SORTING OUT SEA LEVEL

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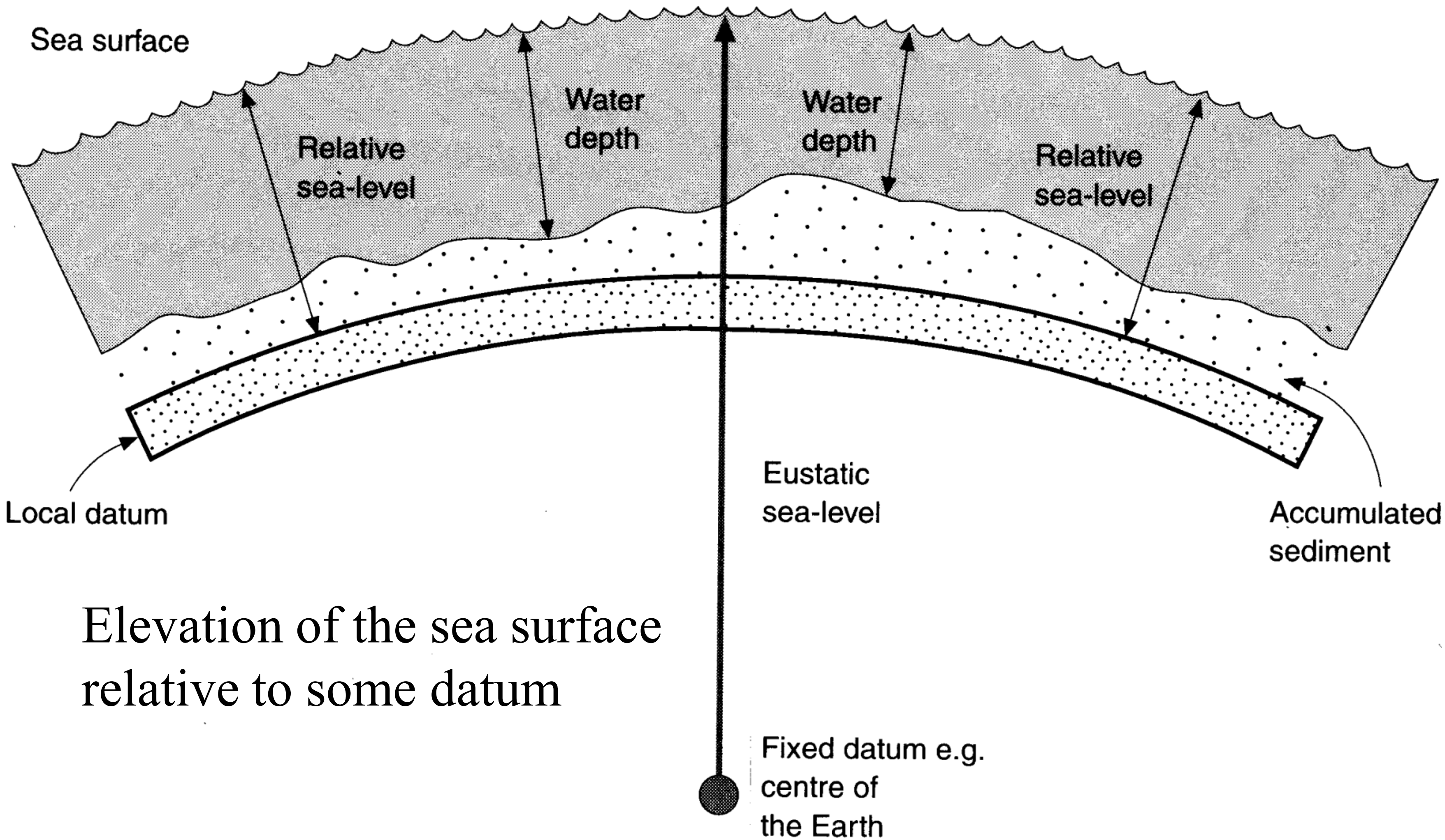
SORTING OUT SEA LEVEL

What is sea level?
Why does it change?
What does the past tell us?
What's happening now?
What does the future look like?

What do we mean by sea level?

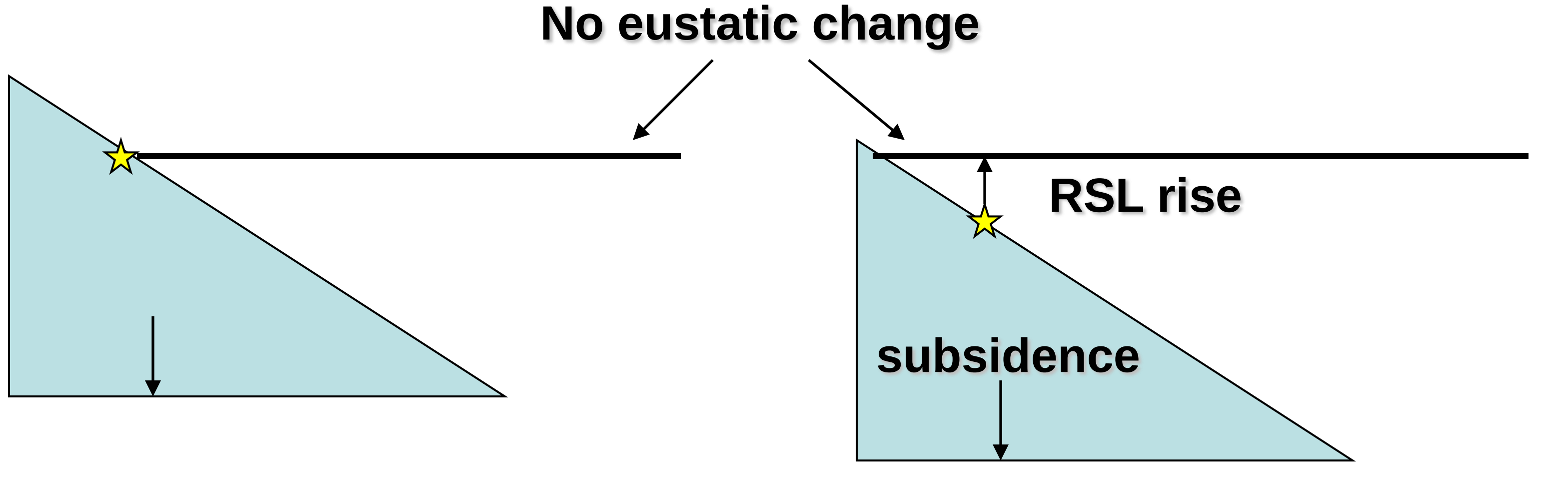


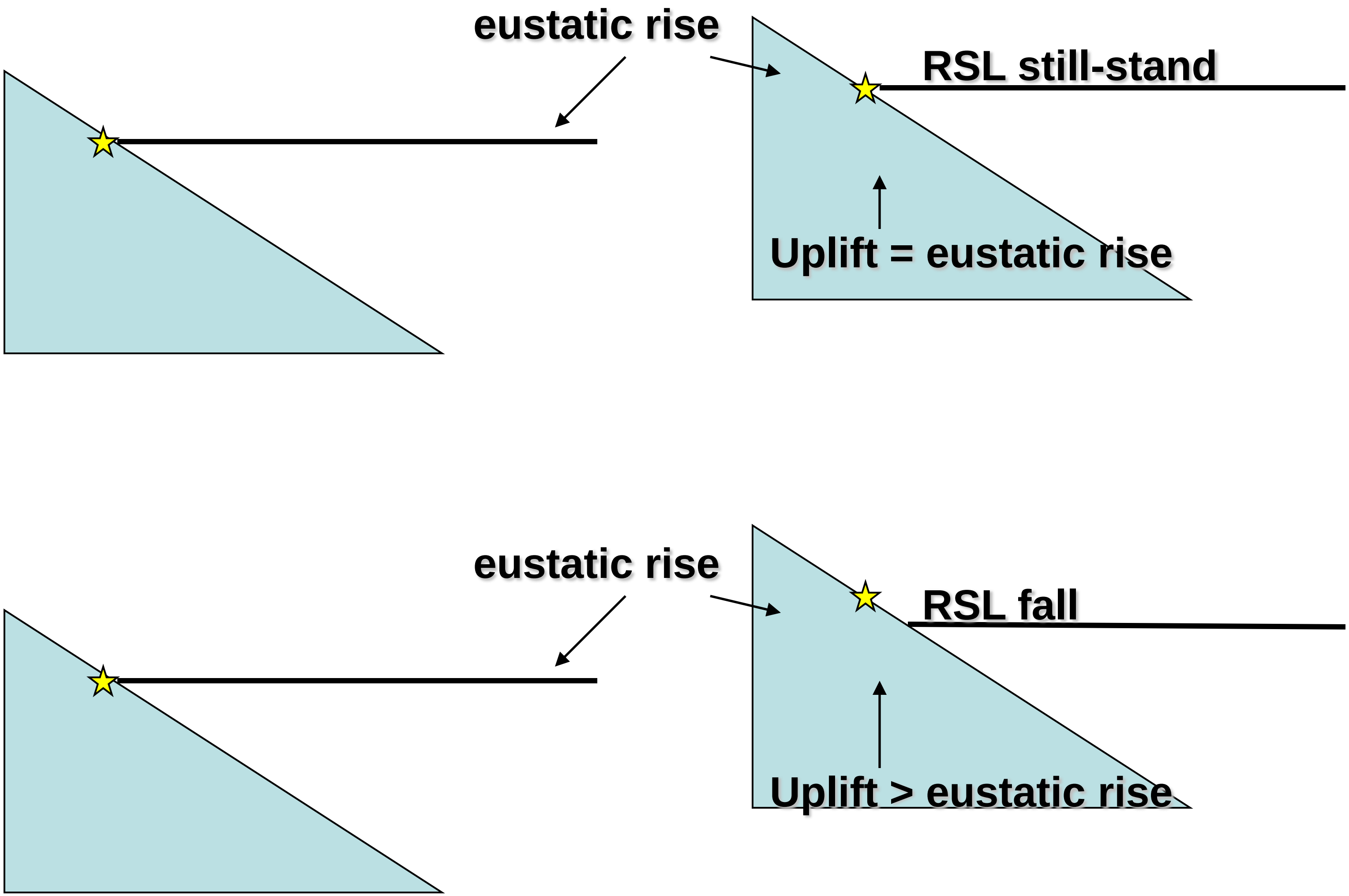
Elevation of the sea surface relative to some datum

Terminology (after Van Wagoner et al.)

Eustasy – sea level change as measured relative to a fixed datum (e.g., the center of the Earth).

Relative sea level – incorporates local factors (e.g. vertical land motion); sea level relative to a local datum (e.g. crystalline basement)




eustatic rise
RSL still-stand
Uplift = eustatic rise
eustatic rise
RSL fall
Uplift > eustatic rise

CAUSES OF SEA-LEVEL CHANGE

Eustatic (Global or Absolute) Changes

Driven by changes in the total <u>volume</u> of water

Or by changes in the <u>volume</u> of the ocean basins

- Rates of seafloor spreading
- Sedimentation
- Juvenile water
- Land-ice volume
- Deep sea hydro-isostasy
- Density changes (steric)
- Terrestrial water storage

Relative Changes – Eustatic + the following local/regional effects

Tectonism – local vertical land motion

Glacial and hydro-isostasy – local variations

Geoid changes

Sediment compaction

Groundwater extraction

Redistribution of water masses

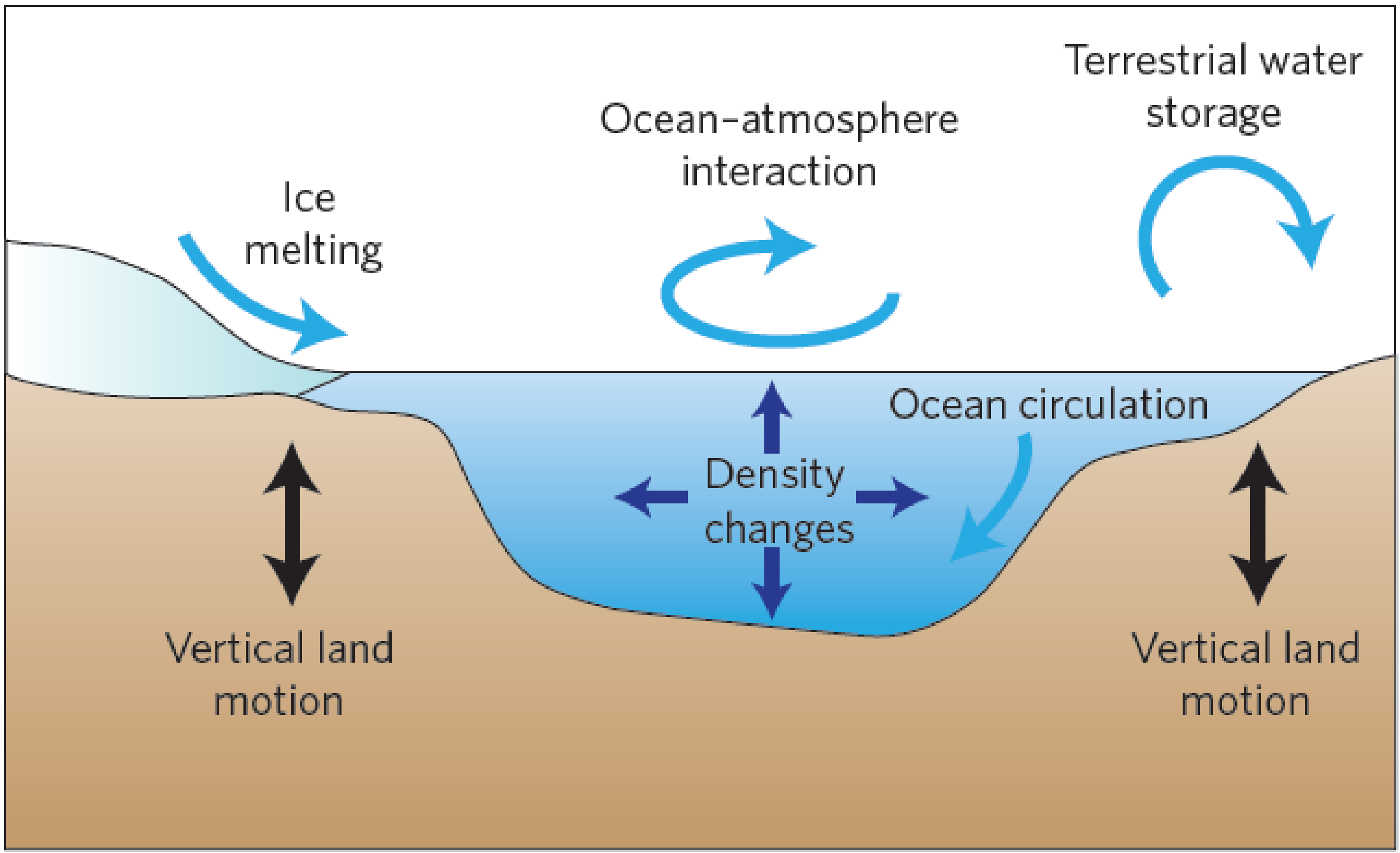
Currents, Tides

Wind patterns

nature geoscience
REVIEW ARTICLE
PUBLISHED ONLINE: 14 JUNE 2009 | DOI: 10.1038/NGEO544

Identifying the causes of sea-level change

Glenn A. Milne[1]*, W. Roland Gehrels[2], Chris W. Hughes[3] and Mark E. Tamisiea[3]

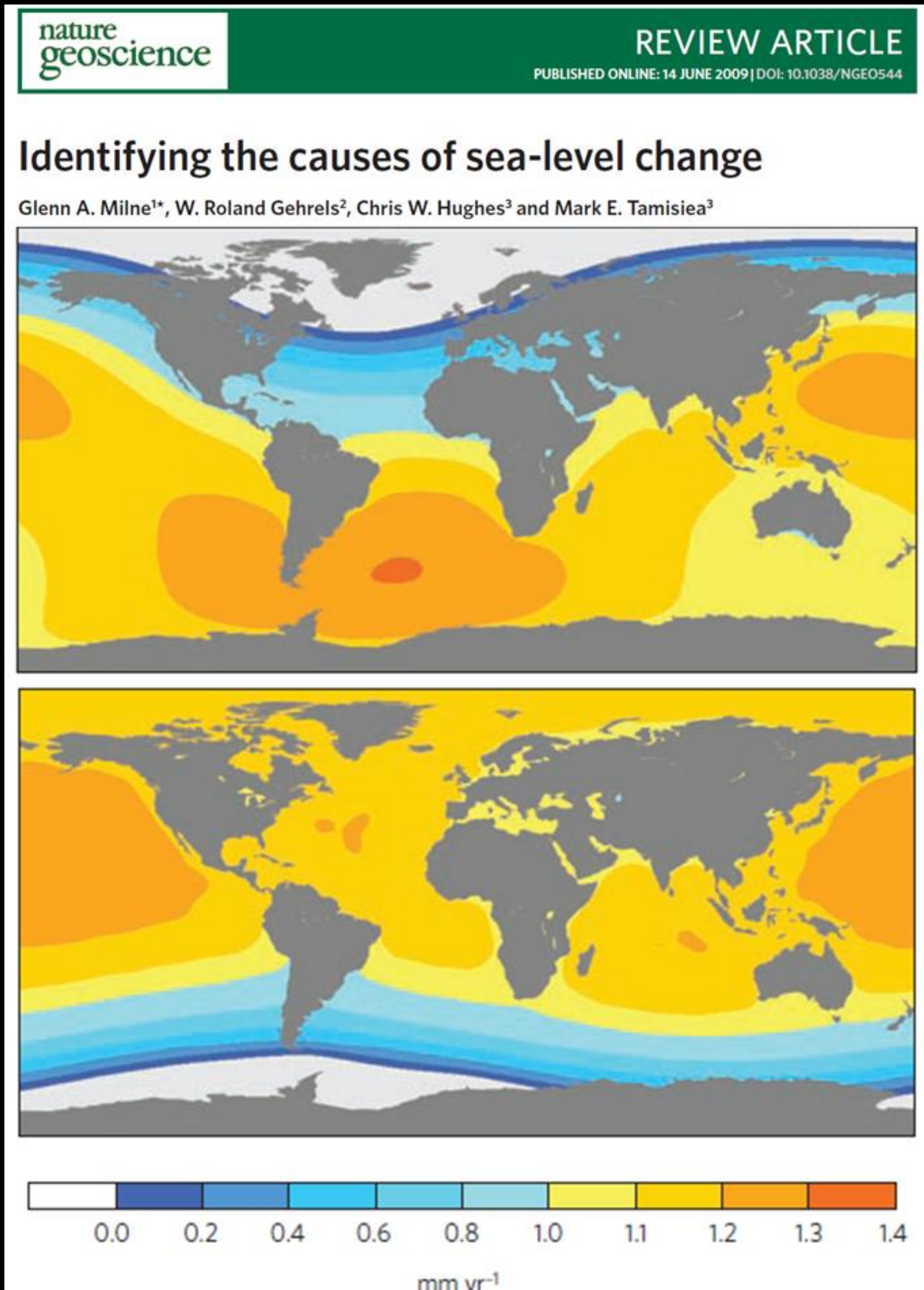


General Relative Sea-Level Equation

For each location (ϕ) the change in RSL (Δrsl) at time τ can be expressed schematically as (Peltier et al. 2002; Shennan and Horton 2002):

$$\mathbf{\Delta rsl(\tau,\phi) = \Delta eus(\tau) + \Delta iso(\tau,\phi) + \Delta tect(\tau,\phi) + \Delta local(\tau,\phi)}$$

$\Delta eus(\tau)$ is the time-dependent eustatic function,
$\Delta iso(\tau,\phi)$ is the total isostatic effect of the glacial rebound process including both the ice (glacio isostatic) and water (hydro isostatic) load contributions,
$\Delta tect(\tau,\phi)$ is any tectonic effect, and
$\Delta local(\tau,\phi)$ is the total effect of local processes.



Mass contribution To SL change from ice-sheet melting

Sea level is not level

The panel shows model predictions of the change in global sea level if the

Greenland (top) or

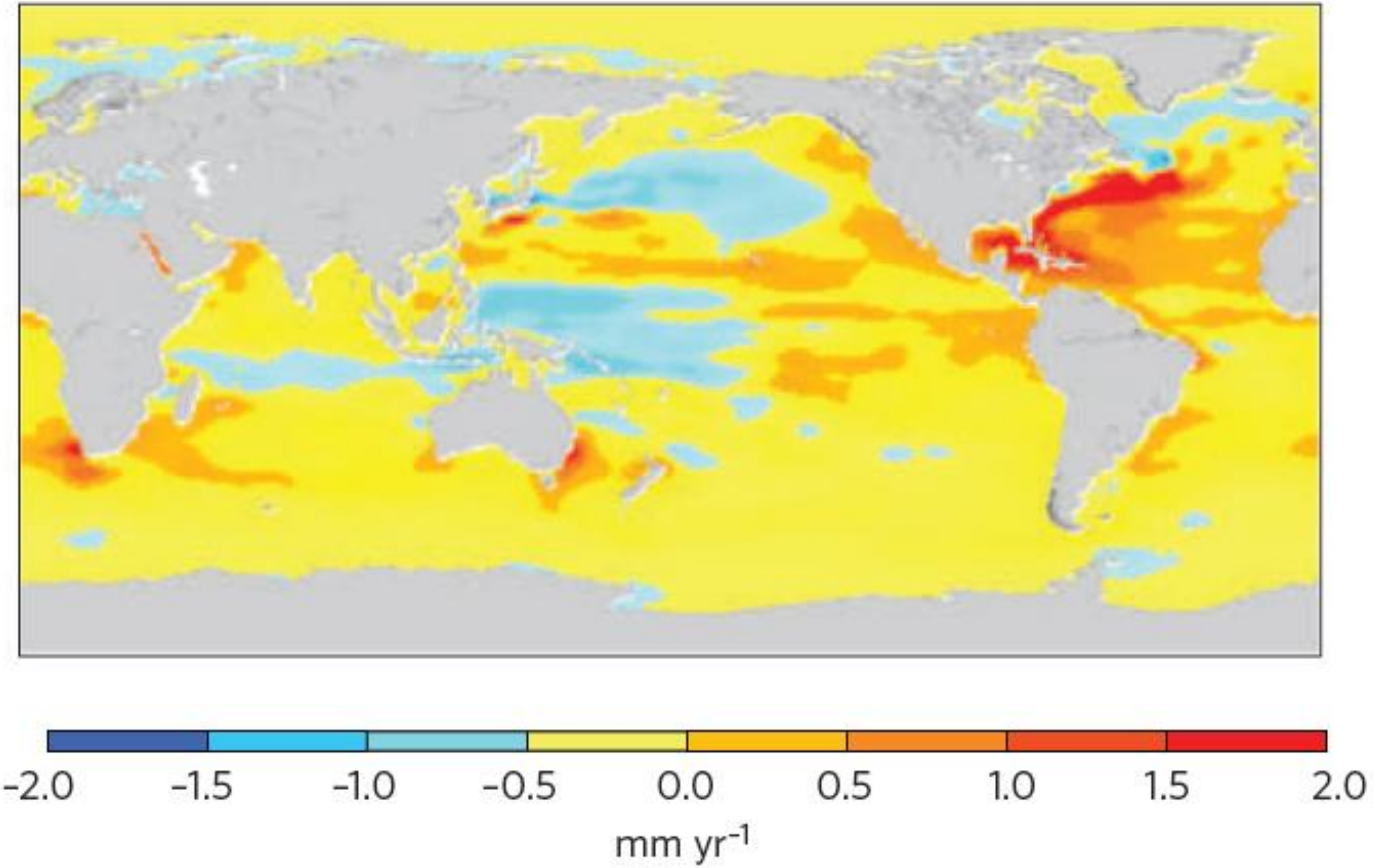
West Antarctic (bottom)

ice sheets were to lose mass at 1 mm yr^{-1}

(10 cm per century)

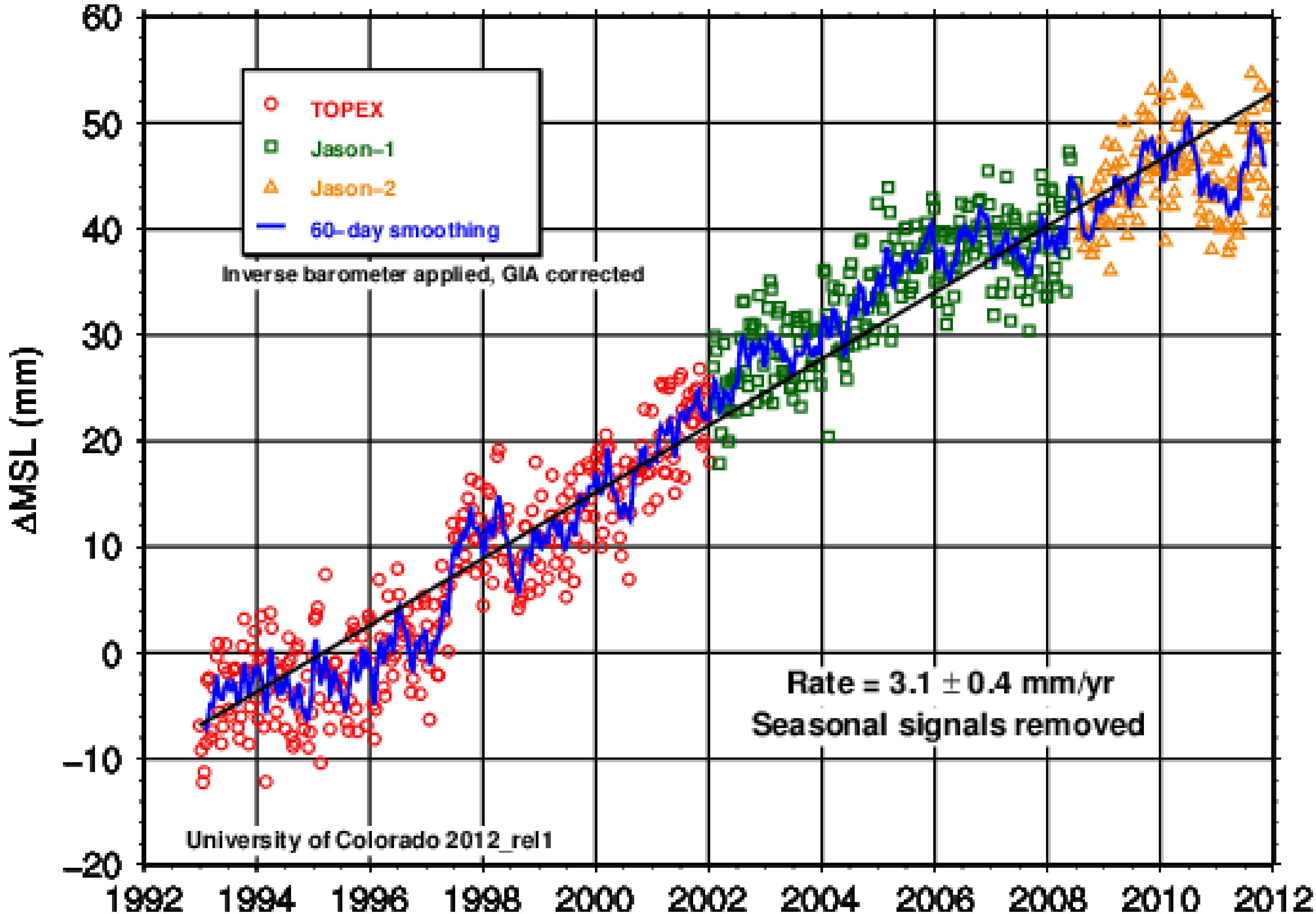
of global mean sea-level equivalent.

Steric (density) contribution to SL change (1950-2003)

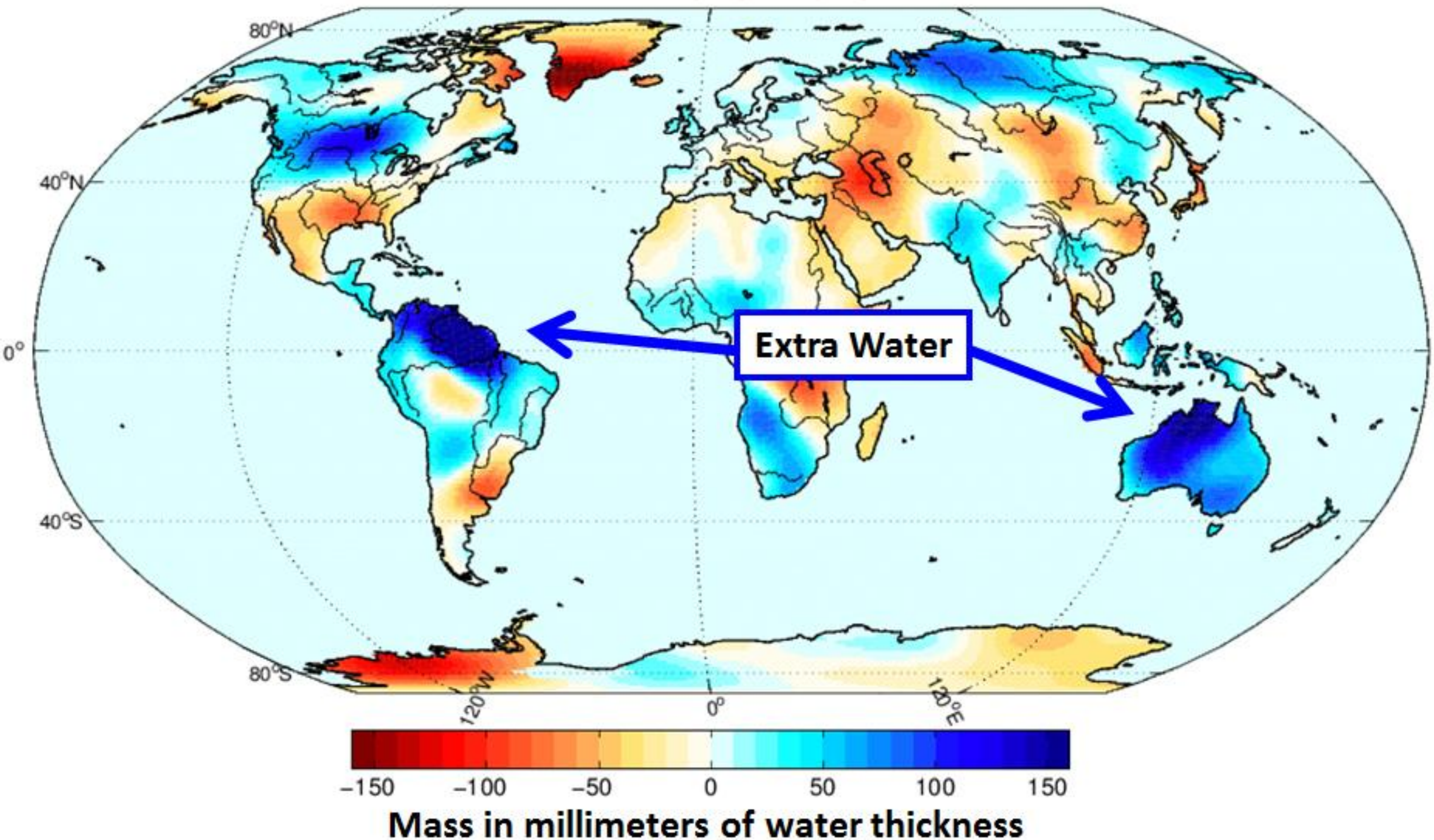


Milne et al. 2009. Nature Geoscience. DOI 10.1038

Contribution of terrestrial water storage and meteorological phenomena



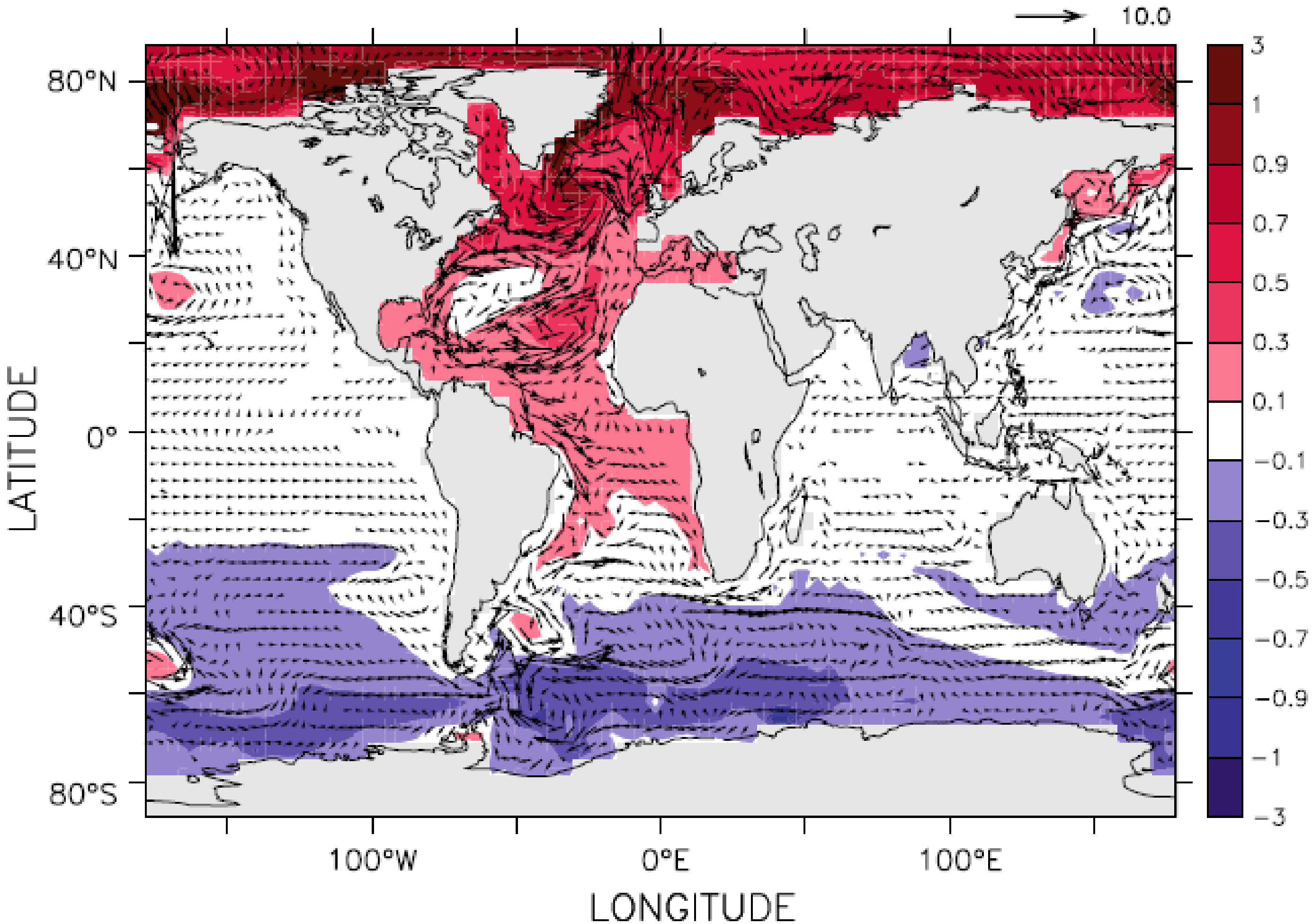
GRACE shows change in water from March 2010 to March 2011



Effect of slowing thermohaline circulation

Levermann et al.: Dynamic sea level changes following changes in the thermohaline circulation 351

Fig. 5 Dynamic sea level changes (in m) after the collapse of the THC (colours), and difference of surface current velocities (arrow in the upper right corner corresponds to 10 cm s^{-1})



Levermann et al. 2005. Climate Dynamics 24, 347-354.

GLACIO-ISOSTATIC EFFECTS
Near-field

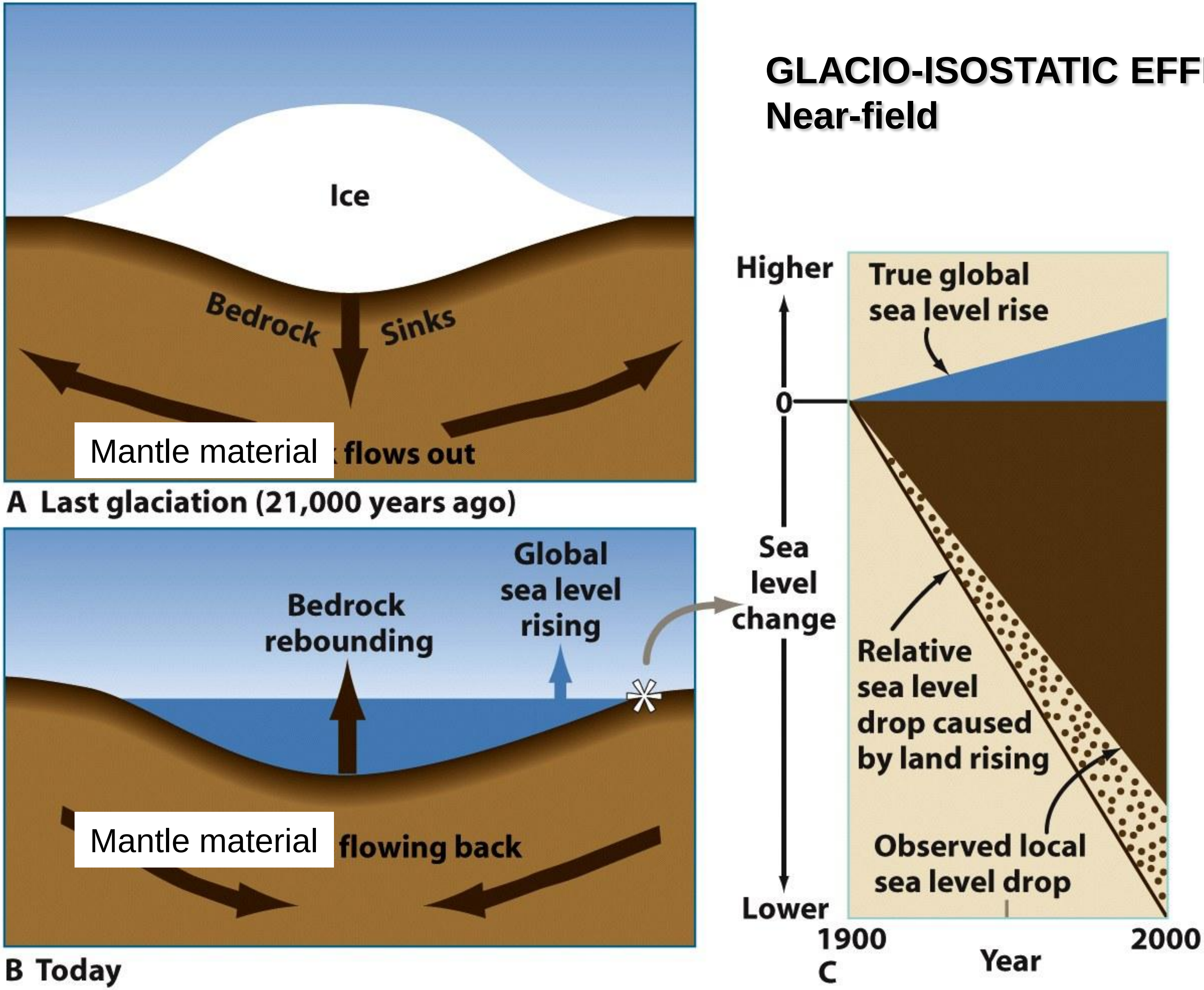


Figure 17-3
Earth's Climate: Past and Future, Second Edition

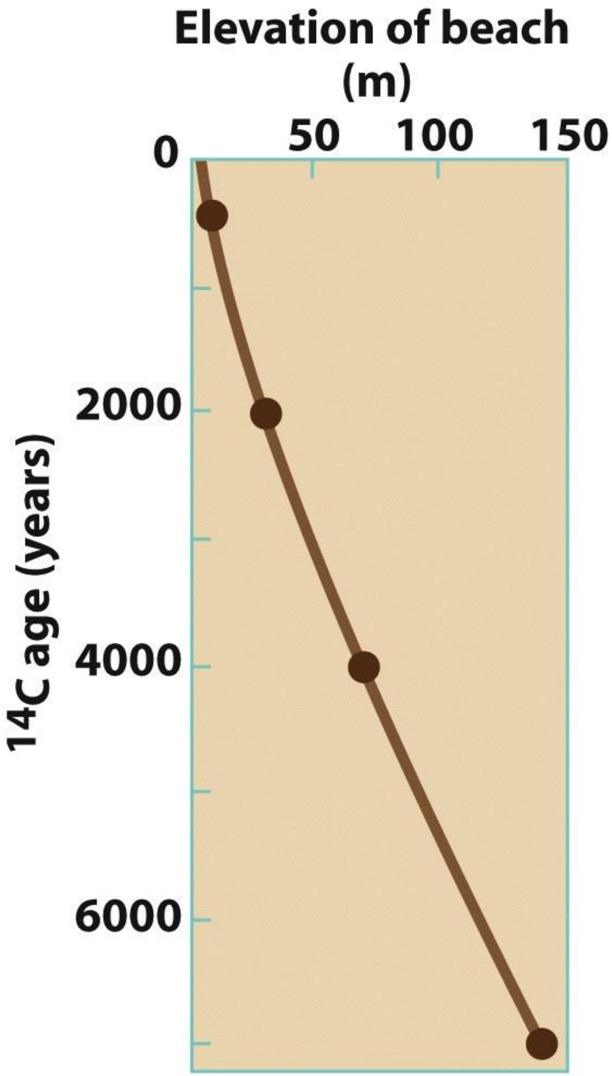
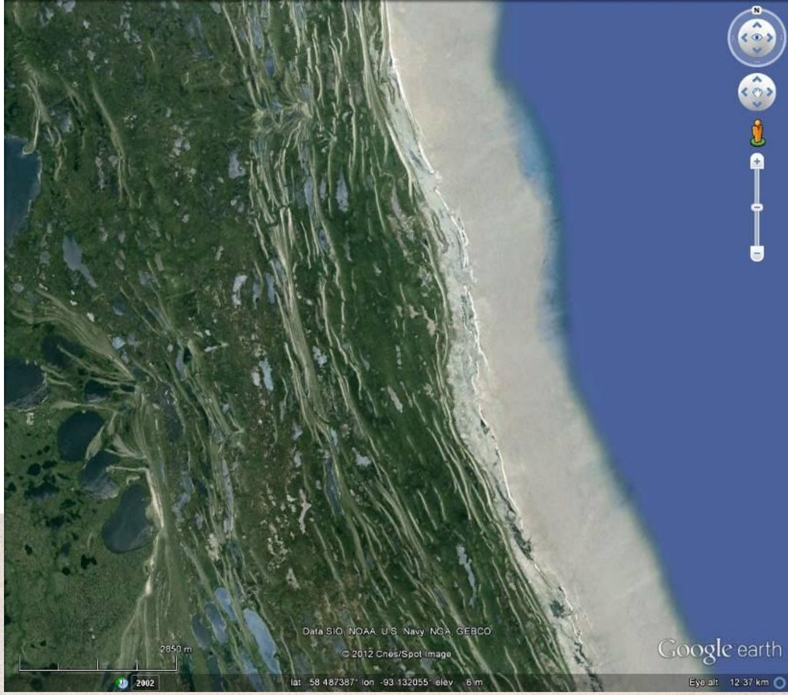
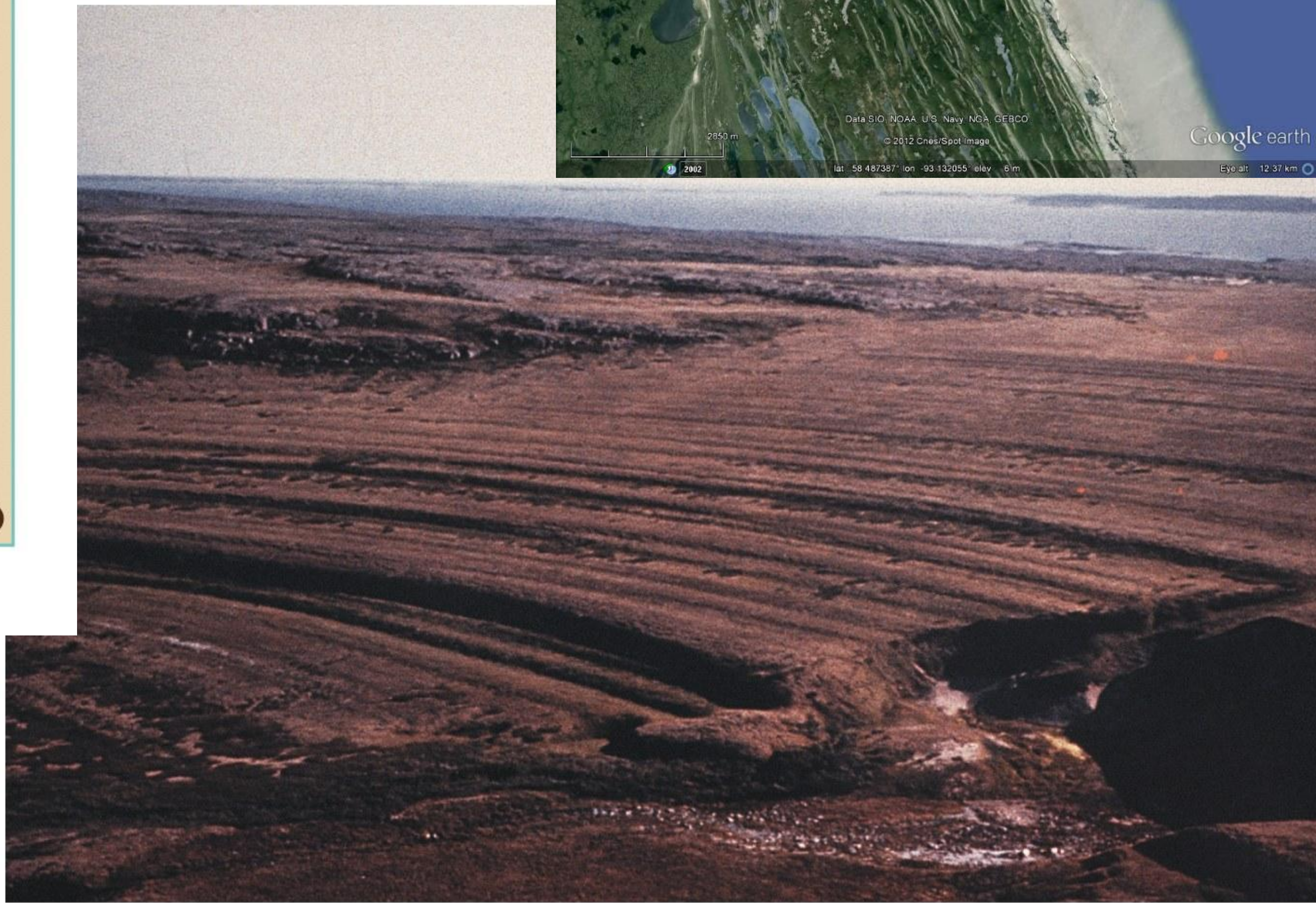


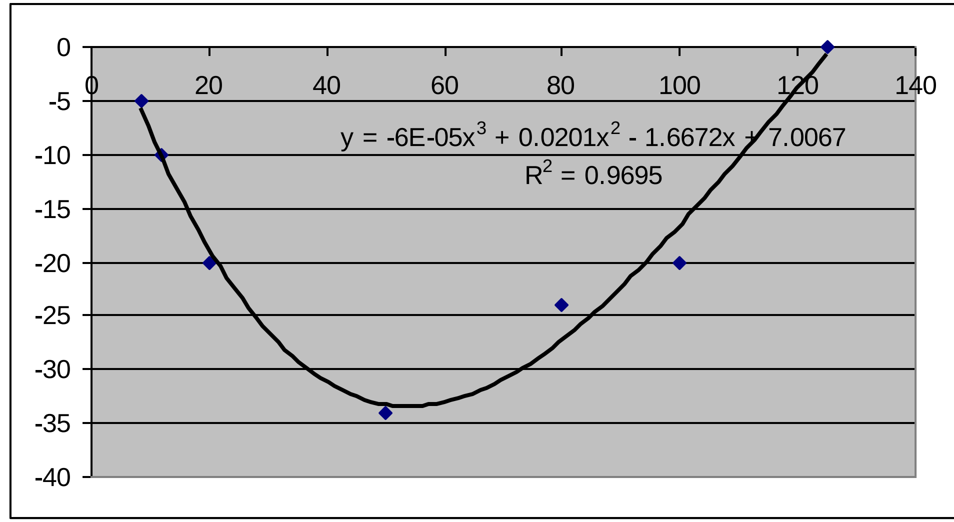
Figure 17-4b
Earth's Climate: Past and Future, Second Edition

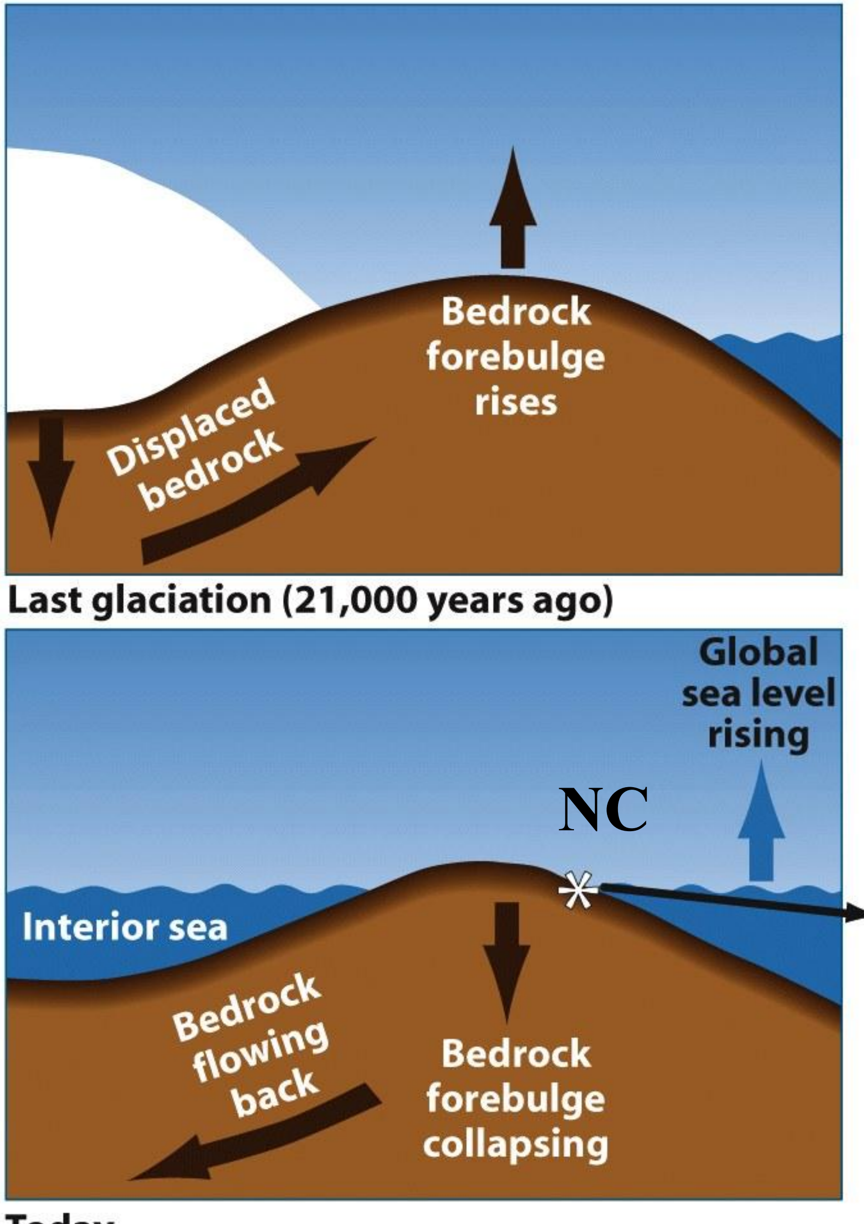
Hudson Bay rebounding paleoshorelines





GLACIO-ISOSTATIC EFFECTS intermediate-field





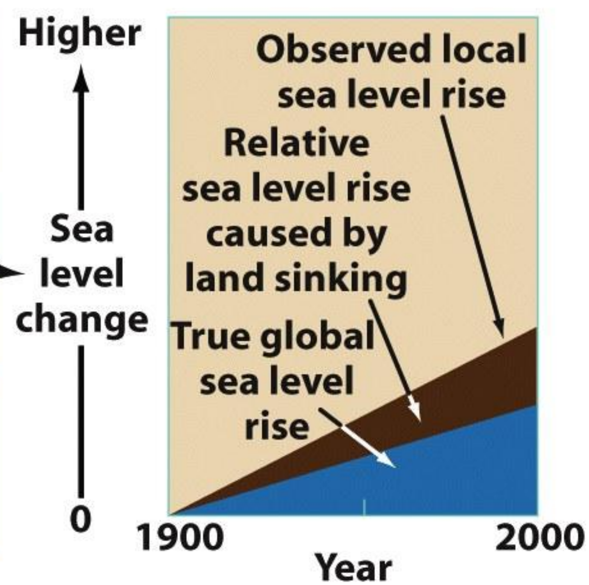


Figure 17-5
Earth's Climate: Past and Future, Second Edition

GLACIO-ISOSTATIC AND HYDRO-ISOSTATIC EFFECTS
Far-field

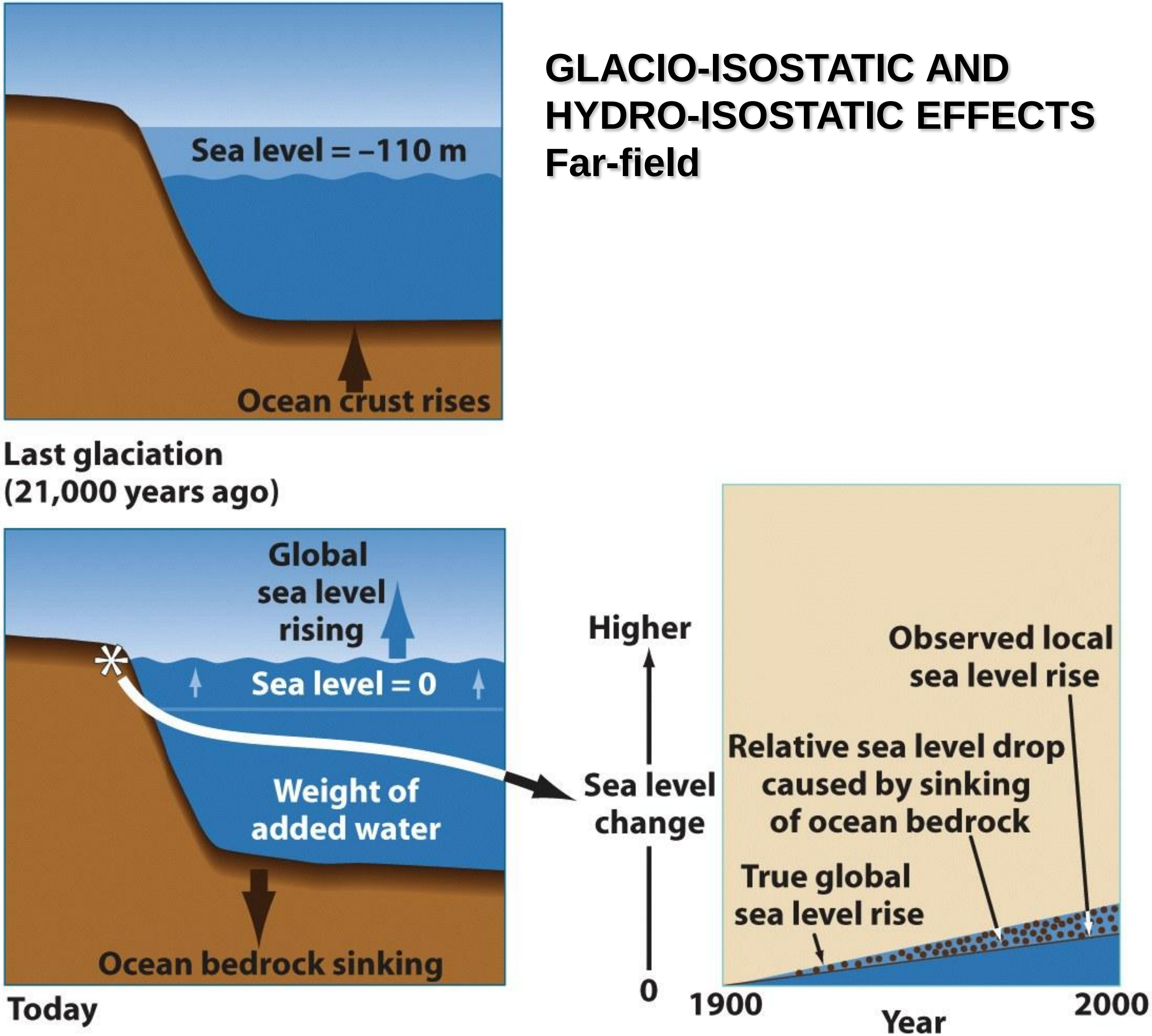


Figure 17-6
Earth's Climate: Past and Future, Second Edition

Glacio-isostasy

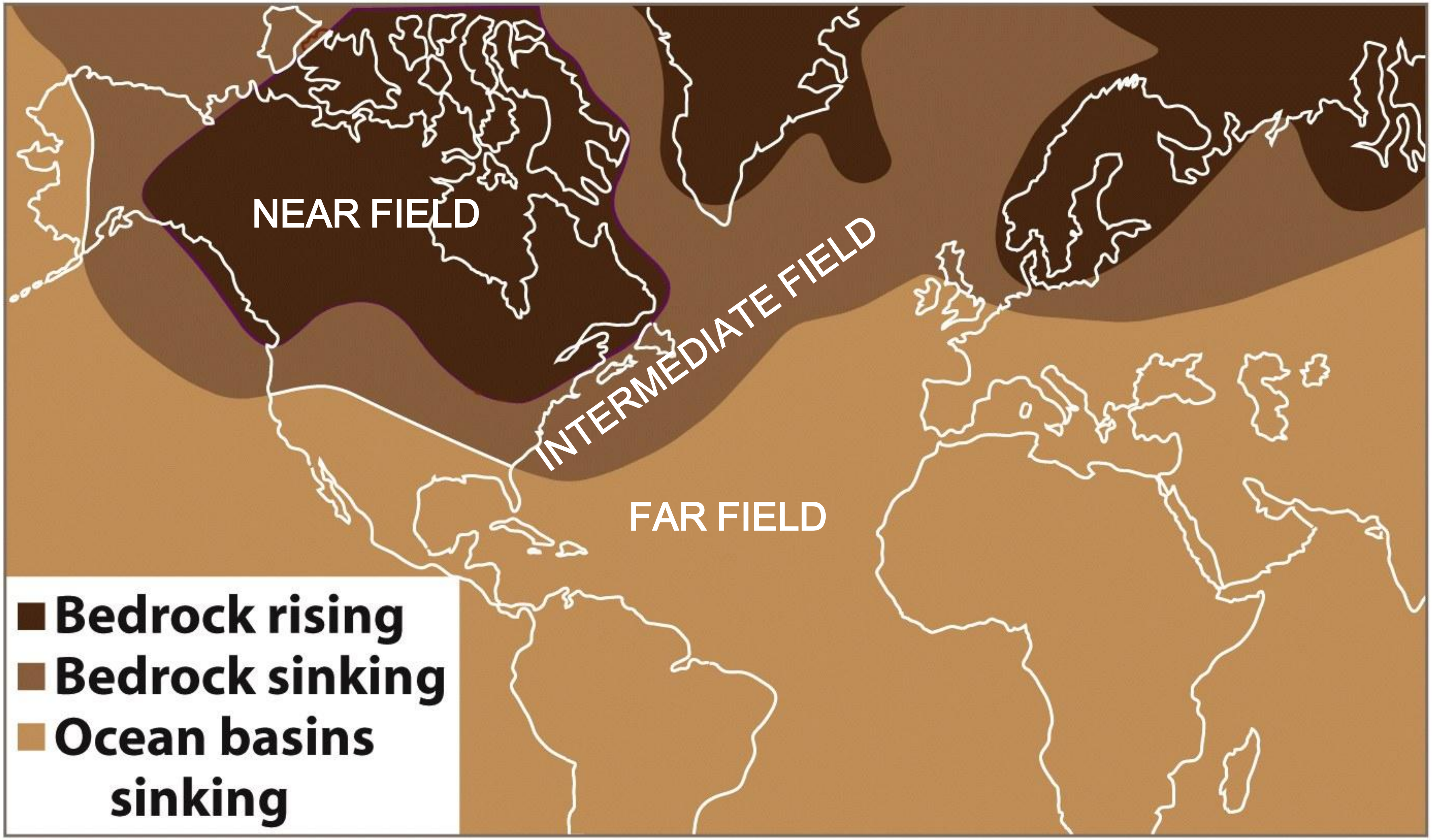


Figure 17-2
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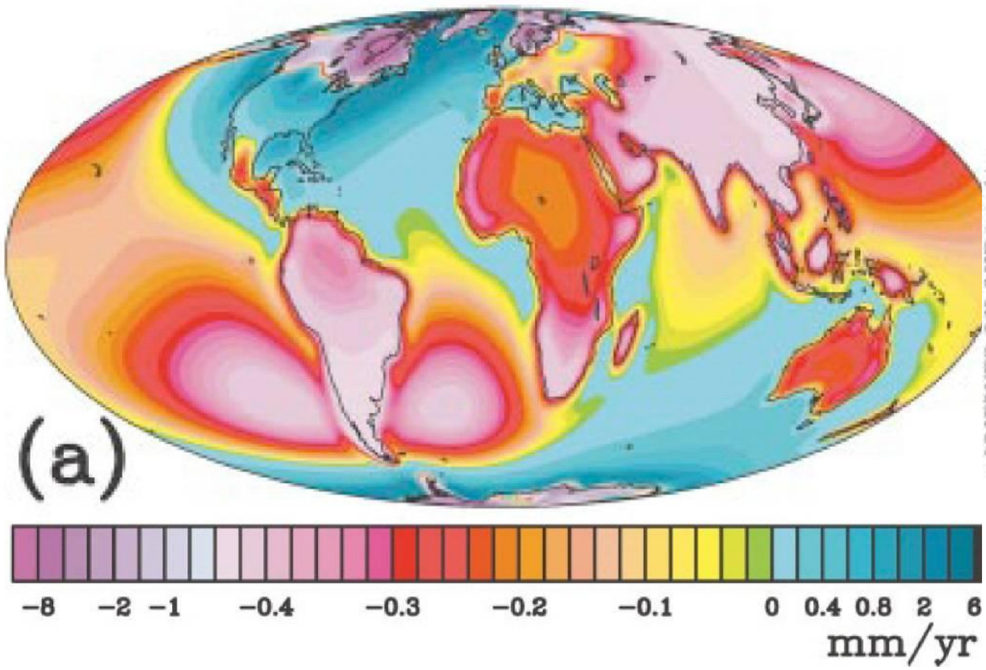
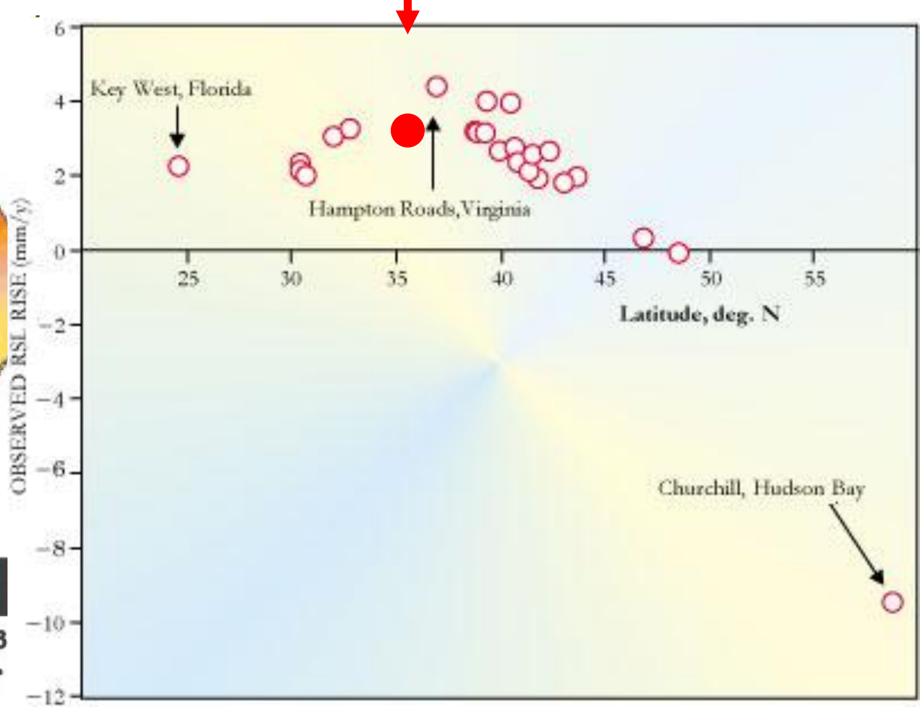
Forebulge collapse due to GIA
(ICE5G VM2 Model of Peltier, 2004)

Forebulge collapse ~1 mm/yr in our area



SL change in response
Only to glacio-isostasy

Our study area
Ca. 3 mm/y (Horton, Kemp et al.)



North

South

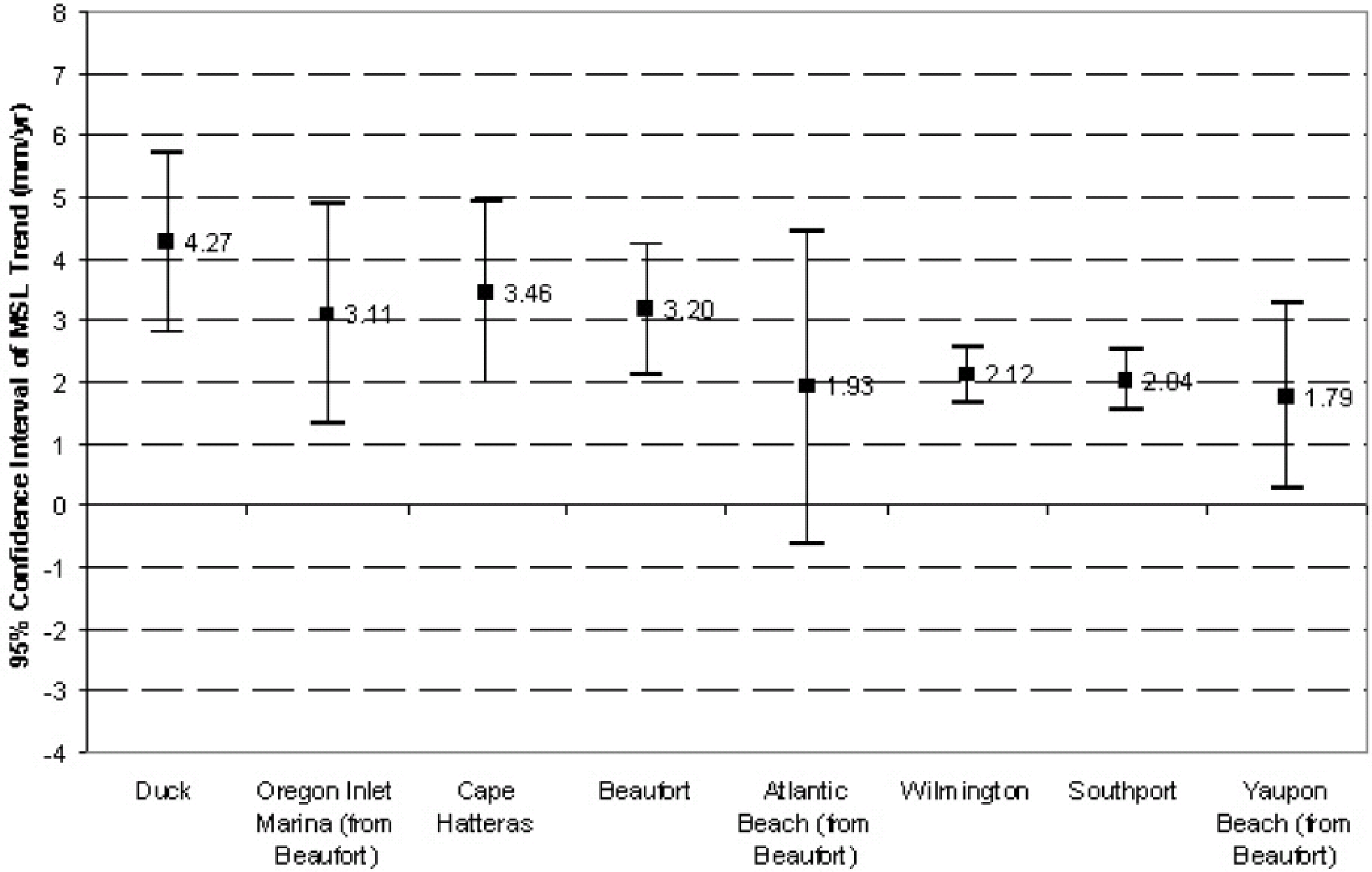


Figure 4. Mean sea level trends and 95% confidence intervals for North Carolina water level stations with trends for Oregon Inlet Marina, Atlantic Beach, and Yaupon Beach based on water level differences with Beaufort.

Zervas, 2004

Church et al. 2011. Geophy. Res. Let.

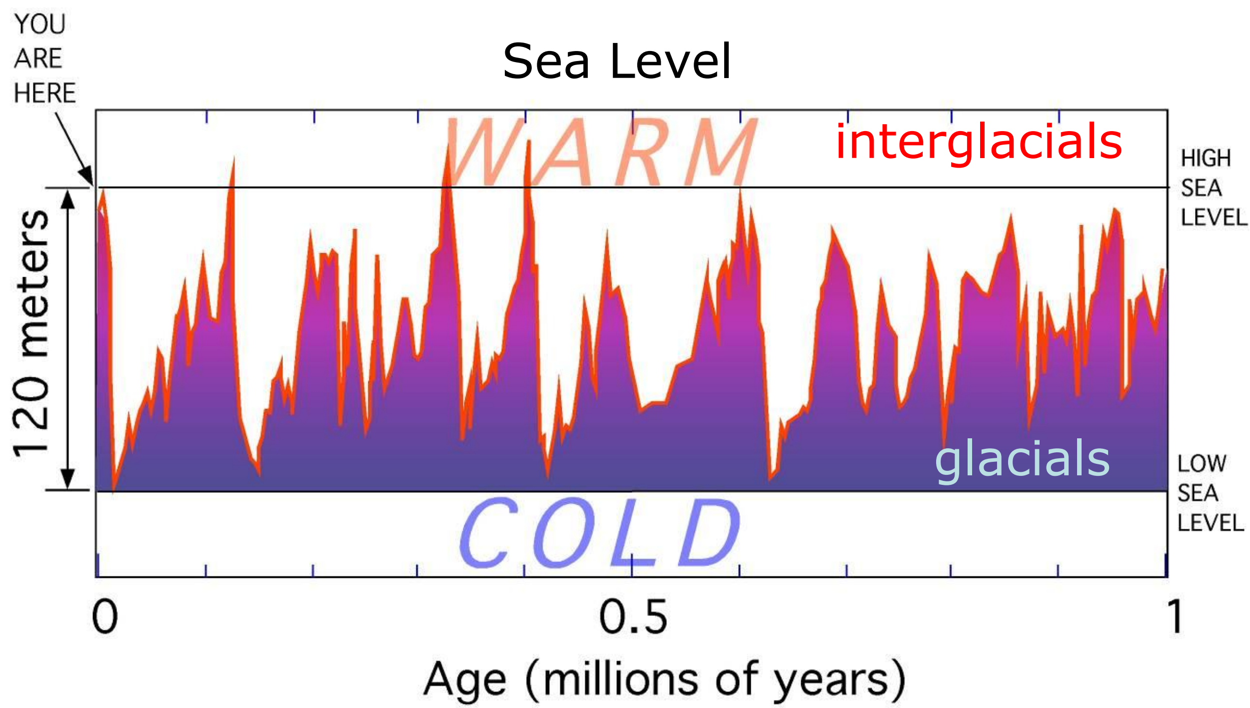
Table 1. The Sea-Level Budget[a]

Component	1972 → 2008	1993 → 2008
Total s.l. (t.g. only)	**1.83 ± 0.18**[b]	**2.61 ± 0.55**
Total s.l. (t.g. + sat)	**2.10 ± 0.16**	**3.22 ± 0.41**
Shallow thermal (0–700m)	0.63 ± 0.09	0.71 ± 0.31
Deep thermal (700–3000m)	0.07 ± 0.10	0.07 ± 0.10
Abyssal thermal (3000m-bottom)	0.10 ± 0.06	0.10 ± 0.06
Total thermal (full depth)	**0.80 ± 0.15**	**0.88 ± 0.33**
Glaciers & Ice Caps	0.67 ± 0.03	0.99 ± 0.04
Greenland Ice Sheet	0.12 ± 0.17	0.31 ± 0.17
Antarctic Ice Sheet	0.30 ± 0.20	0.43 ± 0.20
Land ice (G&IC, GIS, AIS)	**1.09 ± 0.26**	**1.73 ± 0.27**
Thermal (full depth) + Land ice	**1.89 ± 0.30**	**2.61 ± 0.42**
Dam retention	−0.44 ± 0.15	−0.30 ± 0.15
Groundwater depletion	0.26 ± 0.07	0.35 ± 0.07
Natural terrestrial storage	0.07 ± 0.10	−0.14 ± 0.10
Total terrestrial storage	**−0.11 ± 0.19**	**−0.08 ± 0.19**
Total mass contributions	**0.98 ± 0.33**	**1.66 ± 0.33**
Total thermal + Mass	**1.78 ± 0.36**	**2.54 ± 0.46**
Residual (t.g. only)	**0.05 ± 0.40**	**0.08 ± 0.72**
Residual (t.g. + sat)	**0.32 ± 0.39**	**0.69 ± 0.62**

[a]Linear trends in mm yr^{-1} (with one standard deviation error estimates) are shown for the sea-level time series from the reconstructed tide-gauge data (t.g.) and from joining the altimeter data to the reconstructed data in 1993 (t.g. + sat) and for each term in the sea-level budget for two separate time intervals. Uncertainty estimates for the sea level, shallow thermal expansion and the ground water depletion are from our analysis and all other uncertainty estimates are from the relevant publications as cited in the text.

[b]Bold numbers indicate sum of other rows, as indicated in first column.

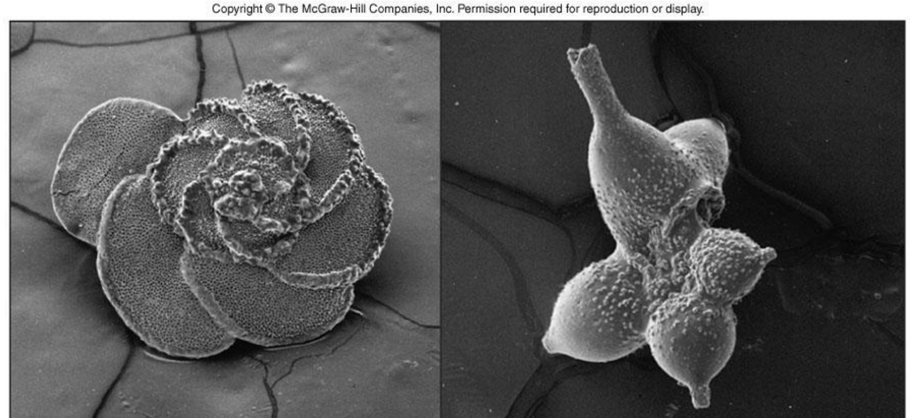
The Geologic Record of ΔSL



$\delta^{18}O$ (basically ^{18}O:^{16}O)

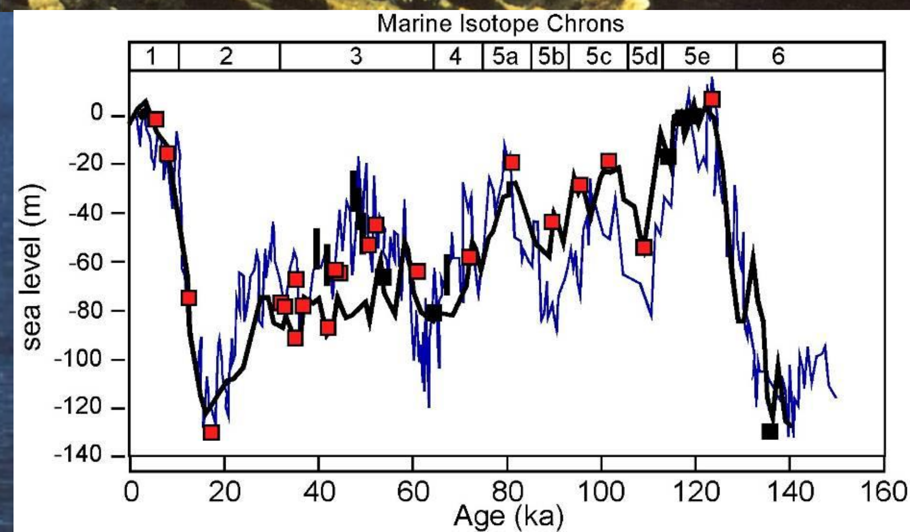
Can measure it on ice from glaciers or on $CaCO_3$ in marine organisms

Represents a "proxy" for sea level, ice volume, and temperature



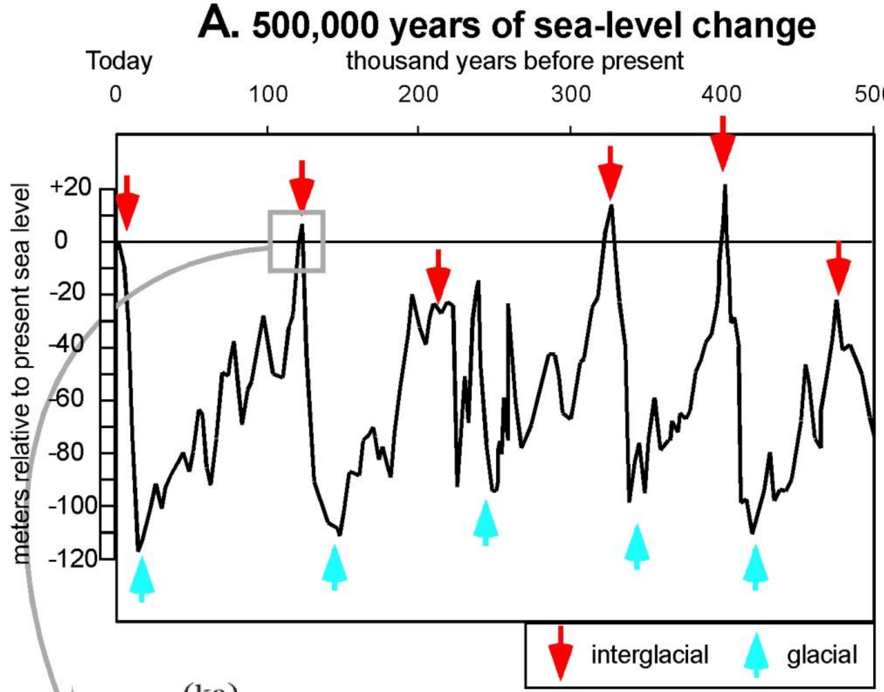
Coral reef terraces indicate where the sea surface once was.

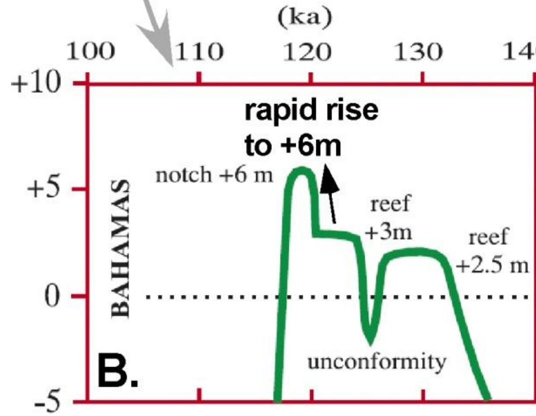
Huon Peninsula, Papua New Guinea

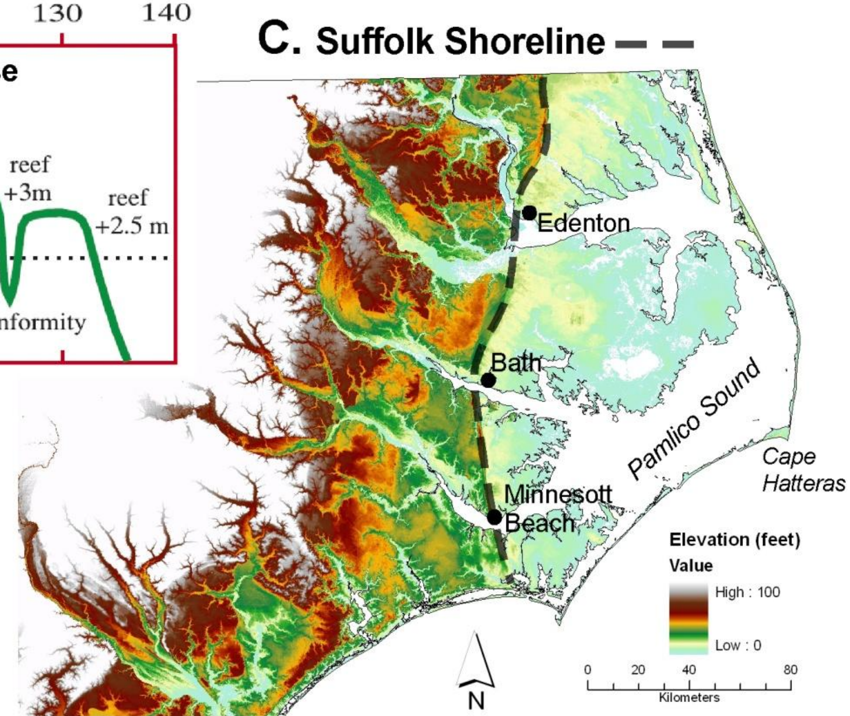


The Geologic Record allows us to understand process relationships and what is possible.

The last time conditions were like today,
SL was +2 m and rose very quickly to at least +6 m



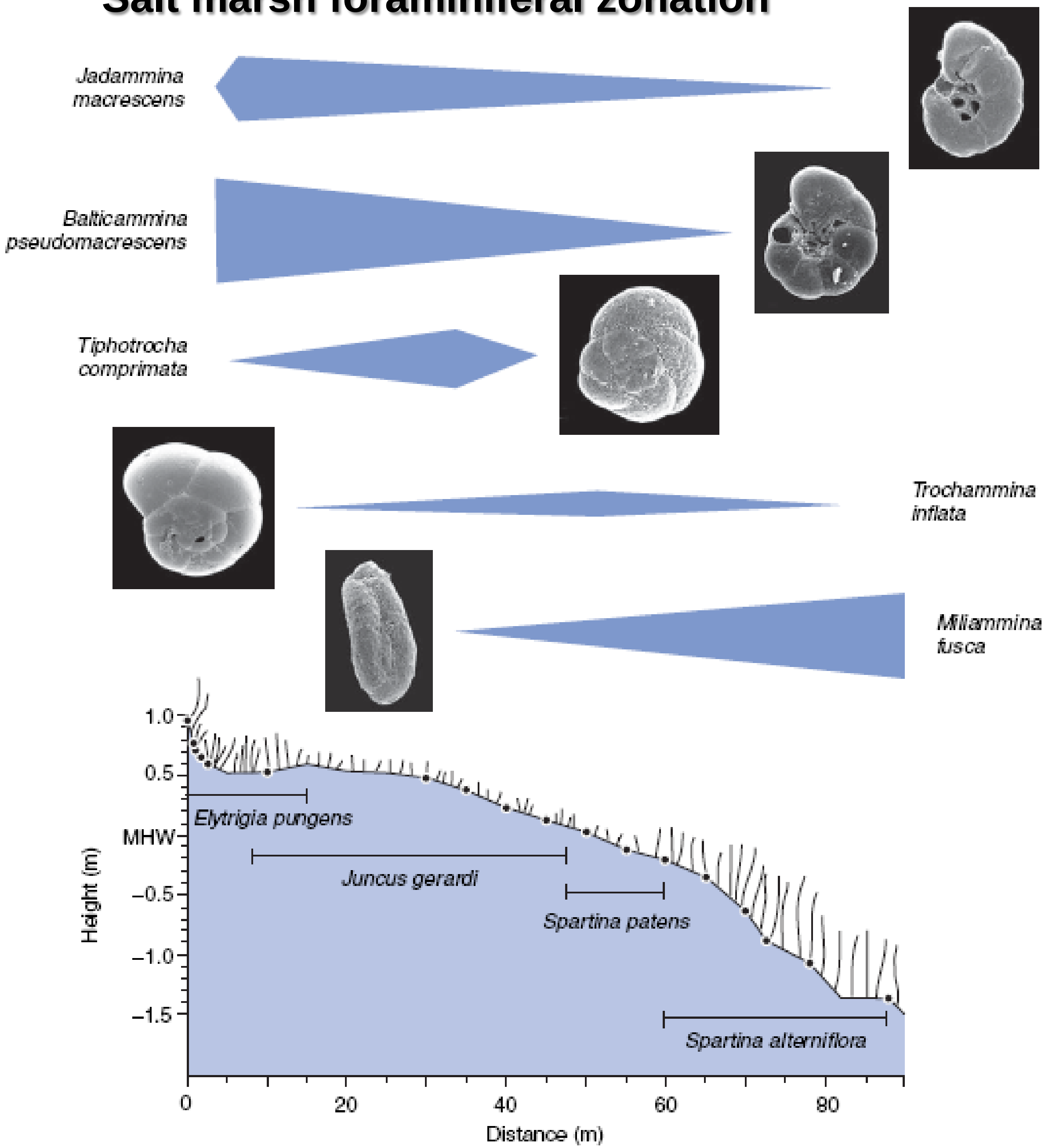




The Geologic Record

Peat coring on a Roanoke Island marsh

Salt marsh foraminiferal zonation



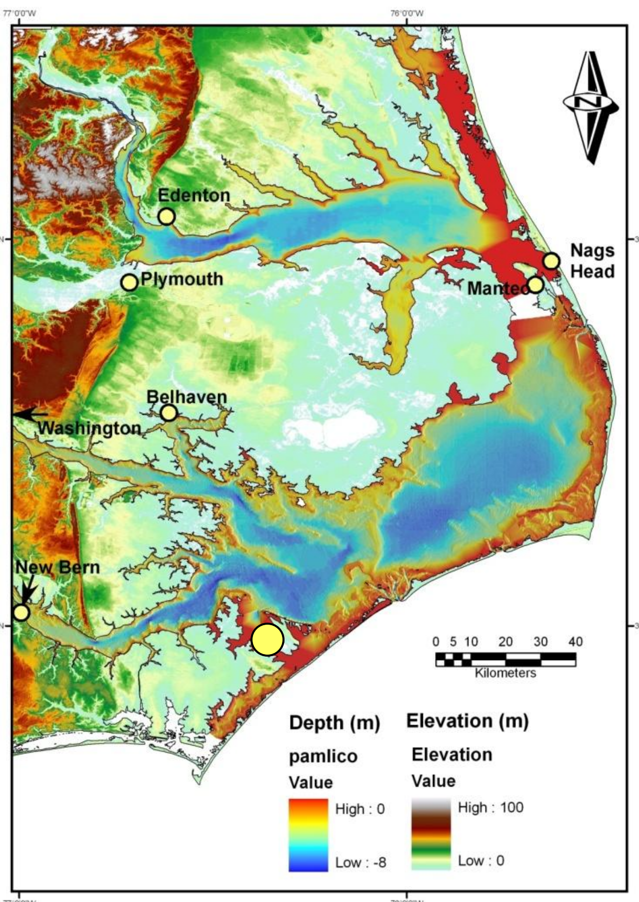
Culver and Horton, 2005
Horton and Culver, 2008
Kemp et al., 2009

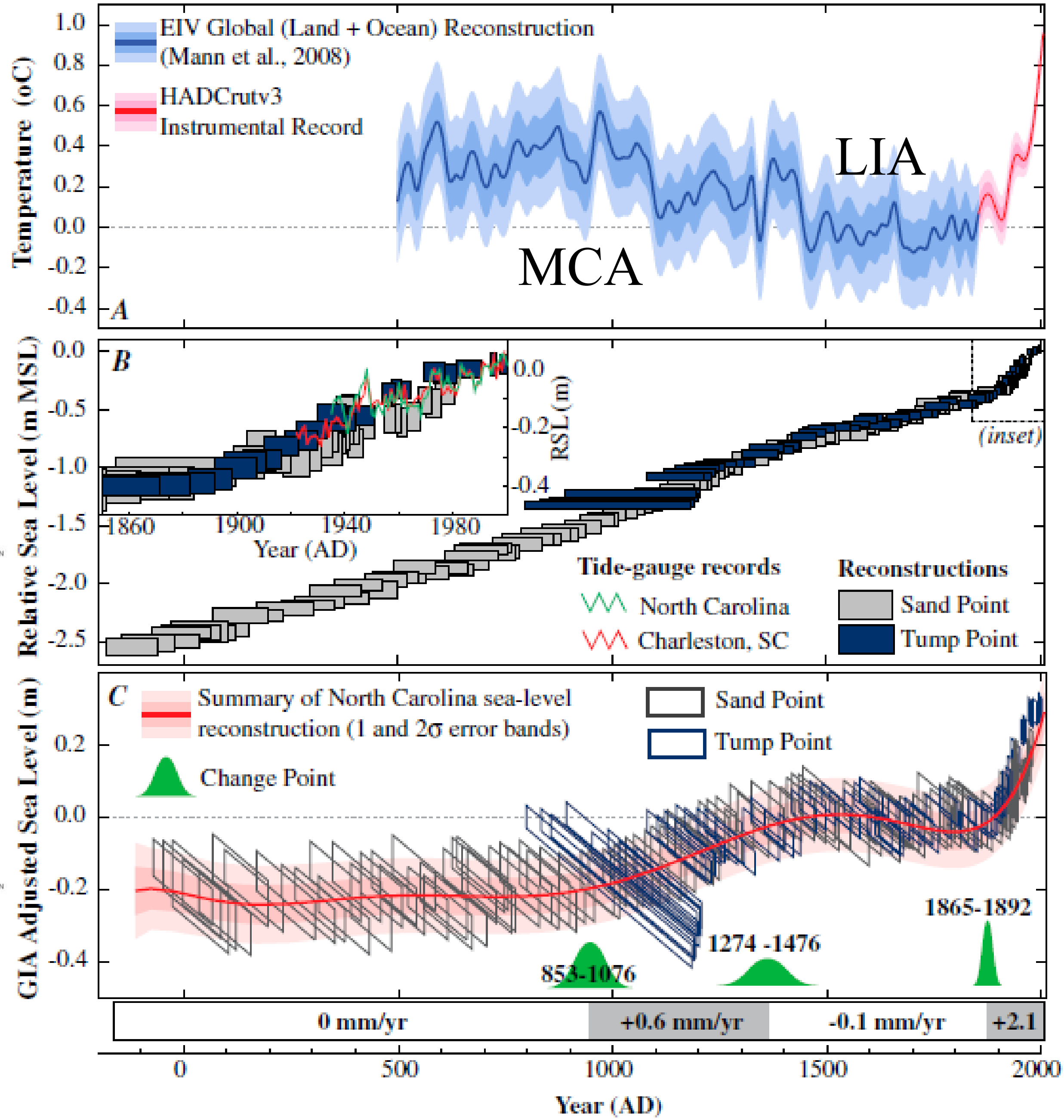
Foram assemblages related to marsh elevation above mean tide level (the indicative meaning)

Can convert assemblages to a sea-level index point (SLIP) using a transfer function

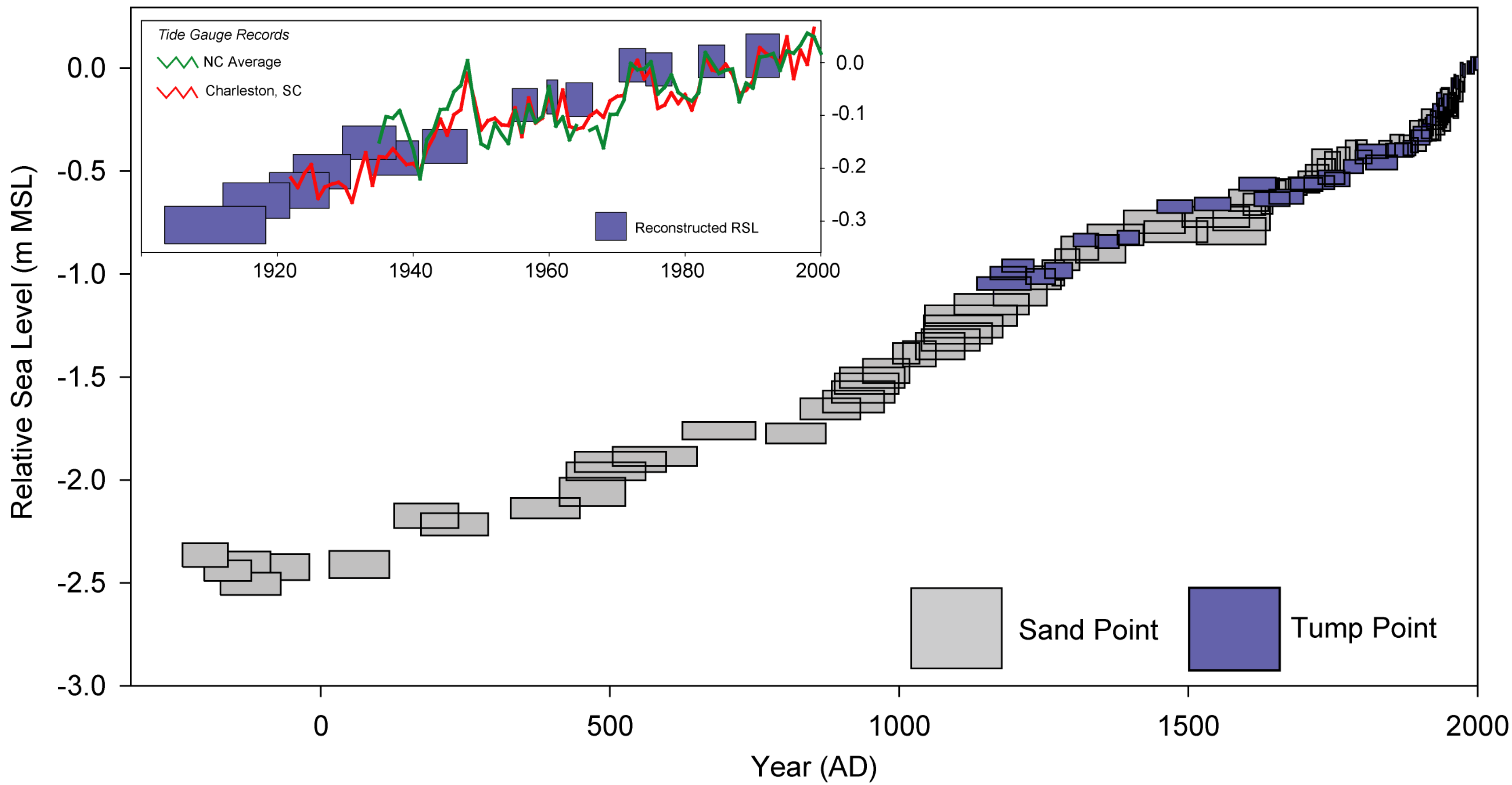
Climate related sea-level variations over the past two millennia

Andrew C. Kemp[a,b], Benjamin P. Horton[a,1], Jeffrey P. Donnell
Martin Vermeer[e], and Stefan Rahmstorf[f]





Kemp et al., 2009 (Geology)



2000 year record of relative sea-level change from Sand Point Roanoke Island) and a 1000 year record from Tump Point (Cedar Island). Includes eustatic and isostatic signals.

The Historic Record

Measuring Sea Level using Tide Gauge Stations

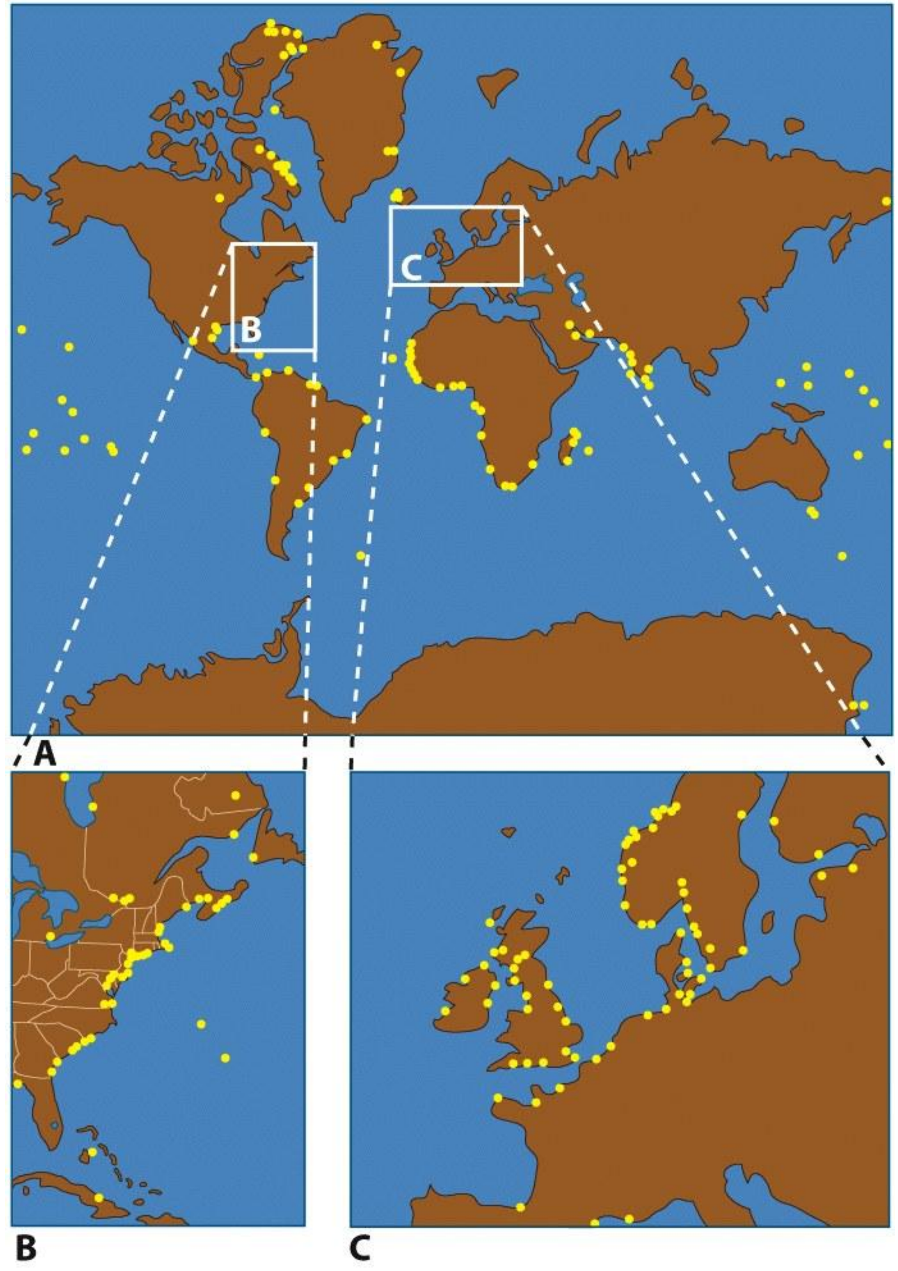
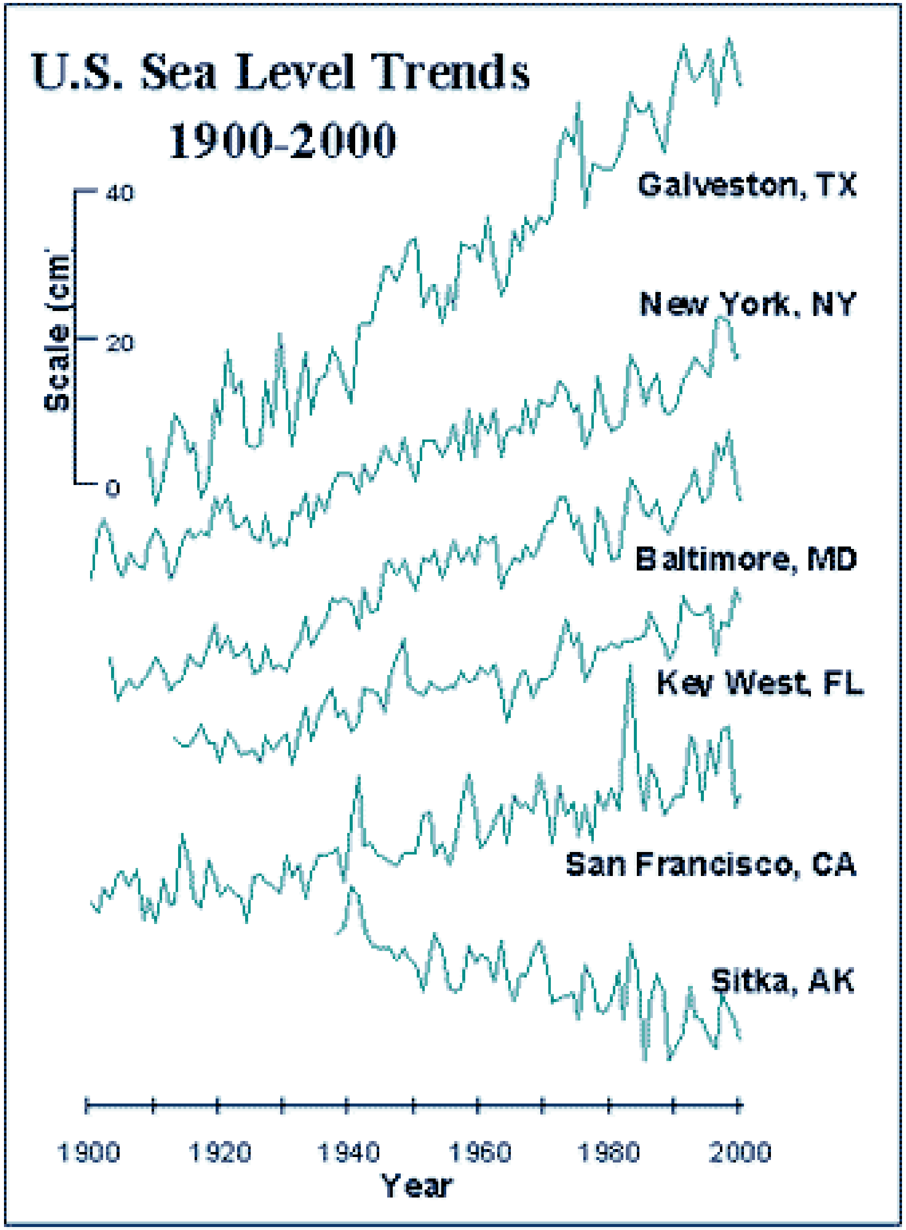
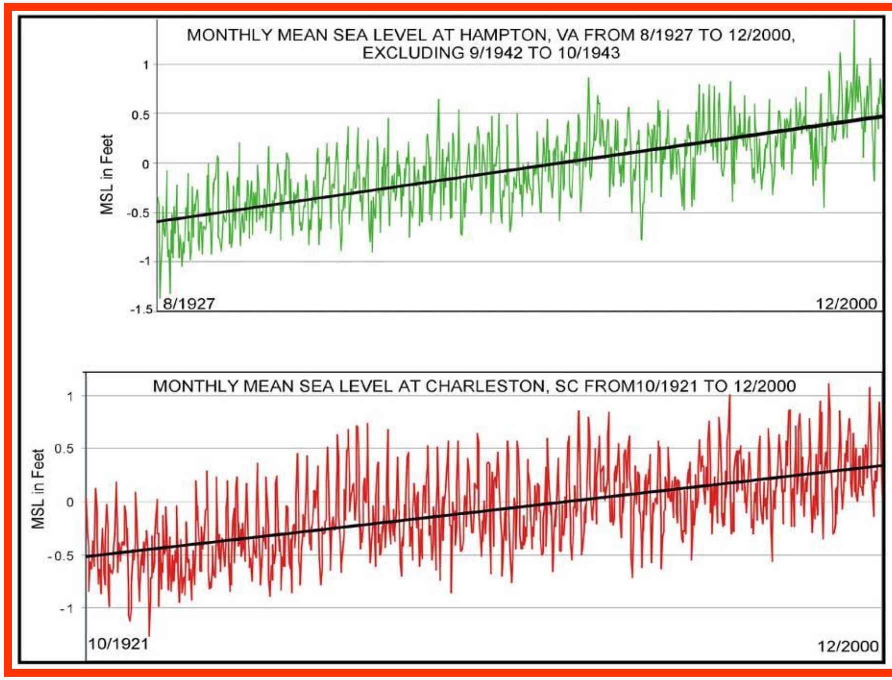


Figure 17-1

Earth's Climate: Past and Future, Second Edition





Note high variability, and non-uniformity.

Cazaneva and Llovel, 2010. Ann. Rev. Mar. Sci. 2, 147-173

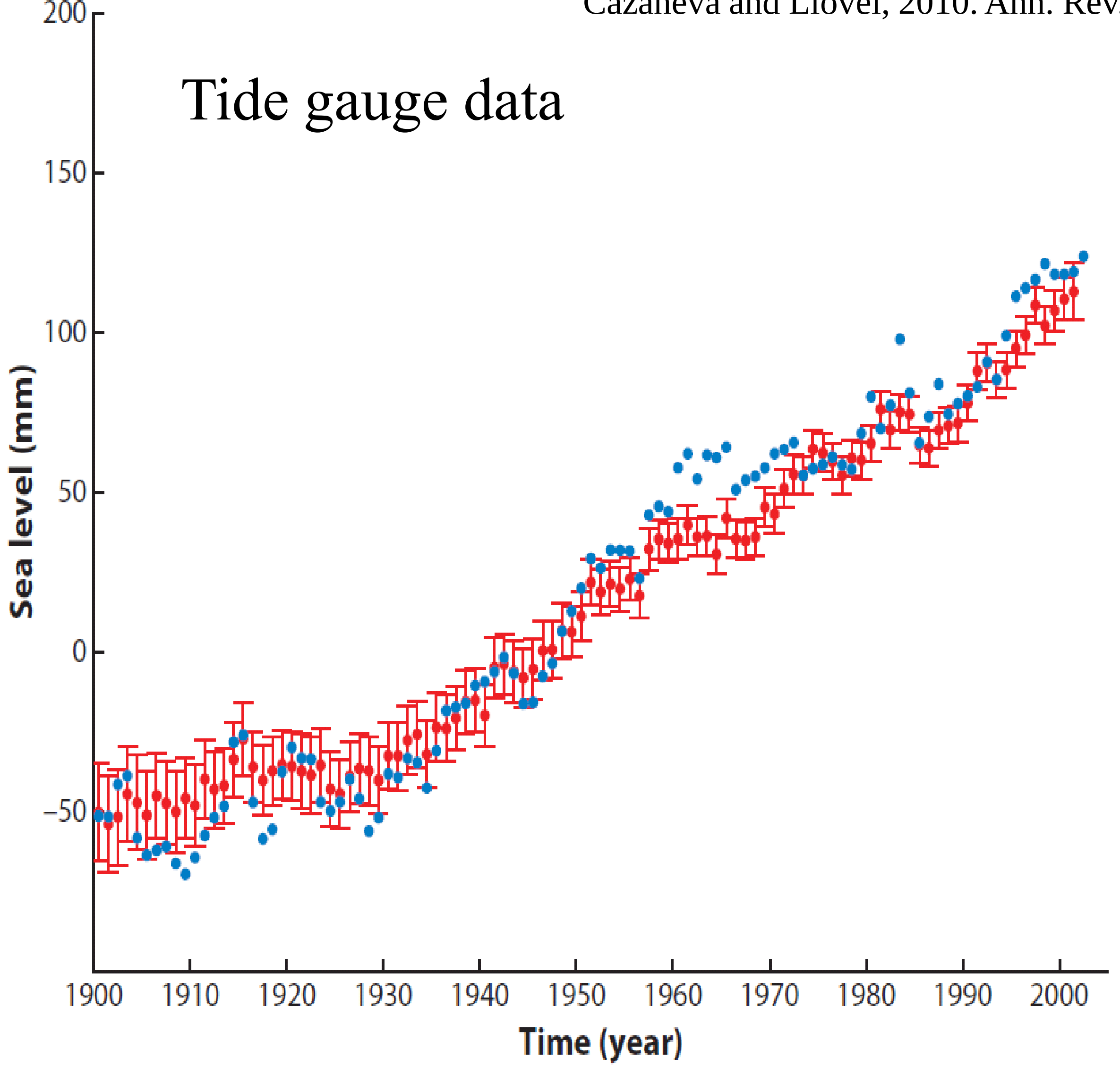


Figure 1

Observed global mean sea level (from tide gauges) between 1900 and 2001. Red dots are from Church et al. (2004). Blue dots are from Jevrejeva et al. (2006).

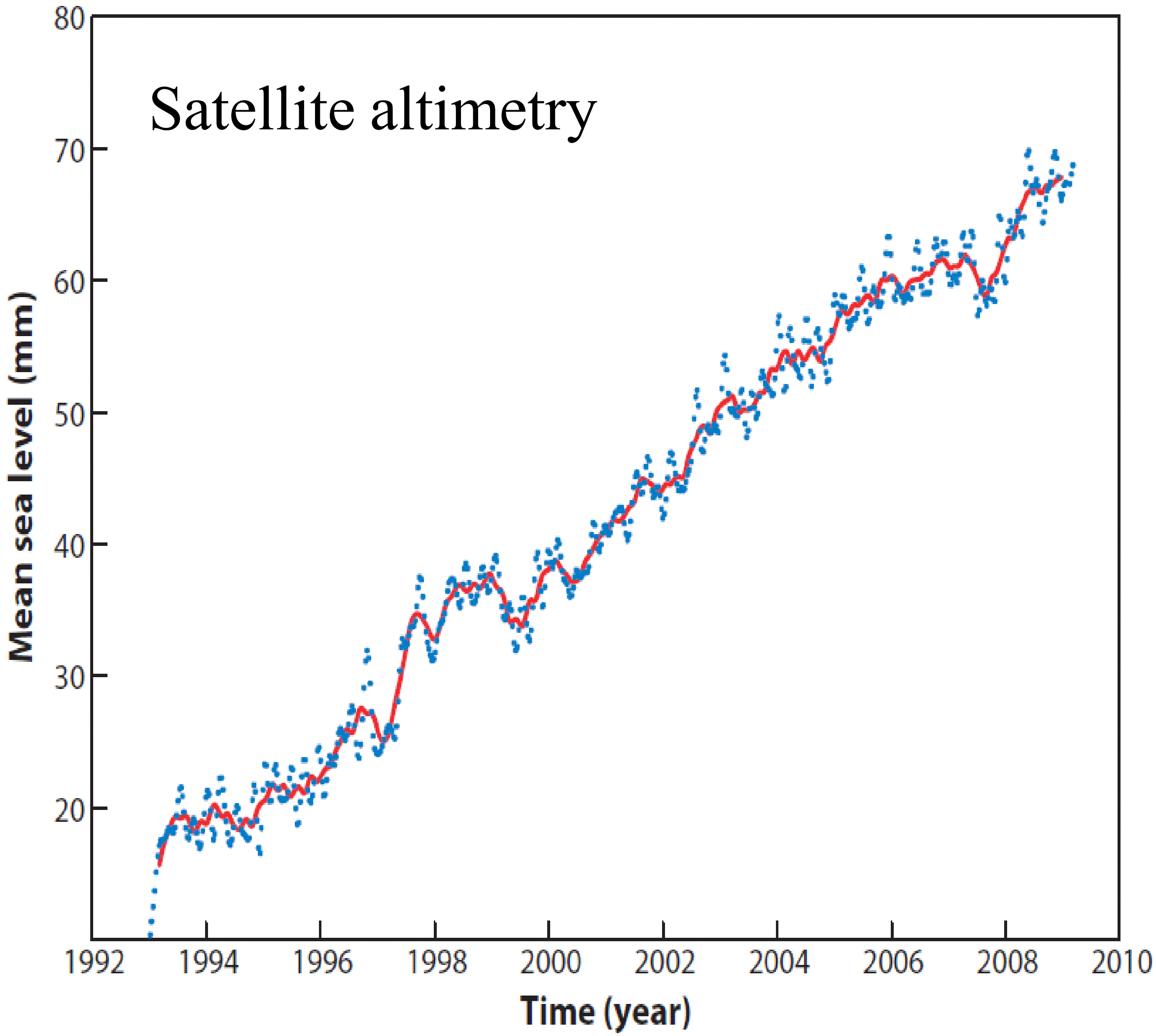
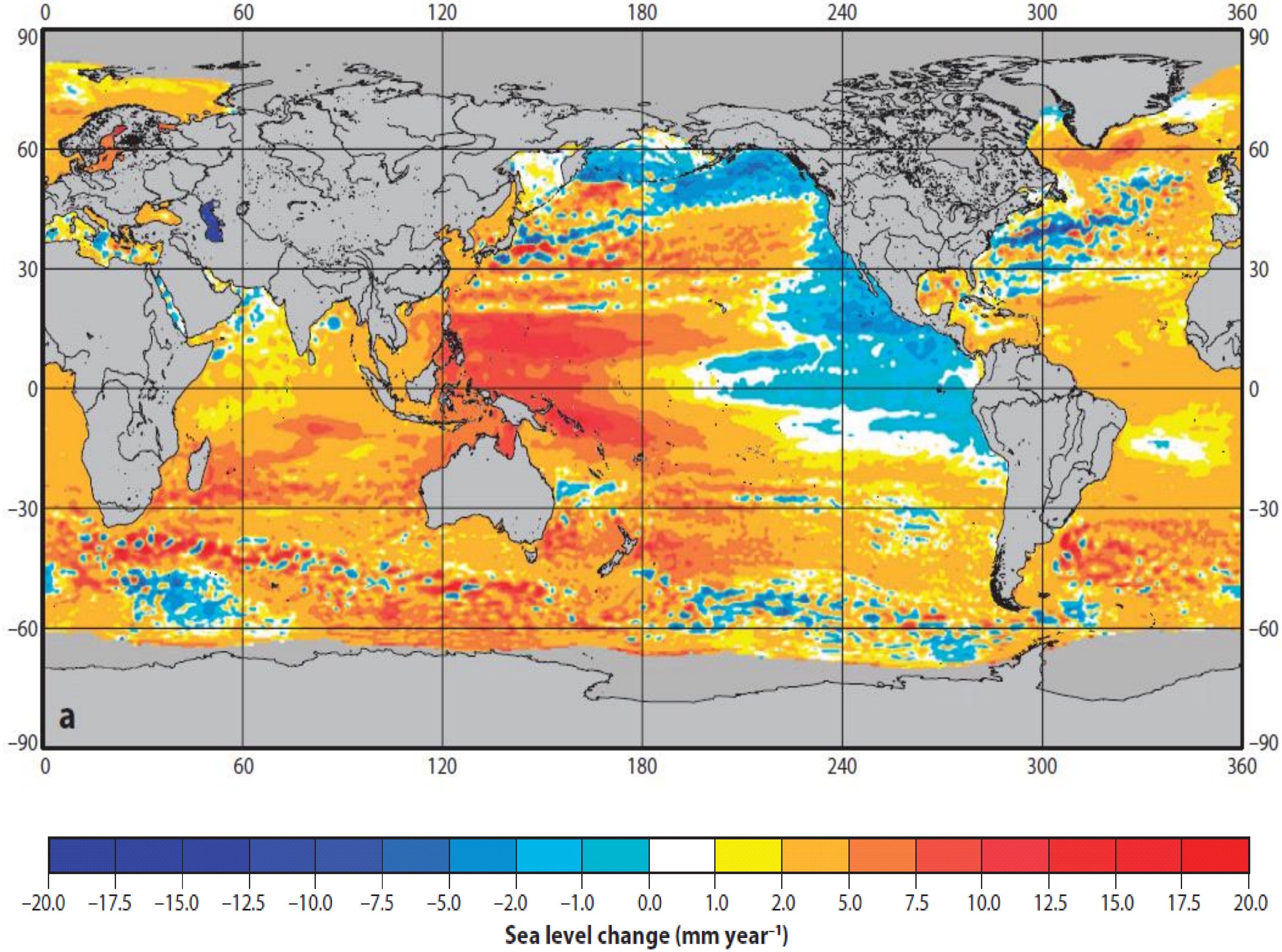


Figure 2

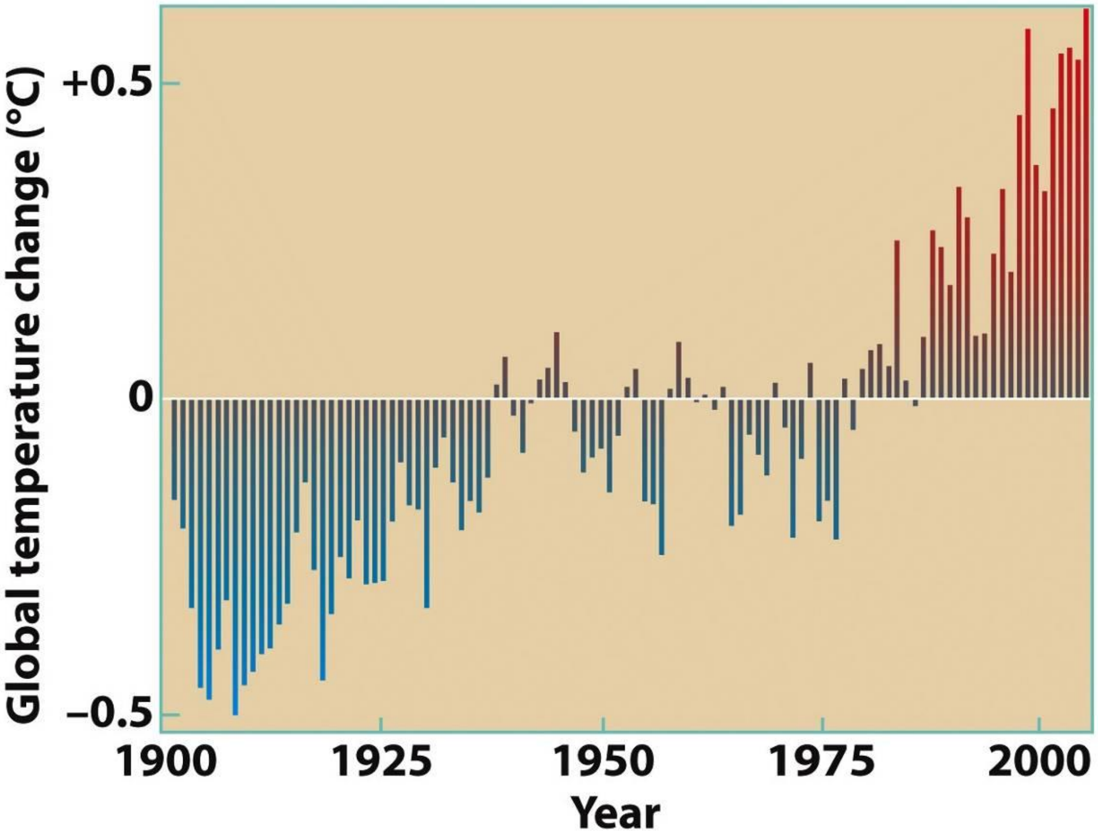
Global mean sea level from satellite altimetry between January 1993 and December 2008. Annual cycle has been removed. Blue dots are raw 10-day data. Red line corresponds to a 90-day smoothing of the raw data. The −0.3 mm year^{-1} GIA correction has been removed.

Spatial trends in sea level 1993-2008.
Data indicate global average rise of 3.4 ± 0.4 mm/y



To forecast future SL changes we must understand past temperature and SL changes

Global average temperature change adjusted for the urban heat island effect. Diagram represents T anomaly relative to the 1900-2000 average.



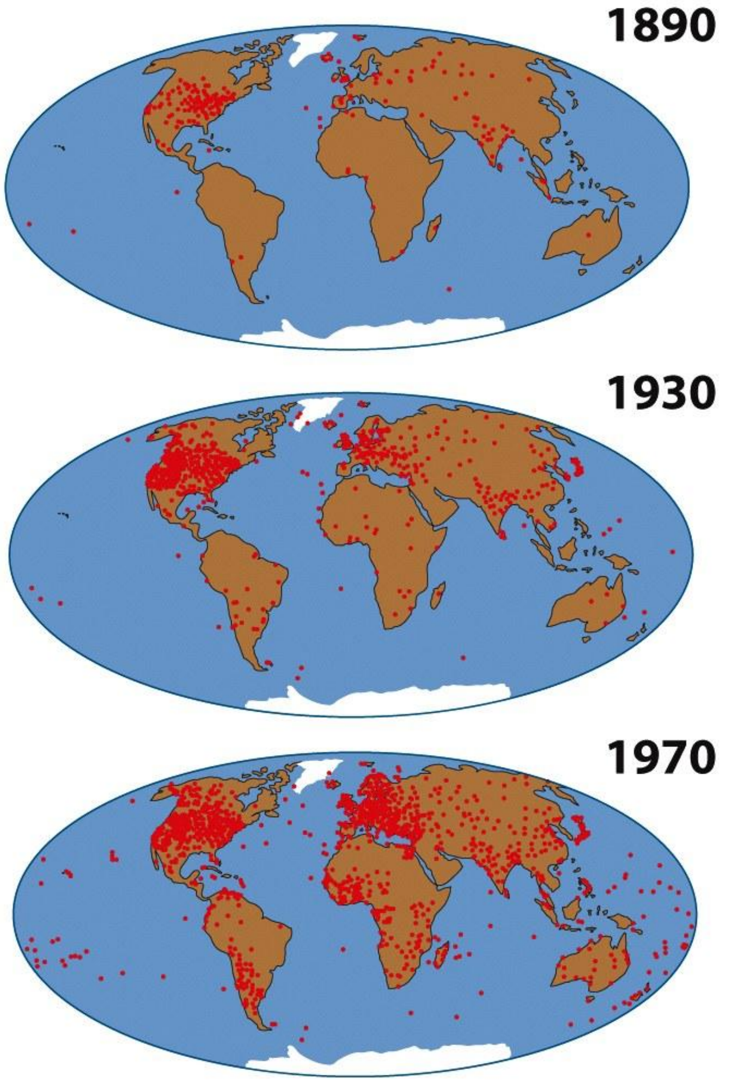


Figure 17-8
Earth's Climate: Past and Future, Second Edition

OCEAN WARMING

Heat moves downward by conduction, molecular diffusion and mass transport (convection and advection)

Total integrated warming for latter half of 1900s is 0.06ºC. 10x greater than the atmospheric heat storage.

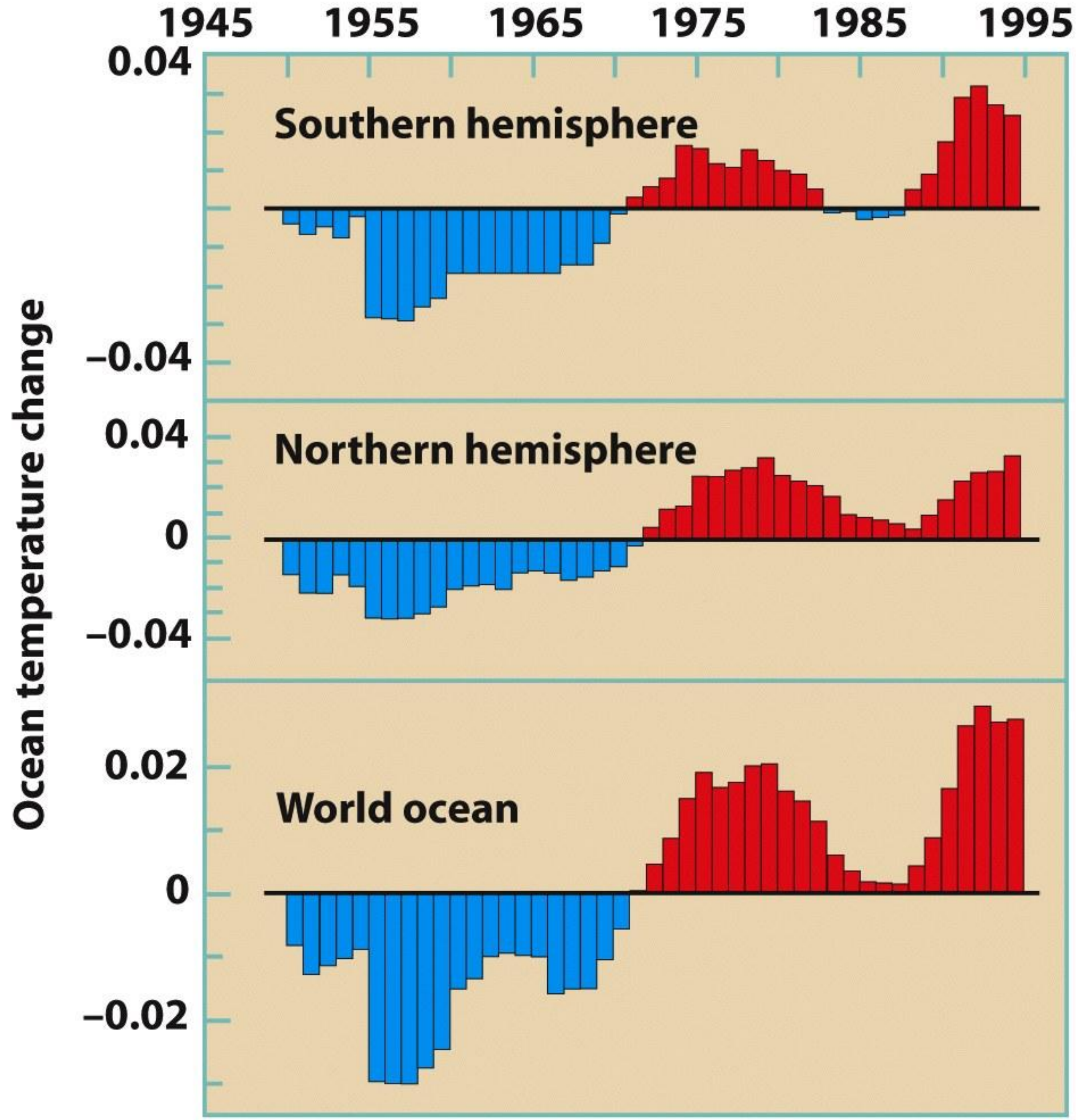


Figure 17-10
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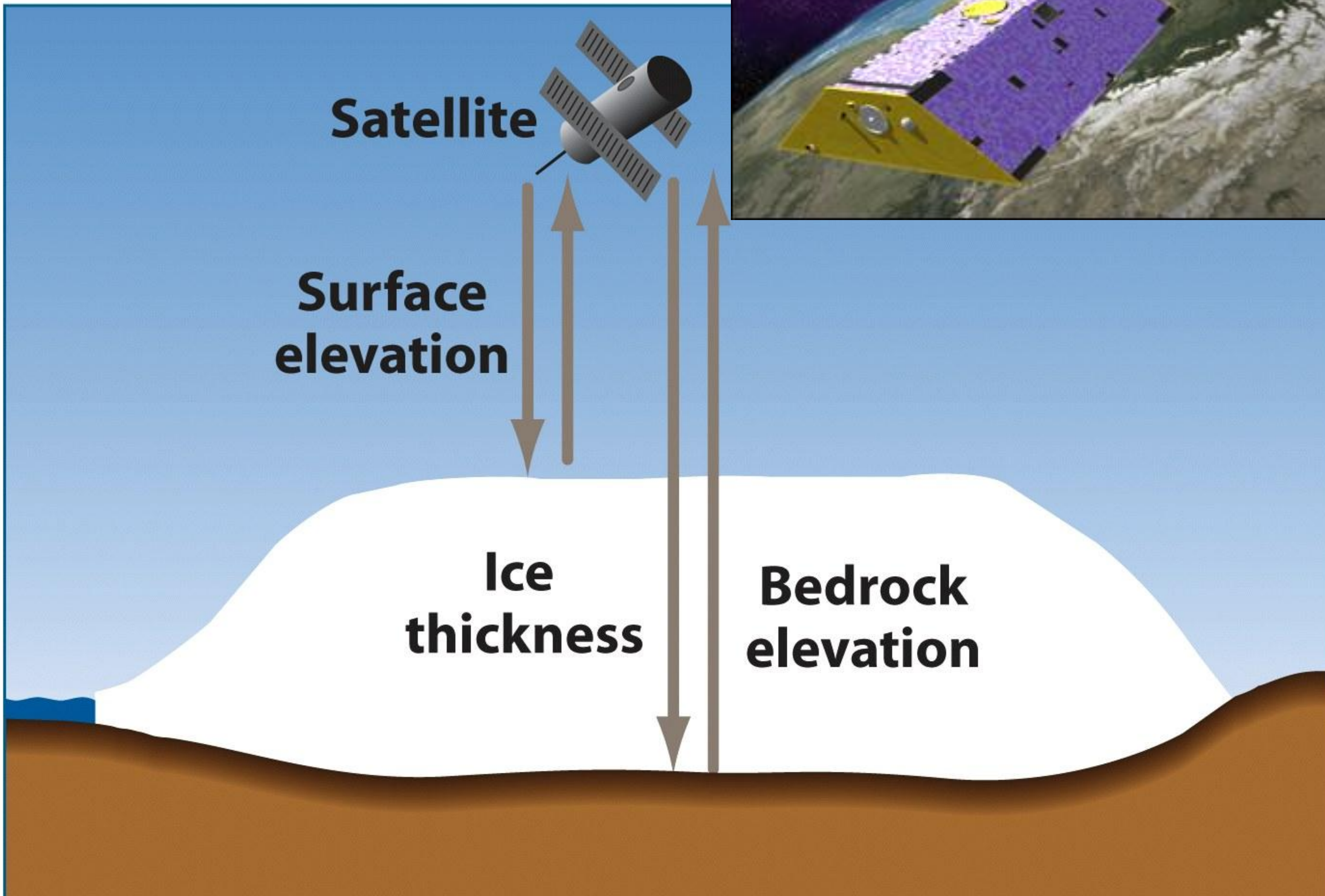
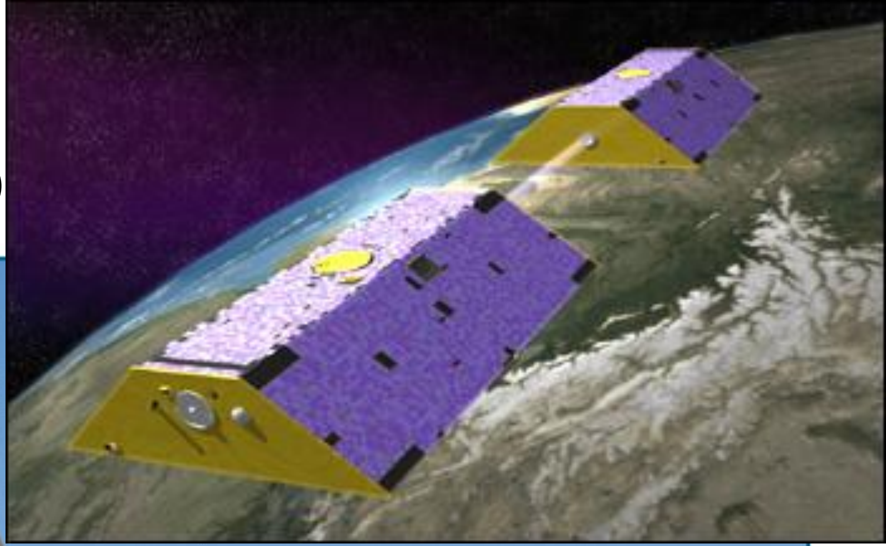
Gravity Recovery and Climate Experiment

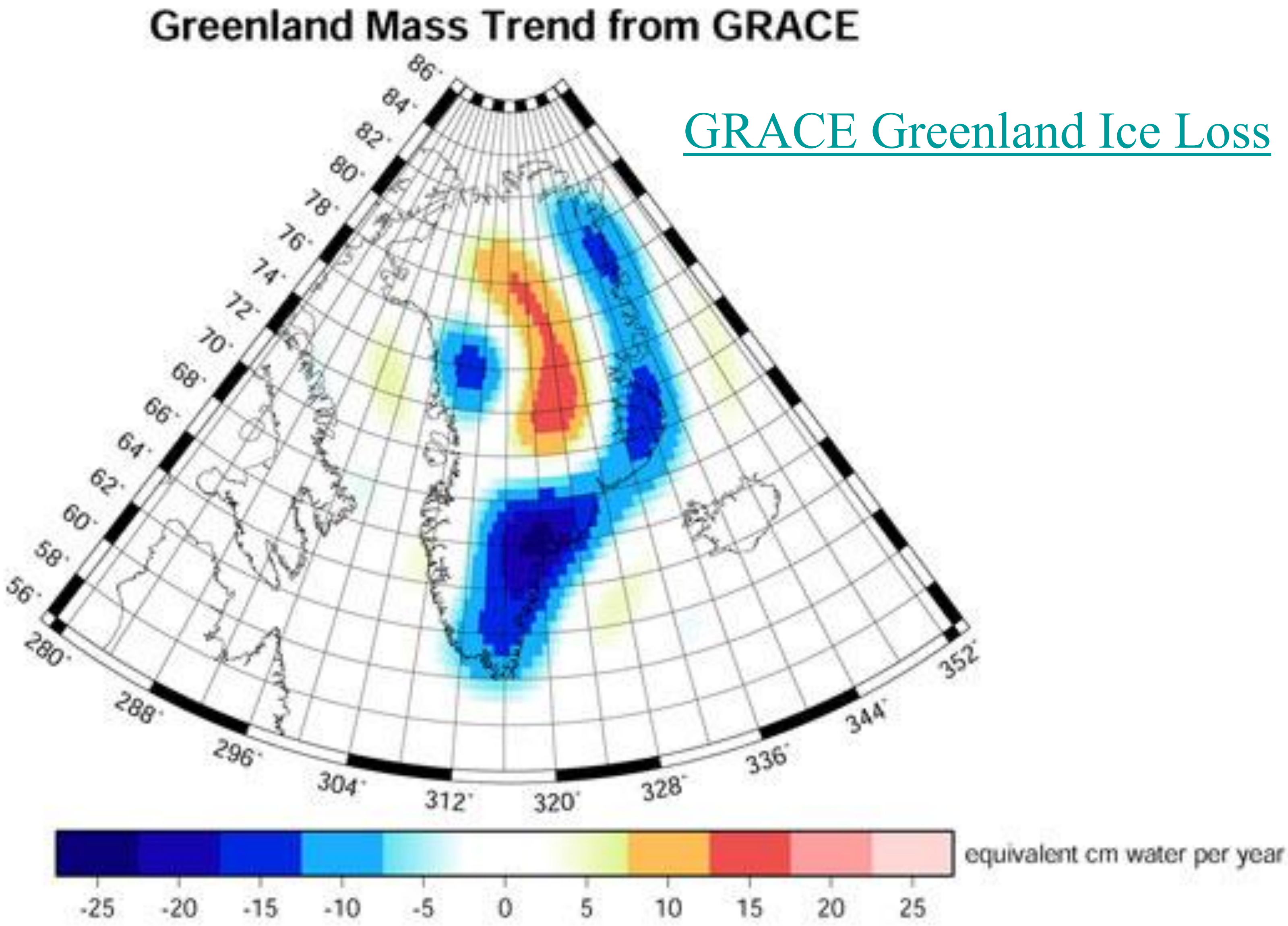
Geoscience Laser Altimetry System (GLAS)





Data indicate Greenland is losing 20% more mass than it receives in new snowfall each year

[GRACE Greenland Ice Loss]



Melting affects sea level as well as deep water formation

Reduced deep water formation may cool temps in Europe

Meltwater from Greenland alone is adding ~0.5 mm/y of sea-level rise

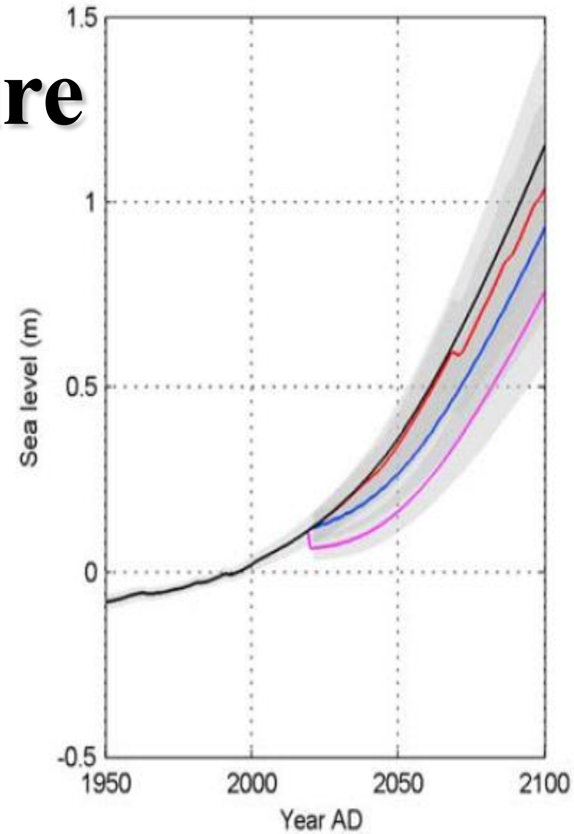
Ice sheet melting is contributing to 80% of the rise now (up from 50% in 2003)

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L07703, doi:10.1029/2010GL042947, 2010

How will sea level respond to changes in natural and anthropogenic forcings by 2100?

S. Jevrejeva,[1] J. C. Moore,[2] and A. Grinsted[3]

The Future



Current rate of rise is ~3.2-3.4 mm/y
Has accelerated over the last century from ~1.8 mm/y.

Models regress past temperature or radiative forcing with sea-level change to project into the future using emission scenarios (which dictate future radiative forcing).

Rahmstorf, 2007. Science 315

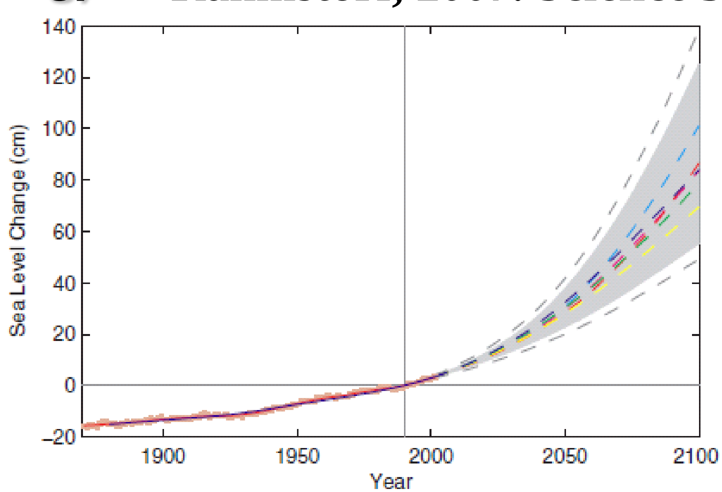


Figure 3. Sea level projection using model parameters based on fitting past sea level to forcings from *Crowley et al.* [2003] with A1Fi IPCC scenario (black solid line) since 2001; with A1Fi plus impacts from volcanic forcing scenarios "13th century" (red); with A1Fi and effect of a Pinatubo eruption every four year (blue) since 2020; with A1Fi and effect of Pinatubo eruption every two year (magenta) since 2020.

Sea level projections to AD2500 with a new generation of climate change scenarios

S. Jevrejeva [a,*], J.C. Moore [b,c,d], A. Grinsted [e]

Global and Planetary Change 80–81 (2012) 14–20

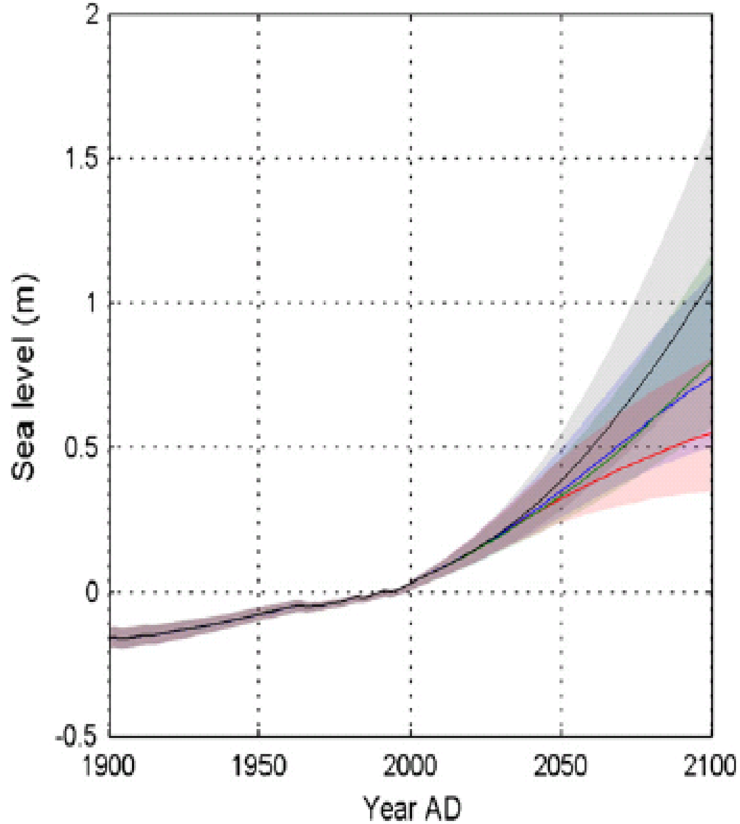


Fig. 3. Sea level projections by 2100 with RCP scenarios; red– RCP3PD, blue– RCP4.5, green– RCP6 and black – RCP8.5. Shadows with similar colour around sea level projections are upper (95%) and low (5%) confidence levels.

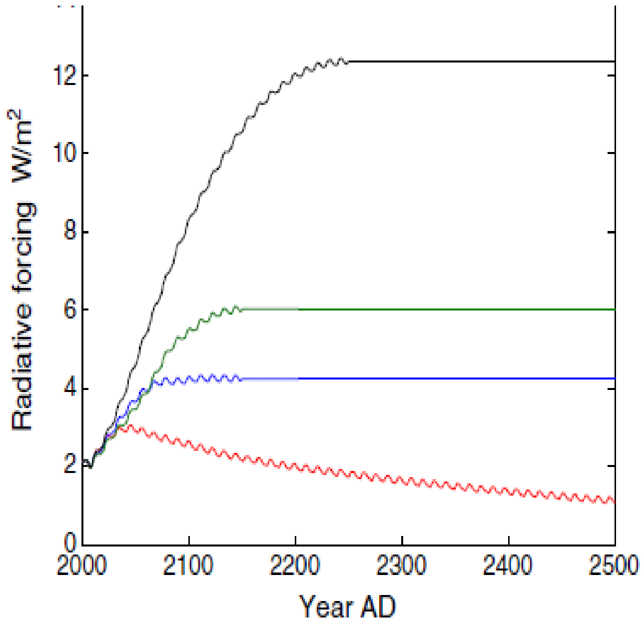


Fig. 1. Radiative forcings for the RCP scenarios; red– RCP3PD, blue– RCP4.5, green– RCP6 and black – RCP8.5.

Table 3
Projected sea level rise (m) by 2100 for the RCP scenarios. Results presented as median, upper (95% confidence interval) and lower (5% confidence interval) limits, calculated from 2,000,000 model runs. Sea level rise is given relative the period 1980–2000. Results are give as average of the experiments named CBK_2003 [Crowley et al., 2003], TBC_2006 [Tett et al., 2007] and GRT_2005 [Goosse et al., 2005].

RCP scenarios	Sea level rise (m)		
	5%	50%	95%
RCP8.5	0.81	1.10	1.65
RCP6	0.60	0.84	1.26
RCP4.5	0.52	0.74	1.10
RCP3PD	0.36	0.57	0.83

Testing the robustness of semi-empirical sea level projections

Stefan Rahmstorf · Mahé Perrette · Martin Vermeer

Clim Dyn
DOI 10.1007/s00382-011-1226-7

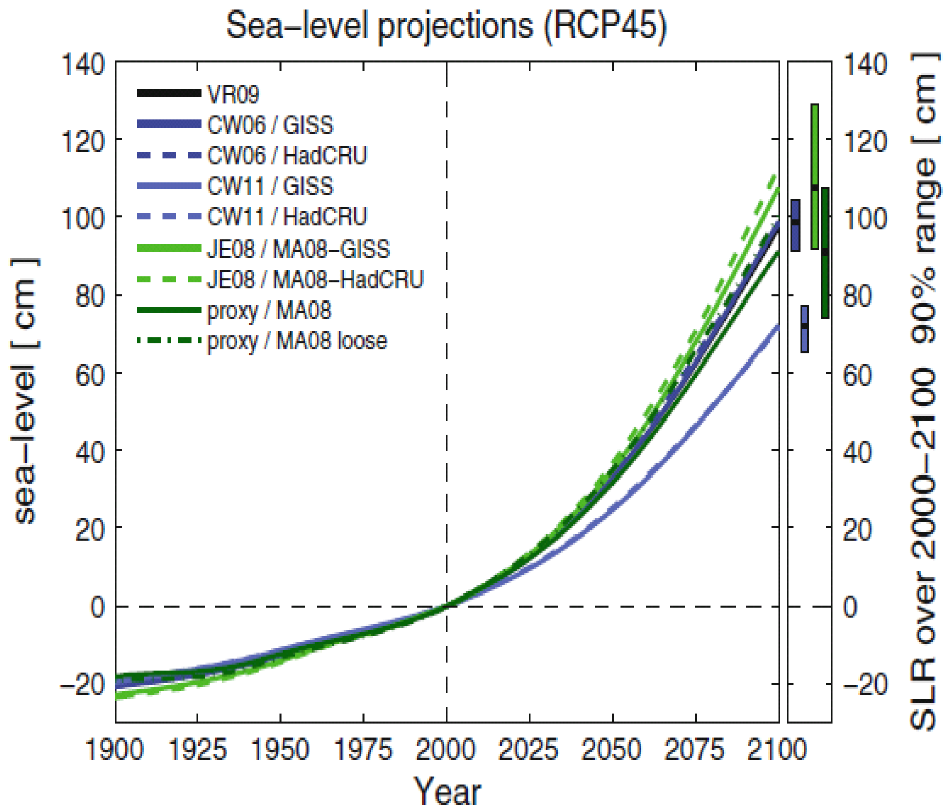


Fig. 8 Sea level hindcasts and projections driven by the temperature scenario shown in Fig. 4 for different models calibrated with different temperature and sea level data. The *error bars* on the *right* indicate 90% confidence intervals (5–95 percentile, using the GISS temperature dataset); for the proxy-based projection the uncertainty is as presented in Kemp et al. (2011)

IPCC Temperature Forecasts are right on the money

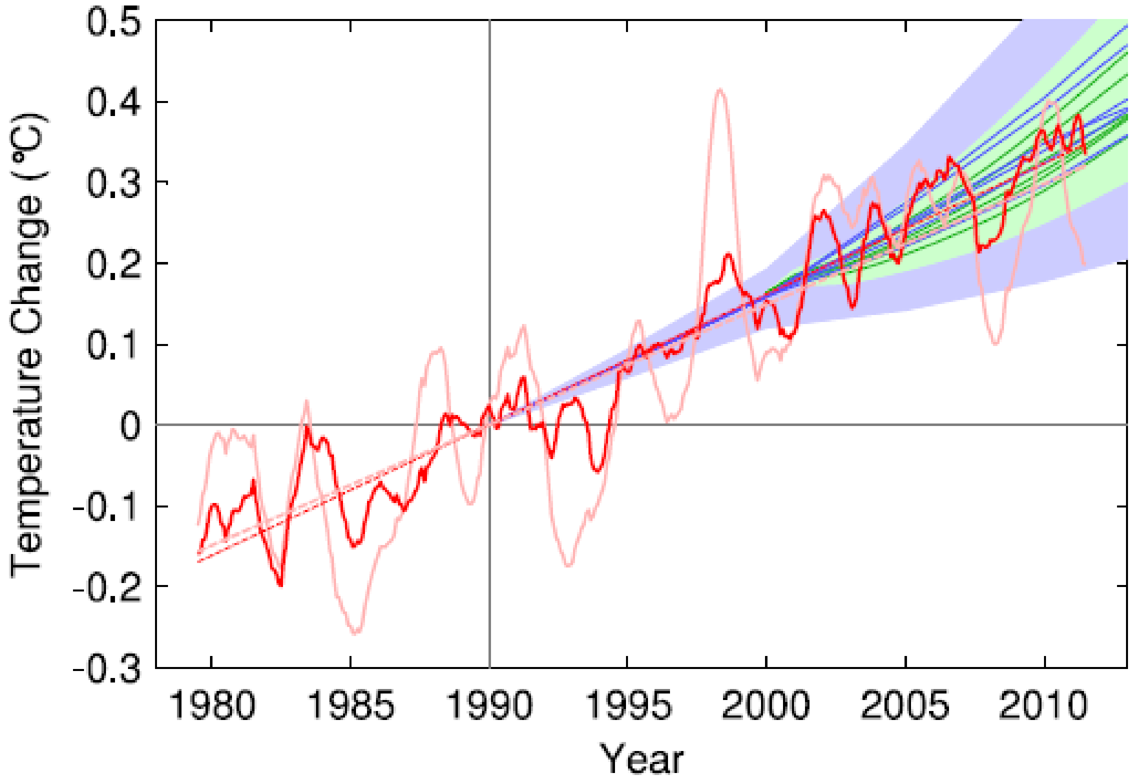


Figure 1. Observed annual global temperature, unadjusted (pink) and adjusted for short-term variations due to solar variability, volcanoes and ENSO (red) as in Foster and Rahmstorf (2011). 12-months running averages are shown as well as linear trend lines, and compared to the scenarios of the IPCC (blue range and lines from the third assessment, green from the fourth assessment report). Projections are aligned in the graph so that they start (in 1990 and 2000, respectively) on the linear trend line of the (adjusted) observational data.

Rahmstorf et al. 2012, Environmental Research Letters 7, 044035

Sea-level rise is at the uppermost limit of IPCC forecasts

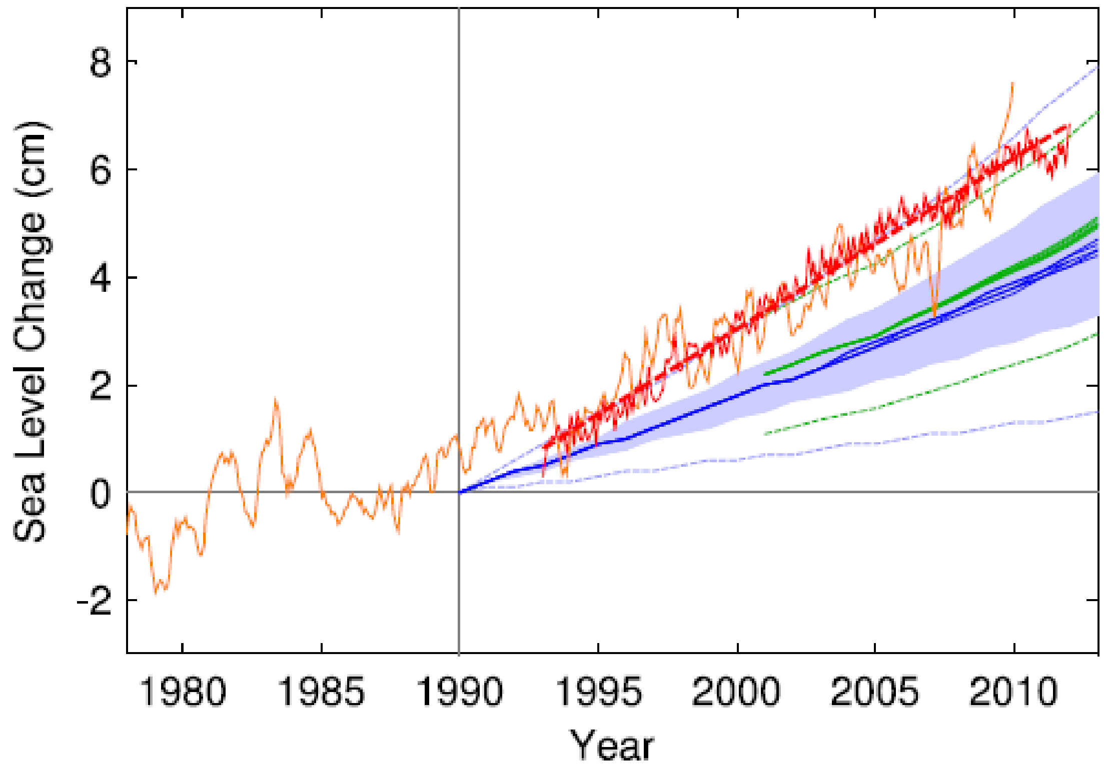


Figure 2. Sea level measured by satellite altimeter (red with linear trend line; AVISO data from (Centre National d'Etudes Spatiales) and reconstructed from tide gauges (orange, monthly data from Church and White (2011)). Tide gauge data were aligned to give the same mean during 1993–2010 as the altimeter data. The scenarios of the IPCC are again shown in blue (third assessment) and green (fourth assessment); the former have been published starting in the year 1990 and the latter from 2000.

Rahmstorf et al. 2012, Environmental Research Letters 7, 044035

A new view on sea level rise

STEFAN RAHMSTORF

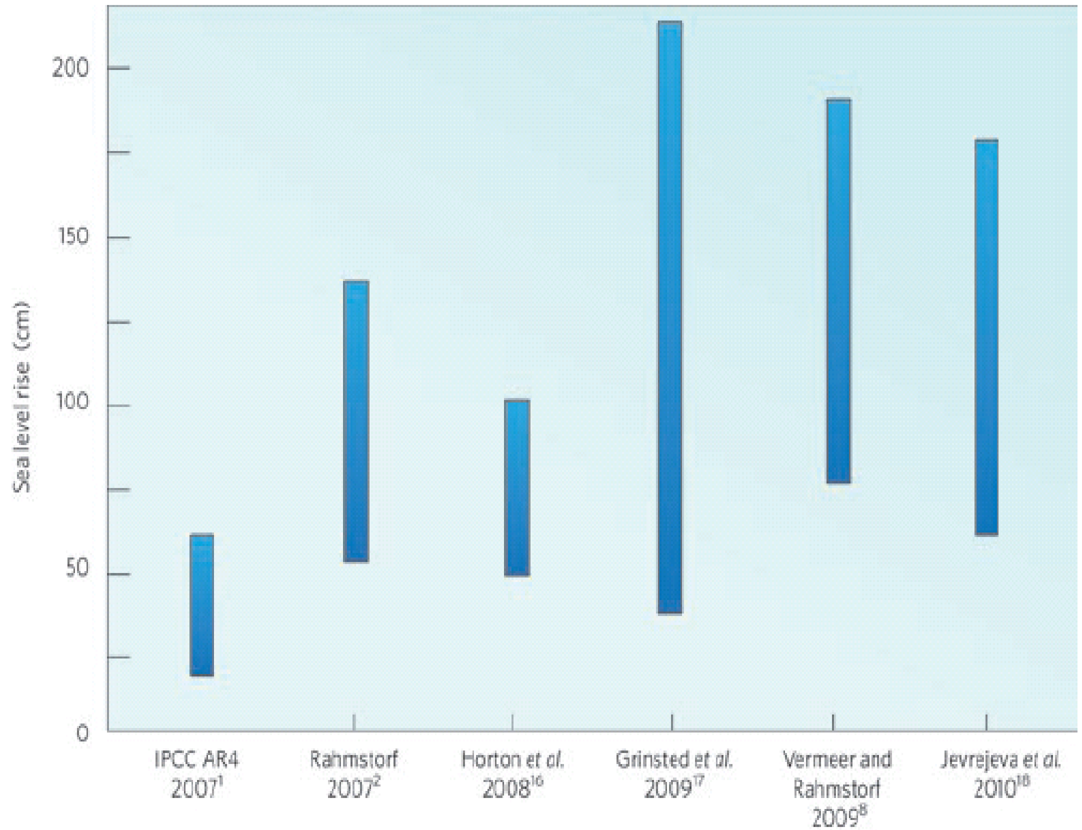
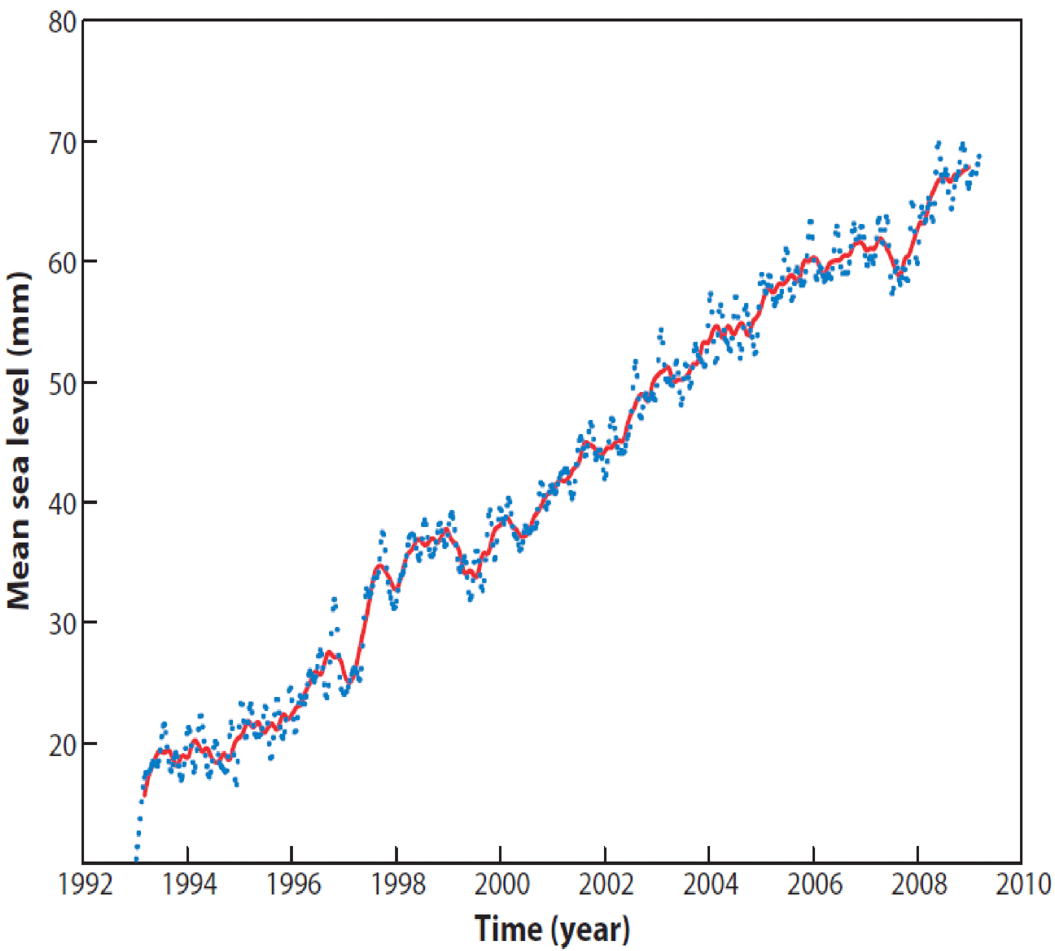
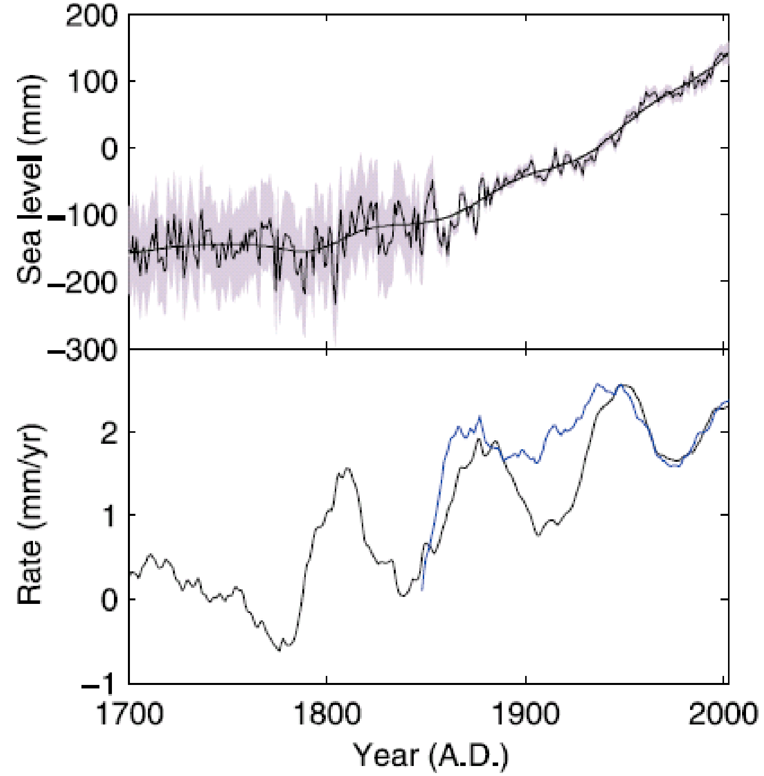


Figure 1 Range of rises. Estimates for twenty-first century sea level rise from semi-empirical models[2,8,16–18] as compared to the IPCC Fourth Assessment Report (AR4)[1]. For exact definitions of the time periods and emissions scenarios considered, see the original references.

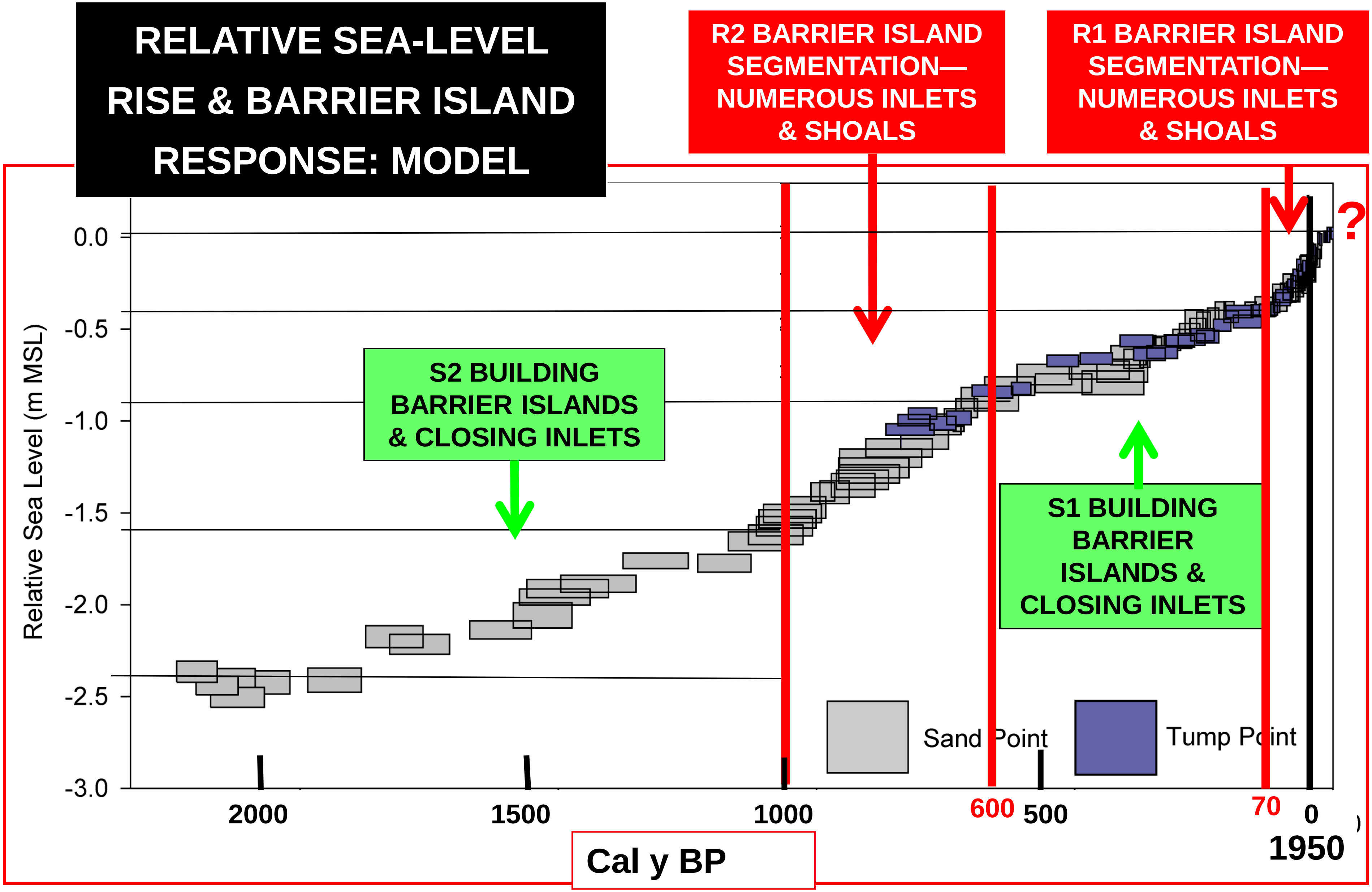
But, is it accelerating now?

Good question. Can't say with any confidence, statistically. Need another 5-10 years of data, depending upon how rapidly it might be accelerating (the more rapid, the sooner we'll know). Regardless, it certainly has accelerated in the past (at ~0.01 mm/y^2).





Jevrejeva et al. 2008. GRL 35

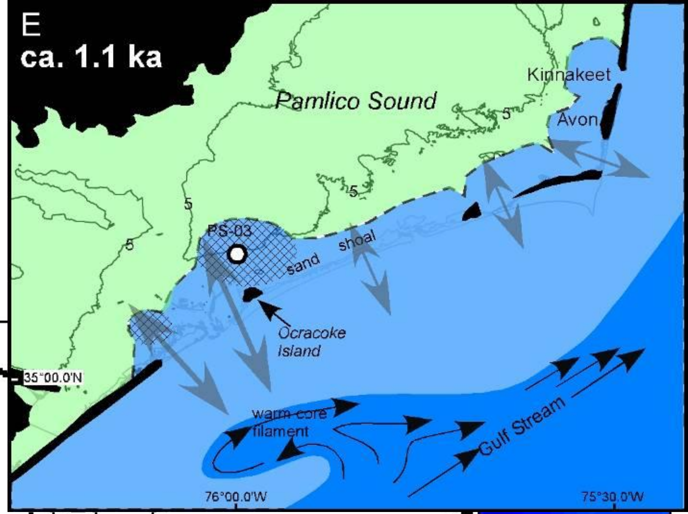


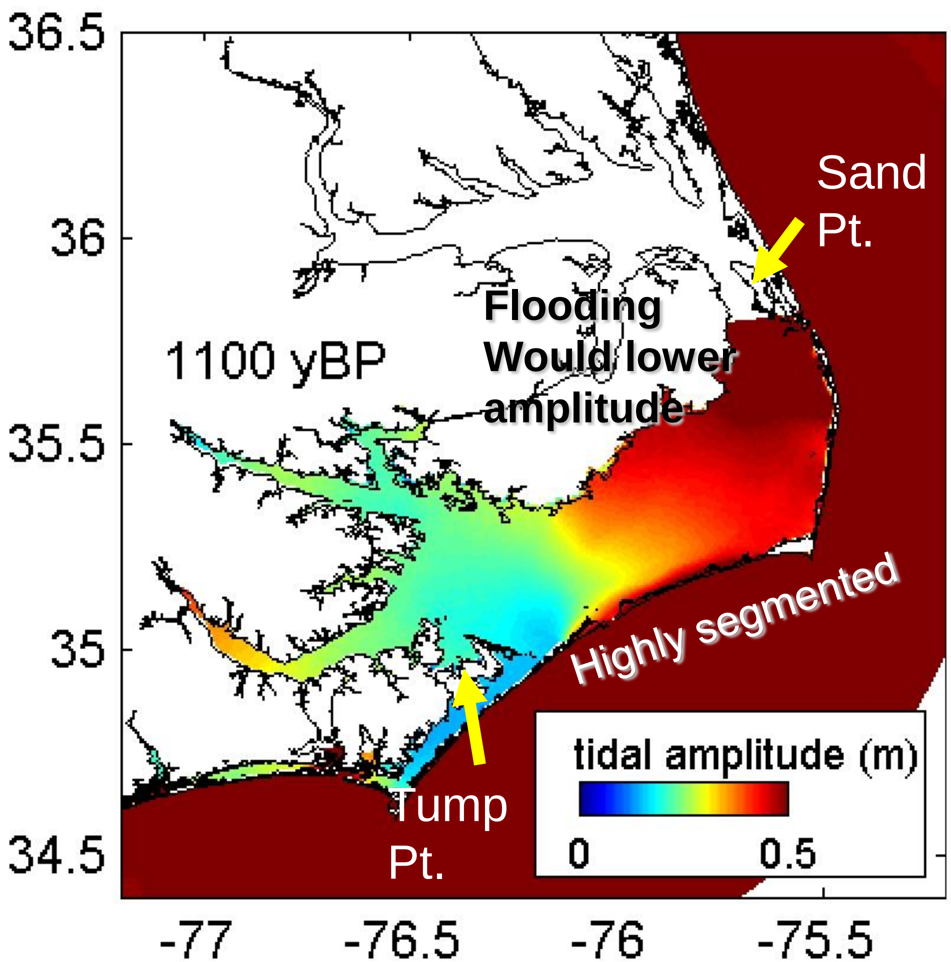
2100 YEAR NC RECORD OF RELATIVE SEA-LEVEL CHANGE

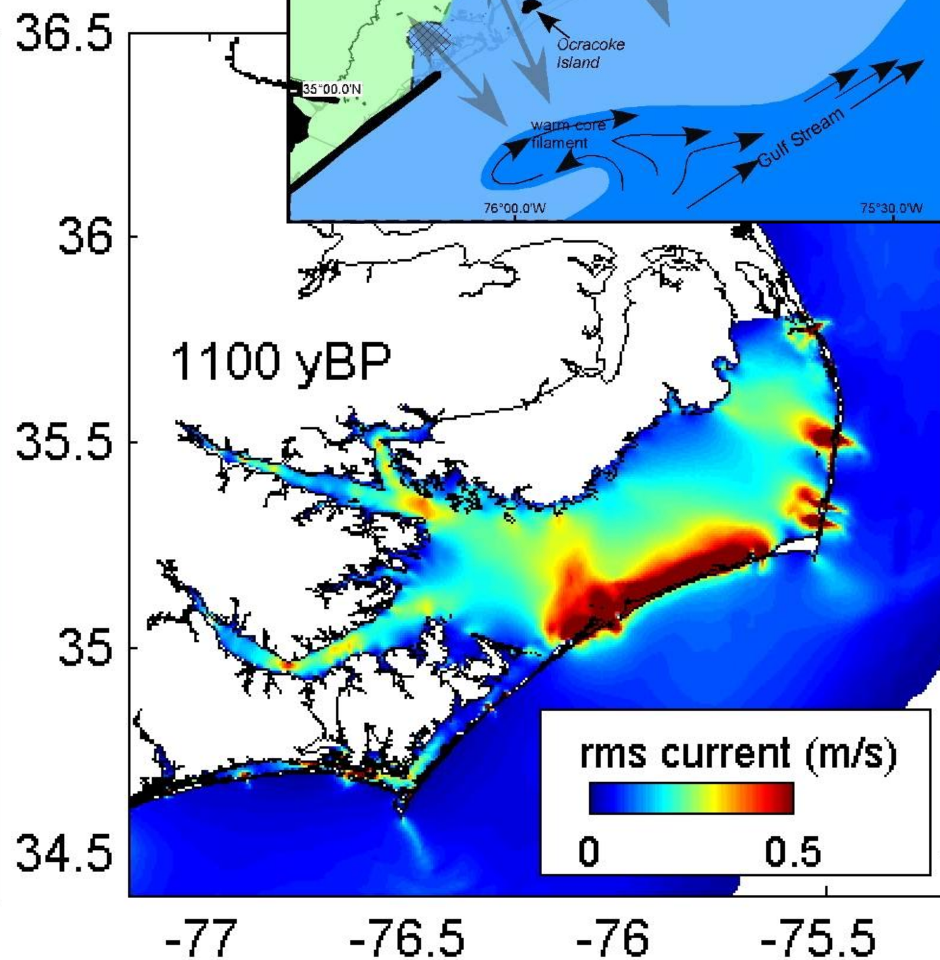
(Modified from Kemp et al., 2009 & Kemp et al., 2011)

DELFT3D MODEL

No bathymetric change (sed. accum. = ΔRSL);
<u>2 m</u> ave. shoal depth;
<u>CLOSED</u> through Croatan Sound







Suggests a 0.3 to 0.5 m increase in <u>amplitude</u> in northern Pamlico Sound and up the Neuse River

Artificial land/water boundary likely increases amplitude

The biggest future problem may NOT be the slow, steady inundation caused by SLR, but the rapid morphodynamic response that could potentially cause a change to a higher tidal regime.

Thank you!

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- Rob Thieler – USGS – Woods Hole
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