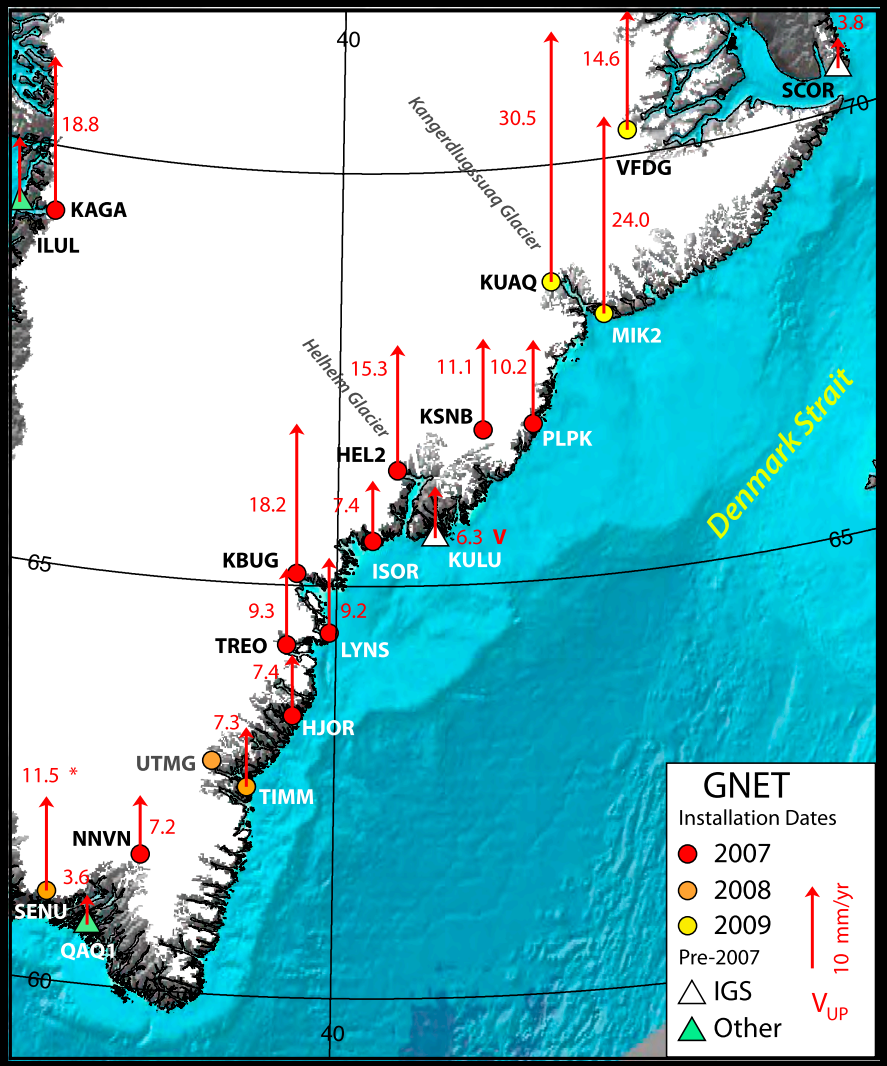
Total ocean mass



Chambers and Schröter [2011]

GNSS Surveying

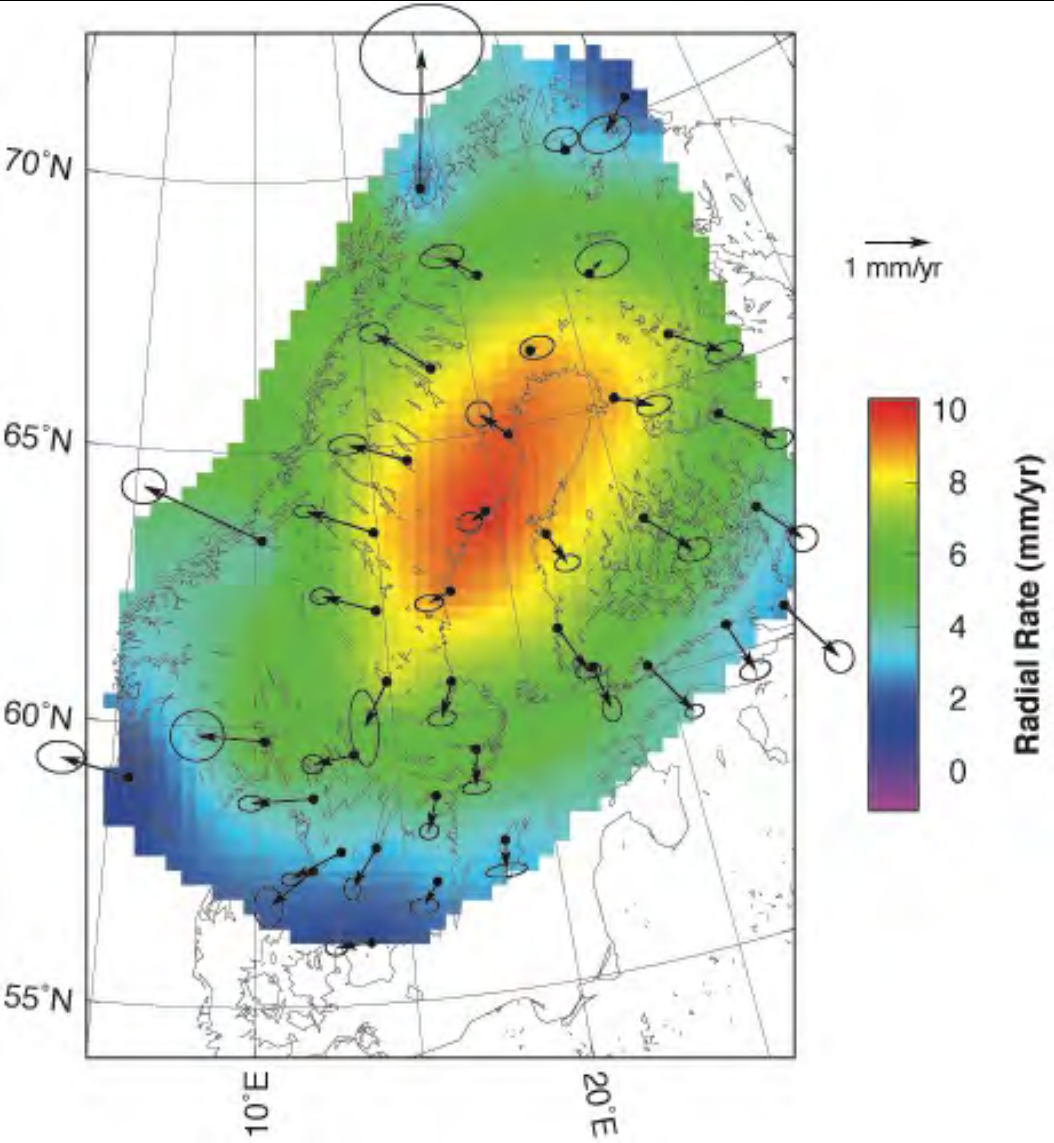
3-D crustal deformation due to load changes



Bevis et al. [2012]

GNSS Surveying

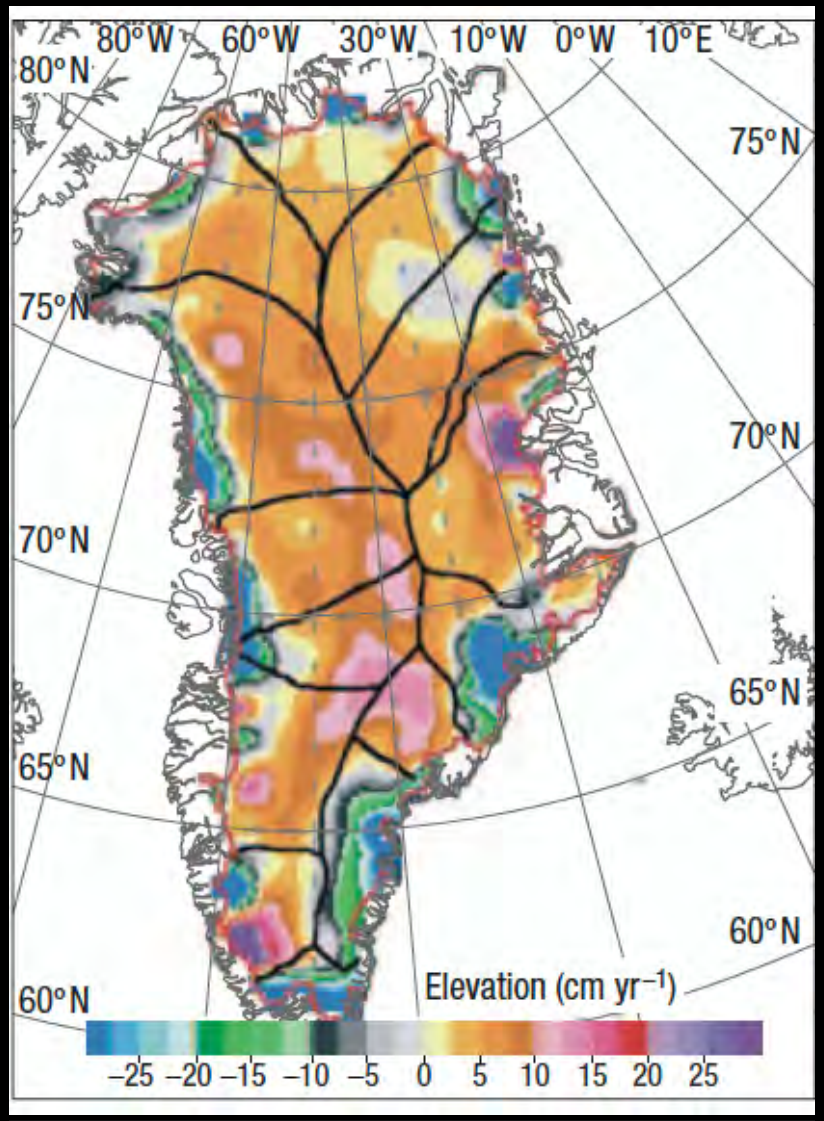
3-D crustal deformation due to GIA



From *Lidberg et al.* [2007]

Radar and laser altimetry

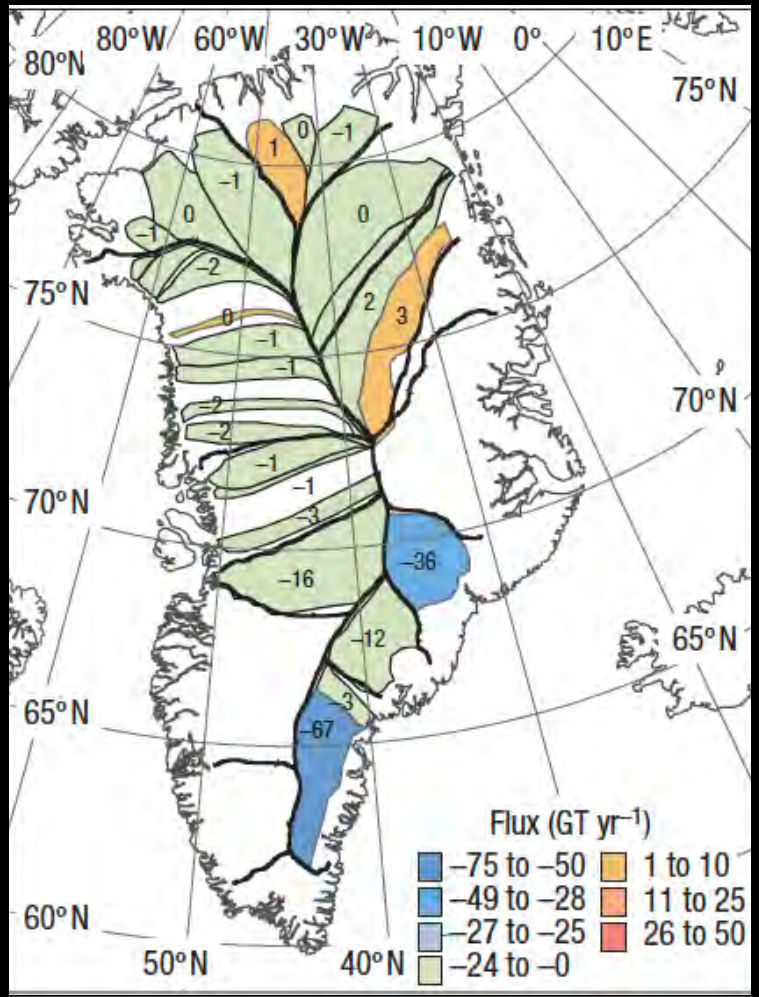
Measures changes in height of ice sheets



Zwally et al. [2005]; *Bell et al.* [2008]

InSAR

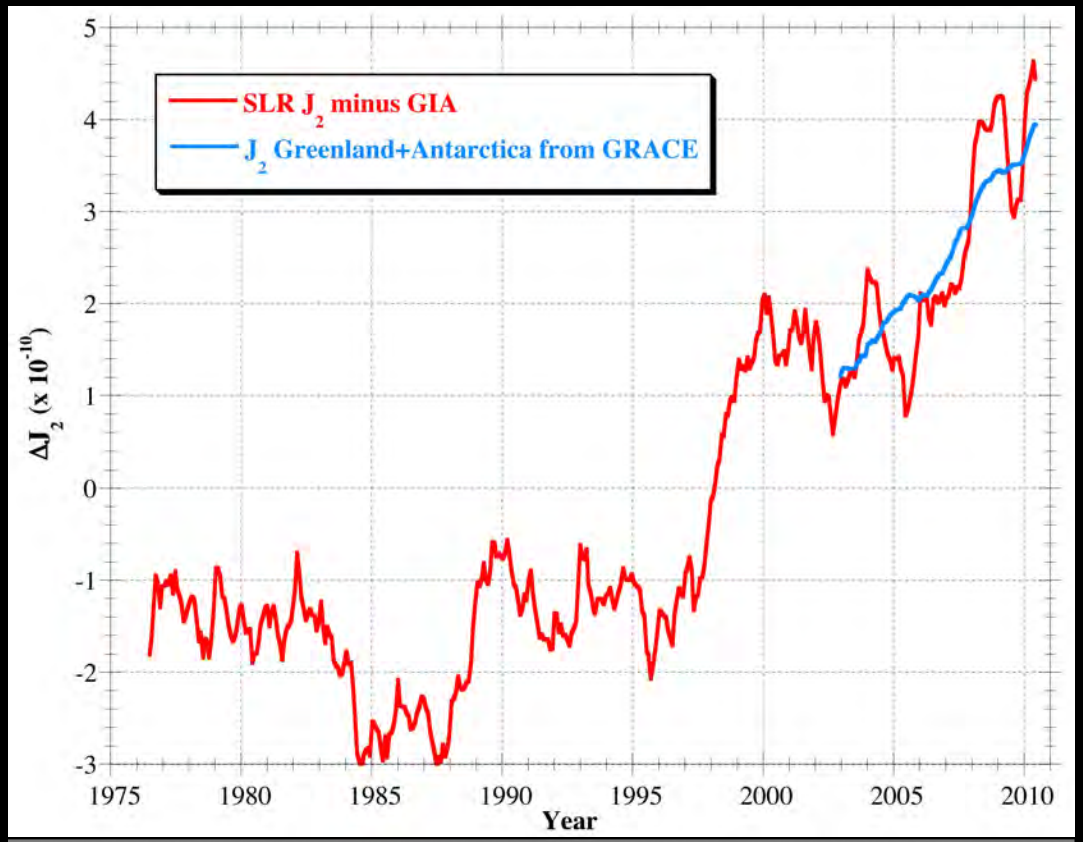
Flux of glacier mass flow



Rignot and Thomas [2002]; *Bell et al.* [2008]

Satellite laser ranging

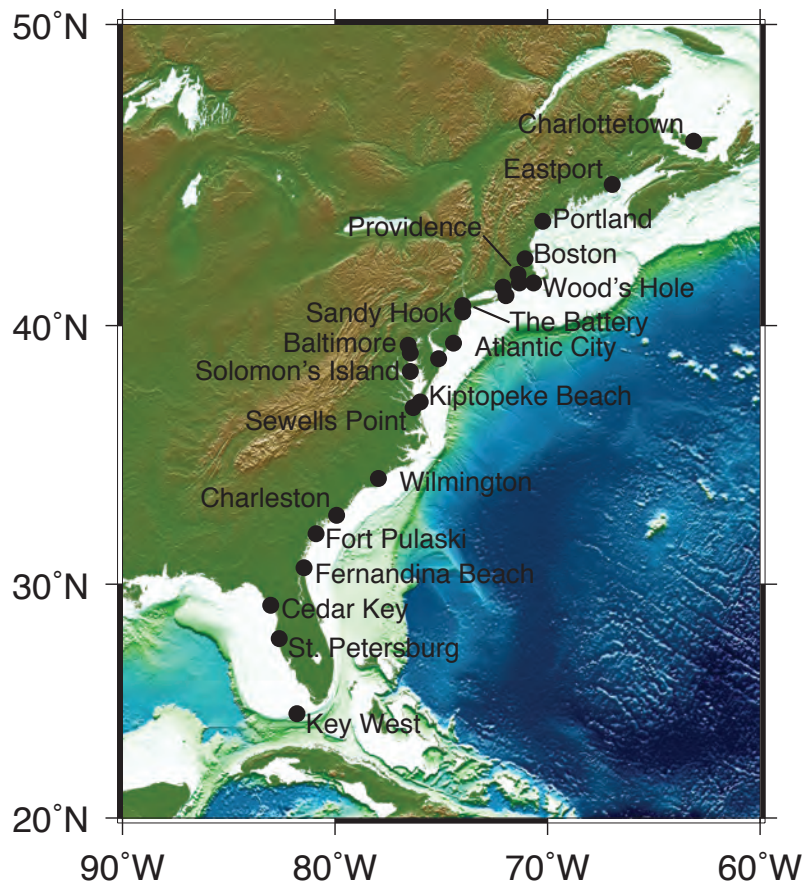
Stable satellite orbits yield changes in Earth's shape



Nerem and Wahr [2011]

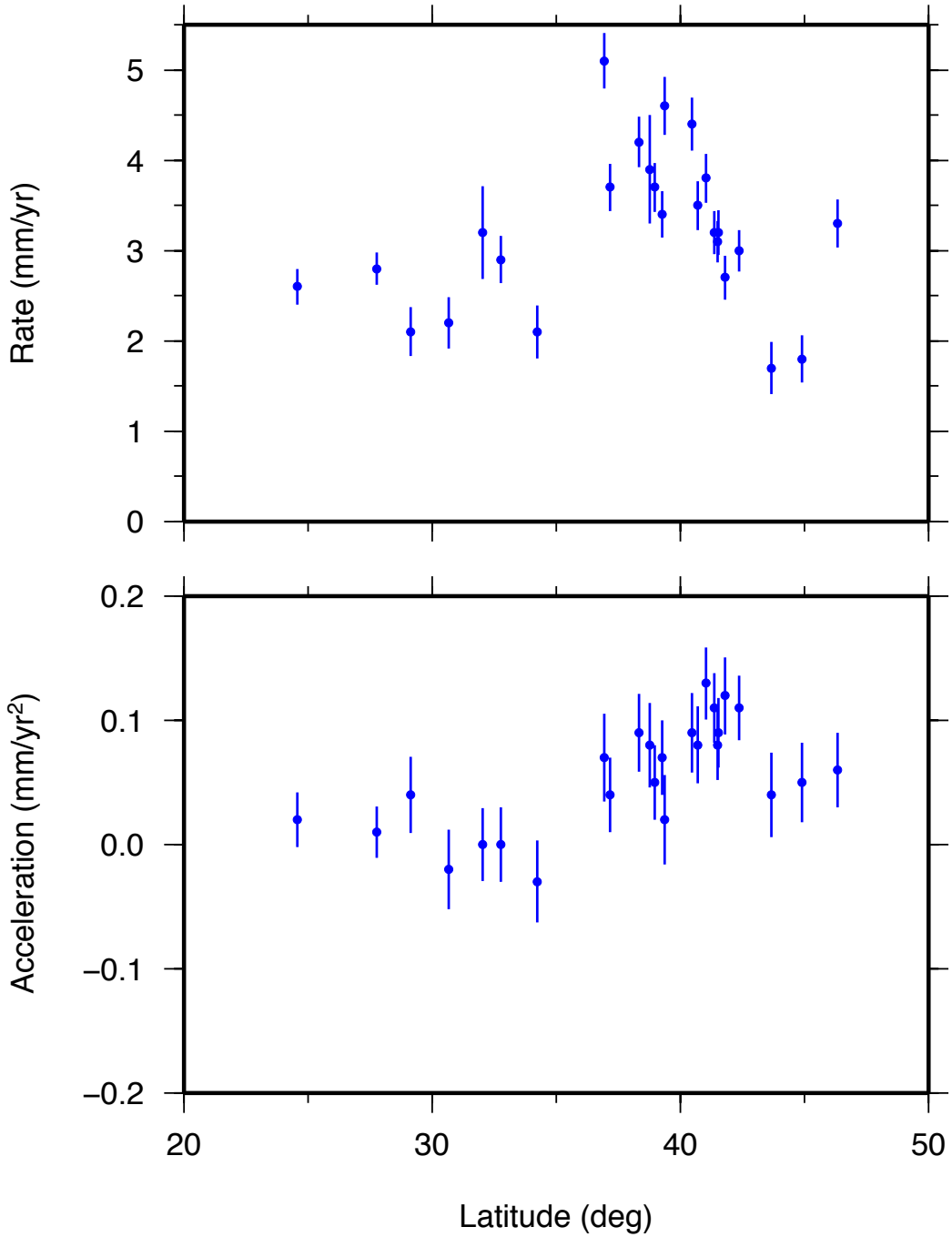
Example: Modeling Present-Day Sea-Level Change on the East Coast of North America

- TG rates on ECNA have great spatial variability
- GIA plays large role
- Within fingerprint of Greenland ice-mass loss
- At right: TGs used in study (continuous record since 1955, avoid rivers)
- Estimate rates and accelerations



Estimated rates and accelerations from TG record of ECNA

TG data from PSMSL.org

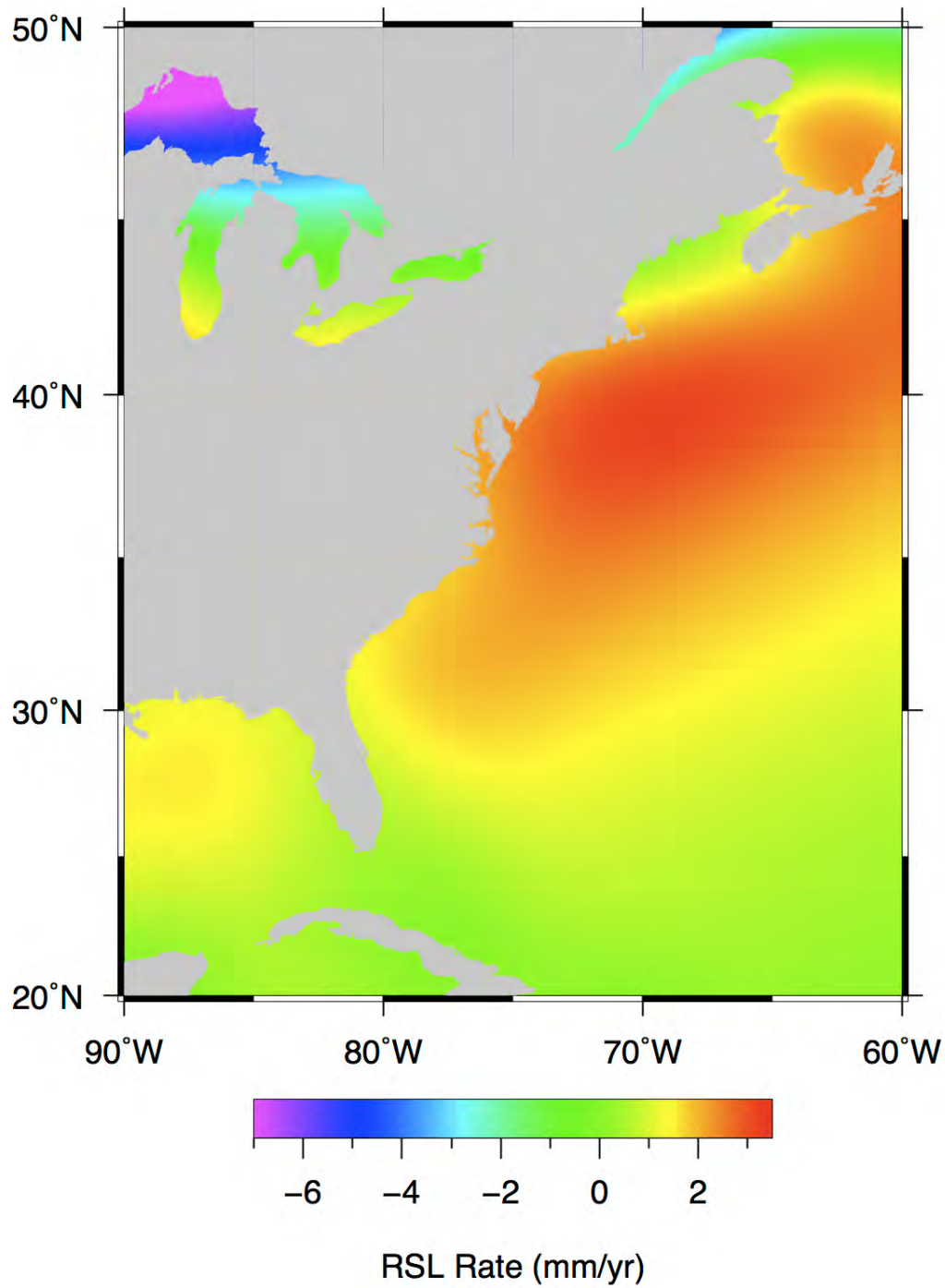


Modeled Contributions to SL change:

- Solution to SLE for mass loss from Greenland Ice Sheet (model abstracted from various publications)
- Contributions from all other ice sheets and glaciers (approximated as constant value, from various publications)
- Steric change from World Ocean Atlas (NOAA)
- GIA using Earth model from *Davis and Mitrovica* [1996] and ICE-5G [*Peltier*, 2004], calculations by Jerry Mitrovica

GIA

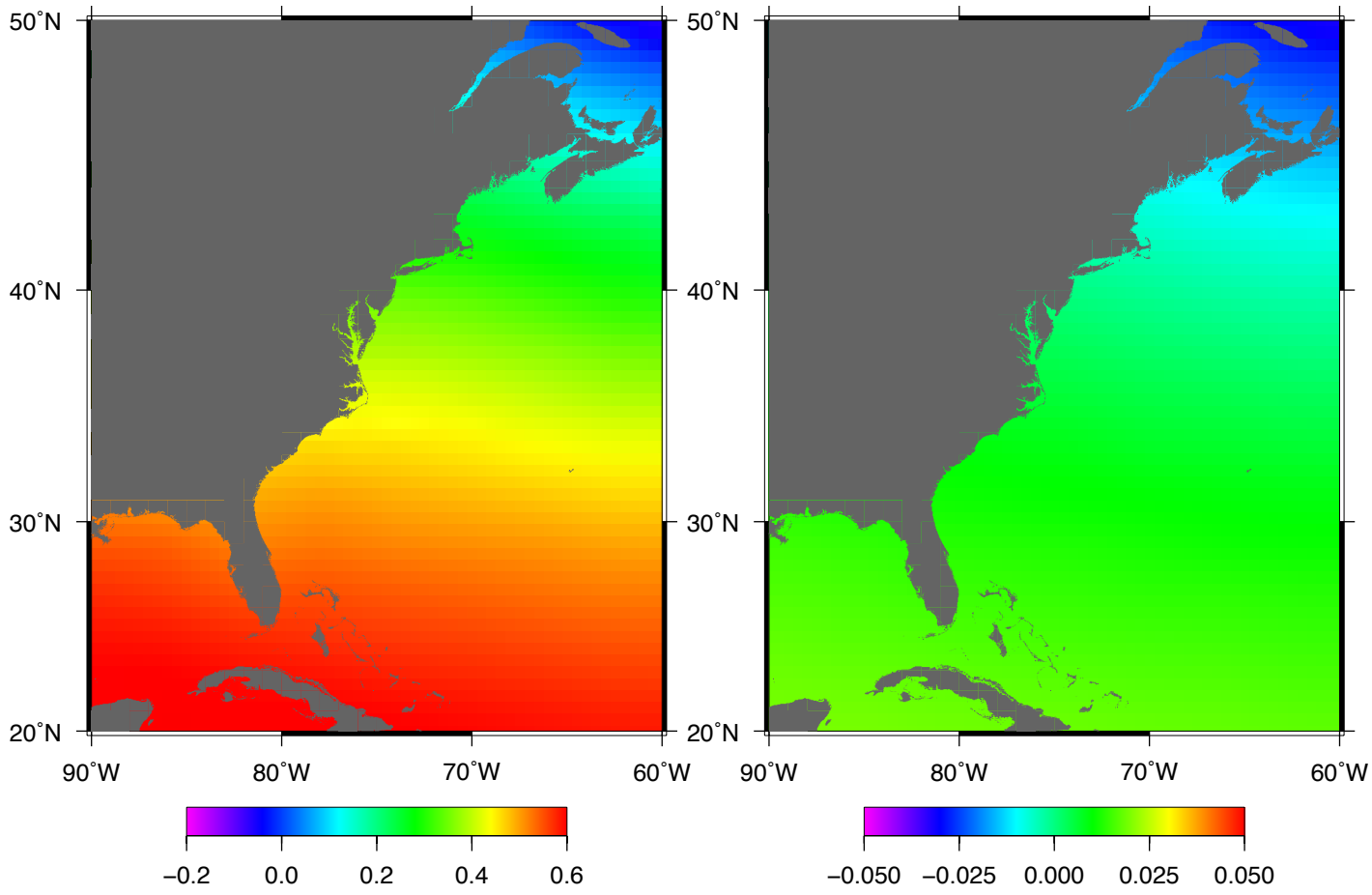
Rate only



GIS Contribution

Left: Rate (mm/yr)

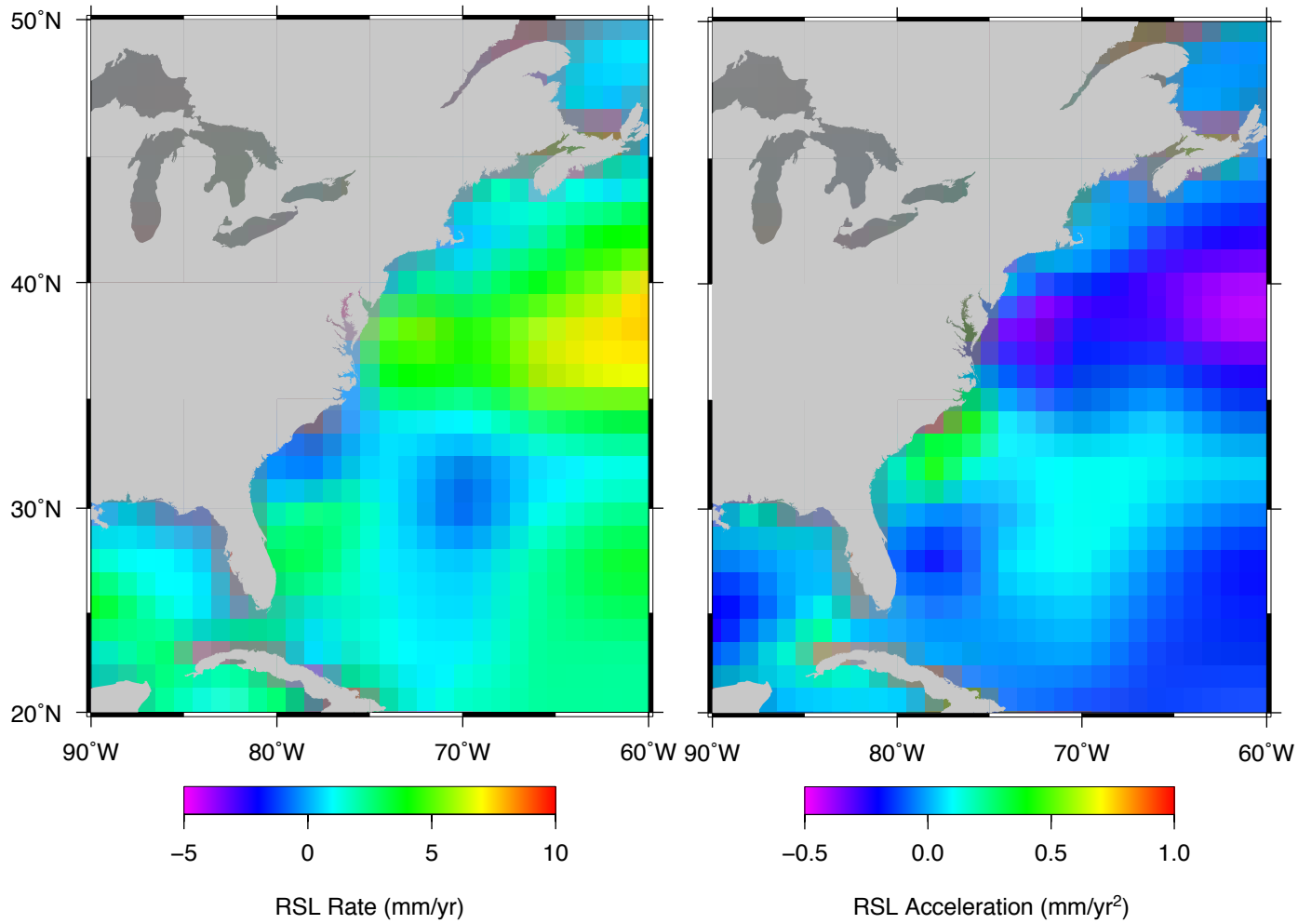
Right: Acceleration (mm/yr^2)

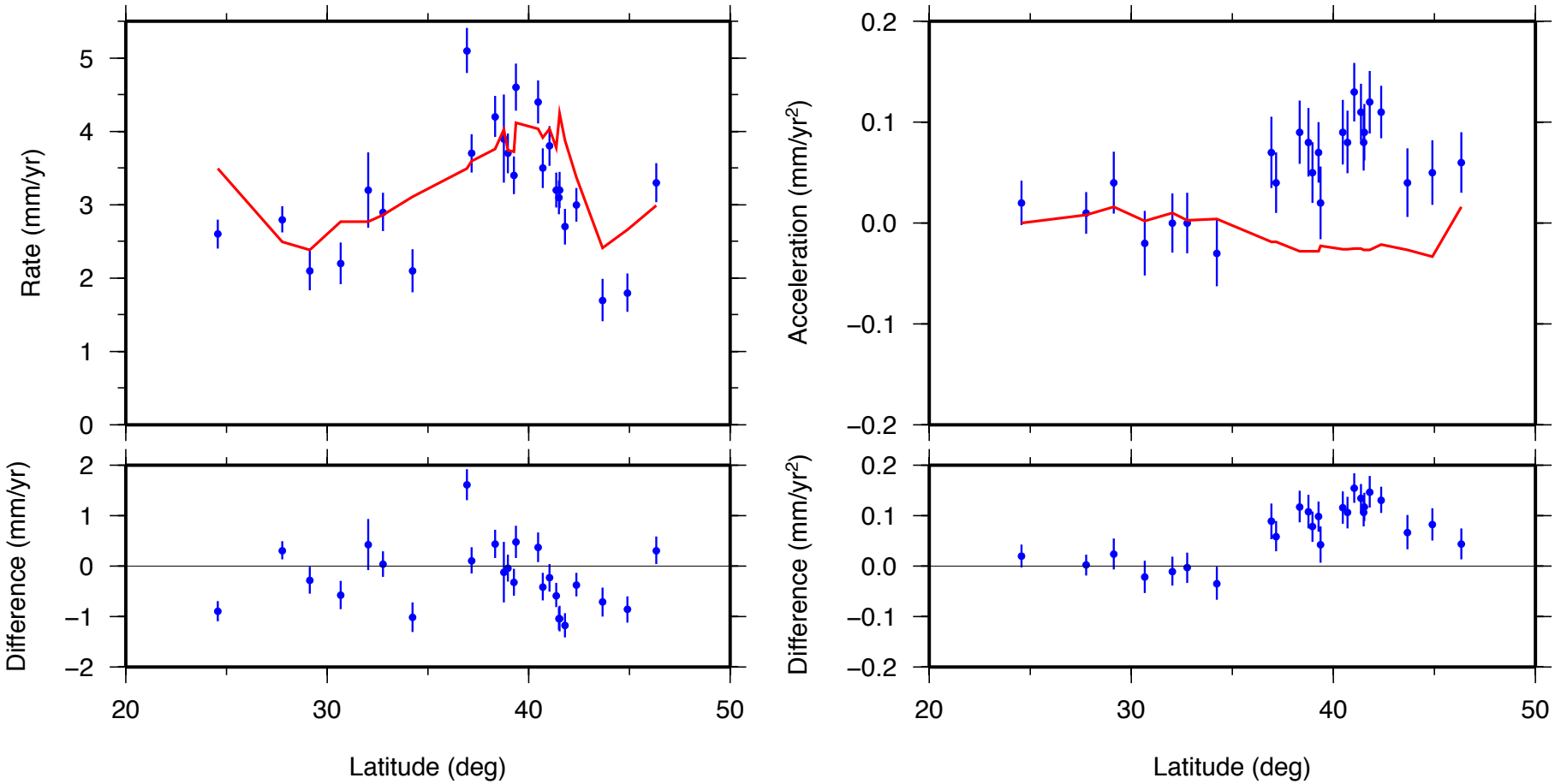


Steric Contribution

Left: Rate

Right: Acceleration

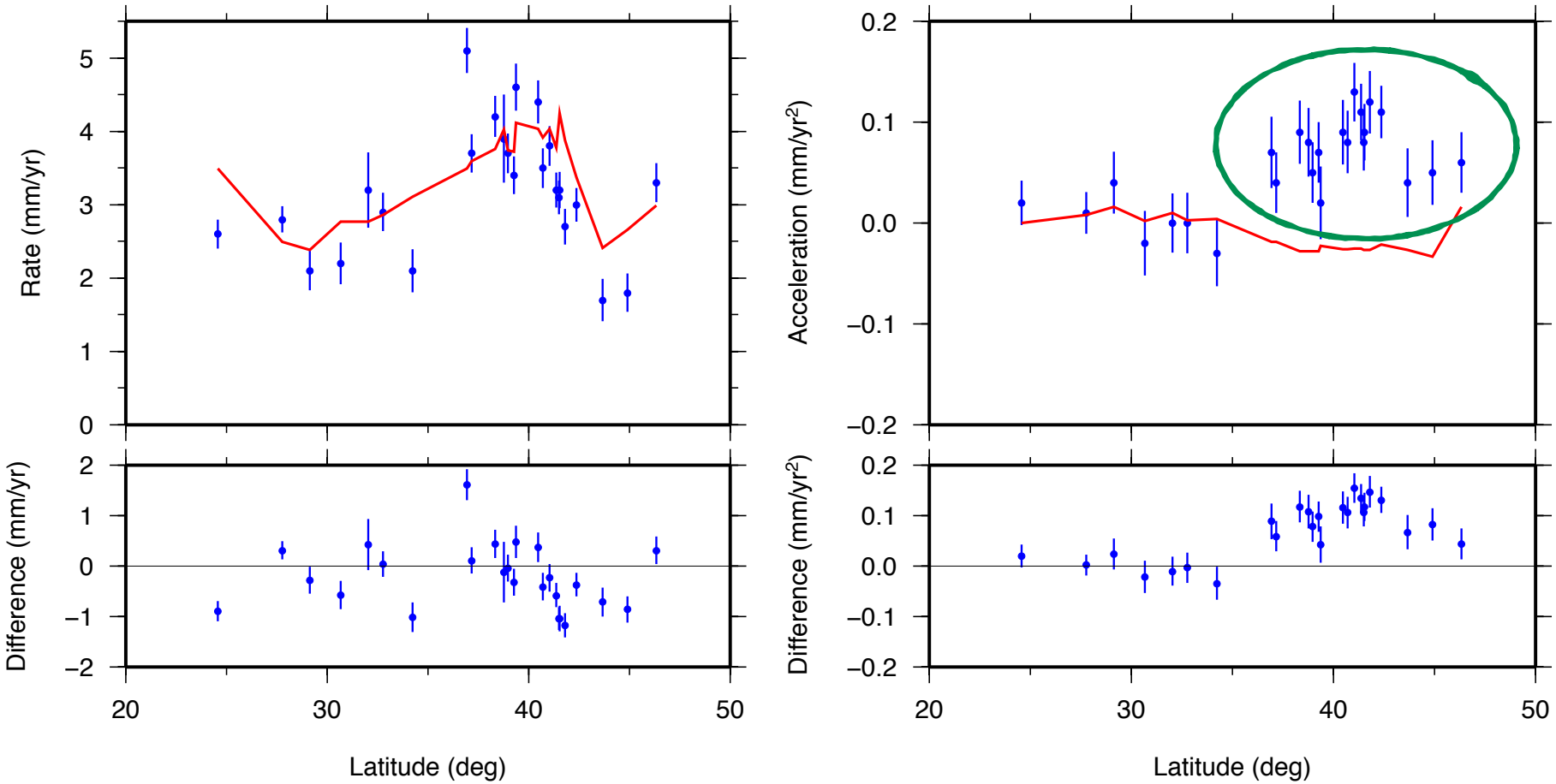




Red lines: Model

RMS rate residual = 0.7 mm/yr

RMS Acceleration residual = 0.09 mm/yr^2



Red lines: Model

RMS rate residual = 0.7 mm/yr

RMS Acceleration residual = 0.09 mm/yr^2

Northeast Hotspot

- Hotspot of accelerated sea-level observed in TG record by *Sallenger et al.* [2012] and others
- Assumed to be associated with ocean dynamics, including steric effects
- We have shown not associated with steric or GIS
- *Piecuch and Ponte* (in press) show that ~25% due to inverted barometer

Final thoughts

- To model/predict SL change at one location, solid Earth response is crucial
- Modeling past rates is different than predicting future rates in era of climate change
- Best way of determining what is happing globally with SL may be to monitor what's happening on land
  - Ice mass plus SLE is accurate, not impacted by ocean dynamics IF we have accurate mass estimates
  - Ocean dynamic models not accurate enough on interannual time scale to model TG variability?
- TG still best way to measure RSL at point, but interpretation on short term (< 20–40 yrs) is difficult