Sea Level Rise

Global Warming Science, EPS101

Xiaoting Yang and Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

Sea level rise in the news

A submerged burial ground in Fiji's Togoru village. Five seawalls built to protect it have been knocked down by rising waters.

https://www.nytimes.com/interactive/2014/03/27/world/climate-rising-seas.html

St Mark's Square in Venice on Nov 13, 2019. Sea level rise of 1.87 m, highest in more than 50 years, flooding over 85% of the city

https://www.theguardian.com/environment/2019/dec/10/venice-floods-sea-level-rise-mose-

Sea level rise in the news

"Mokbul Ahmed, standing on a Kutubdia beach fortified by concrete blocks, points to where he had lived and farmed. … much of Kutubdia has been swallowed by rising seas"

Sea level rise in the news

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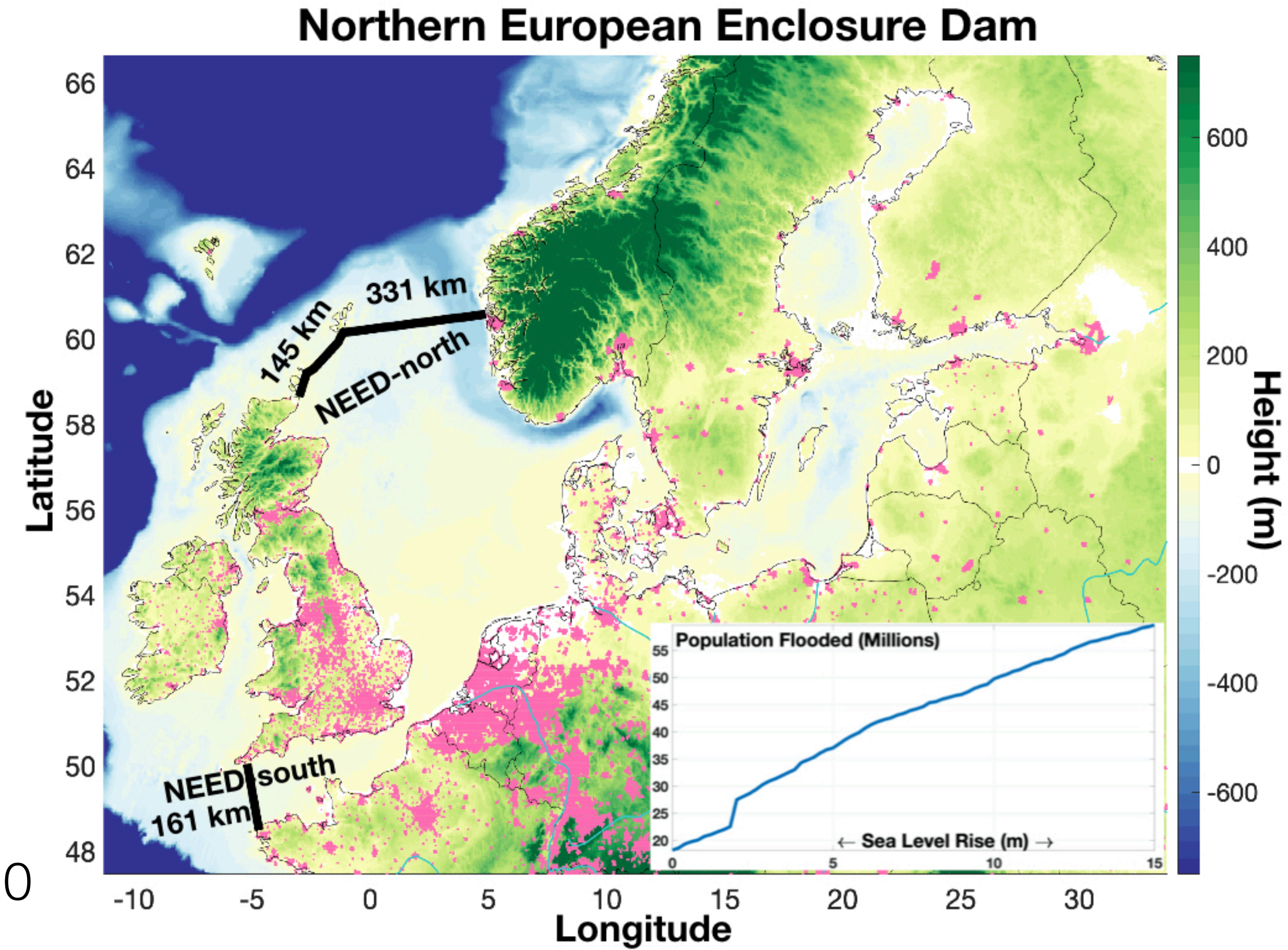
Sea level rise in the news

Current sea level rise is ~3.5 mm/year…

"Mokbul Ahmed, standing on a Kutubdia beach fortified by concrete blocks, points to where he had lived and farmed. … much of Kutubdia has been swallowed by rising seas"

“As Sea Levels Rise, Scientists Offer a Bold Idea: Dam the North Sea”

A proposal to build two huge barriers — one that would connect Norway to Scotland, the other France to England — was described as a warning about the urgency of the climate crisis. (NYTimes, Feb 2020)



Groeskamp and Kjellsson, BAMS 2020


Saemangeum Seawall
Afsluitdijk
Saemangeum Seawall in South Korea and the Afsluitdijk in the Netherlands
Groeskamp and Kjellsson, BAMS 2020

Saving Boston!

A report: "Feasibility of Harbor-wide Barrier Systems"

https://www.greenribboncommission.org/wp-content/uploads/2018/05/Feasibility-of-Harbor-wide-Barriers-Report.pdf

Sea level: definitions

- **Relative** sea level (RSL): the local height of the sea surface above the solid Earth. Can change due to ground uplift or coastal erosion. The global integral of RSL is the total water volume in the oceans.
- **Global mean sea level:** mean distance from Earth's center, reflects ocean volume.
- **Thermosteric sea level change** - Due to thermal expansion of seawater with warming.

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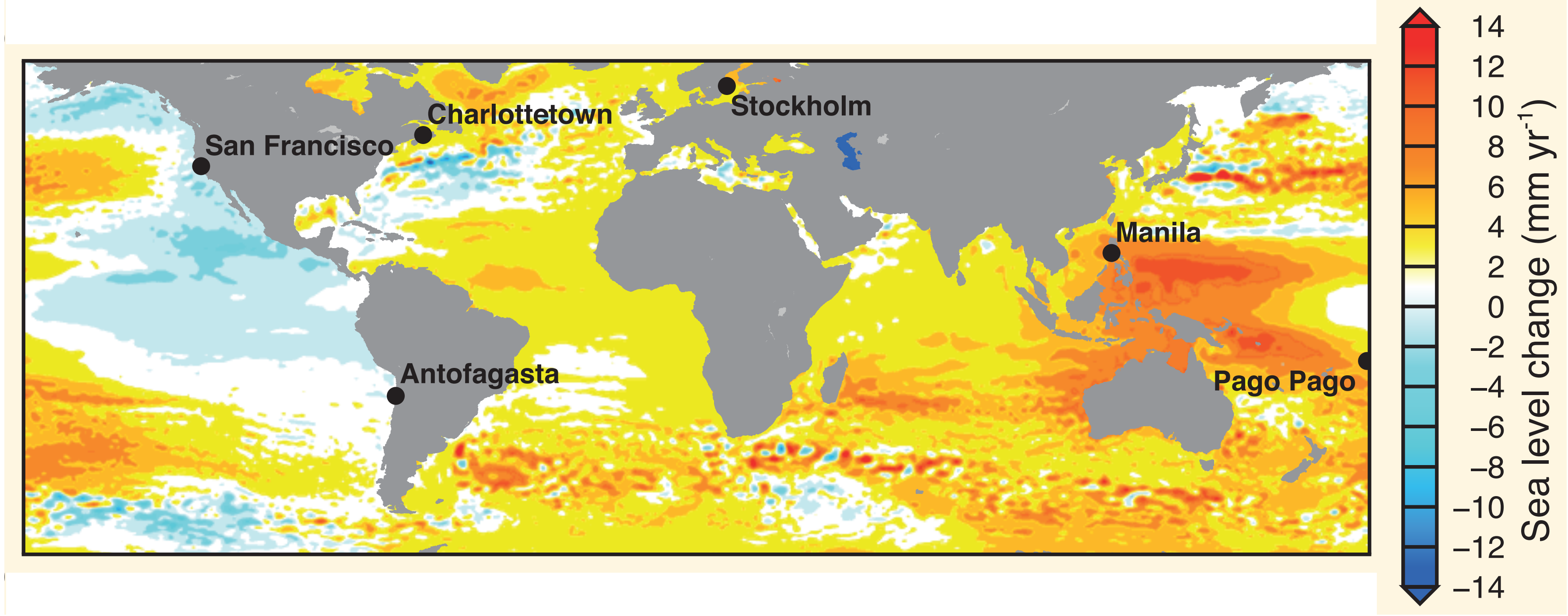
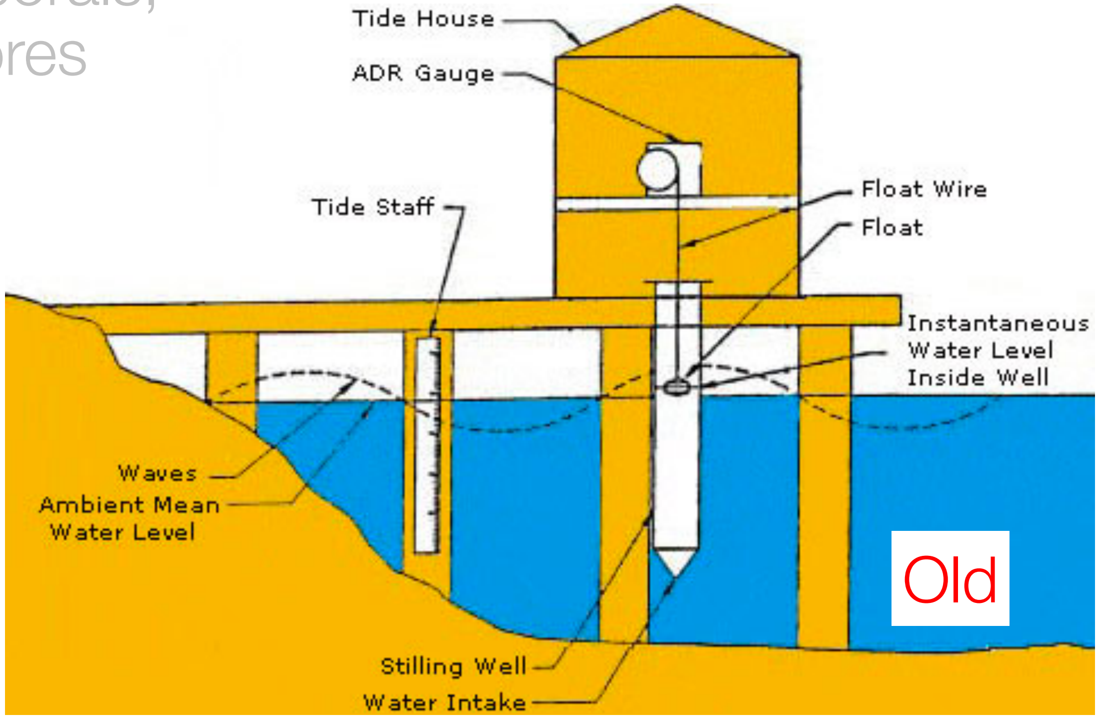


IPCC AR5, 2013

FAQ13.1, Figure 1 | Map of rates of change in sea surface height (geocentric sea level) for the period 1993–2012 from satellite altimetry.

Sea level: observation methods

- **Tide gauges**
- **Seafloor pressure sensors**
- Satellite altimeters
- Paleo proxies: corals, ancient sea shores



analog data recorder with a float

https://oceanservice.noaa.gov/facts/tide-gauge.html

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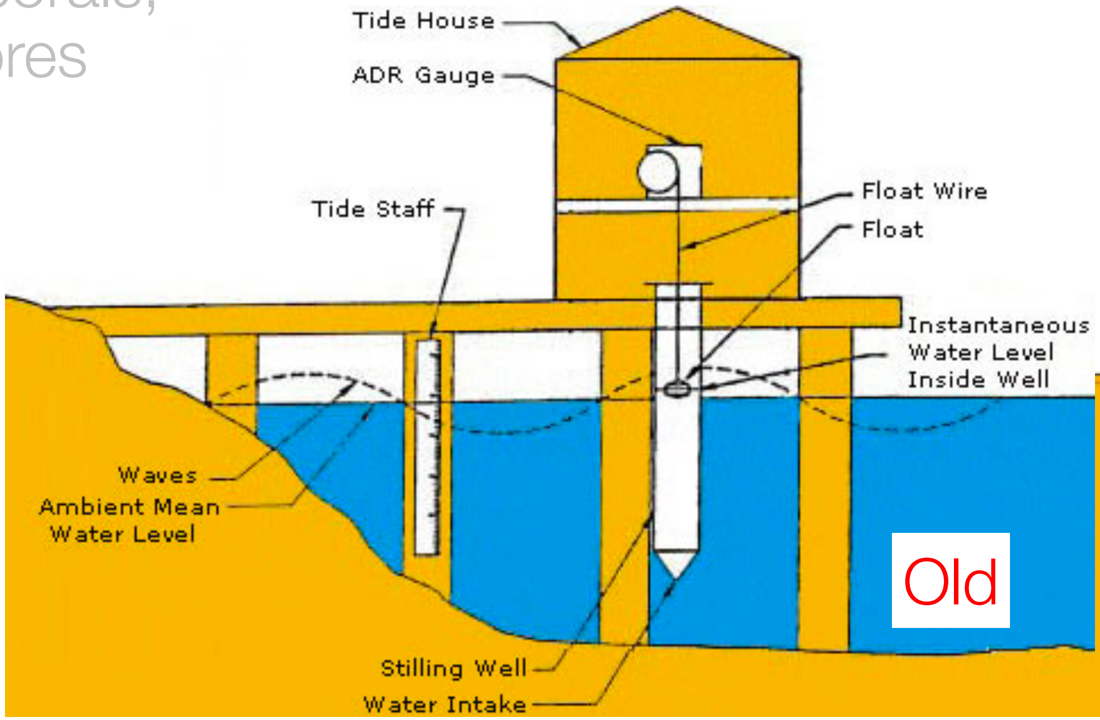

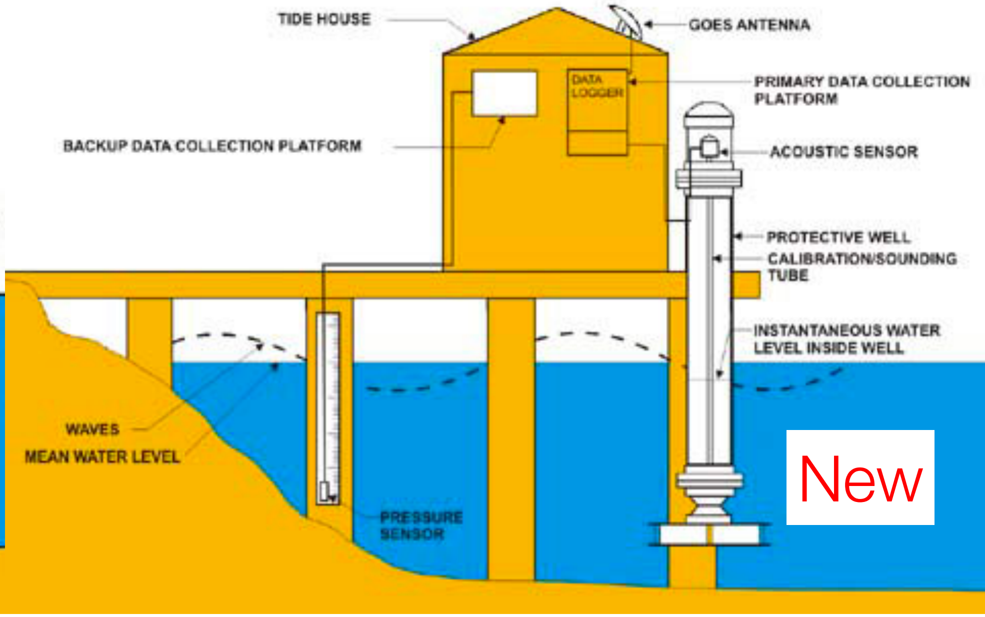

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measure time for audio signal to be reflected from water surface

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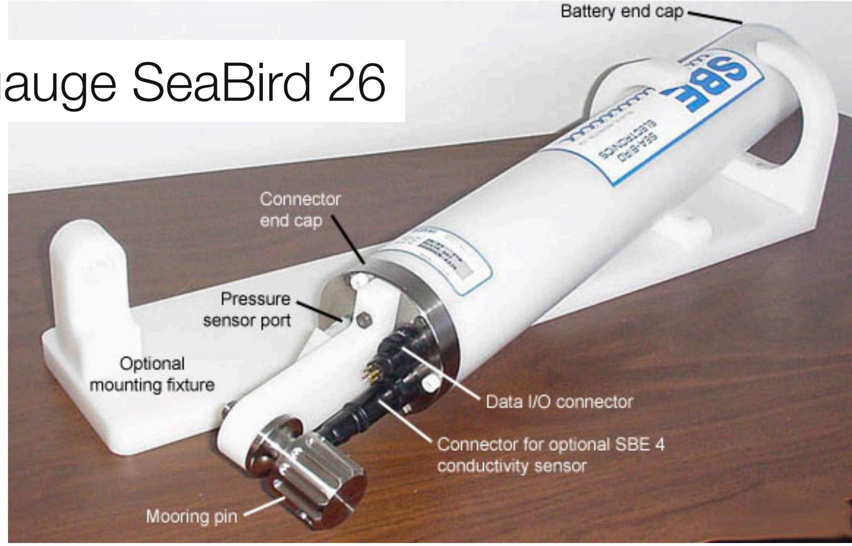
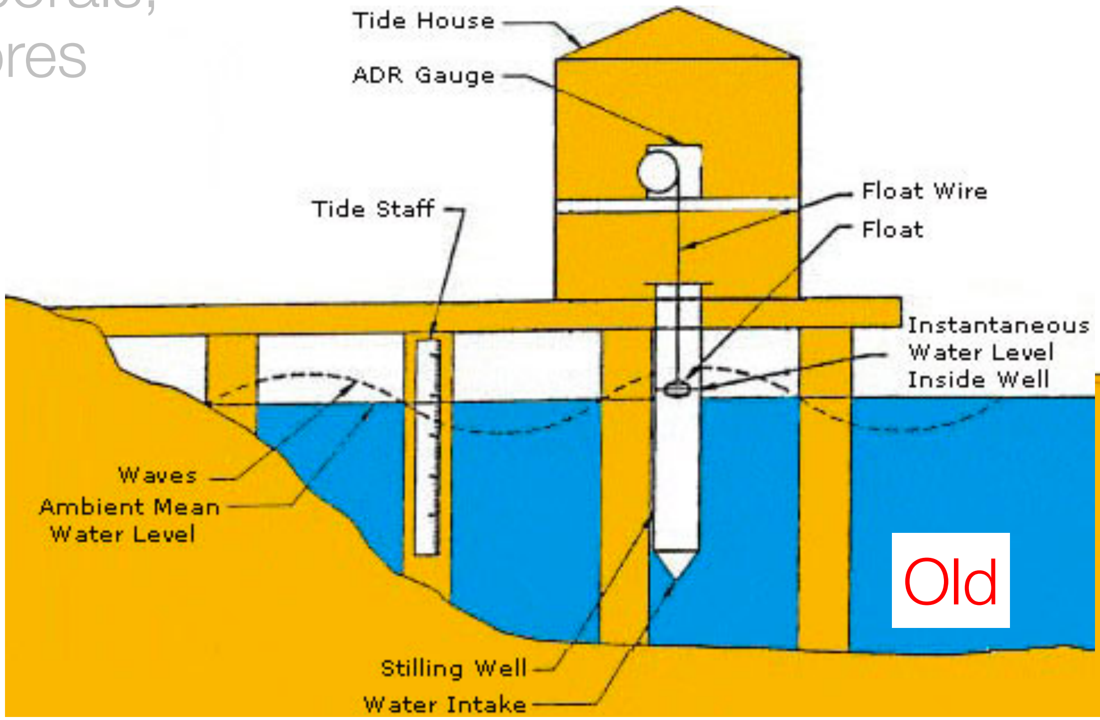
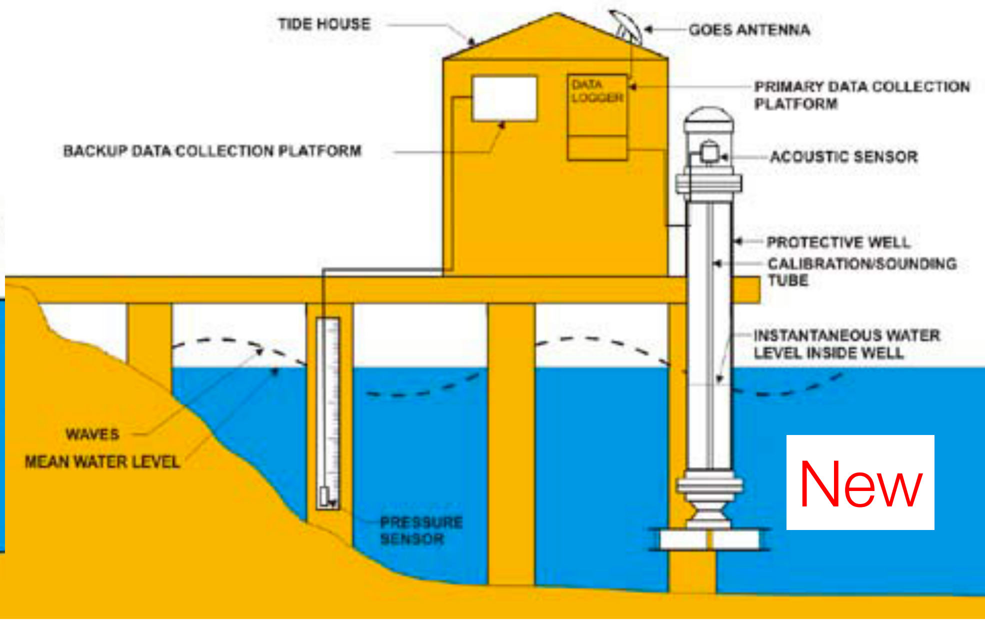
seafloor tide gauge SeaBird 26







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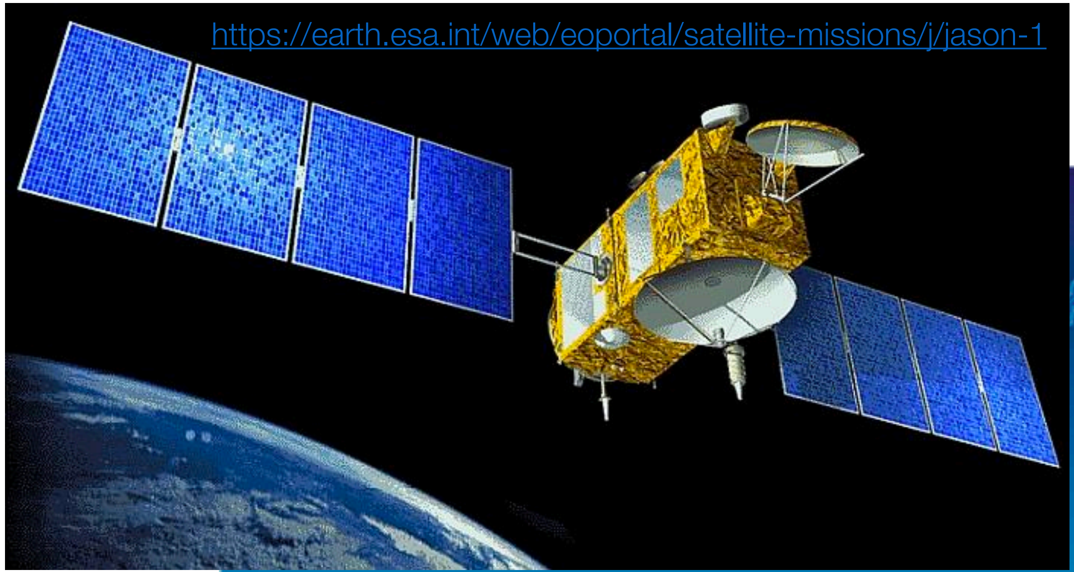

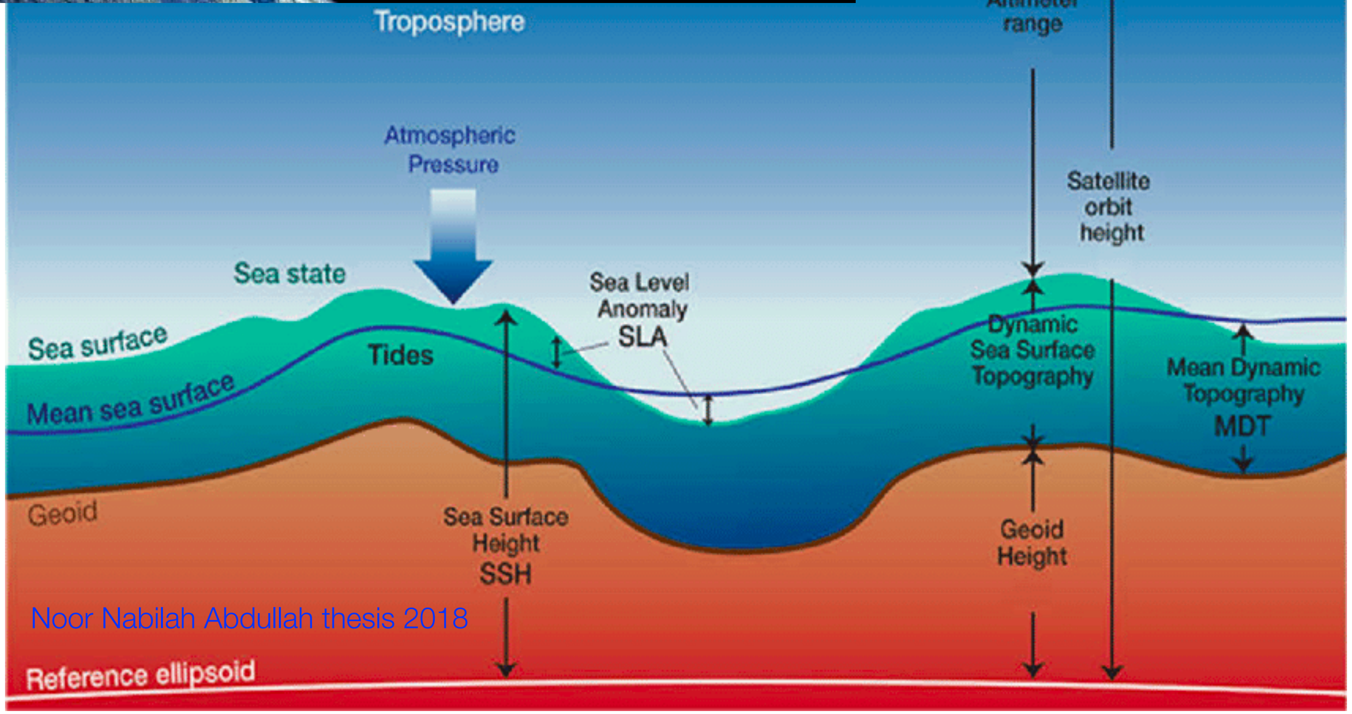

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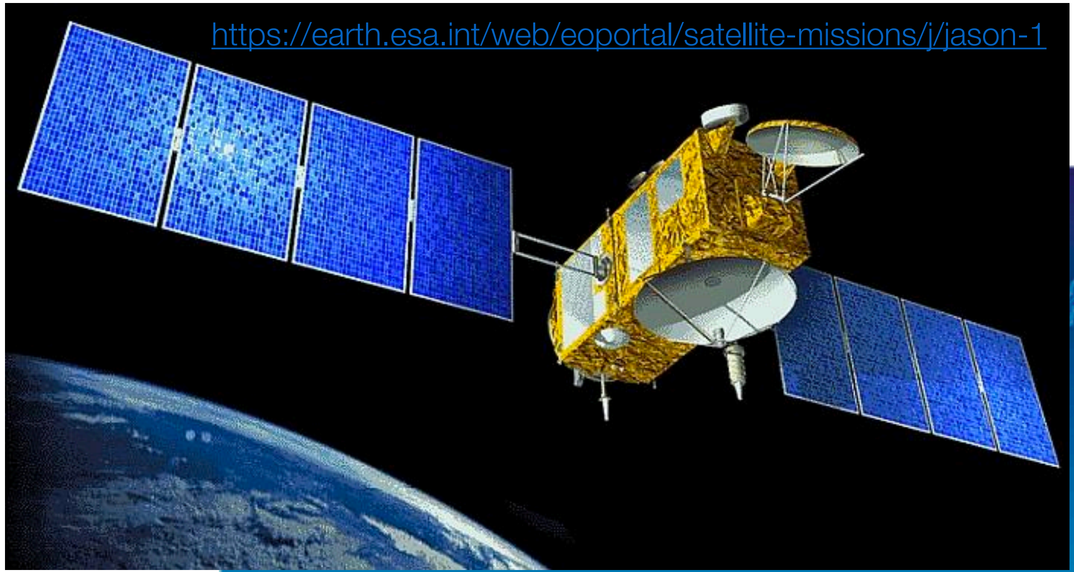

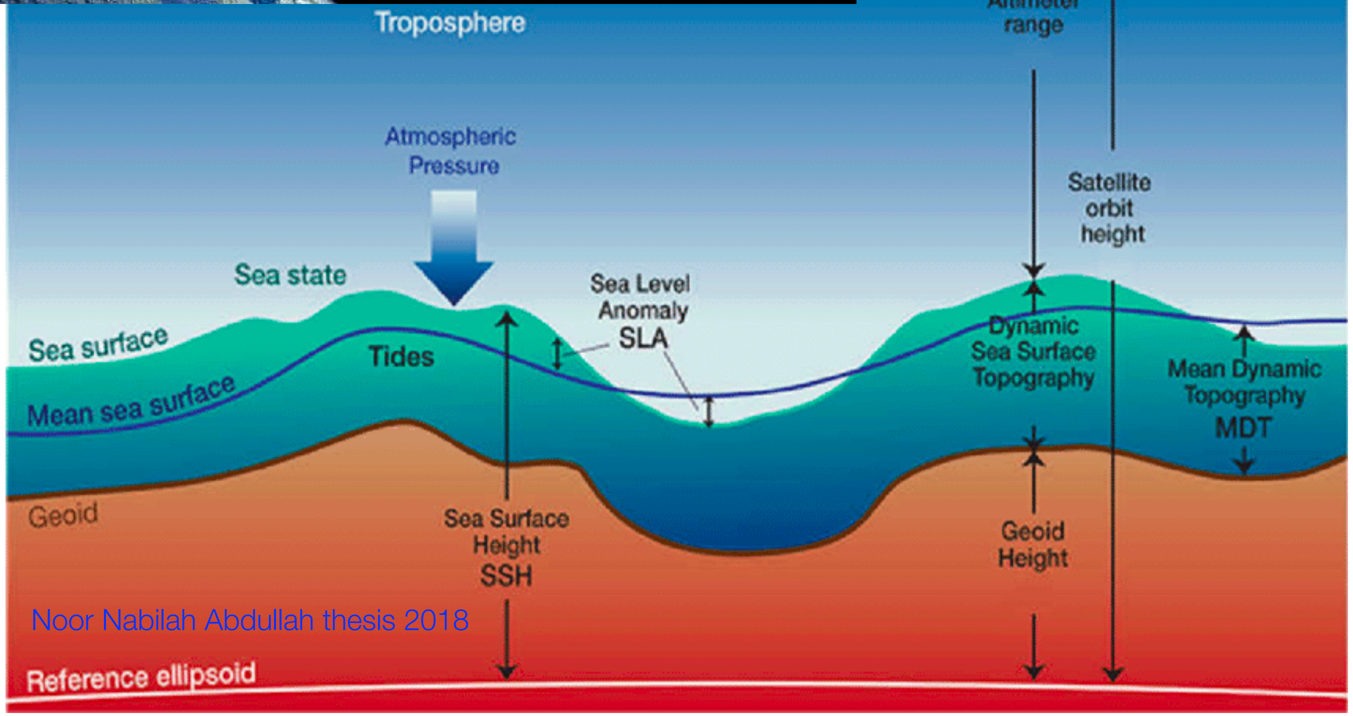

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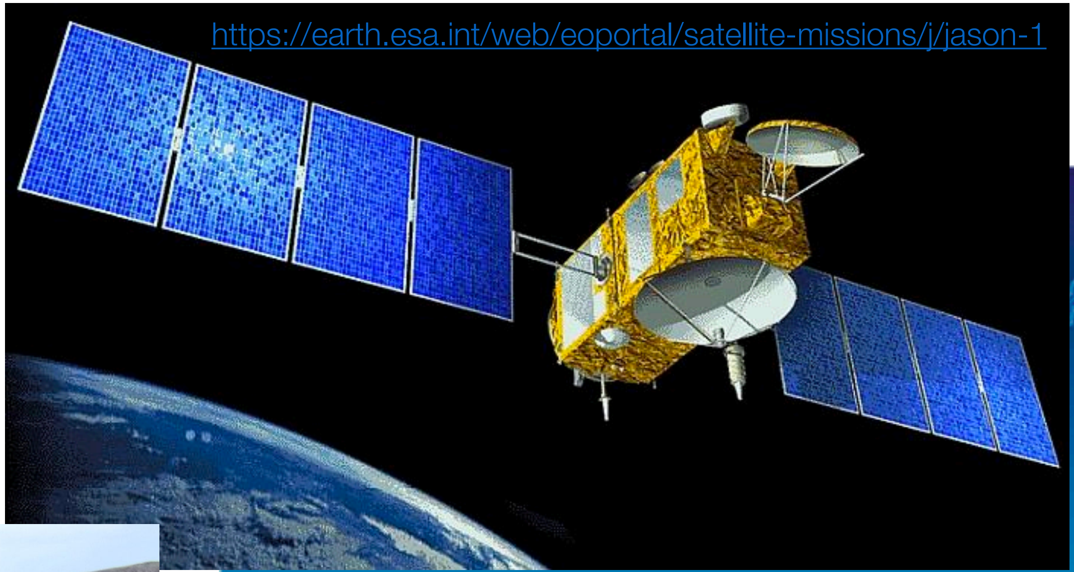

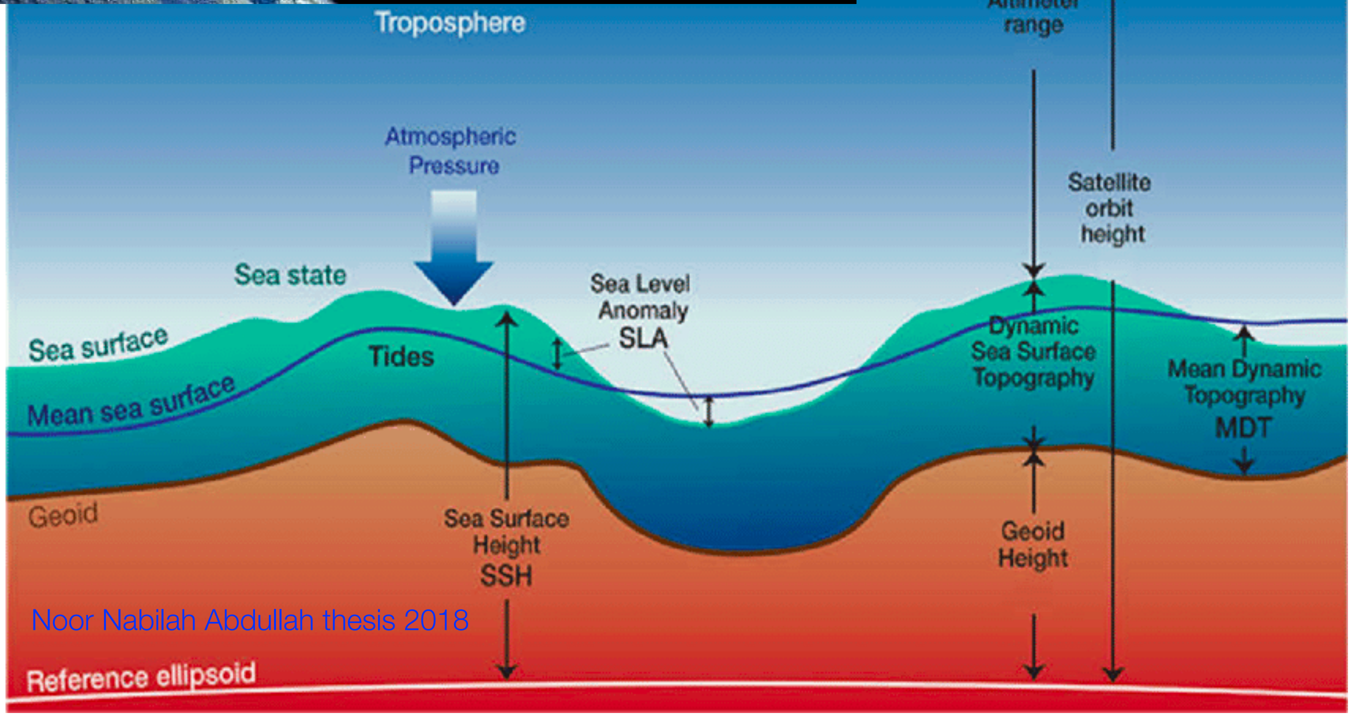

Ancient shorelines, Bathurst Inlet, Arctic Canada

workshop 1 a, b:
characterize sea level rise in time and space

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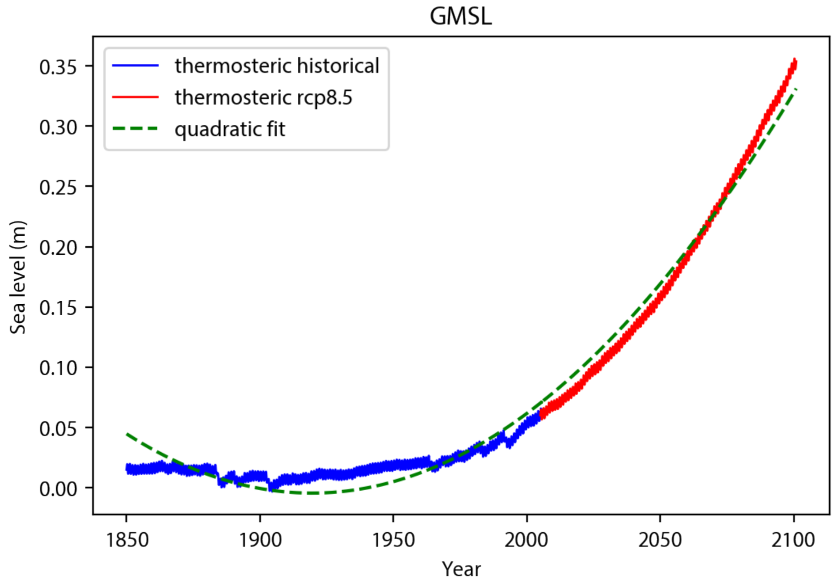
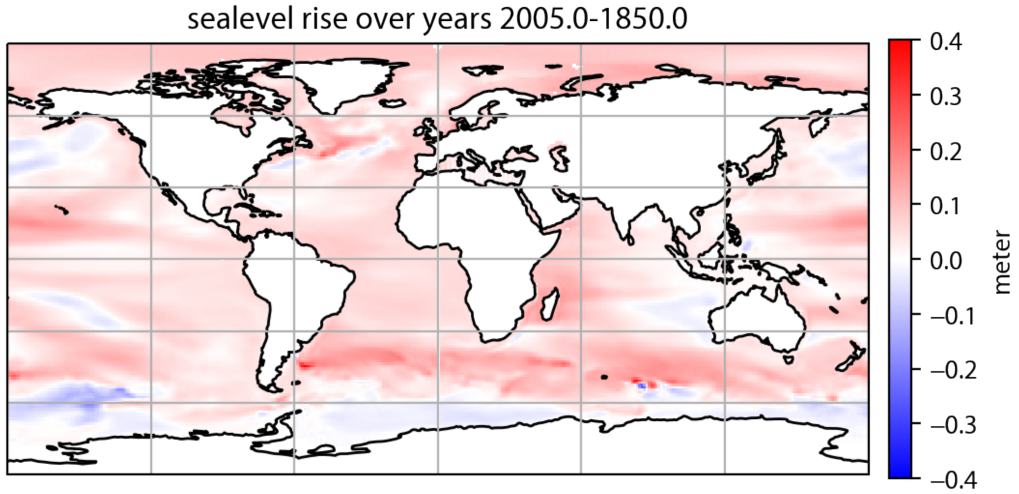
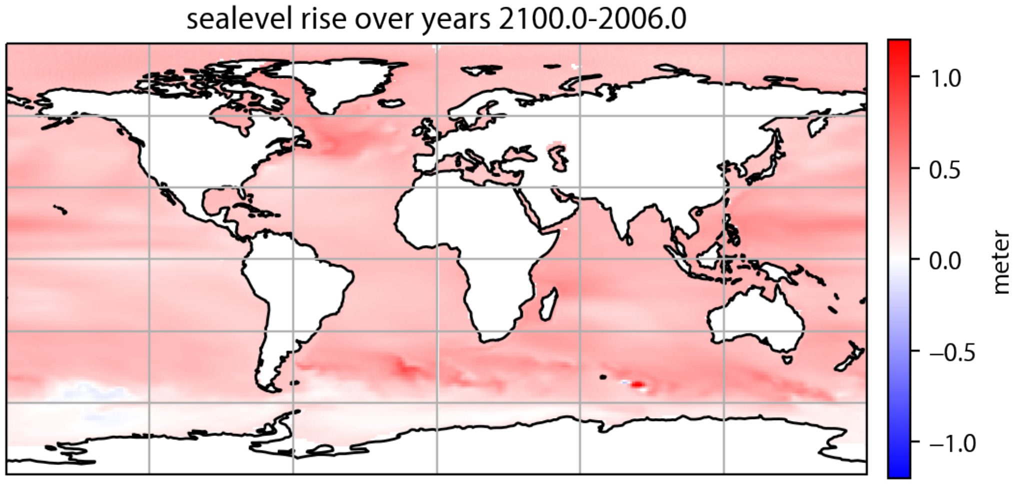
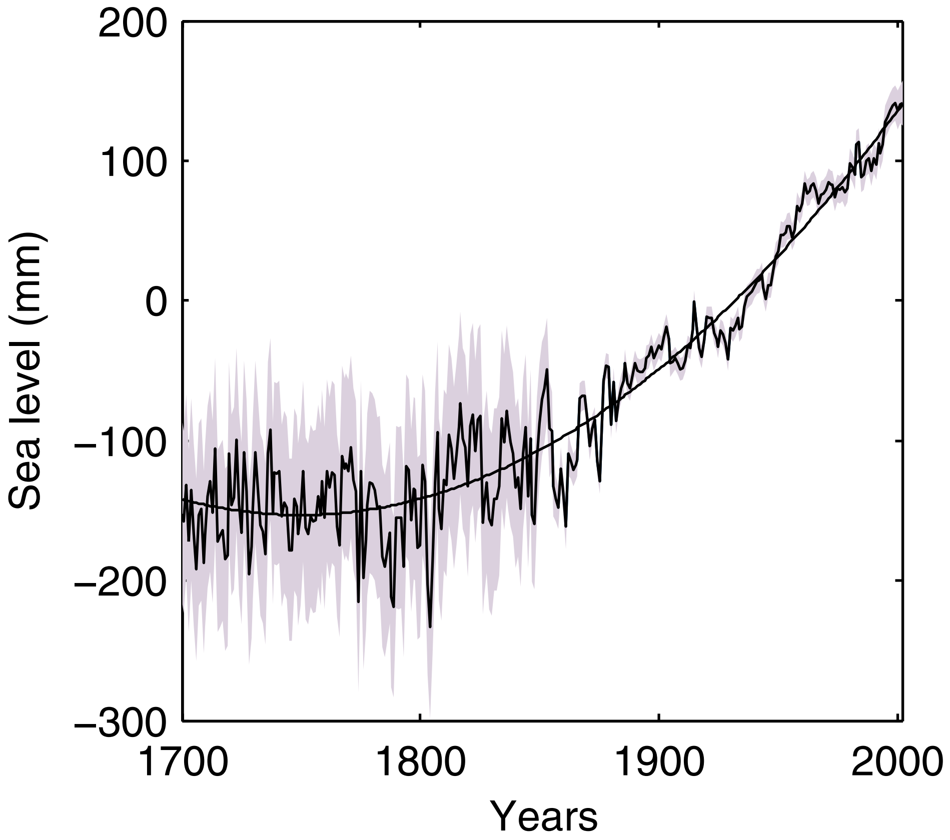
characterize sea level rise in time and space







Sea level is rising

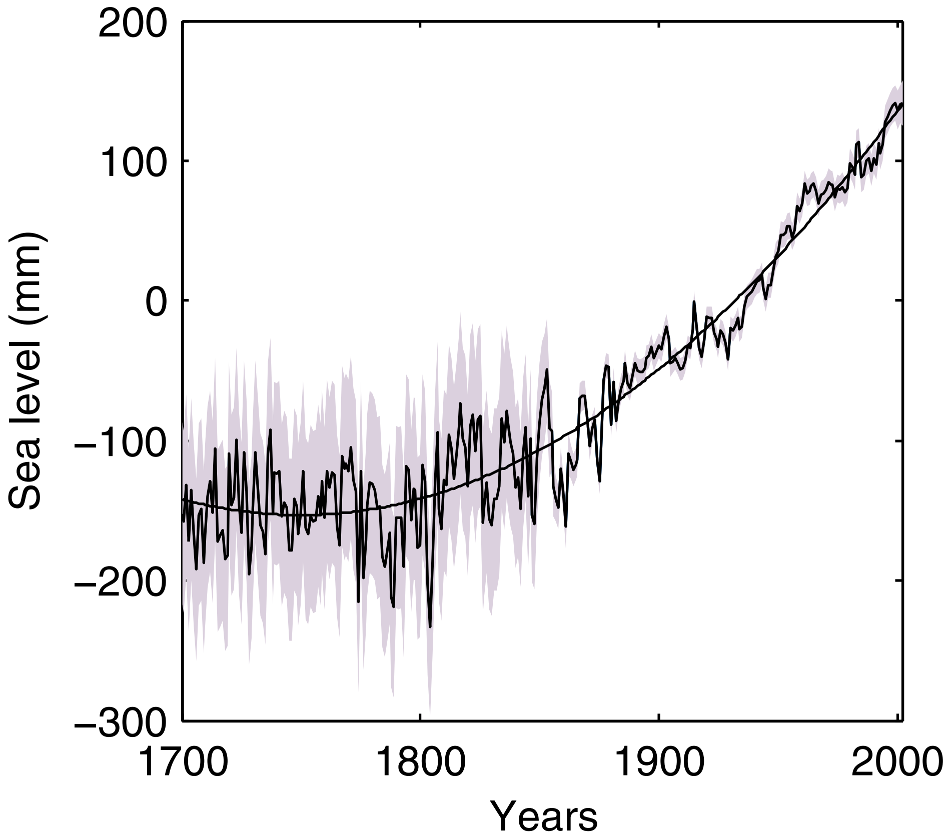


Global sea level over past 200 yrs

(started rising at 1800, probably due to exist from little ice age) (Jevrejeva etal 2008)

Current sea level rise is ~3.5 mm/year…

Sea level is rising



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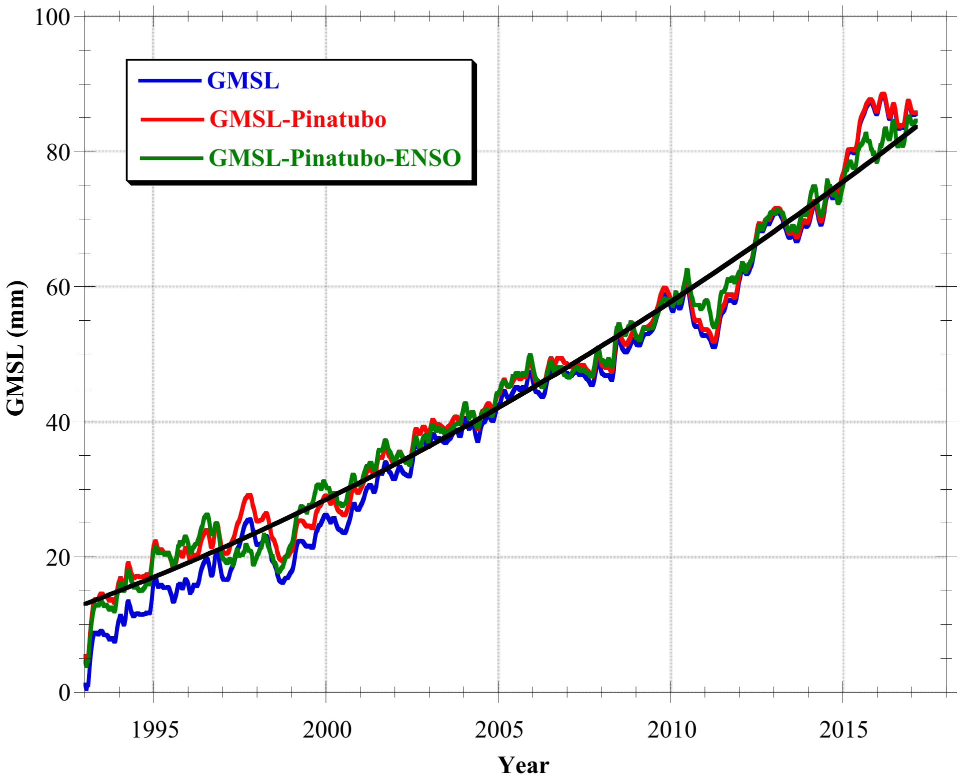

Global mean sea level: satellite data (blue)
without impacts of Mount Pinatubo (red), w/o ENSO (green), a quadratic fit (black). (Nerem et al 2018)

Current sea level rise is ~3.5 mm/year…

Global mean sea level ***rate of change*** time series

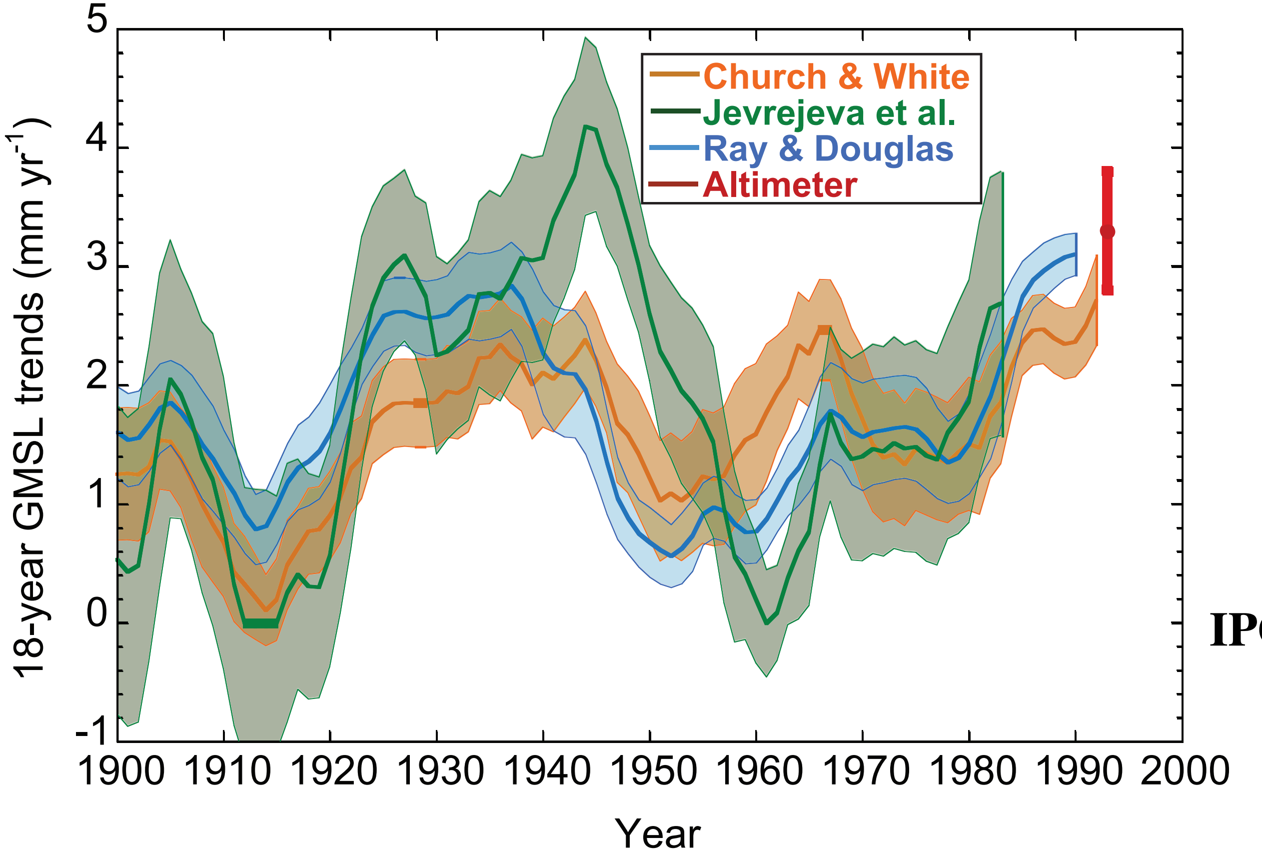

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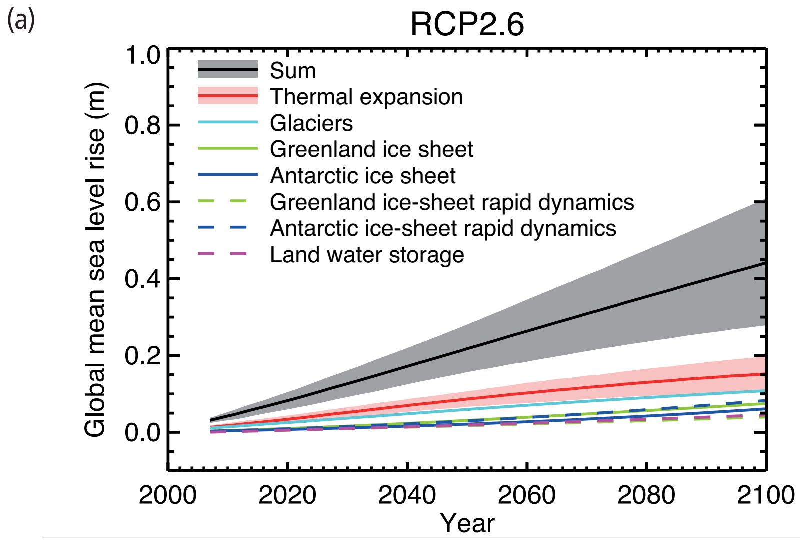
Figure 3.14 | 18-year trends of GMSL rise estimated at 1-year intervals. The time is the start date of the 18-year period, and the shading represents the 90% confidence interval. The estimate from satellite altimetry is also given, with the 90% confidence given as an error bar. Uncertainty is estimated by the variance of the residuals about the fit, and accounts for serial correlation in the residuals as quantified by the lag-1 autocorrelation.

Global Mean Sea Level: future projections



IPCC AR5, 2013

Projections from process-based models of global mean sea level rise relative to 1985–2005, under different representative concentration pathways.

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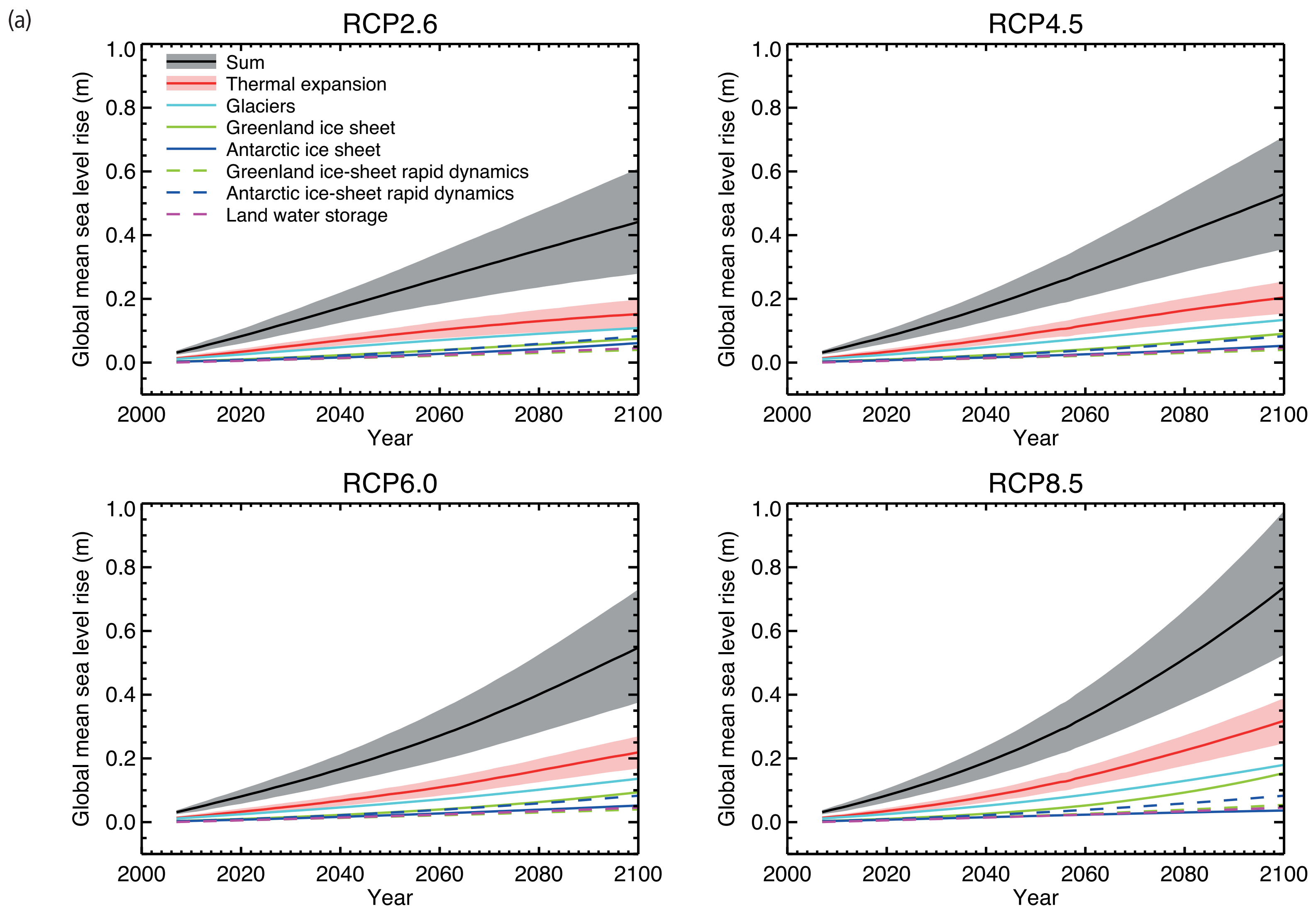

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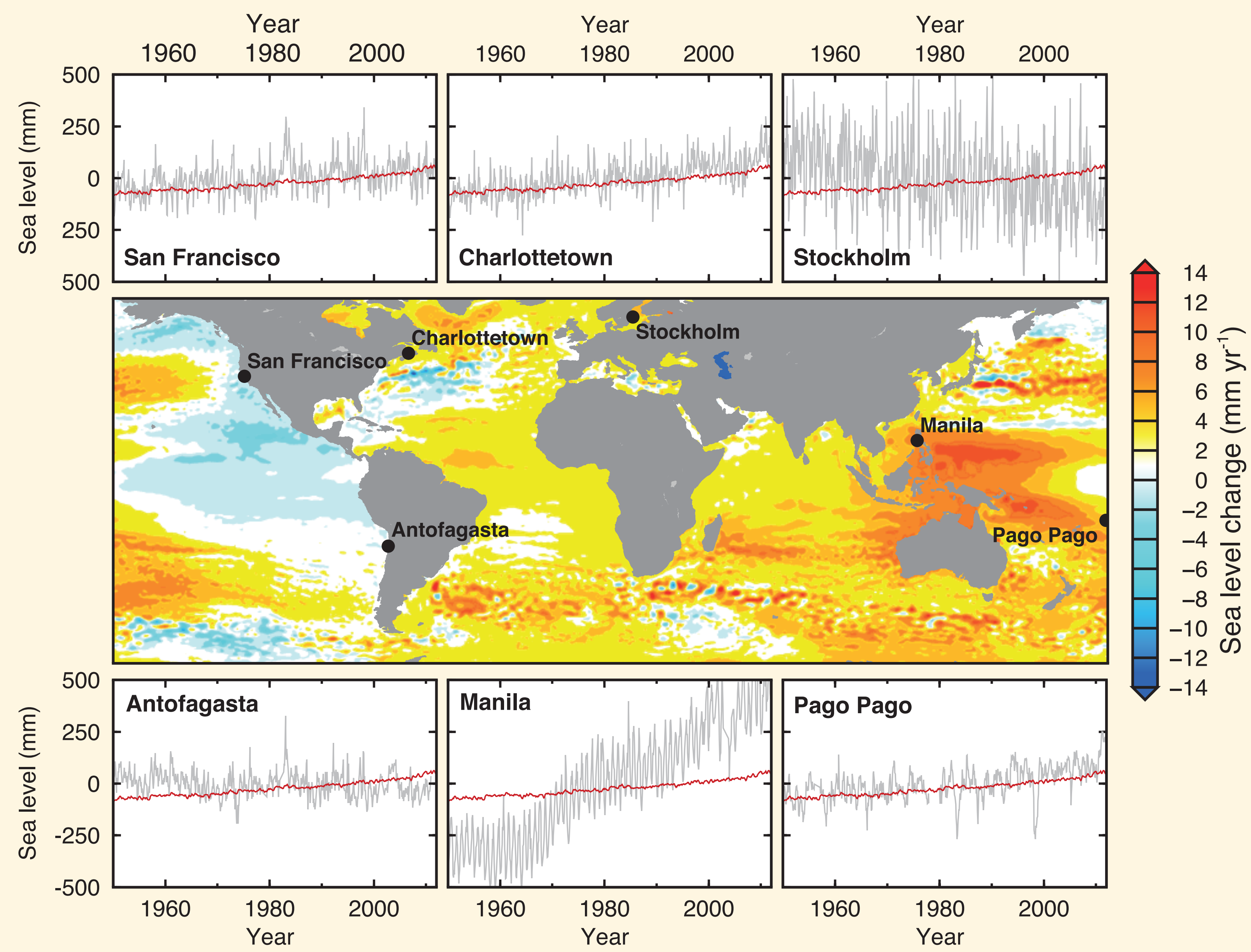
Regional patterns of observed sea-level change



Sea level does not change uniformly!

Map of ***rates of change*** in sea surface height for the period 1993–2012 from satellite altimetry. Also shown are sea level changes (grey lines) from selected tide gauge stations for the period 1950–2012. An estimate of global mean sea level is also shown (red lines) for comparison.

IPCC AR5, 2013

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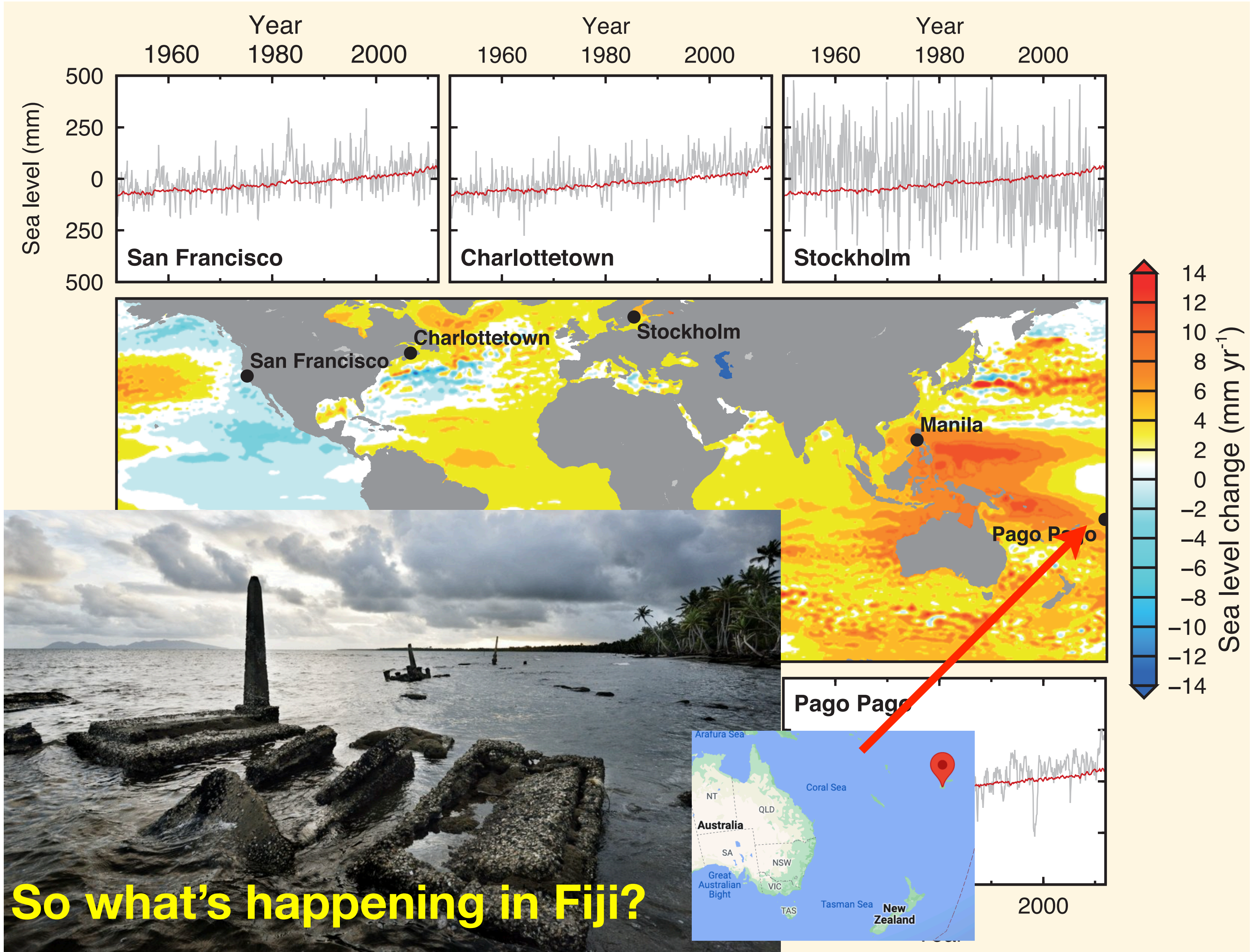

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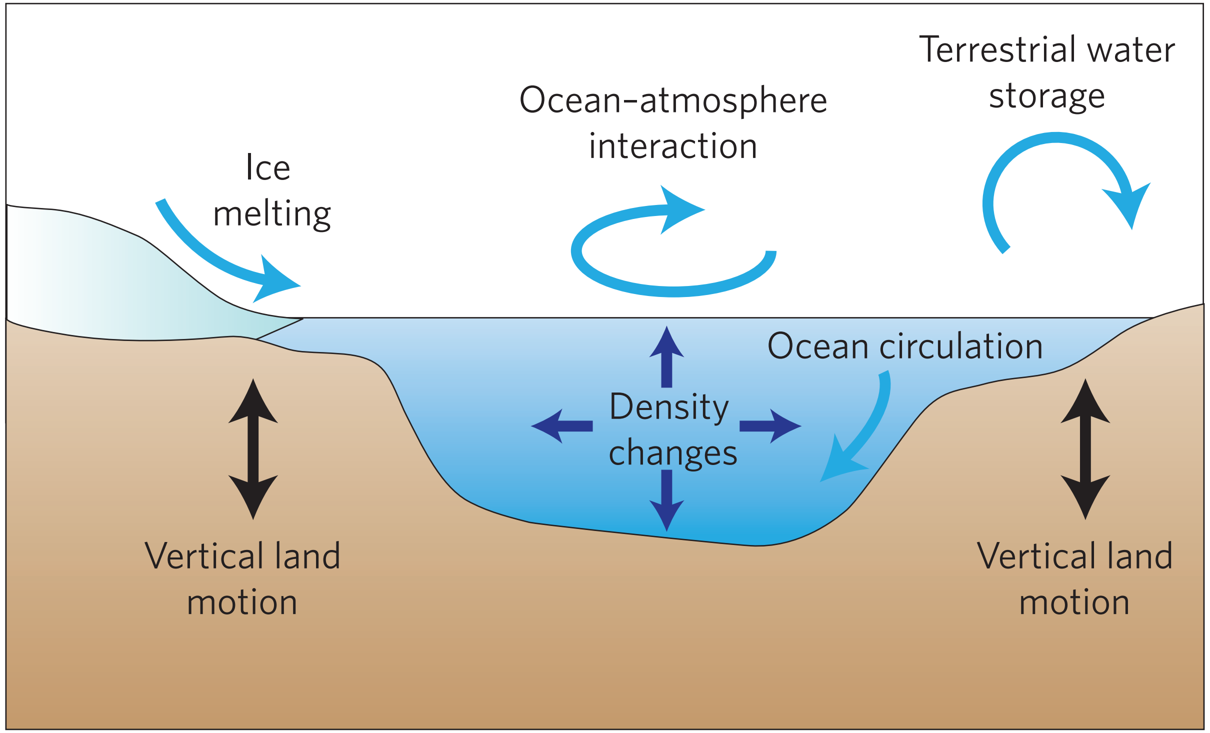
Sea level change: processes

- Thermal expansion
- Glaciers
- Land water storage
- Coastal erosion
- Other factors (atmospheric pressure, wind stresses, ocean circulation…)
- Gravitational effects (fingerprint)



Milne et al 2009

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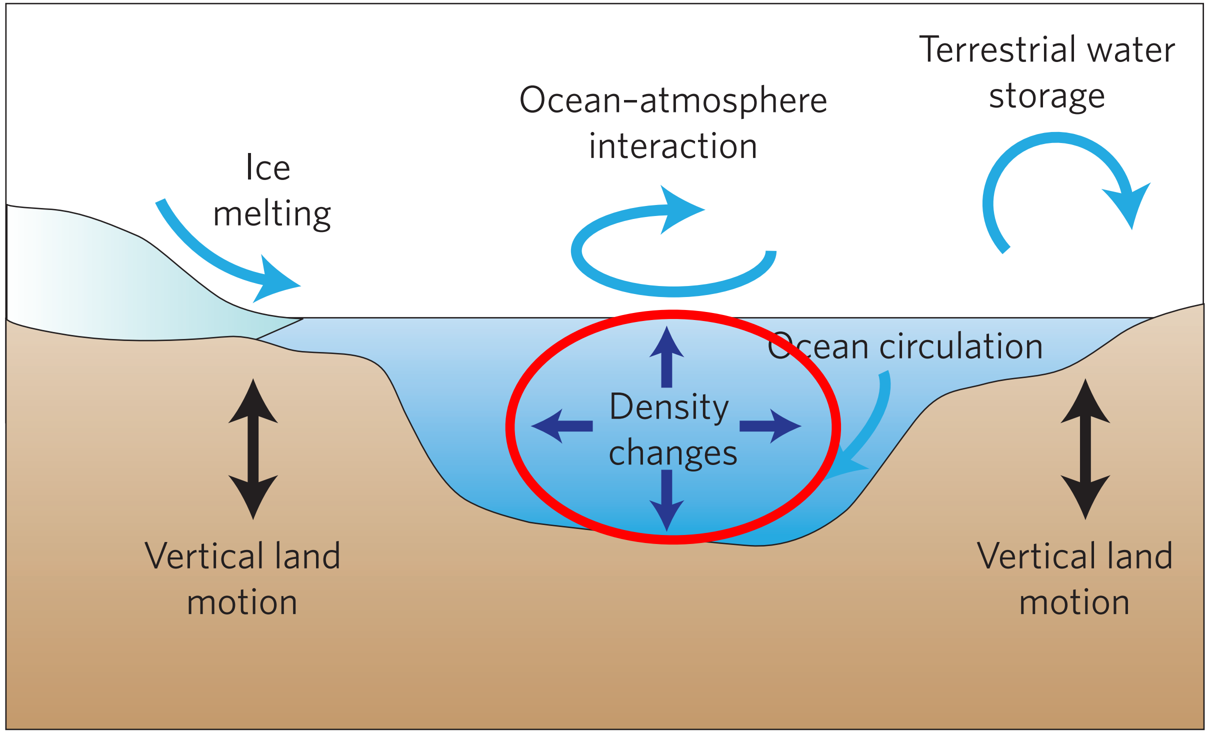
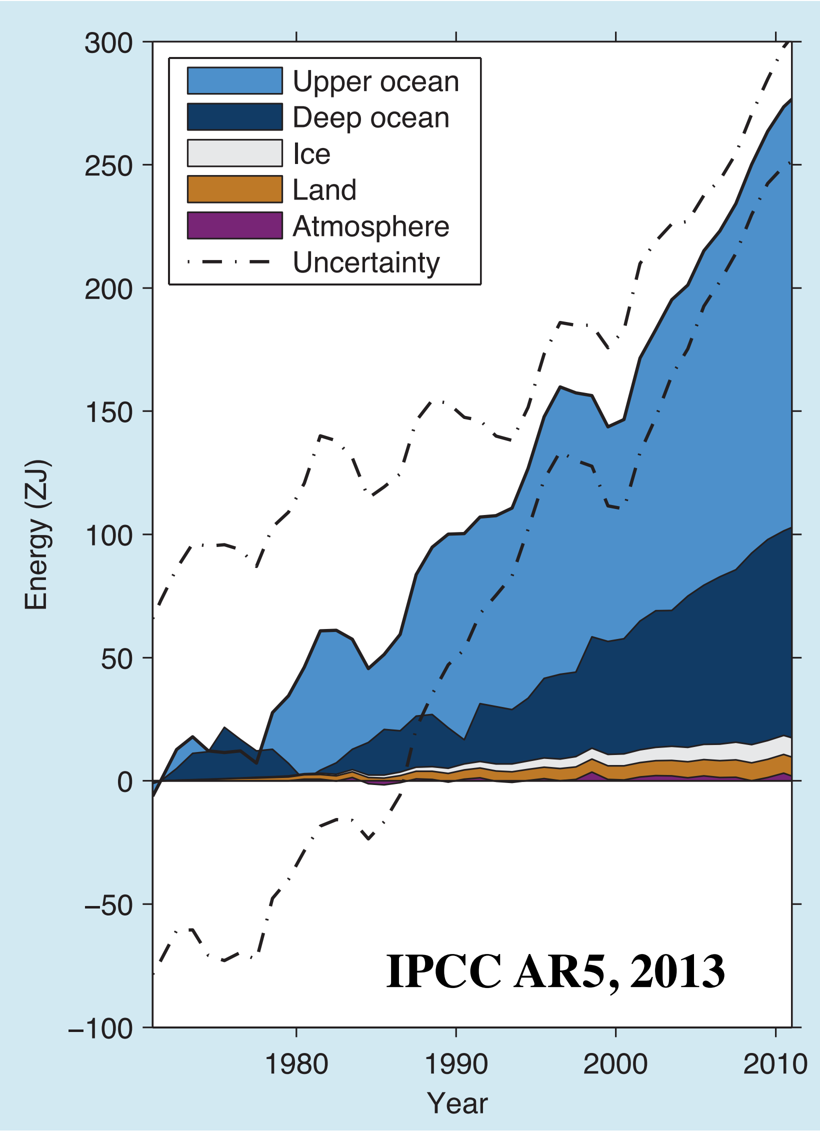


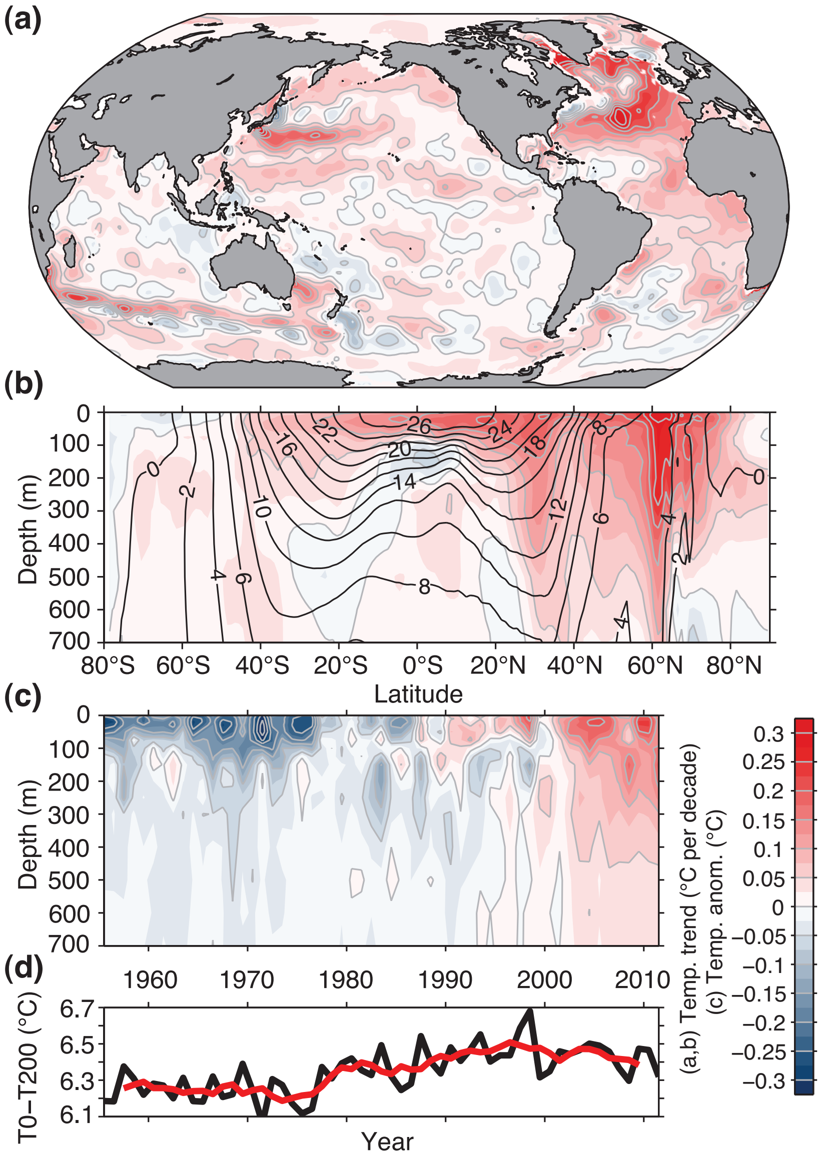
Milne et al 2009

Sea level change: thermal expansion

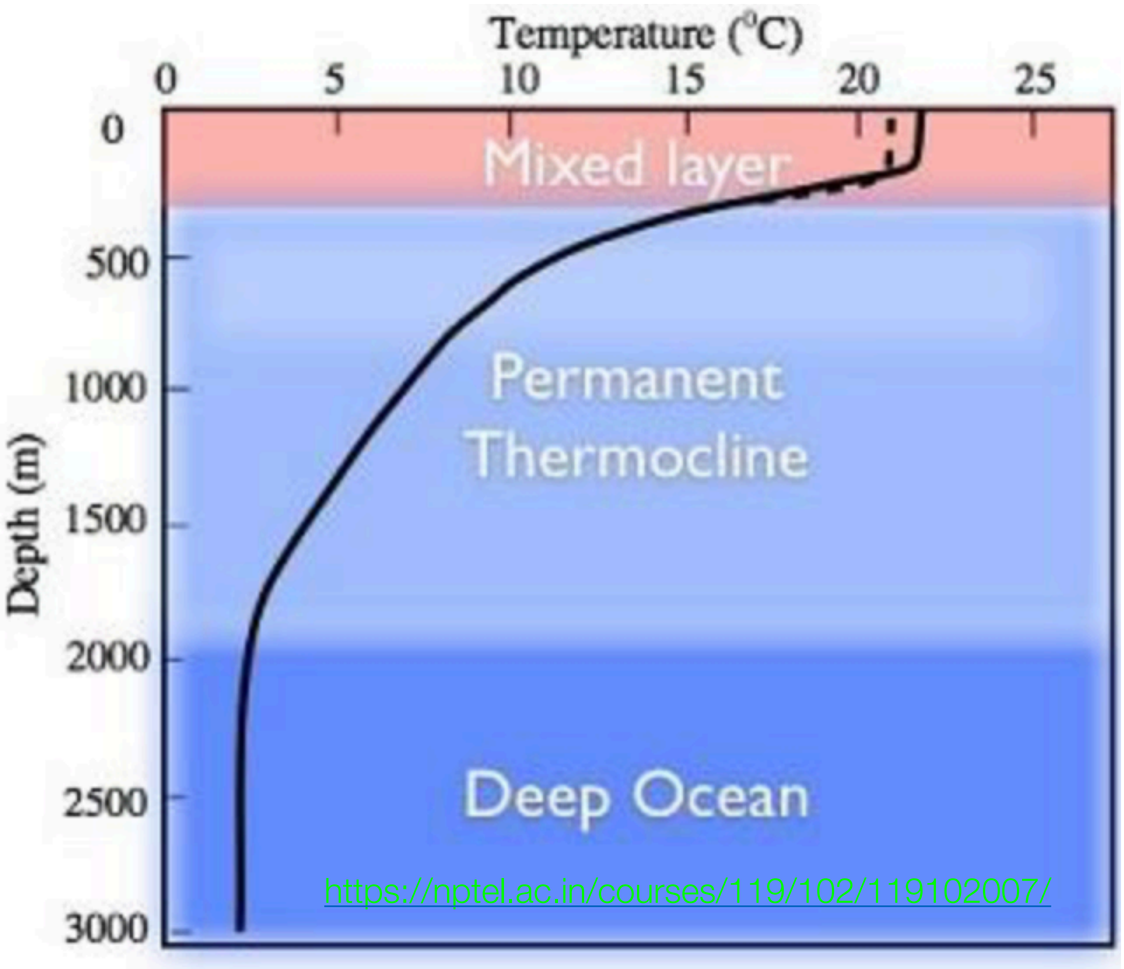
The oceans take the largest increase in the storage of heat in the climate system

Left: energy accumulation of distinct components of the Earth's climate system relative to 1971. **Right**: averaged temperature trend for 1971–2010. **(a)** depth-averaged 0 to 700 m; **(b)** zonally averaged warming trend with zonal mean temperature in black contours. **(c)** globally averaged temperature anomaly. **(d)** globally averaged temperature difference between ocean surface and 200 depth (black: annual mean; red: 5-year running mean.)



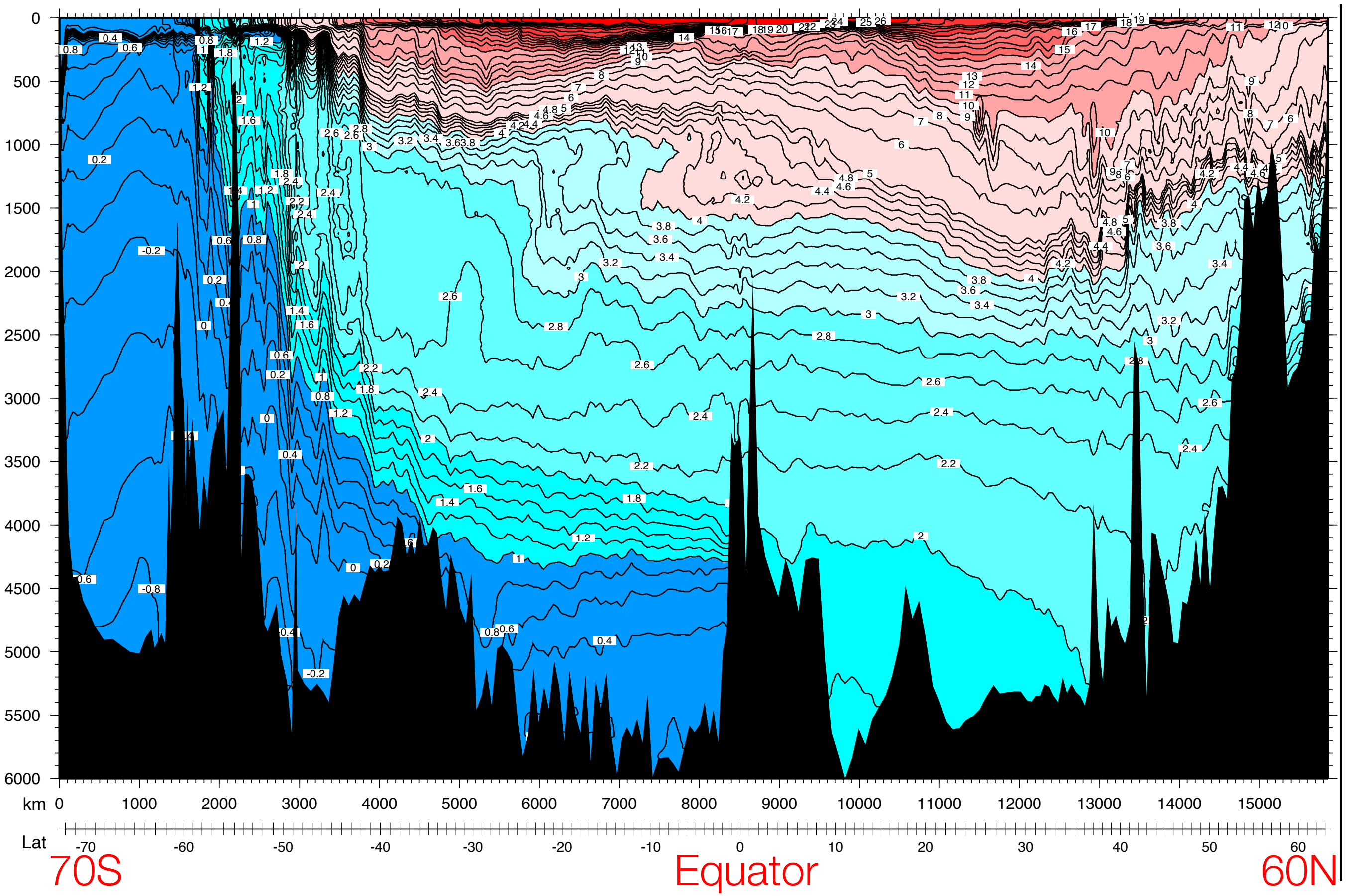


Ocean temperature distribution



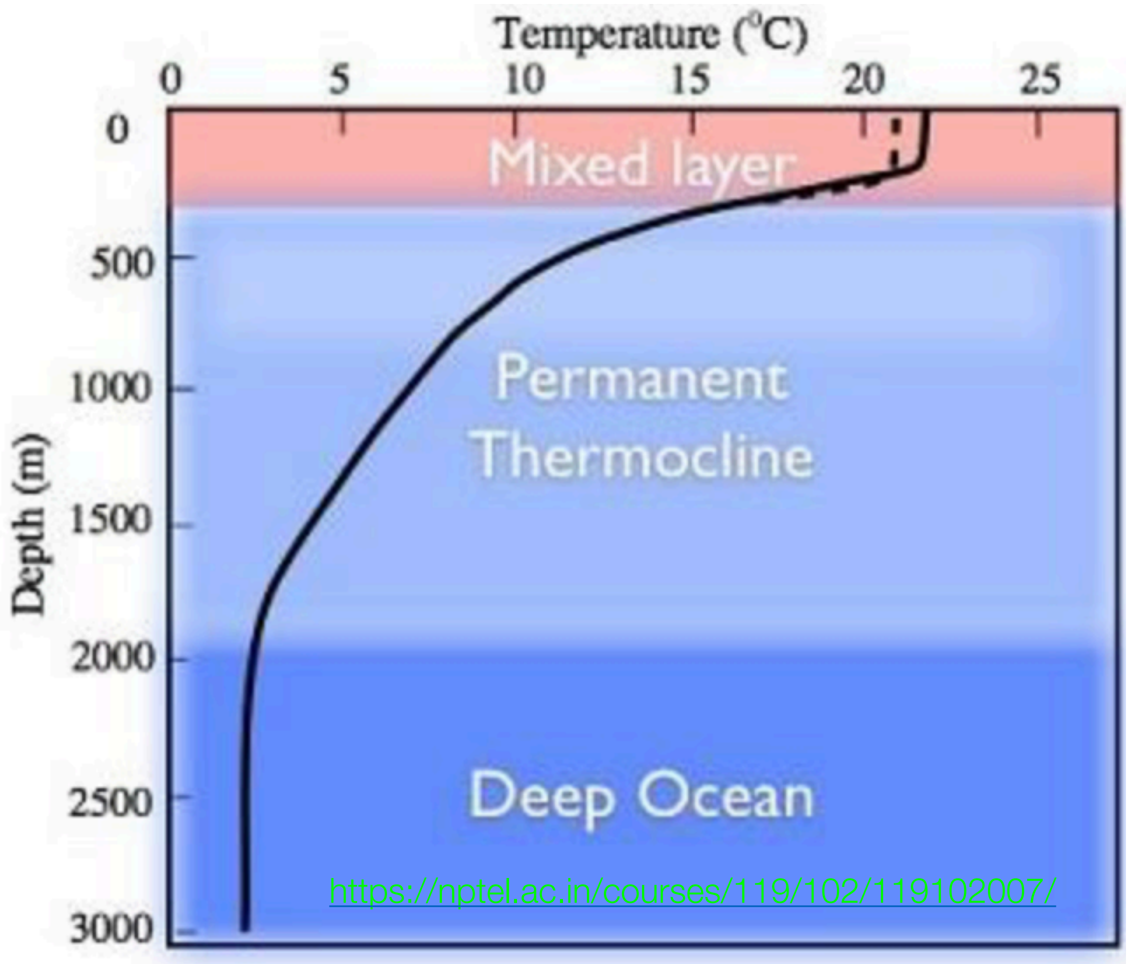
Typical vertical ocean temperature profile

Ocean temperature distribution



Temperature in the Atlantic Ocean

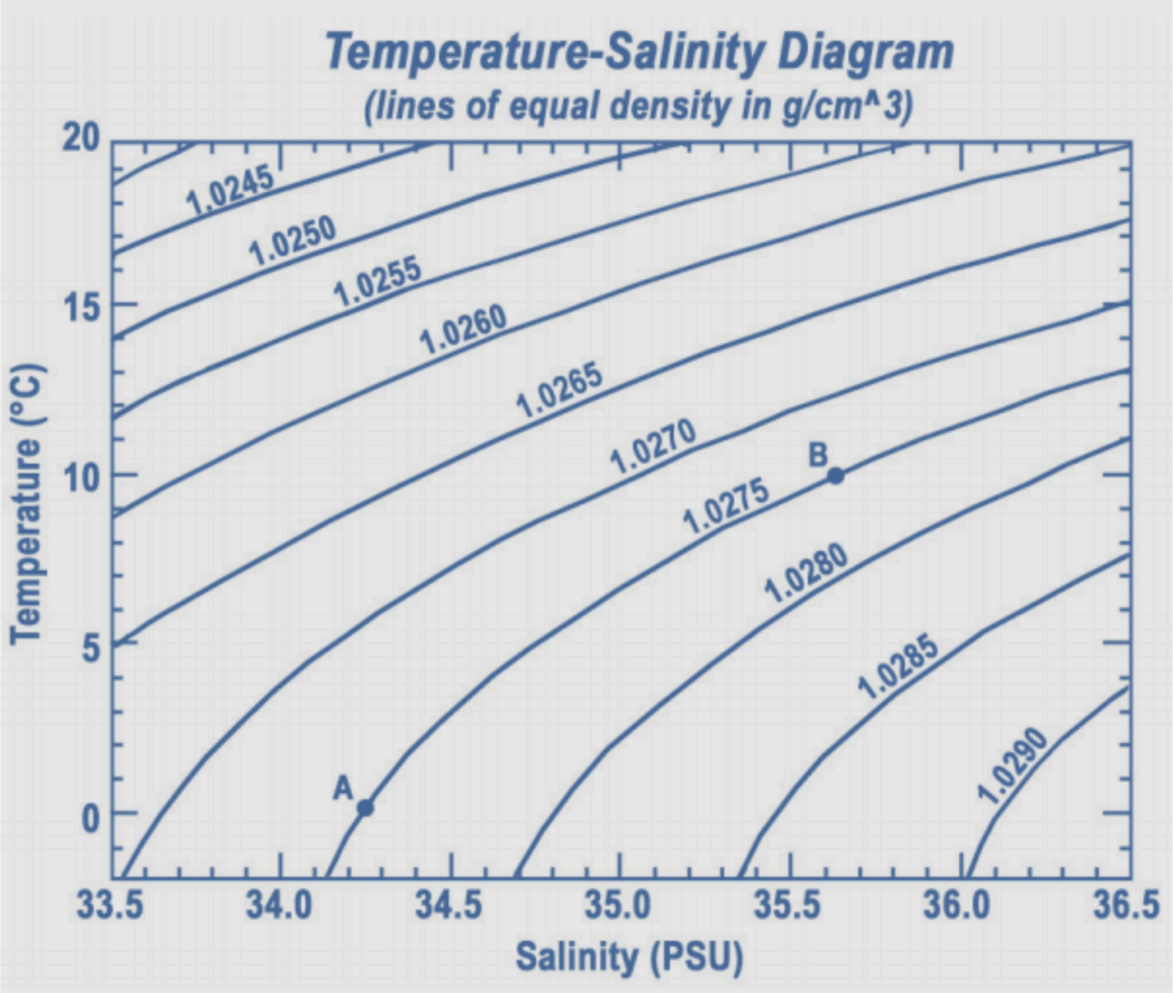
(WOCE section)



Typical vertical ocean temperature profile

Sea level change: thermal expansion

Sea water expands as temperature rises above freezing point due to salinity.



https://aquarius.umaine.edu/activities/density_SWmix_sink.pdf

Temperature increases
➨ density decreases
➨ volume increases
➨ sea level rises

This effect is not spatially uniform:
(1) warming is not uniform as function of lon/lat/depth,

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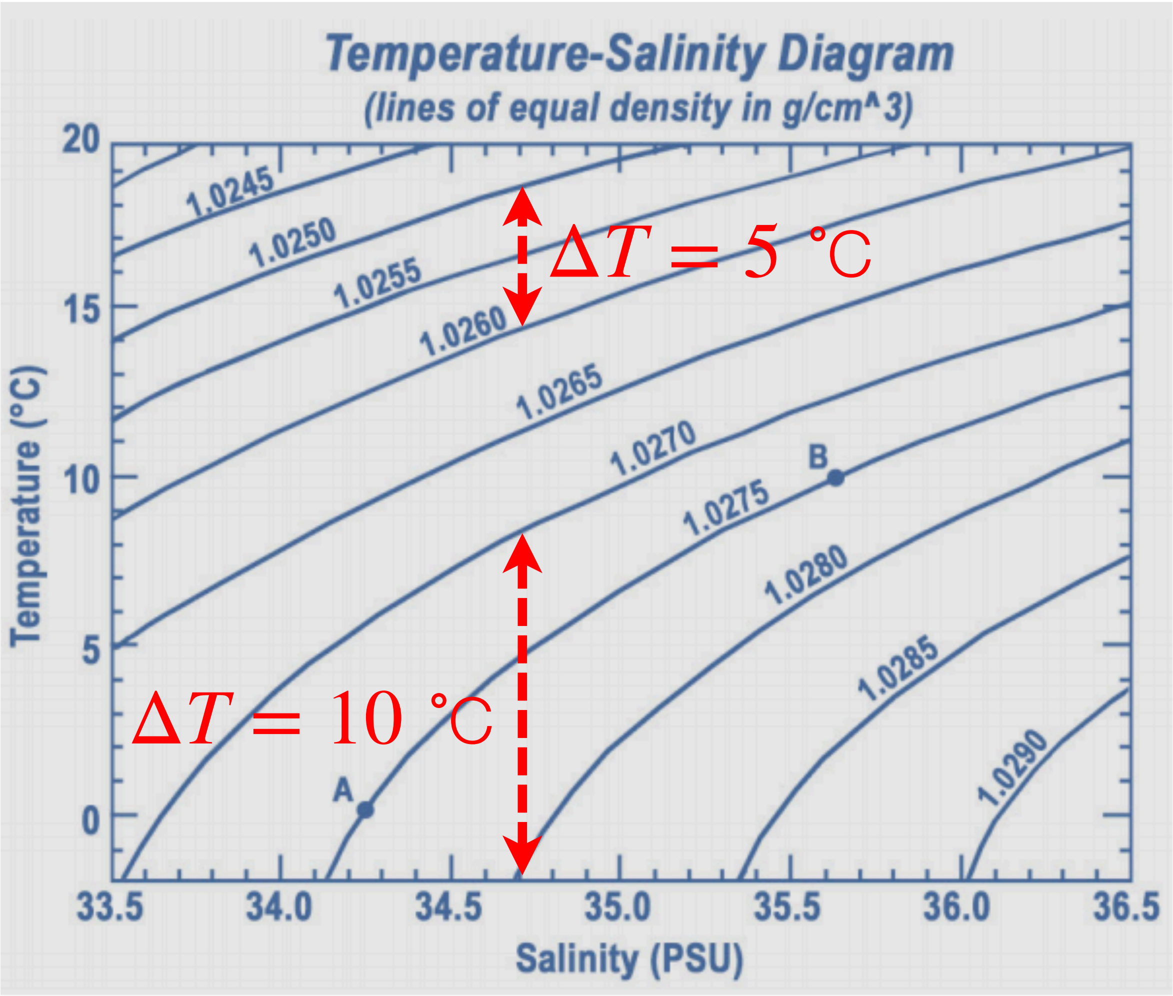

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(2) seawater density response to warming depends on ocean temperature ⇛ also not uniform, even for a given warming.

notes: thermal expansion, section 4.1.1

workshop: 2 a, b (leave c for HW)
temperature, density and sea level rise

Sea level change: processes

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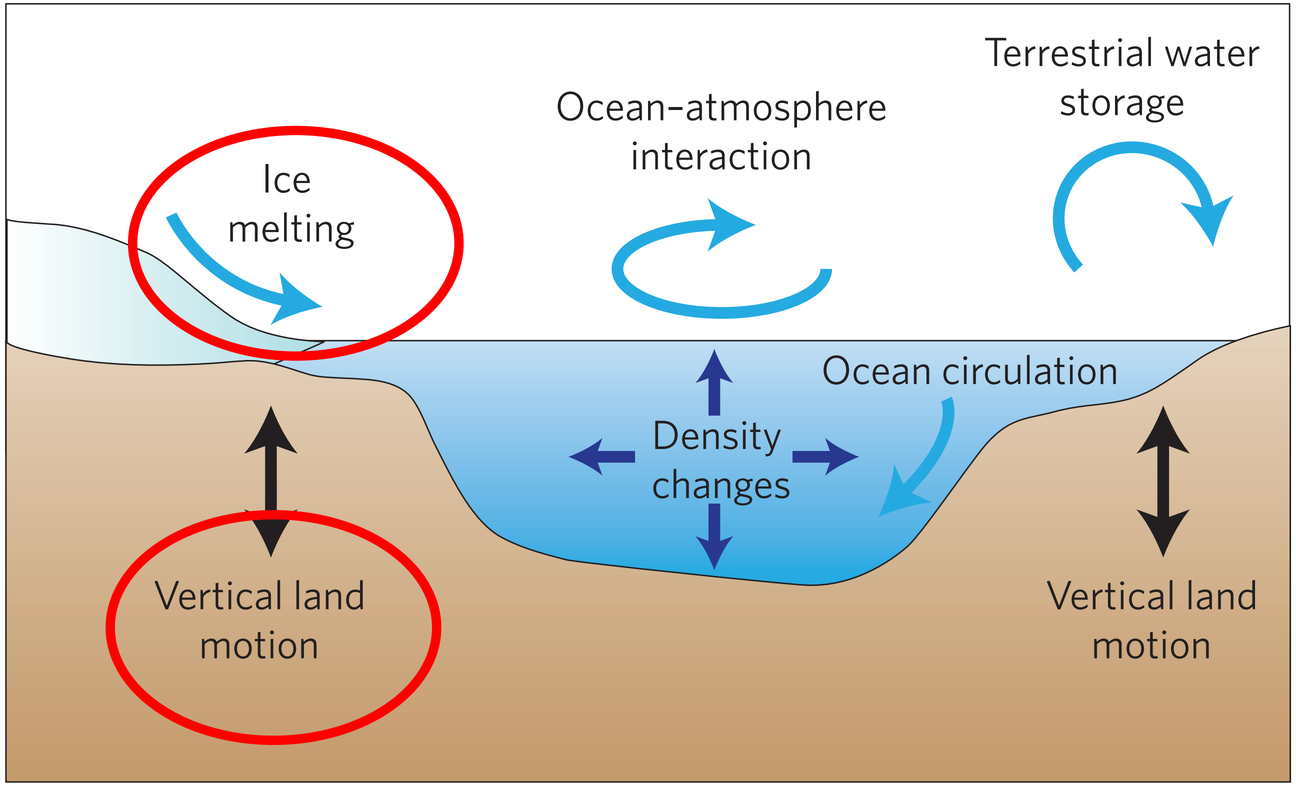
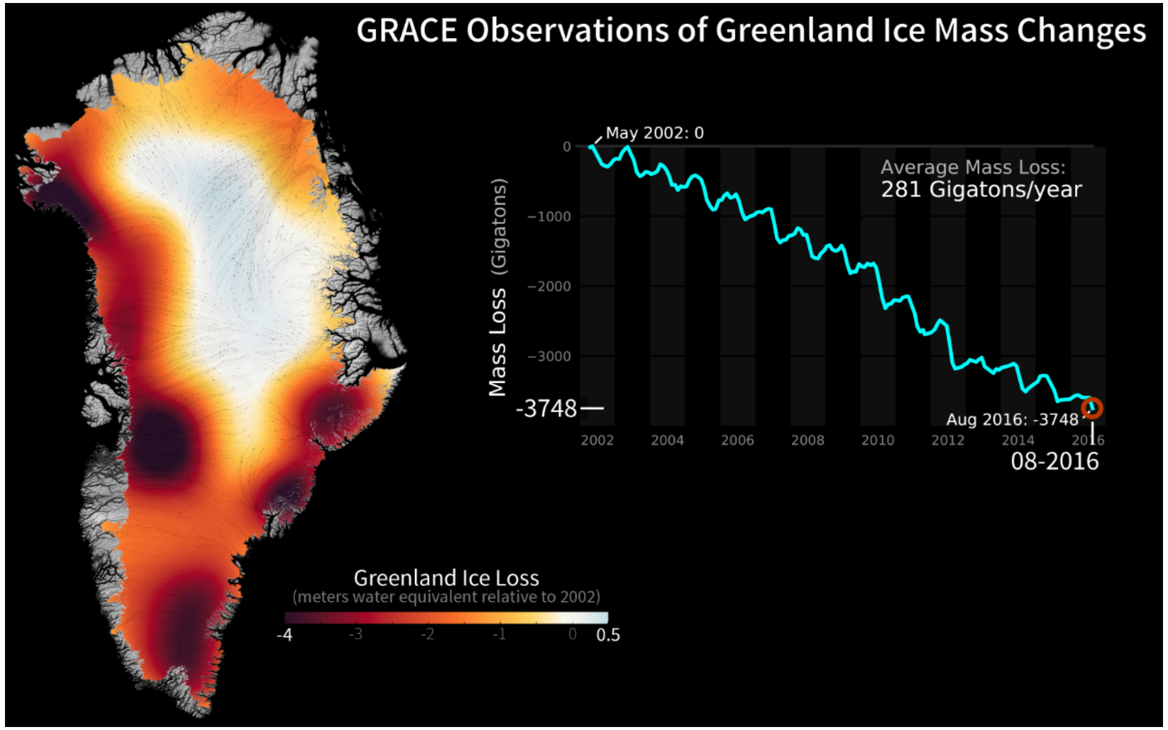
- **Ice sheets**/ Mountain Glaciers
- Land water storage
- Coastal erosion
- Atmospheric pressure, wind stresses, ocean circulation
- Gravitational effects (fingerprint)



Milne et al 2009

Sea level change: Ice Sheets

Greenland and Antarctica glaciers have been observed to lose ice mass in the past decades.



https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/

For 1993–2010, GMSL rise from Greenland was 0.4 mm/yr; from Antarctica 0.27 mm/yr, difficult to estimate how much is due to natural variability vs anthropogenic climate change

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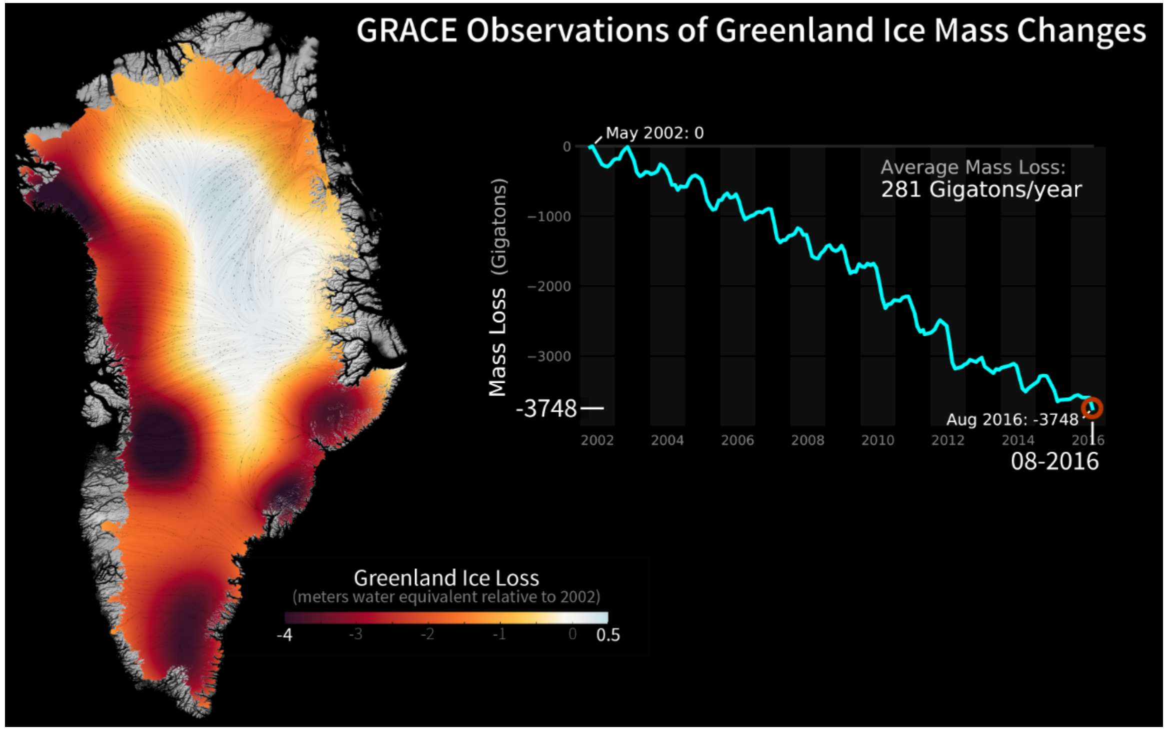

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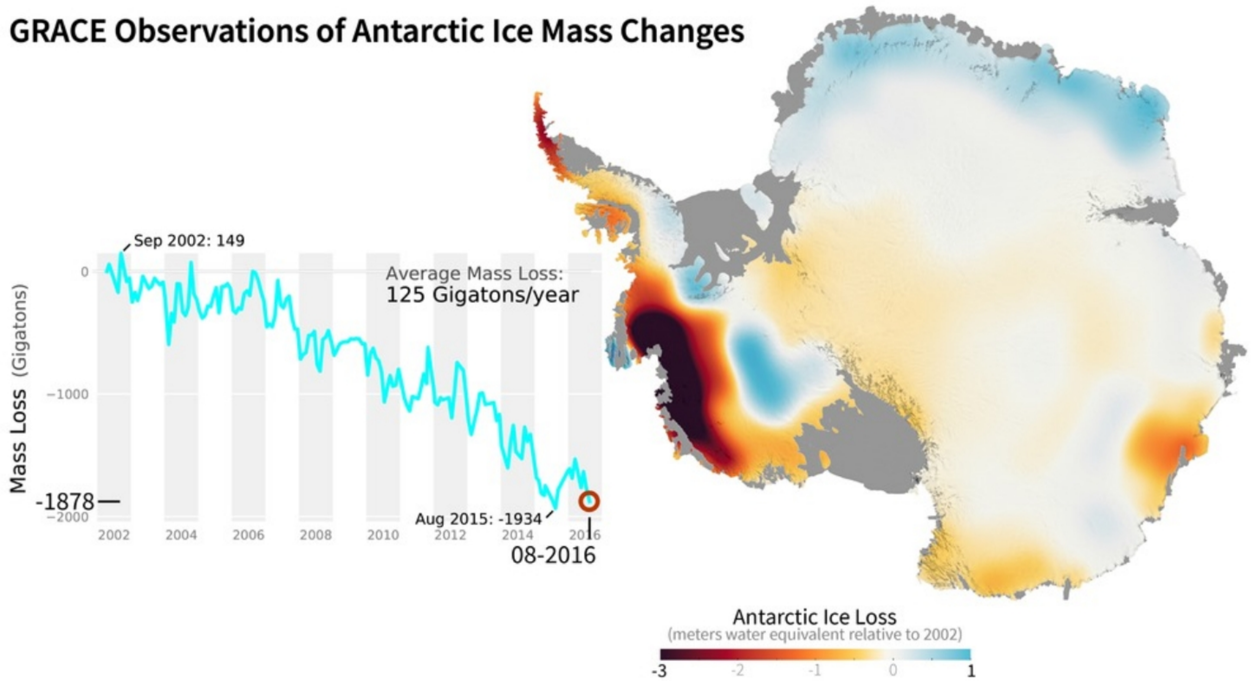

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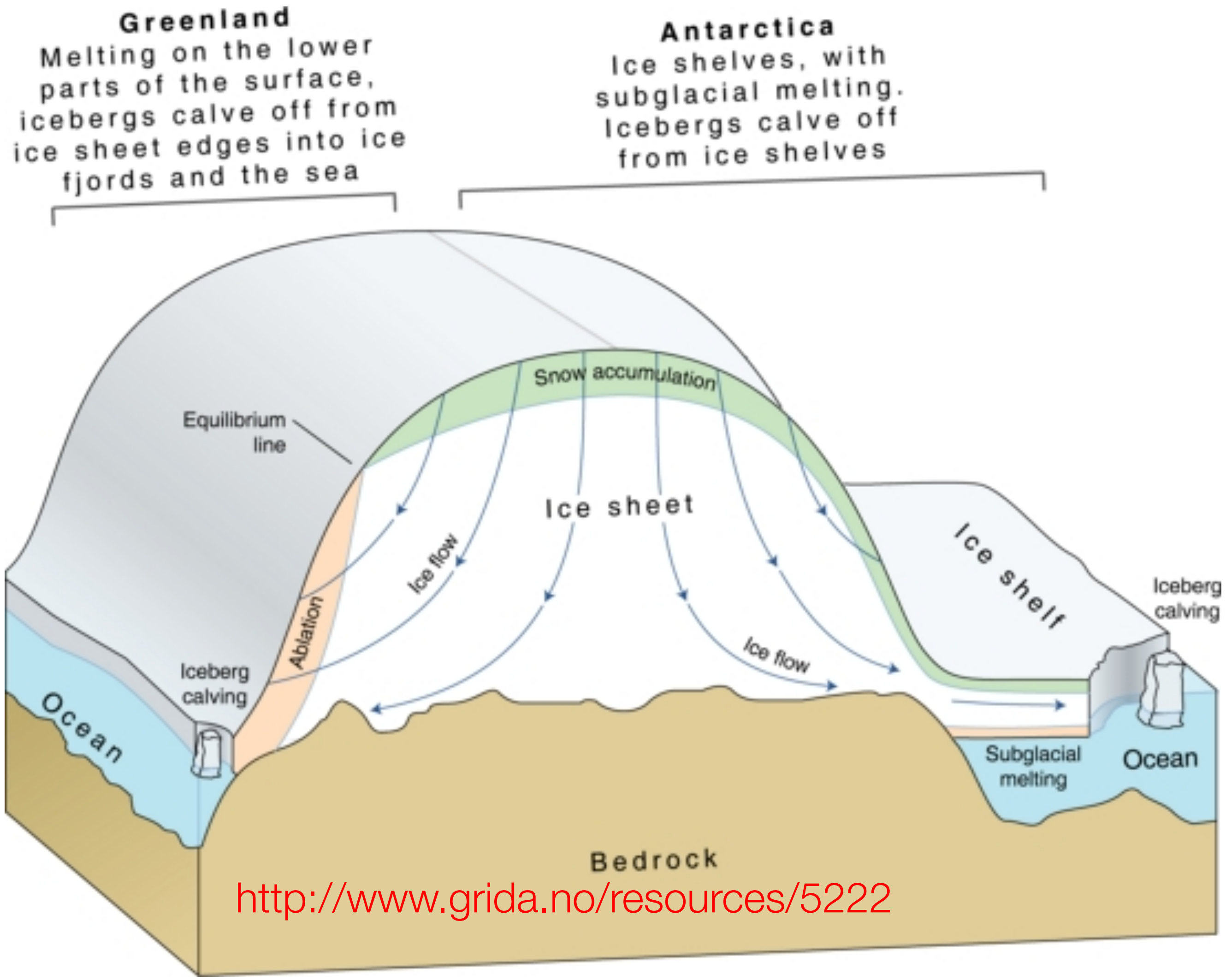
mass balance of a glacier/ ice sheet:



http://www.grida.no/resources/5222

Dominant mass balance:

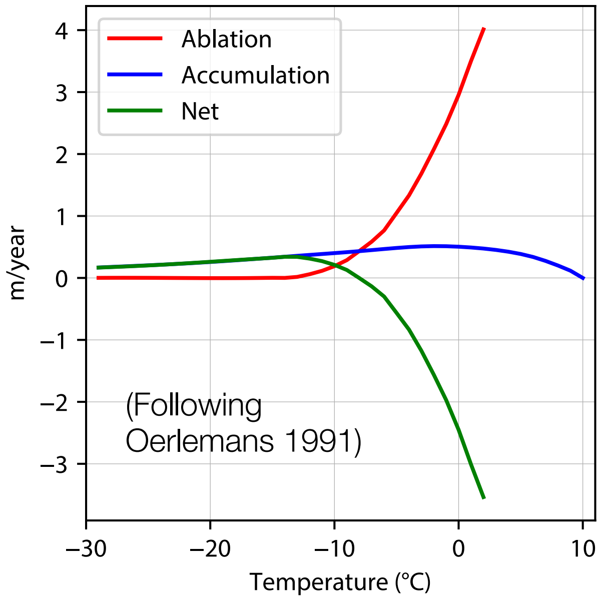
(1) **Greenland** ice sheet: accumulation (snowfall) and ablation (melting and runoff);

(2) **Antarctica** ice sheet: accumulation (snowfall), ice outflow and calving (too cold to melt);

Sea level change: Ice Sheets

Contribution of ice sheets to global mean sea level:

- For both Greenland and Antarctica, **in a warming climate, accumulation will increase** due to increased moisture of warmer air, but melting/ ice streams will also increase



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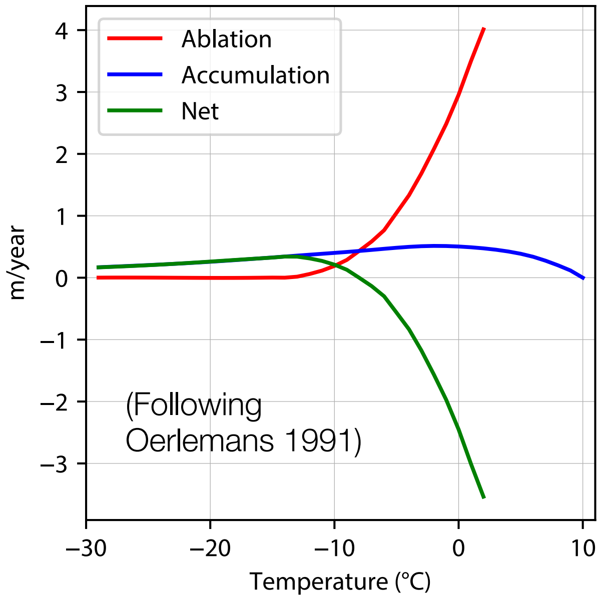

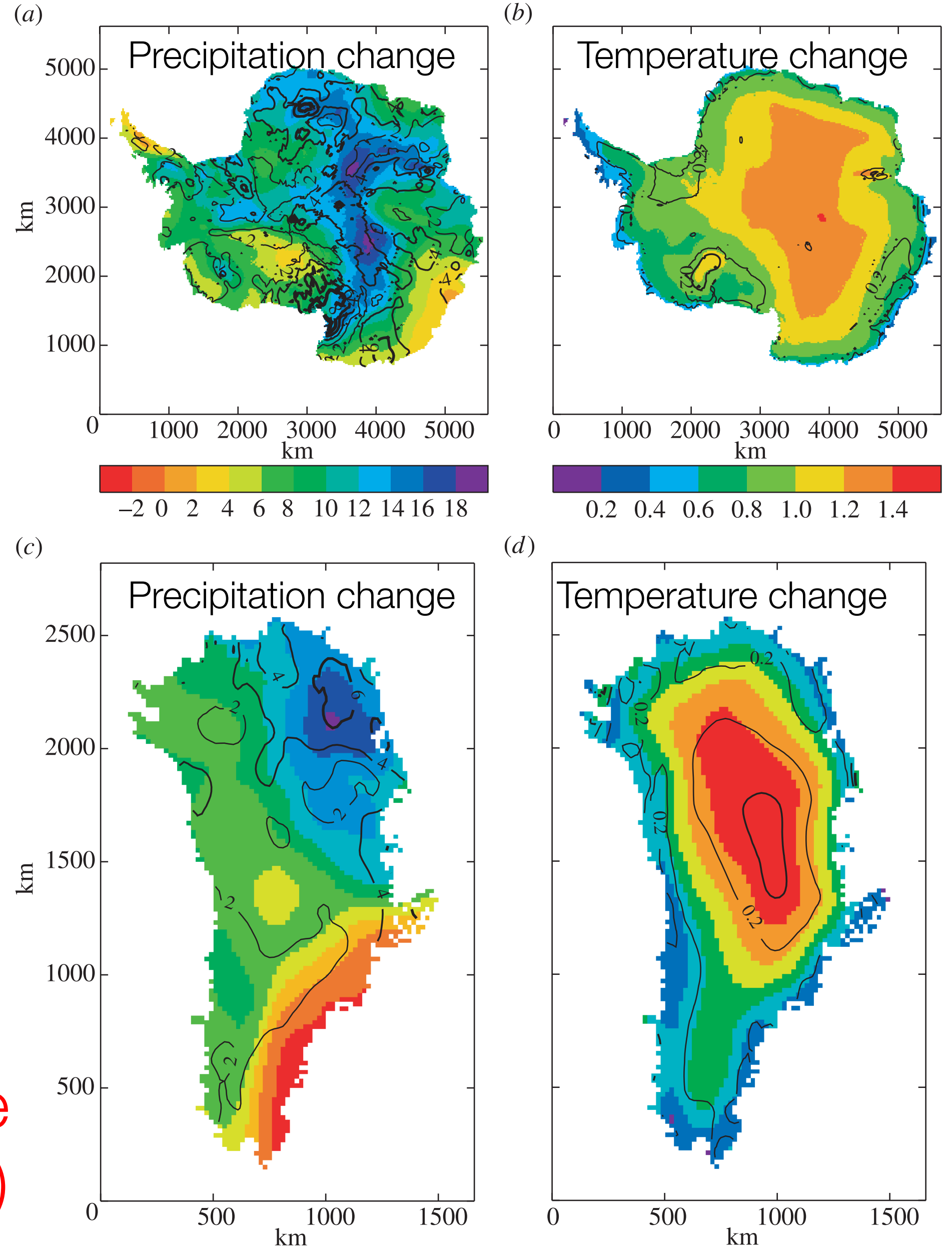

Patterns of projected (2100?) precipitation & temperature change. (a, c) change in annual-mean precipitation. (b, d) change in summer-average temperature.

Gregory and Huybrechts 2006

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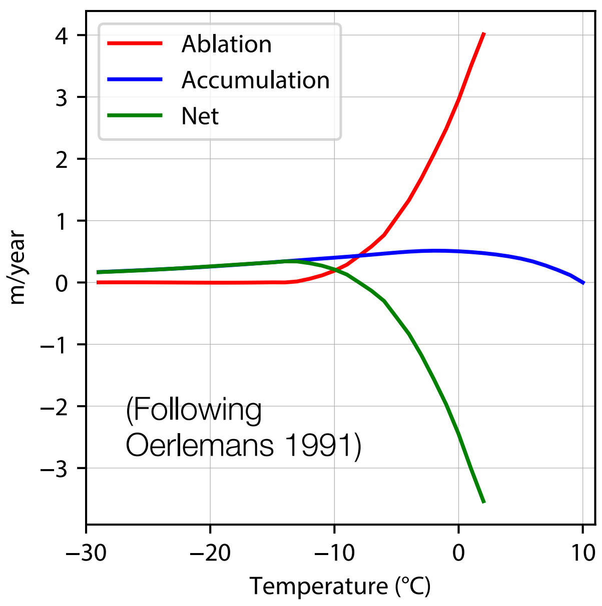

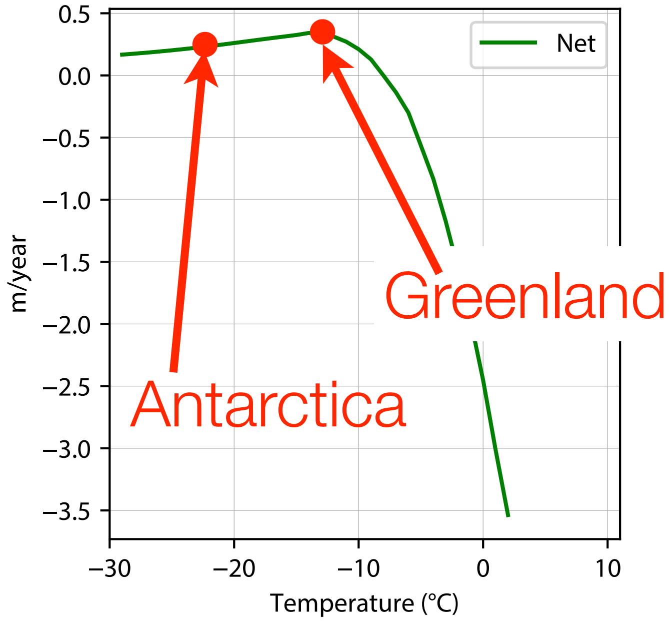

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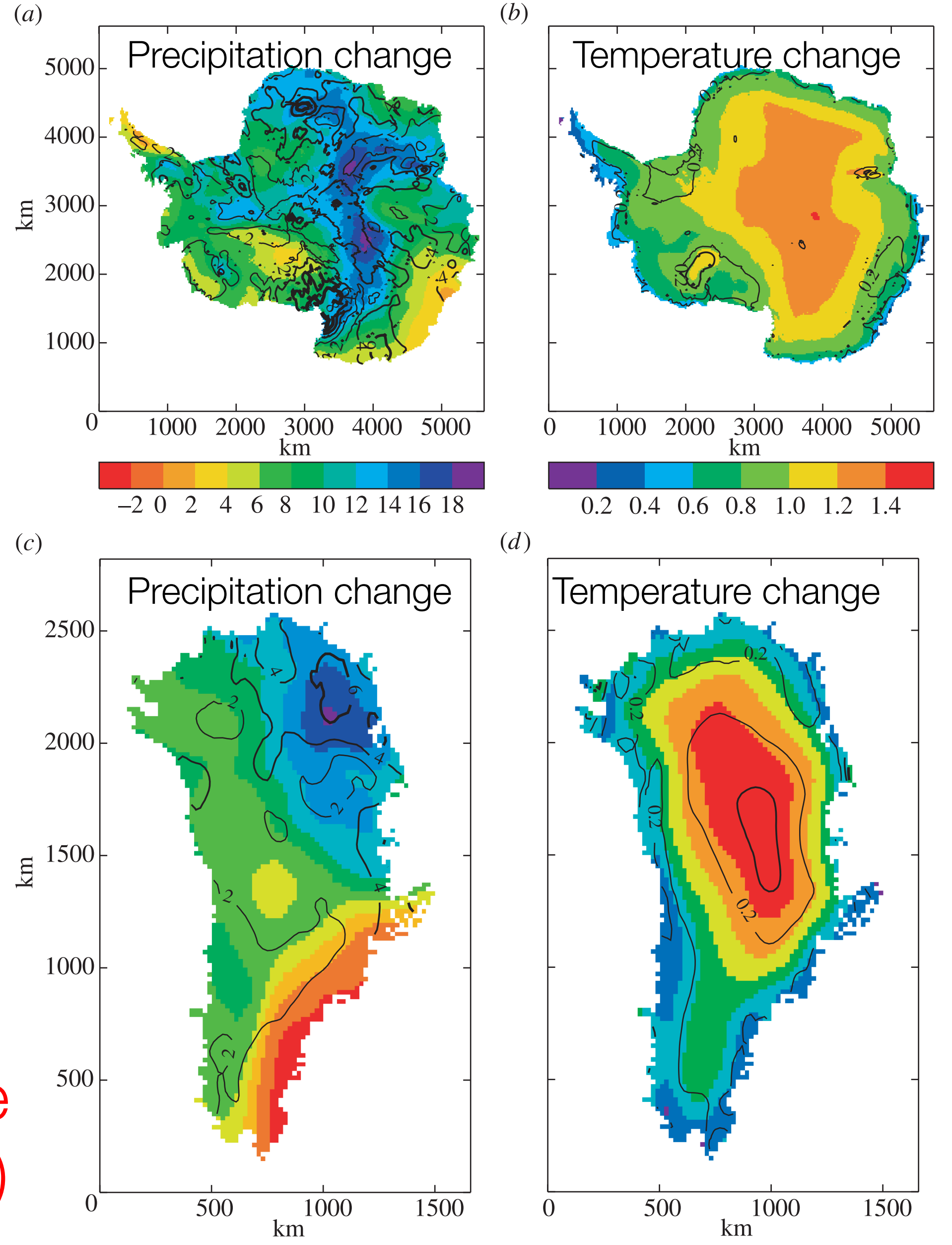

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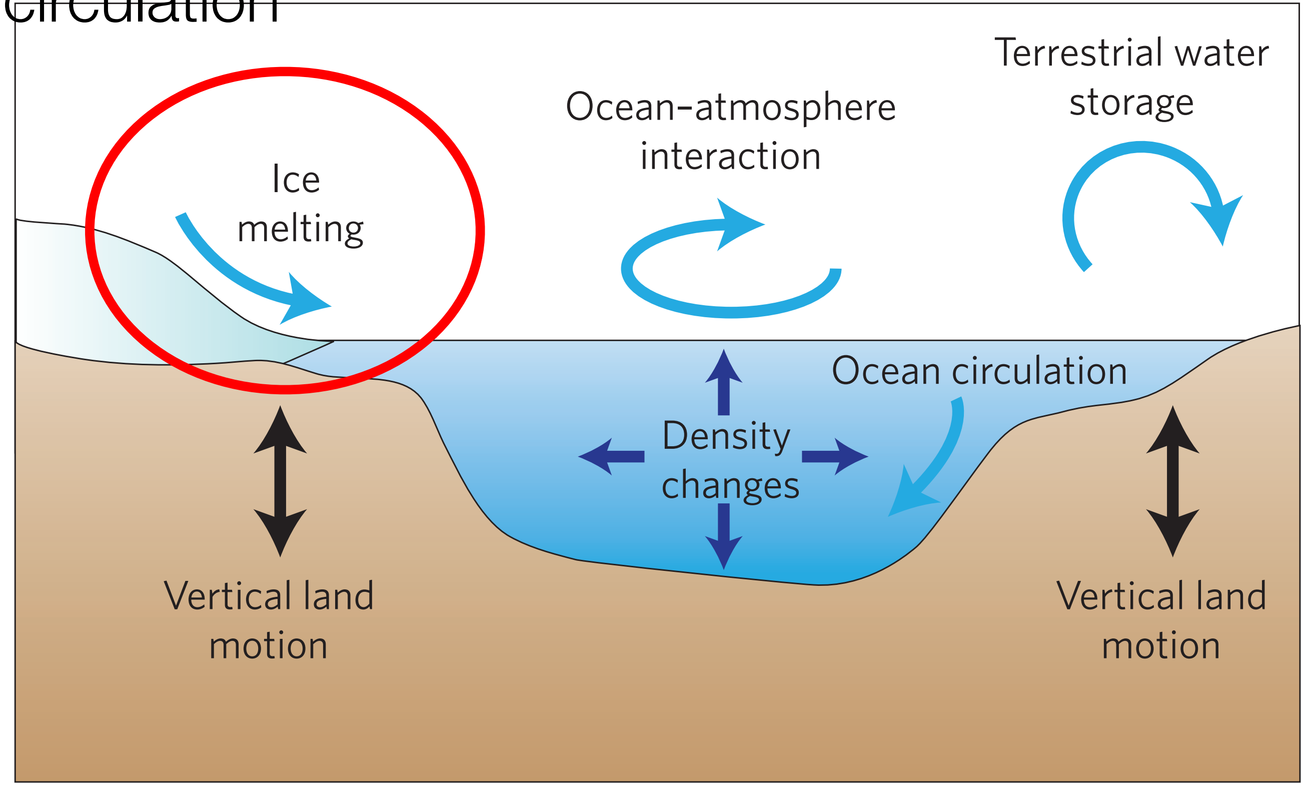

Milne et al 2009

Sea Level change: Mountain glaciers

Stein Glacier, Switzerland, has retreated by 550 m between 2006 (left) and 2015 (right).

(https://newatlas.com/before-after-photos-glaciers-climate-change/49143/#gallery)

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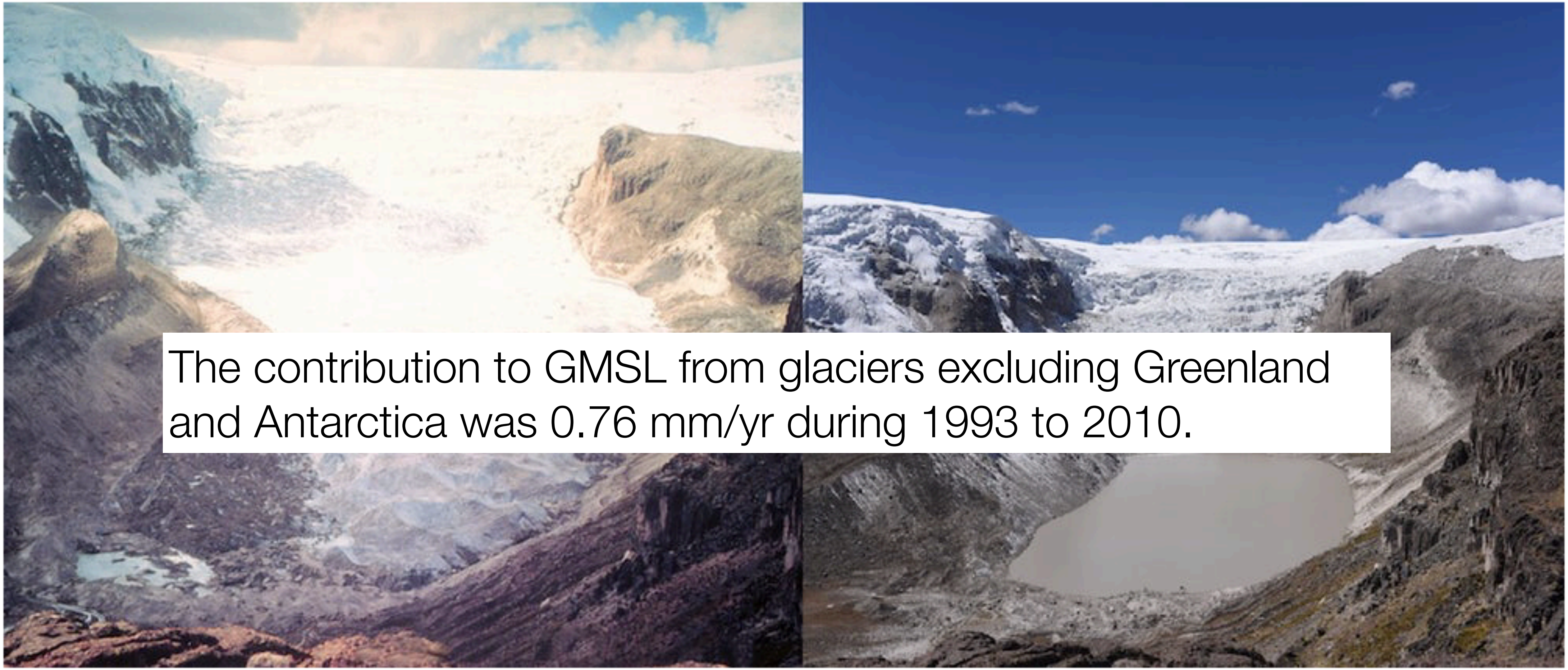

The contribution to GMSL from glaciers excluding Greenland and Antarctica was 0.76 mm/yr during 1993 to 2010.

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workshop: 3
warming-driven sea level change patterns

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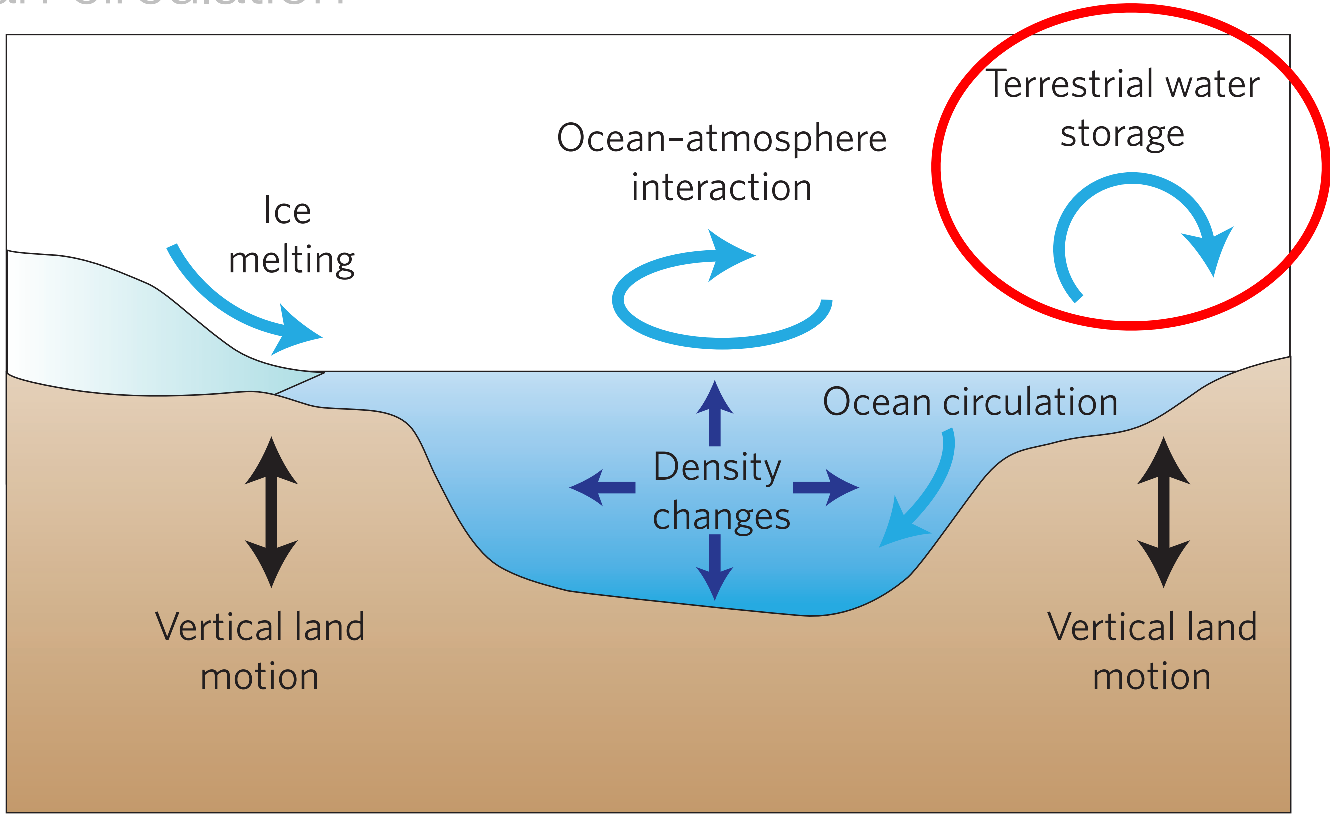
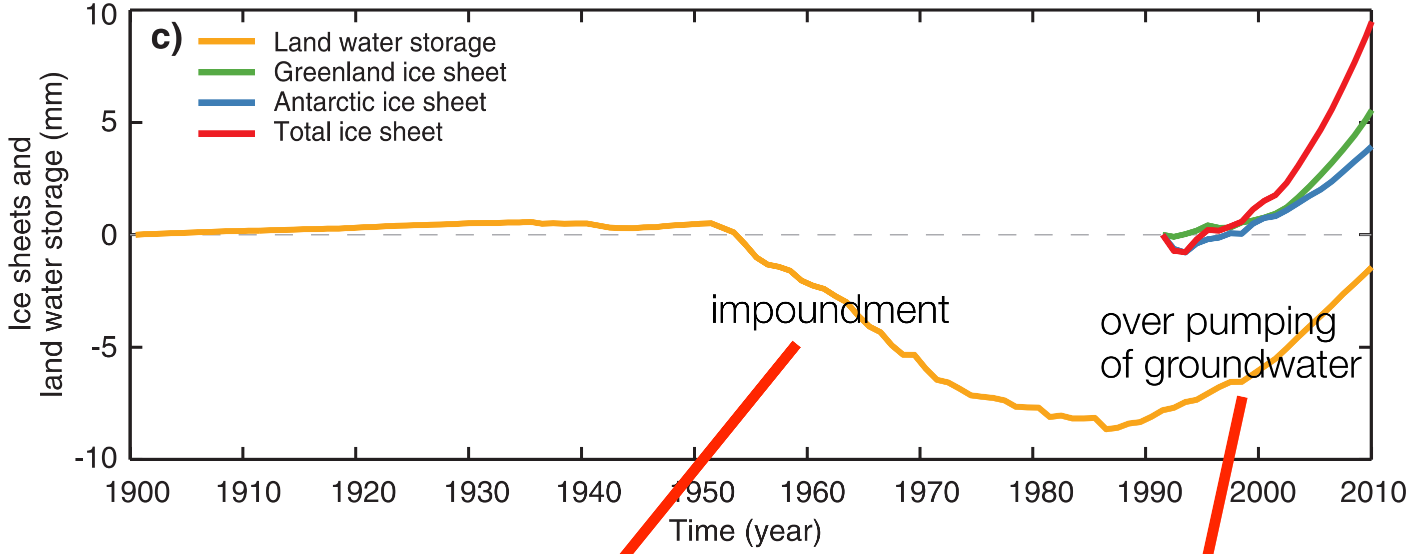
- **Land water storage**
- Coastal erosion
- Atmospheric pressure, wind stresses, ocean circulation
- Gravitational effects (fingerprint)



Milne et al 2009

Sea level change: land water storage

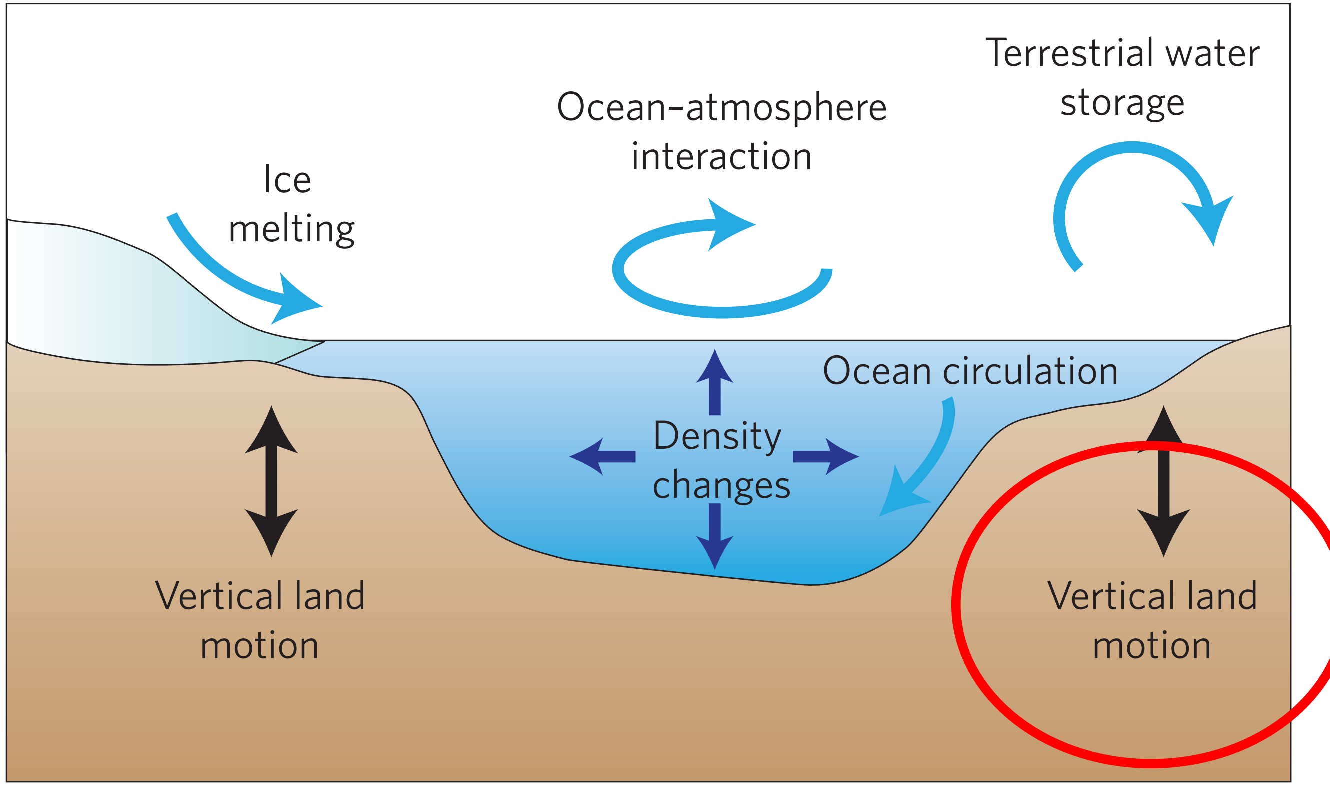
- Water impoundment by human-built reservoirs contributes to sea level fall.
- Groundwater withdrawal makes water that was trapped on land flow into the ocean, contributing to sea level rise. This contribution is slowly overweighting the contribution from water impoundment.



Upper: land water storage and ice sheet contribution to sea level change (IPCC); lower left: Glen Canyon Dam (Wiki); lower right: a sinkhole due to ground water depletion in Florida (https://floridadep.gov/fgs/sinkholes/content/sinkhole-faq)

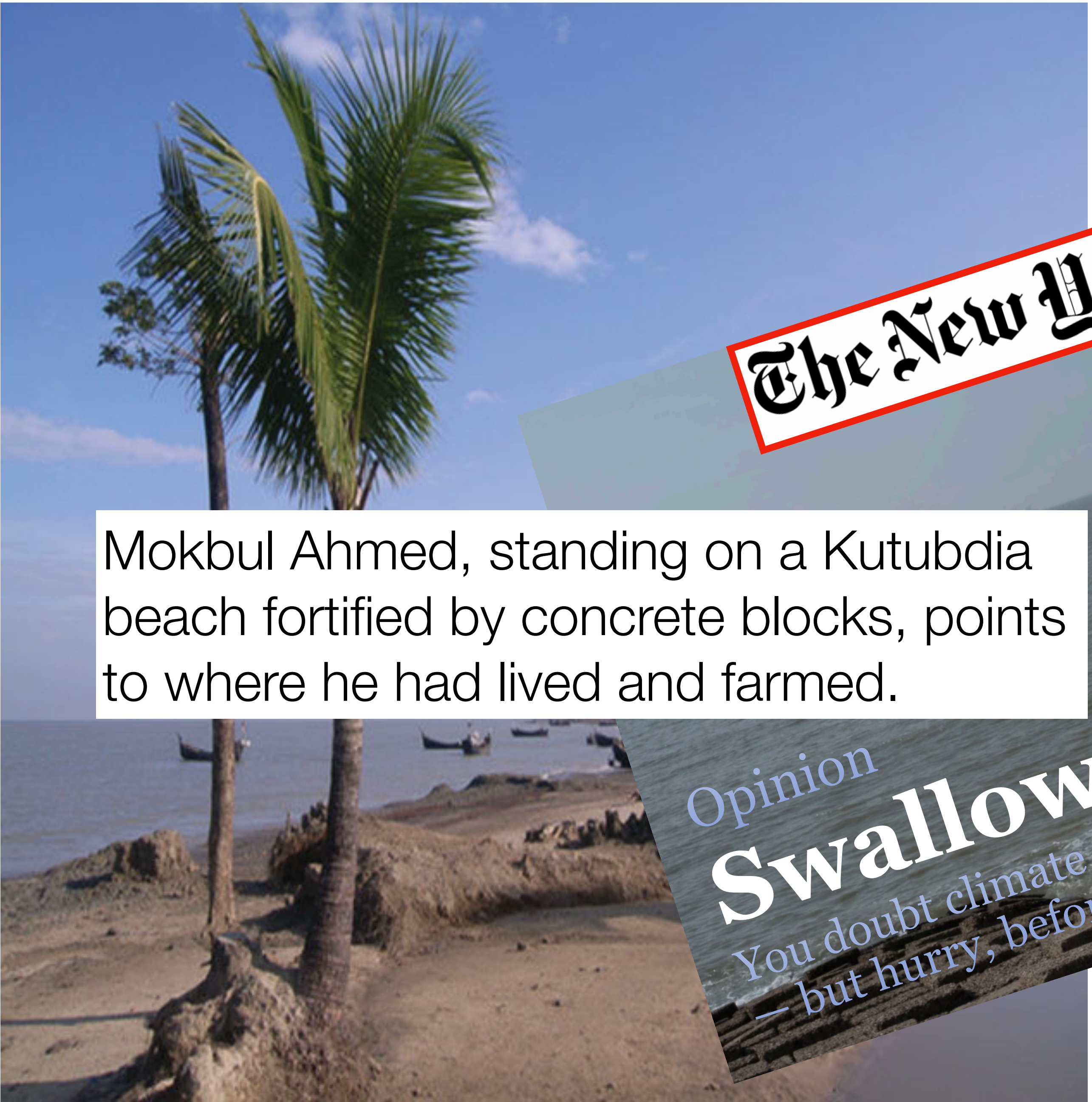
Sea level change: processes

- Thermal expansion
- Glaciers
- Land water storage
- **Coastal erosion**
- Atmospheric pressure, wind stress, ocean circulation
- Gravitational effects (fingerprint)



Milne et al 2009

Sea level: coastal erosion



Mokbul Ahmed, standing on a Kutubdia beach fortified by concrete blocks, points to where he had lived and farmed.

Kutubdia, one of … fshore islands of Banglade… subjected to … destructive … ith diurnal high … m surges, and … t 2012, … erosion and … vaves, high … o days that … e villages … dozen … nto the sea. This … event … in the last … s, flooded nearly 70% of the … area of the island

“Linking Coastal Disasters and Migration: A Case Study of Kutubdia Island, Bangladesh” Rahman et al 2015

Sea level: coastal erosion

Kutubdia, one of sixty offshore islands of Bangladesh, is frequently subjected to coastal erosion caused by destructive ocean waves associated with diurnal high tides, tropical cyclones, storm surges, and coastal flooding. On 4 August 2012, Kutubdia experienced coastal erosion and flooding associated with tidal waves, high winds, and heavy rainfall for two days that flooded twenty of the twenty-nine villages of the island. Lands and several dozen homesteads disappeared into the sea. This was the largest tidal event ... in the last twenty years, flooded nearly 70% of the total area of the island

“Linking Coastal Disasters and Migration: A Case Study of Kutubdia Island, Bangladesh” Rahman et al 2015

Sea level change: coastal erosion

- coastal erosion (loss and displacement of land due to wind and ocean) contributes to local sea level change.
- Coastal erosion is not necessarily related to climate change, but may accelerate in a warming climate due to rising sea level and stronger storms.

Aerial photos of Long Branch, NJ.

(https://coastal.er.usgs.gov/hurricanes/sandy/photo-comparisons/newjersey.php)

Sea level change: coastal erosion

Sea level change: coastal erosion

Sea level change: coastal erosion

Sea level change: coastal erosion

Sea level change: coastal erosion

Erosion along the coast of the Pacific Ocean in Pacifica, just south of San Francisco, Jan 2020(?). Chang W. Lee, NYTimes

Sea level change: processes

- Thermal expansion
- Glaciers
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- **Atmospheric pressure, wind stresses, ocean circulation**
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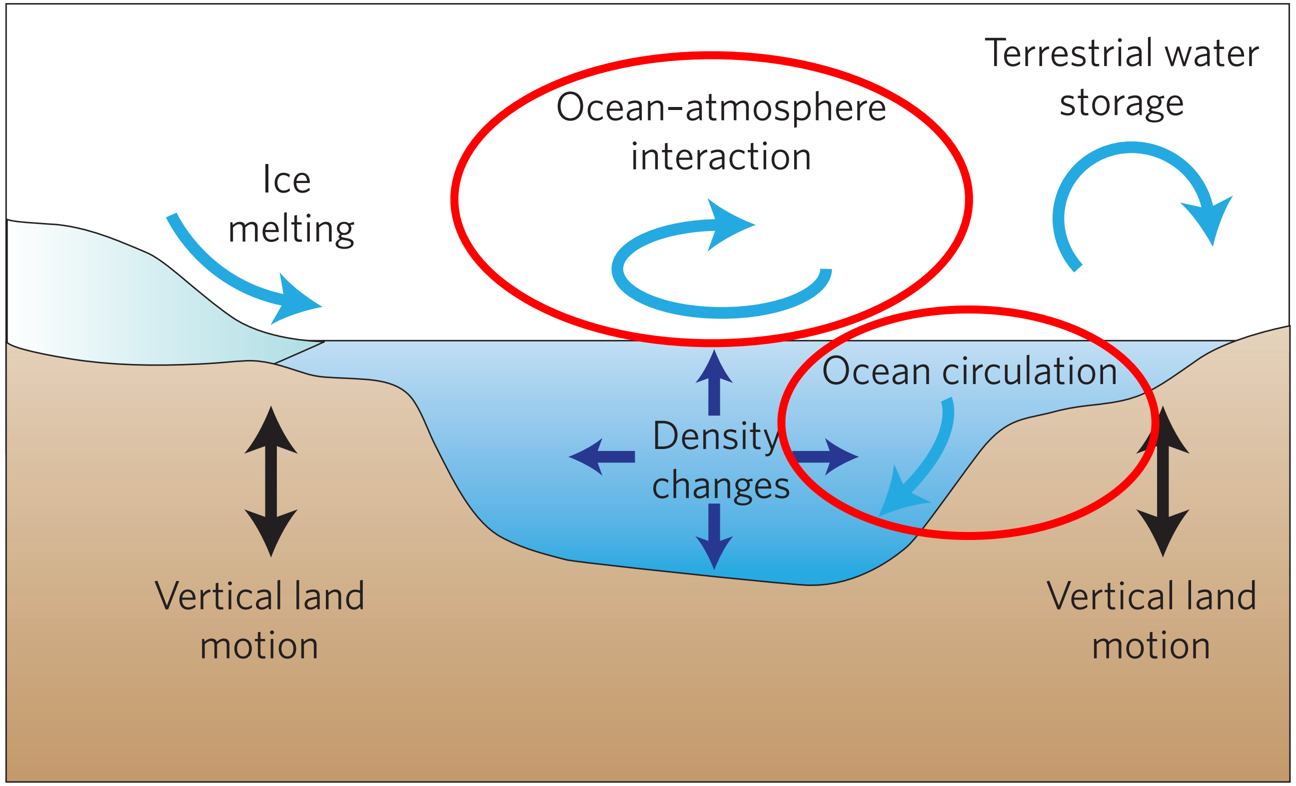
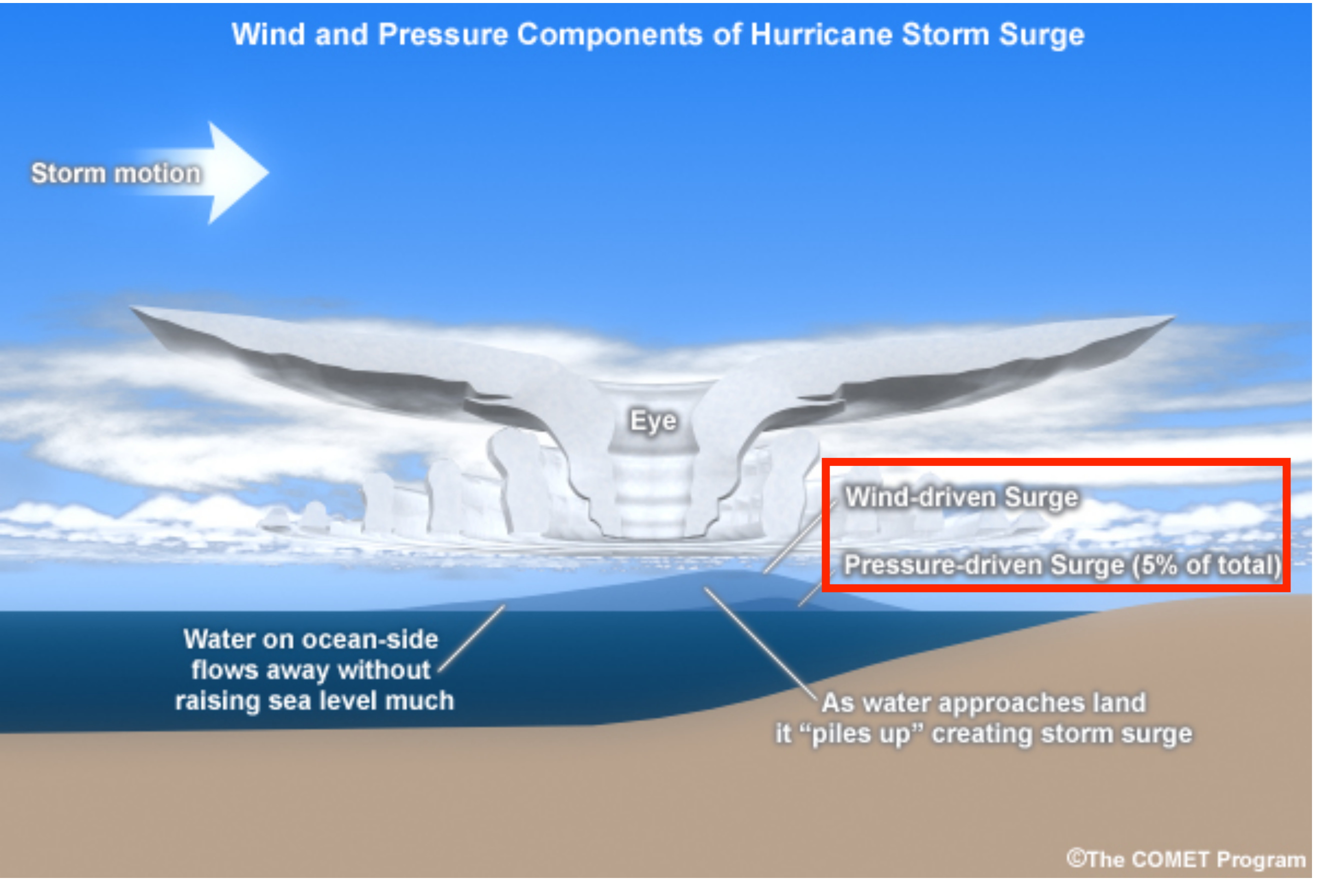


Milne et al 2009

Sea level change: atmosphere pressure

Lower atmospheric pressure gives rise to a higher sea level; a decrease in air pressure of 1 hPa (1 mb) increases the water level by 1 cm.



Schematic of a storm surge
(https://www.nhc.noaa.gov/surge/)

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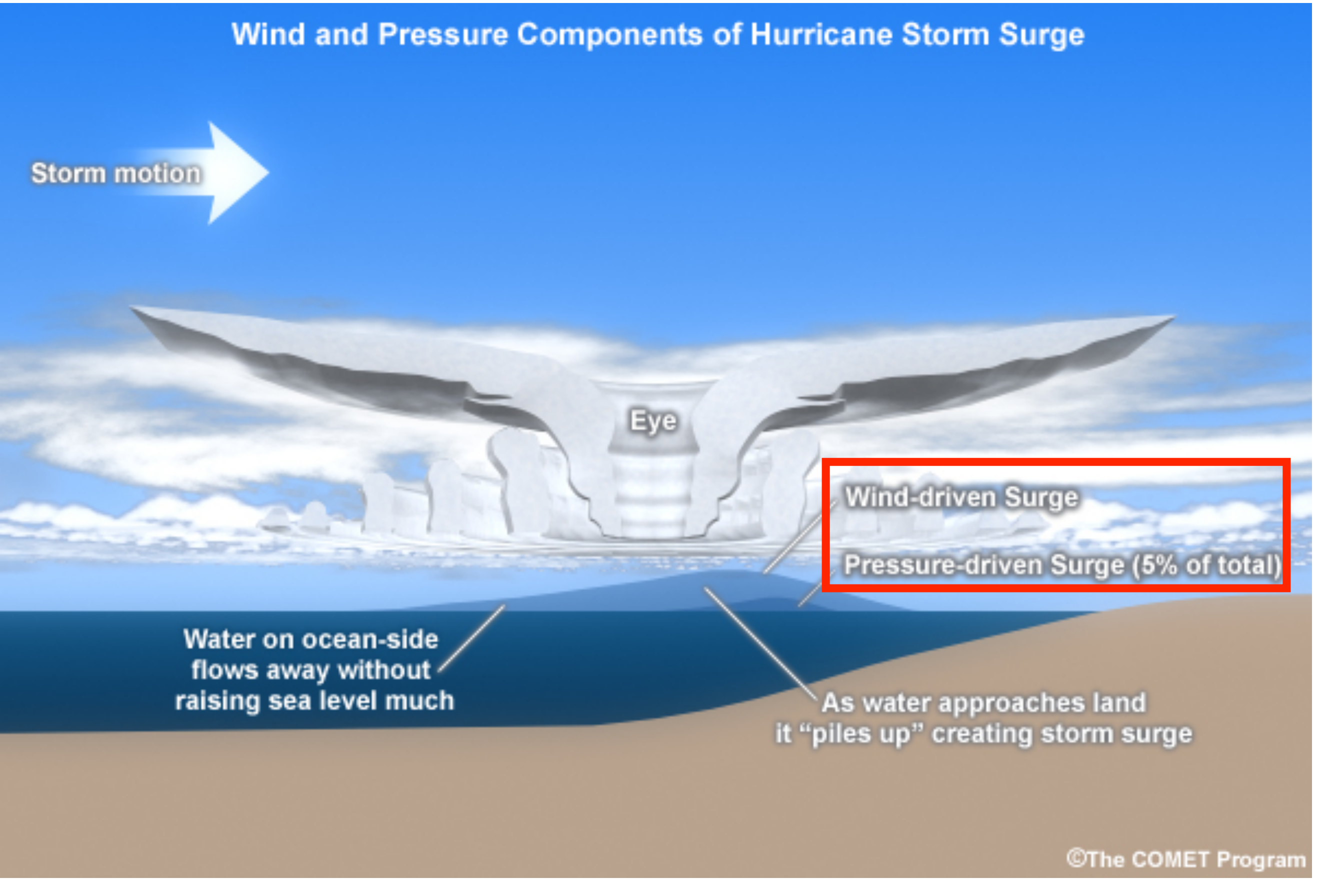

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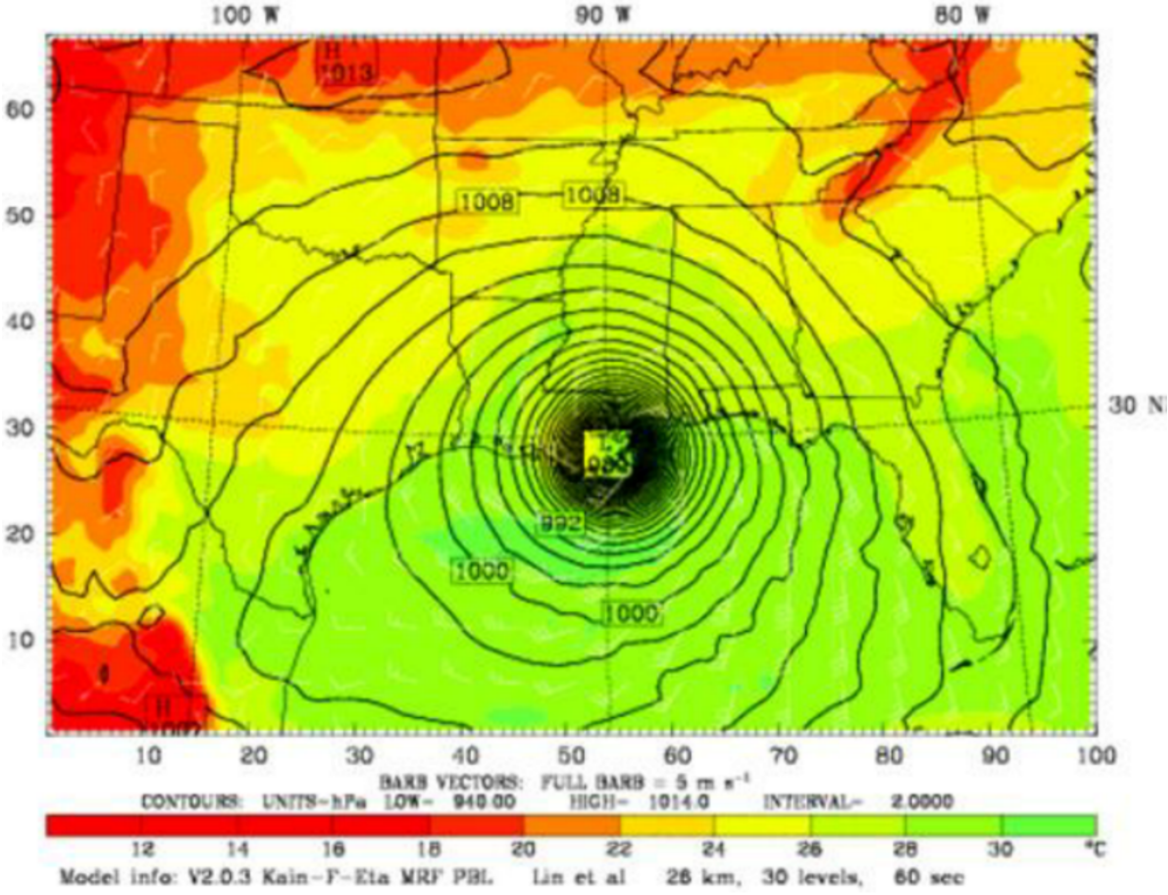
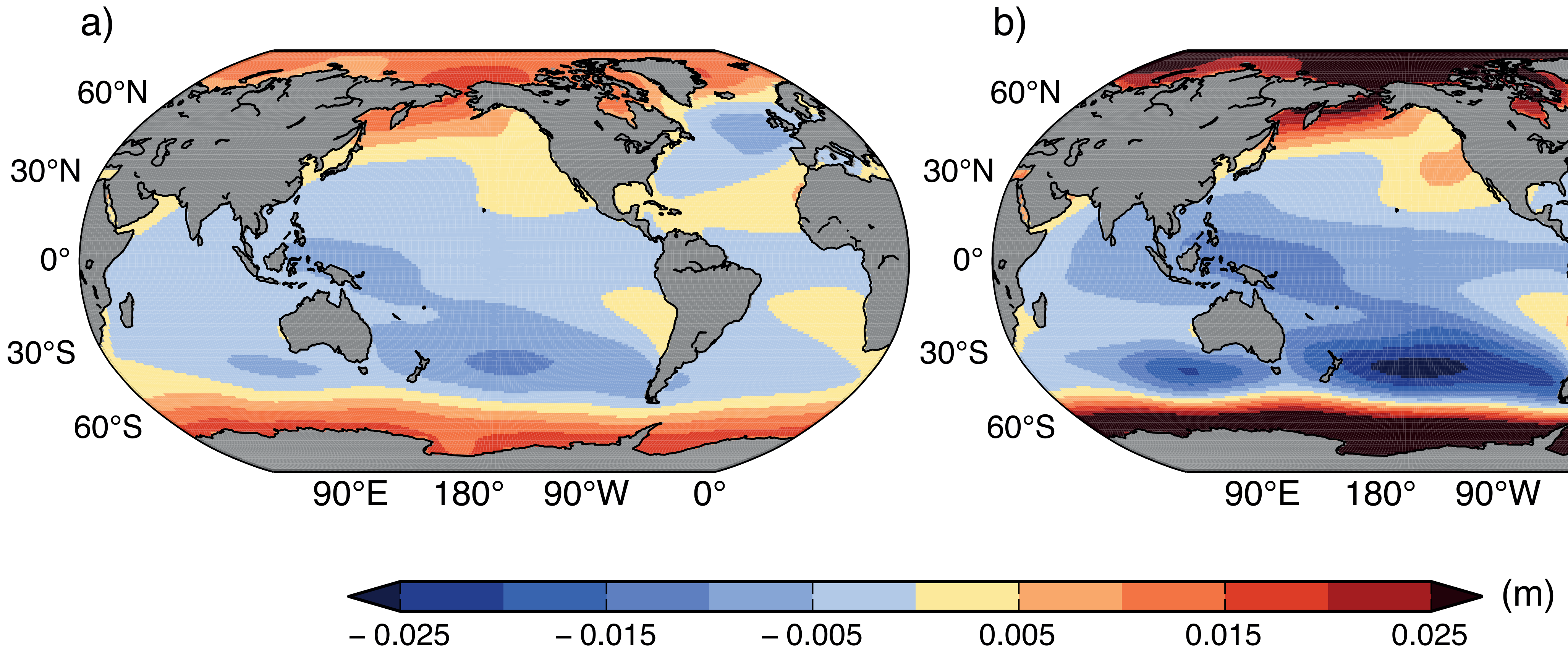


Katrina, central pressure 920 mb, surrounding 1010 mb. SSH ~90 cm!

Sea level change: atmosphere pressure

Lower atmospheric pressure gives rise to a higher sea level; a decrease in air pressure of 1 hPa (1 mb) increases the water level by 1 cm.



IPCC AR5, 2013

Figure 13.17 | Projected ensemble mean sea level change (m) due to changes in atmospheric pressure loading, 1986–2005 to 2081–2100 (a) RCP4.5 and (b) RCP8.5 (contour interval 0.005 m)

notes section 4.2.1 (part I)
wind stress and inverse barometric effect
(use following slides)

Sea level change: atmospheric pressure

The inverse barometer effect: Higher atmospheric pressure will give rise to a lower sea level; an increase in air pressure of 1 hPa lowers the water level by 1 cm.

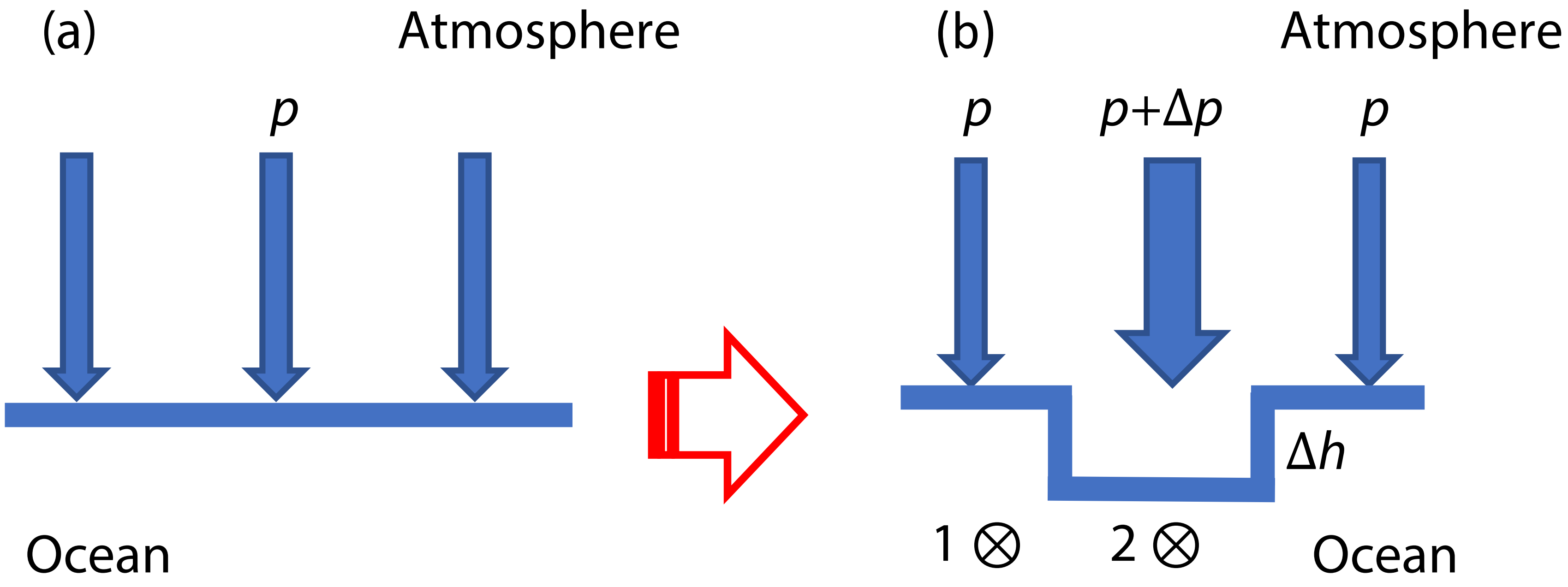


Figure 4.4: Atmospheric pressure loading.
How a change to sea level atmosphere pressure (SLP) from spatially uniform on the left to spatially variable on the right affects regional sea level.

Sea level change: wind stress (Venice flooding 2019)

https://www.youtube.com/watch?v=EDpaQycKsB4

Sea level change: wind stress (Venice flooding 2019)

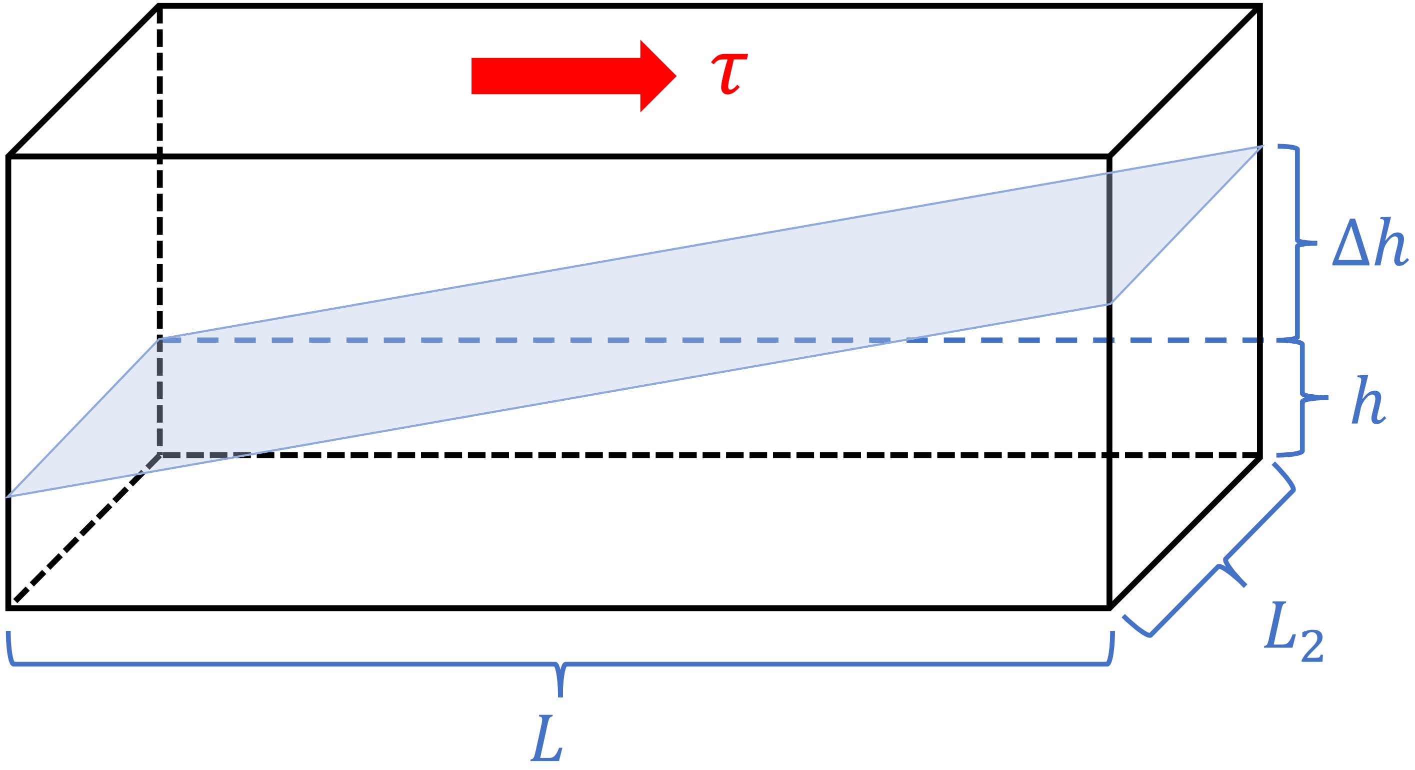
https://www.youtube.com/watch?v=EDpaQycKsB4

Sea level ch… flooding 2019)

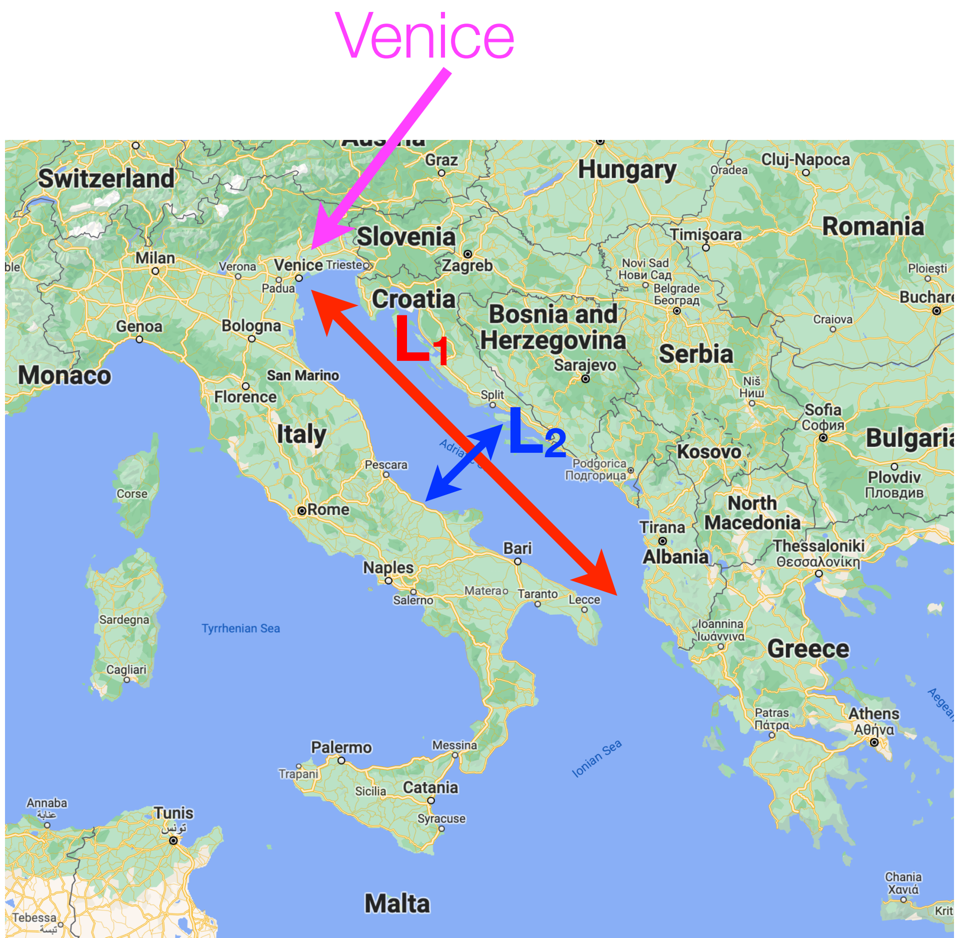
B4

Sea level change: wind stress

Figure 4.5: Wind-driven sea level change. Wind stress drives a sea surface height slope and affects sea level height.

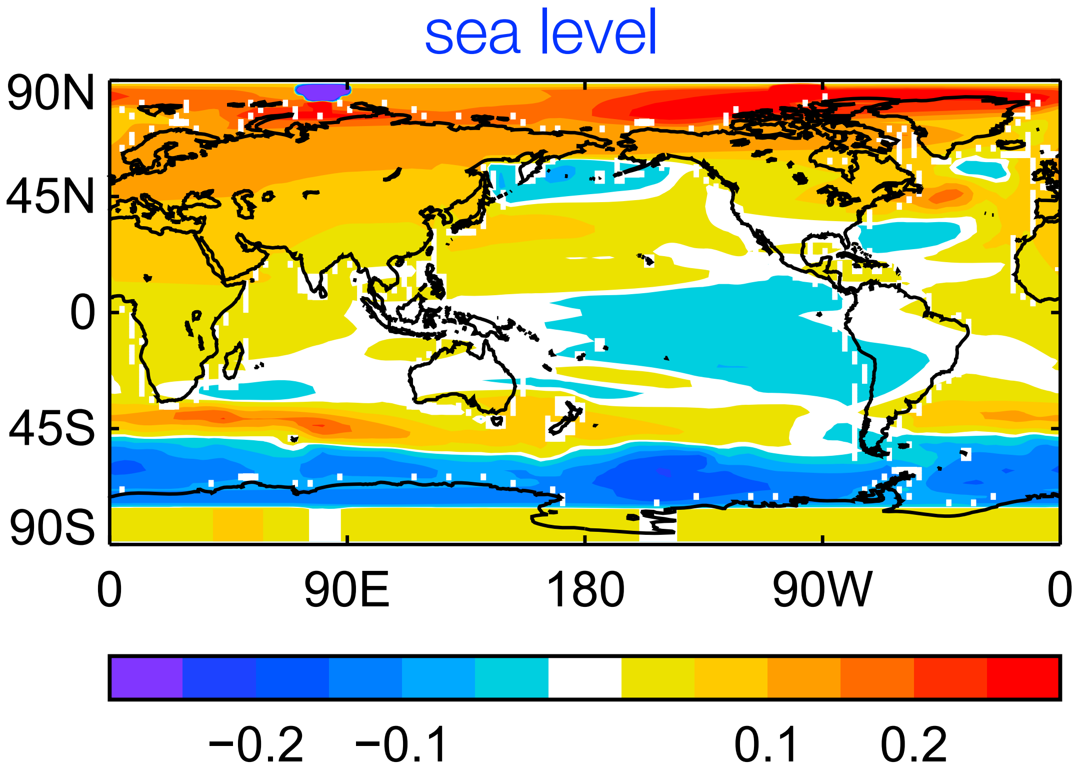


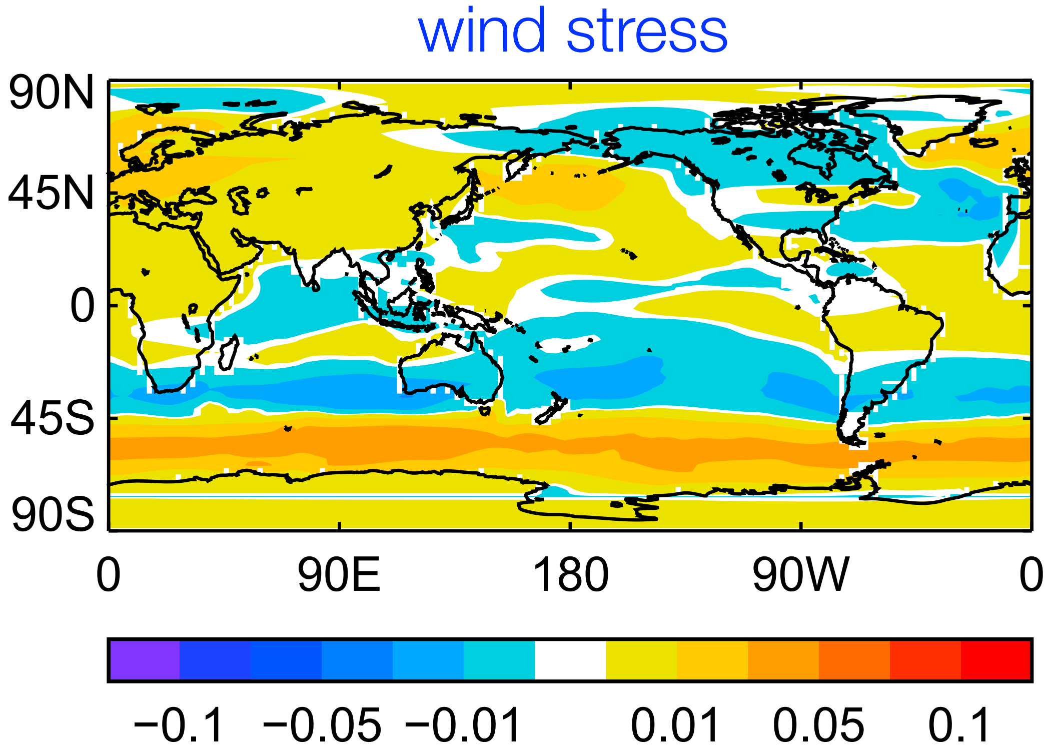
change in wind stress can lead to regional sea level change



Sea level change: wind stress

In a warming climate, models predict the westerlies over the Southern Ocean strengthen & shift southward. This may be related to the predicted sea level fall in Southern Ocean.





Bouttes et al 2012

Left: Sea level (m), right: zonal wind stress (10^{-3} N/m^2) changes (over 21st century?) in CMIP5 models forced by a 1%/yr CO_2 scenario.

notes section 4.2.1 (part II)
ocean currents and the Coriolis force
(use following slide)

Ocean currents and the Coriolis force

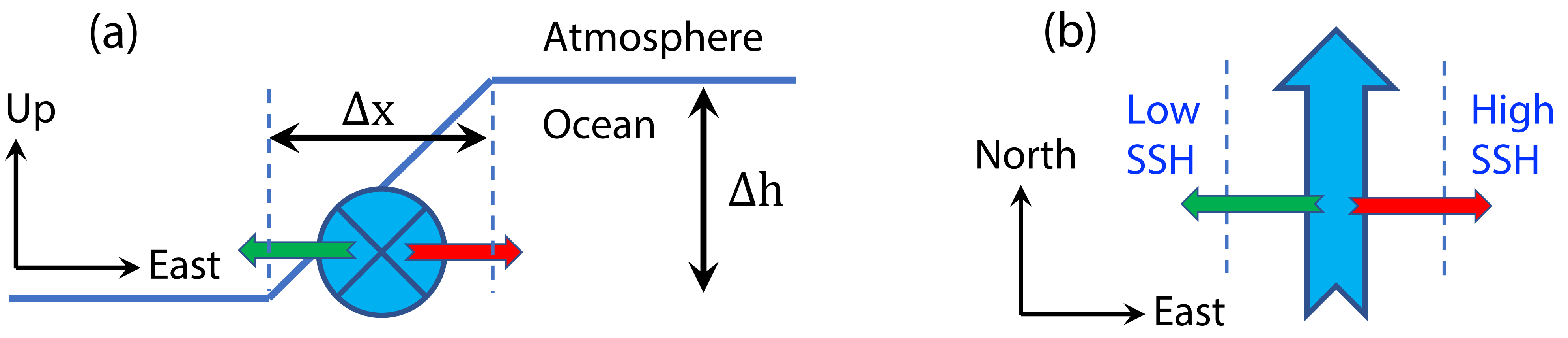


Figure 4.6: The Coriolis force and sea level.

Sea surface height variations across the northward flowing Gulf Stream, showing the pressure force from high to low sea level (green arrows) and Coriolis force to the right of the current (red arrows). (a) A vertical east-west section (current is denoted by the blue symbol of an arrow pointing into the page). (b) A horizontal schematic with the Gulf Stream shown by the blue arrow.

workshop 4
Wind forcing, sea level pressure and the Coriolis force

Sea level change: ice sheets and gravitational effects

- Ice mass loss and water mass redistribution also give rise to regional patterns of sea levels rise that deviate from global mean, at different time scales. On rapid time scale:

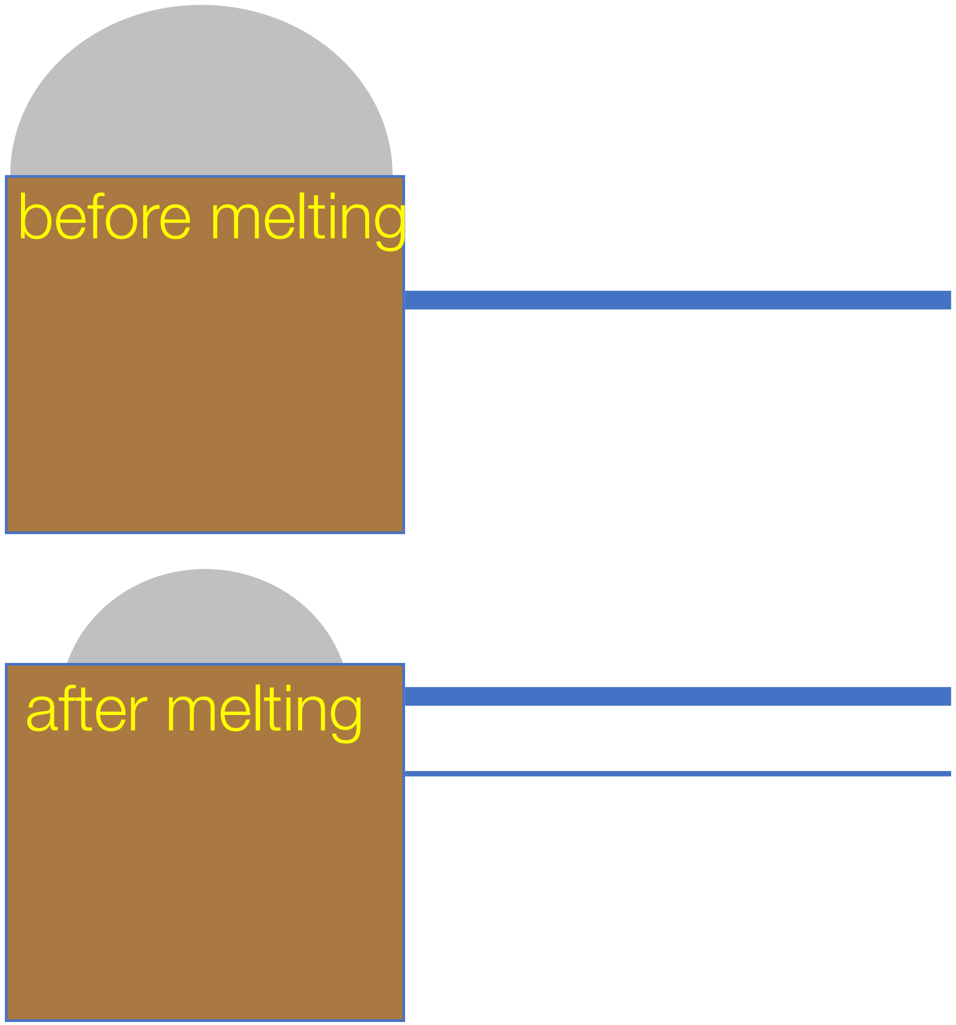


Figure made after a very similar one by Jerry Mitrovica

Sea level change: ice sheets and gravitational effects

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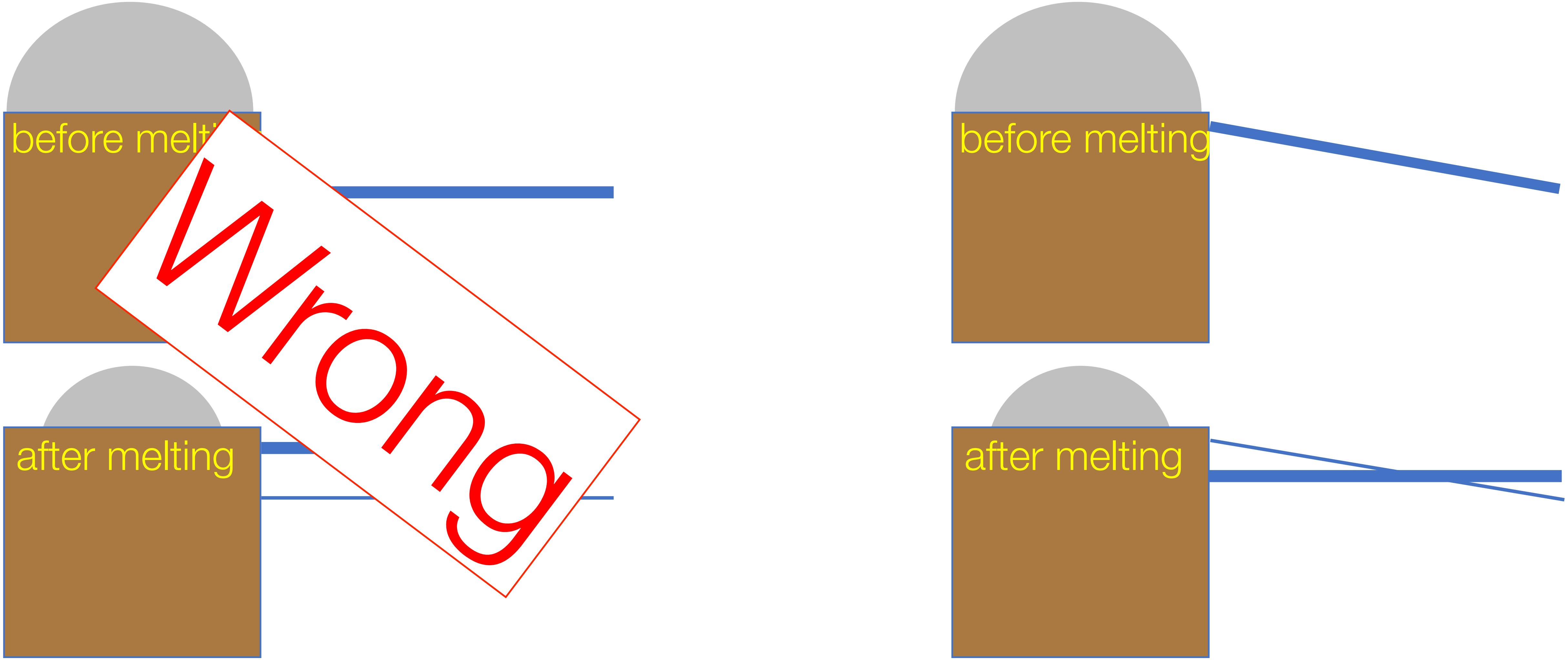

Figure made after a very similar one by Jerry Mitrovica

Sea level change: ice sheets and gravitational effects

Sea level fingerprints. Consider an ice sheet melting, adding water mass to the ocean:

Greenland melting leading to 1 mm/yr GMSL rise ➨ sea level *drop* within 2000 km of Greenland. At the shore of Greenland: a *drop* of up to 10 mm/yr!

Sea level change: ice sheets and gravitational effects

Sea level fingerprints. Consider an ice sheet melting, adding water mass to the ocean:

- The gravitational attraction of surrounding water will decrease (fast time scale);

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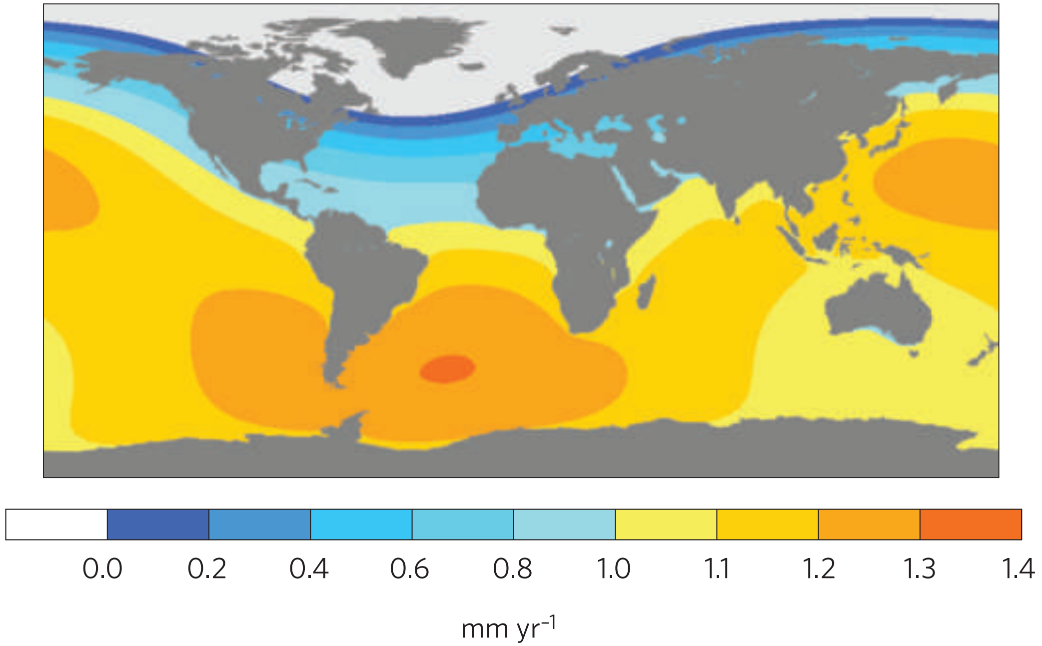

Fingerprint of Greenland melting (Milne et al 2009)

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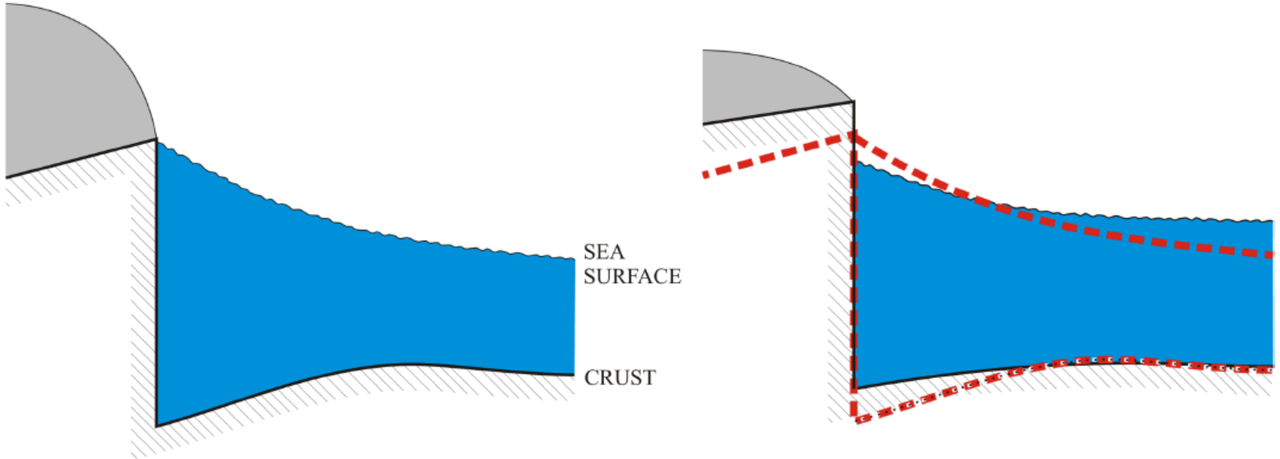
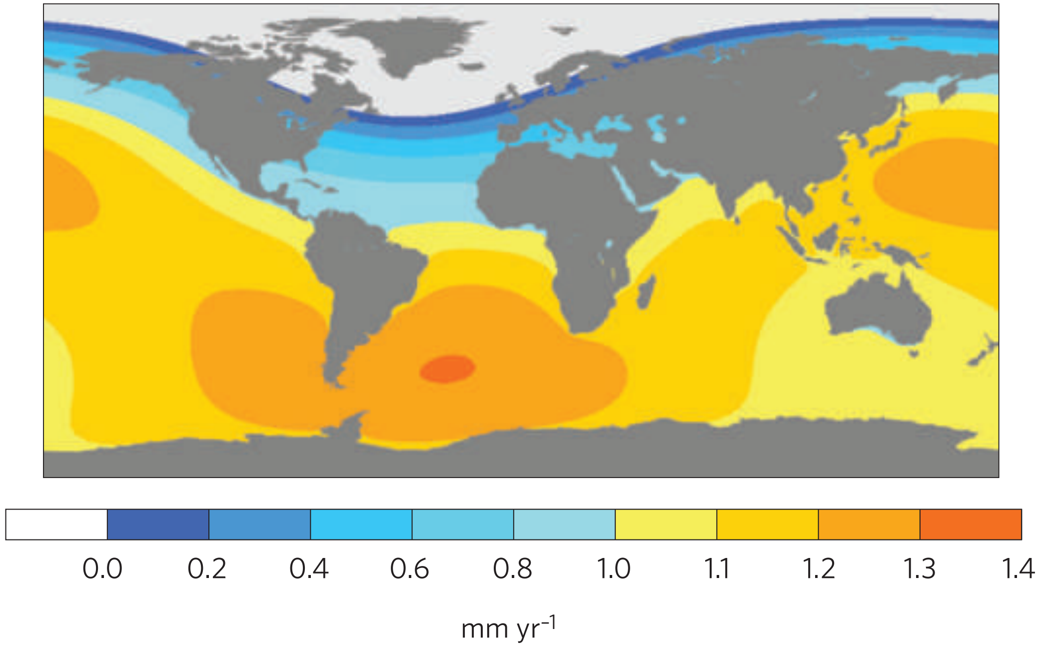
Sea level change: ice sheets and gravitational effects

Sea level fingerprints. Consider an ice sheet melting, adding water mass to the ocean:

- The gravitational attraction of surrounding water will decrease (fast time scale);
- Sea level decreases near melting ice sheet but rises more than global mean in the far field.
- Continent where ice sheet stood will bounce up (1000s years). Ocean floor will rise near ice sheet because water flows away, but sink in the far field because water will pile there.



Schematic of the sea level fingerprint physics.



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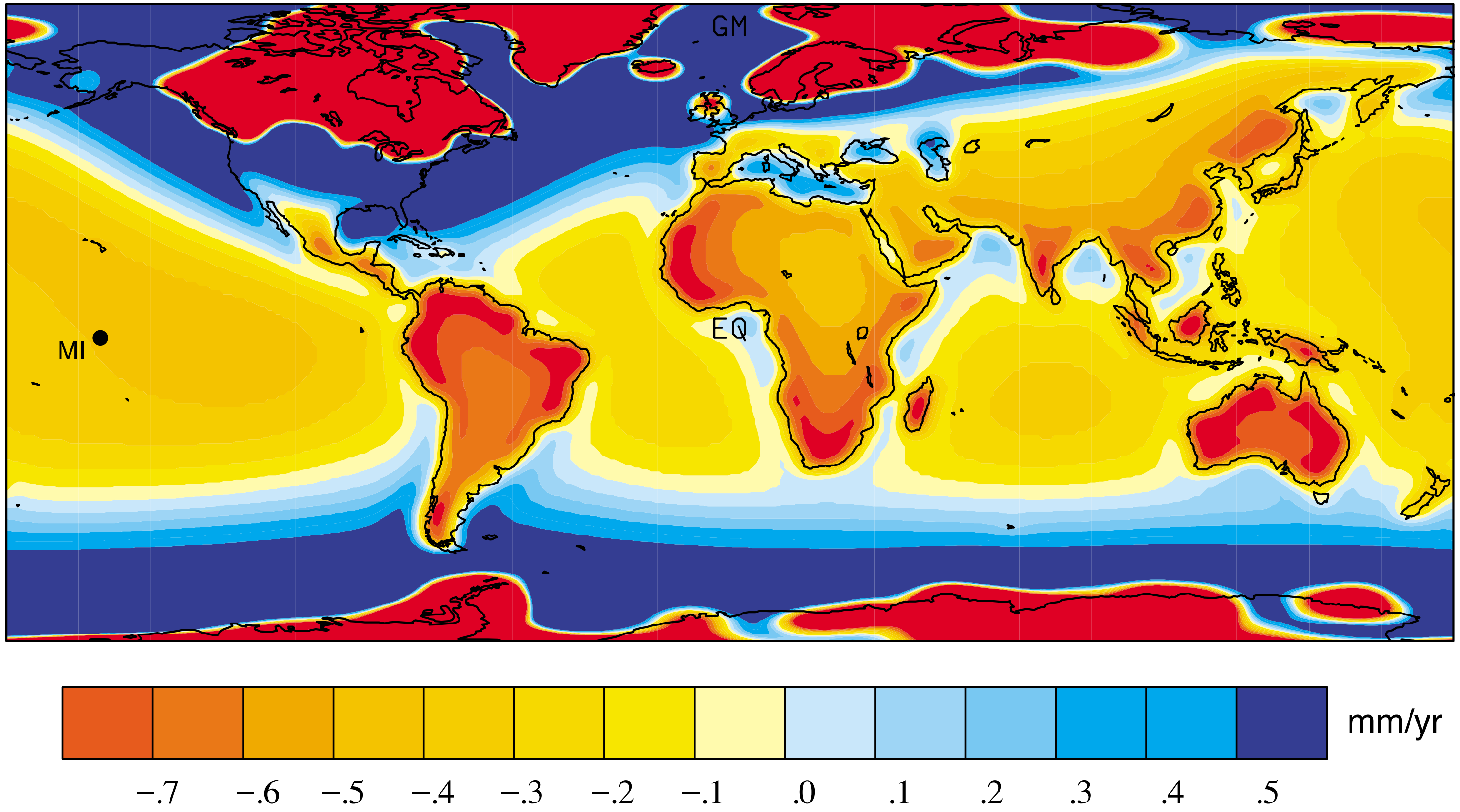
Present-day sea level change due to ice sheet melting since the last glacial maximum 21 kyr

Past melting of the Laurentide ice sheet that covered North America 21 kyr ago causes land rebound and affects sea level today! Should be considered when examining observations.



Present-day rate of change of global sea level due to GIA since late Holocene (Mitrovica and Milne 2002).

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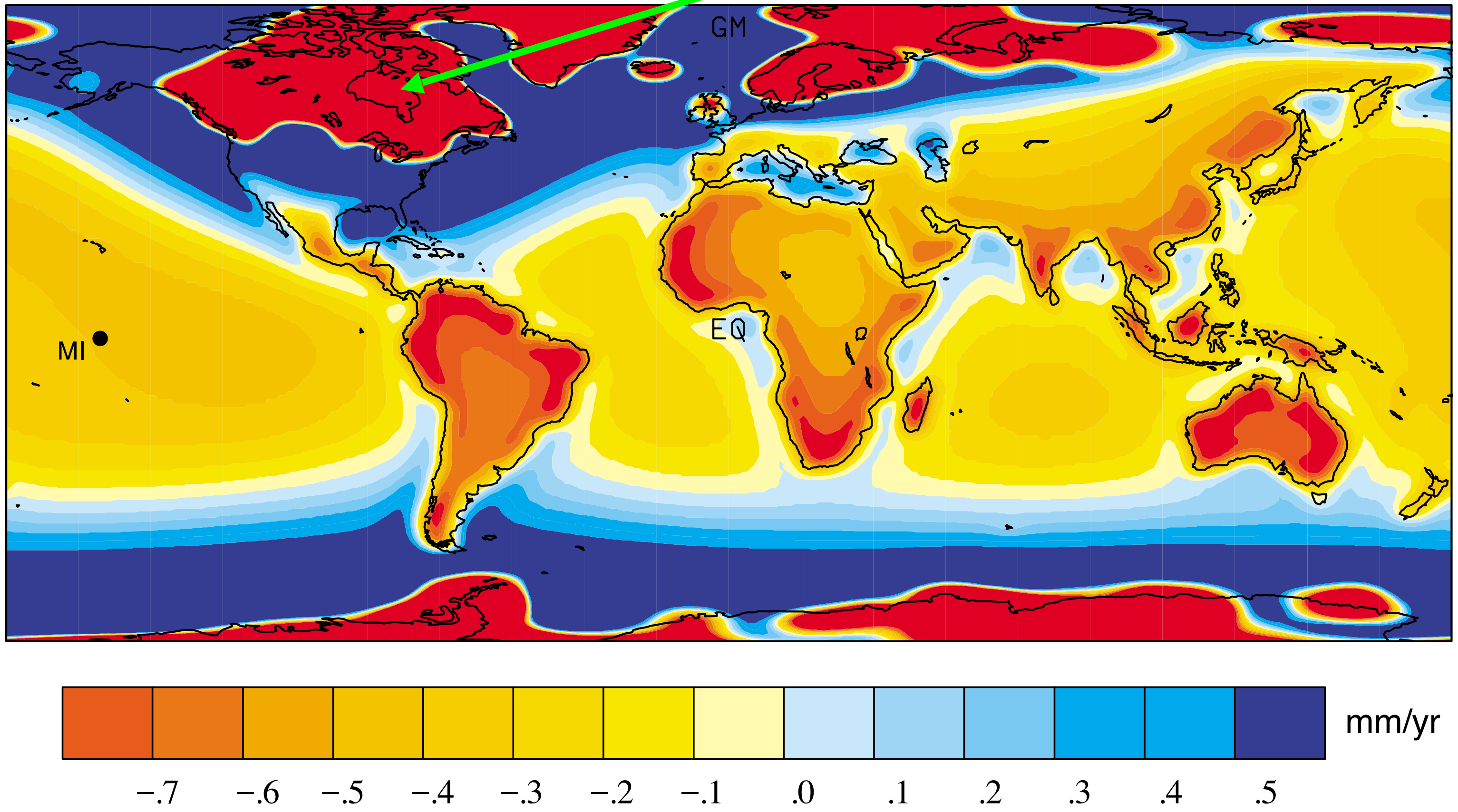
relative sea level decreases due to land rebound



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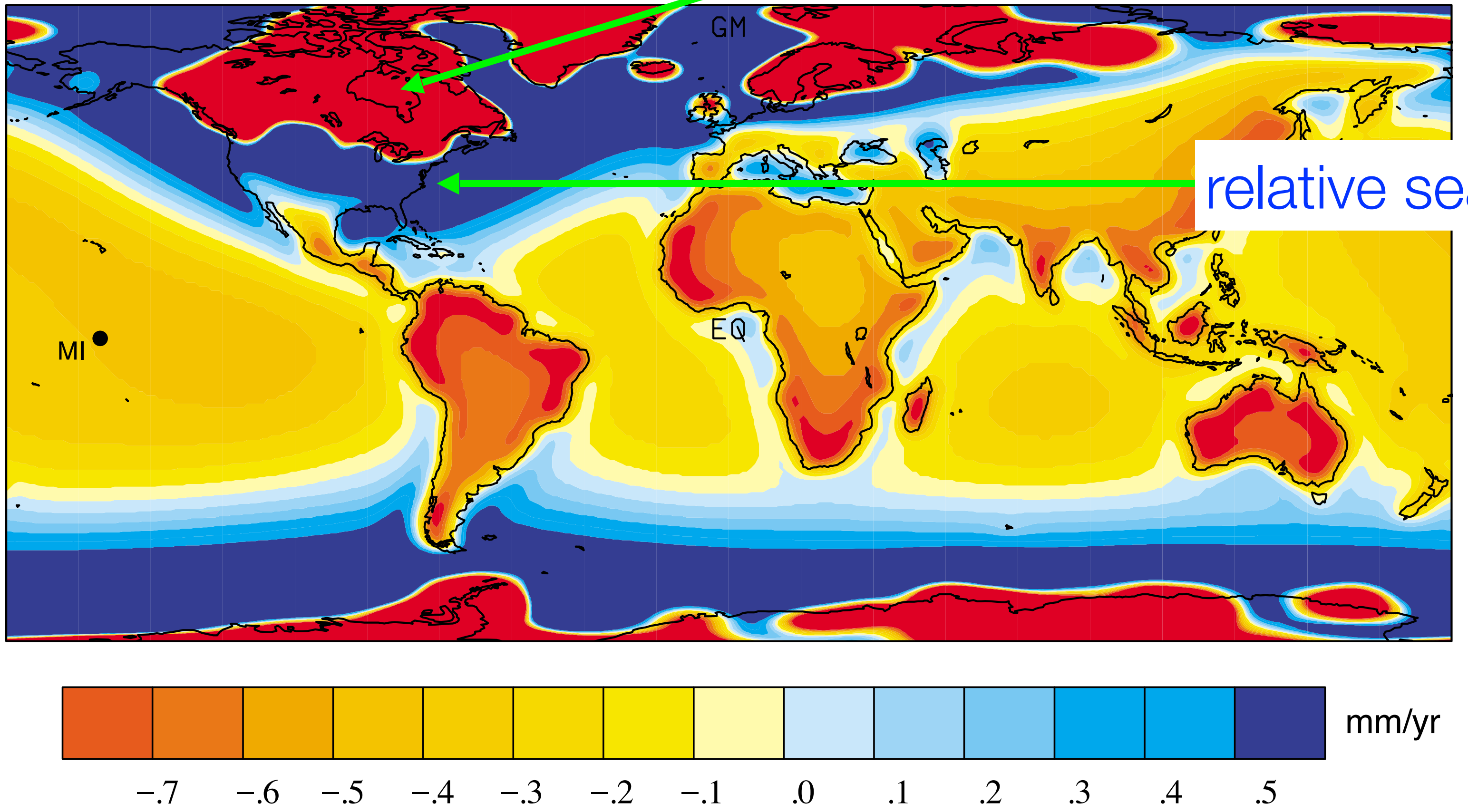
relative sea level decreases due to land rebound

relative sea level increases due to land sinking



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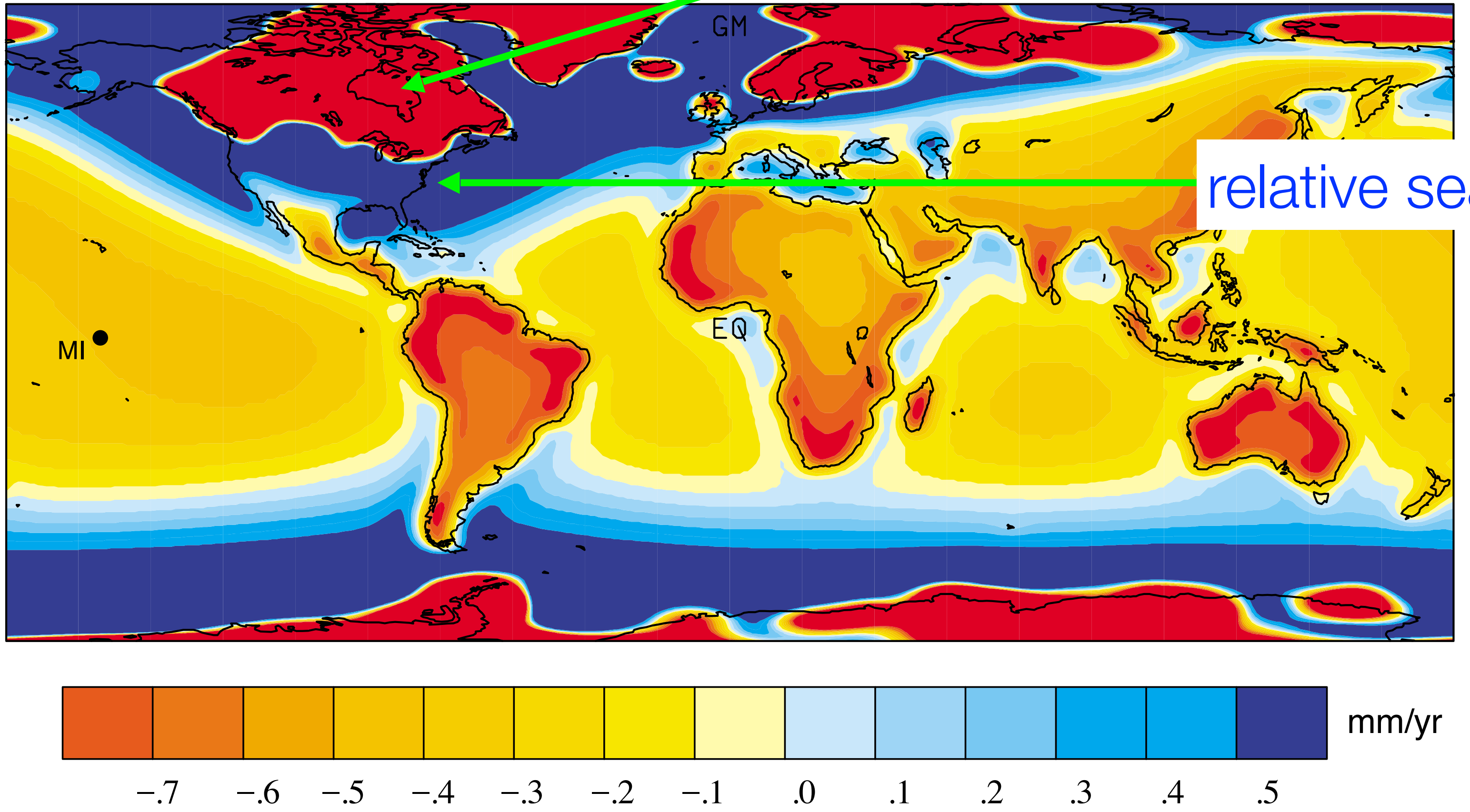

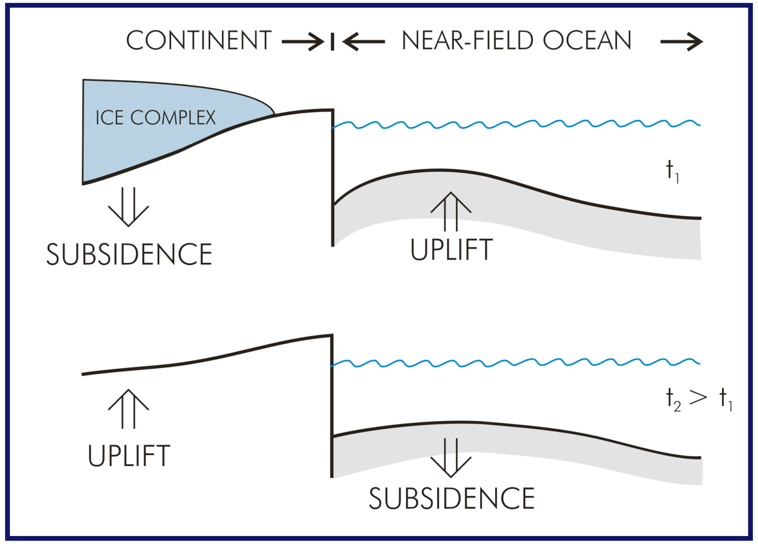

Present-day rate of change of global sea level due to GIA since late Holocene (Mitrovica and Milne 2002).

workshop 5
gravitational effects/ fingerprint

Summary

- Global mean sea level rise vs. relative sea level rise & regional changes

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Bottom line: sea level rise is one of the most robust already observed signals of anthropogenic climate change!

The End