Introduction to mean sea level variability and change

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NATURAL ENVIRONMENT RESEARCH COUNCIL

Sea Level Training Course, St Lucia | 17-21 October 2016

What we will cover

- Characteristics of sea level records
- Global mean sea level changes and their causes
- Regional mean sea level changes and their causes
  - The seasonal cycle
  - Interannual to decadal variations
  - Trends
- Future changes in MSL
- Conclusions

Characteristics of sea level records

- **Wind-generated waves (T ~ 1 to 20 s)**

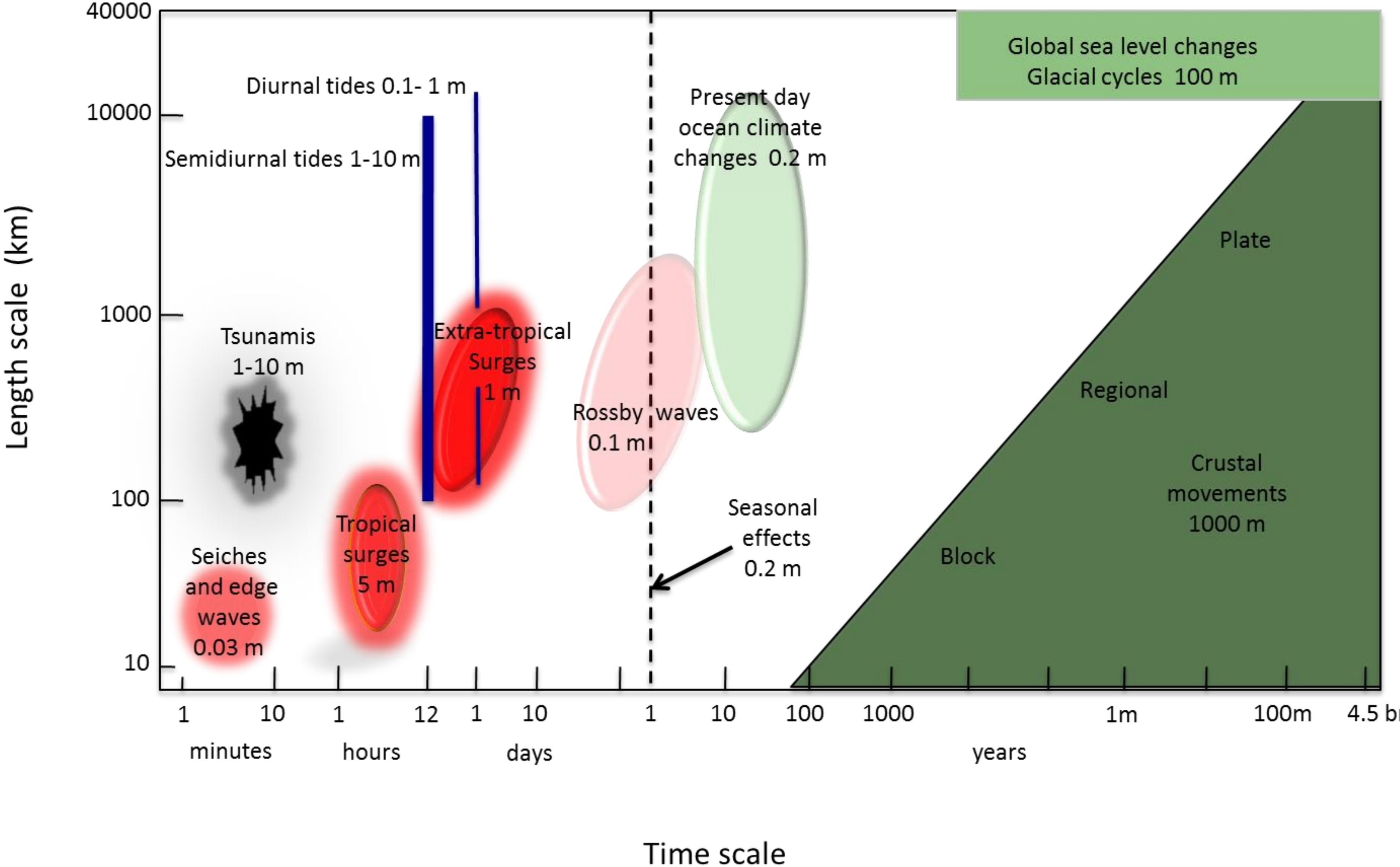
- **Seiches and tsunamis (T ~ minutes to hours)**

- **Tides (T ~ 1/2 to 1 day)**

- **Storm surges (T ~ several days)**

- **Mean sea level (T ~ months – years – centuries – millennia)**

Characteristics of sea level records



Mean sea level for Tide Gauge People

- Daily MSL is calculated by applying a suitable filter (see IOC Manuals for details) to the measured tide gauge data (i.e. not the tidal or non-tidal parts separately, but to the measured values)

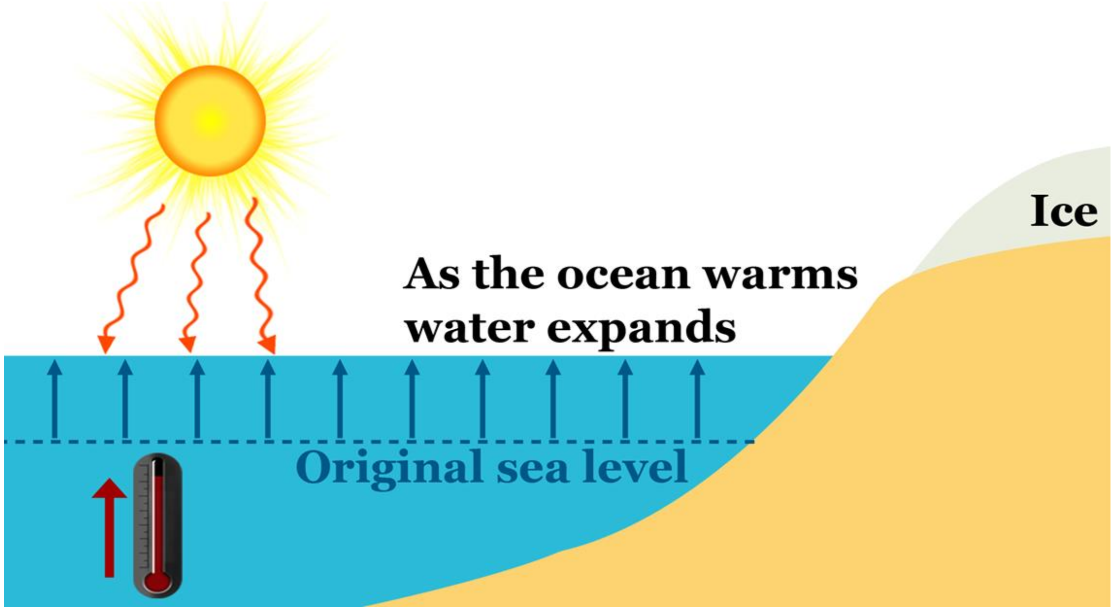
- Monthly MSL is then defined as the arithmetic average of the daily MSL values in that month

- Annual MSL is defined as the average of the daily MSL values in a year

Global MSL changes

What causes global MSL to change?

Thermal expansion of the water



Sea level rise due to water over 1 km warming 1°C

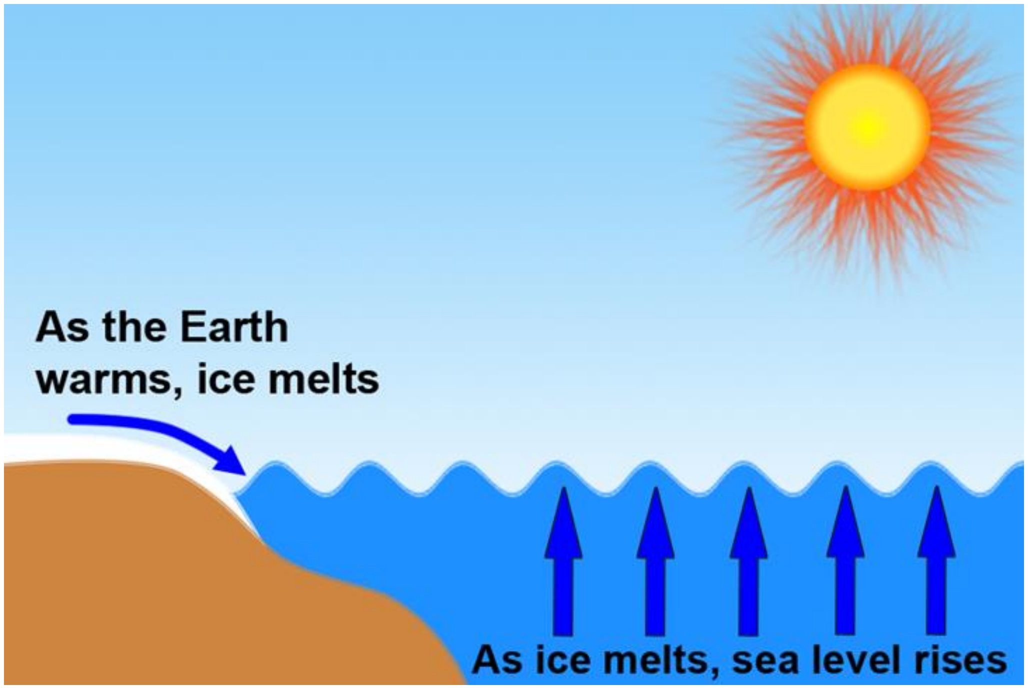
$$\Delta h = \alpha \Delta T H$$

$$= 2 \cdot 10^{-4} \ {}^\circ\mathrm{C}^{-1} \times 1 \ {}^\circ\mathrm{C} \times 10^3 \ \mathrm{m}$$

$$= 20 \, \mathrm{cm}$$

What causes global MSL to change?

Land-based ice melting



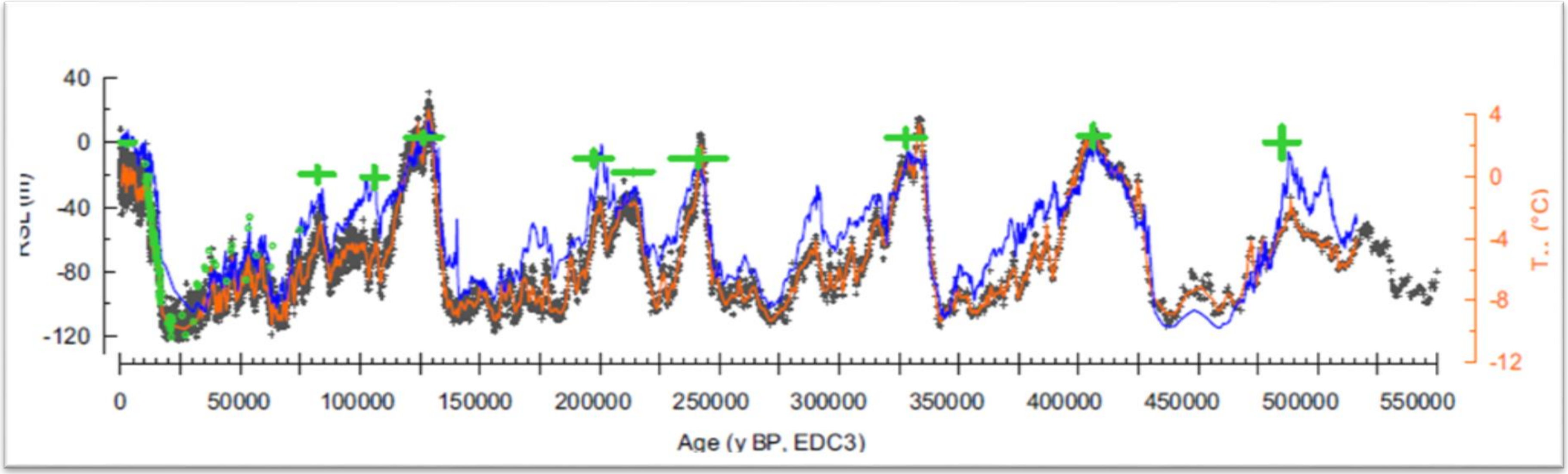
Meltwater from ice sheets and glaciers running into the sea will increase sea level by adding into the total amount of water in the ocean

Same water level

Melting of sea ice does not change sea level!

Sea level over geological timescales

We know from geologists that sea level has changed over many 1000s of years largely as a result of the exchanges of water between the ocean and ice caps



Changes in sea level during the last 500,000 years

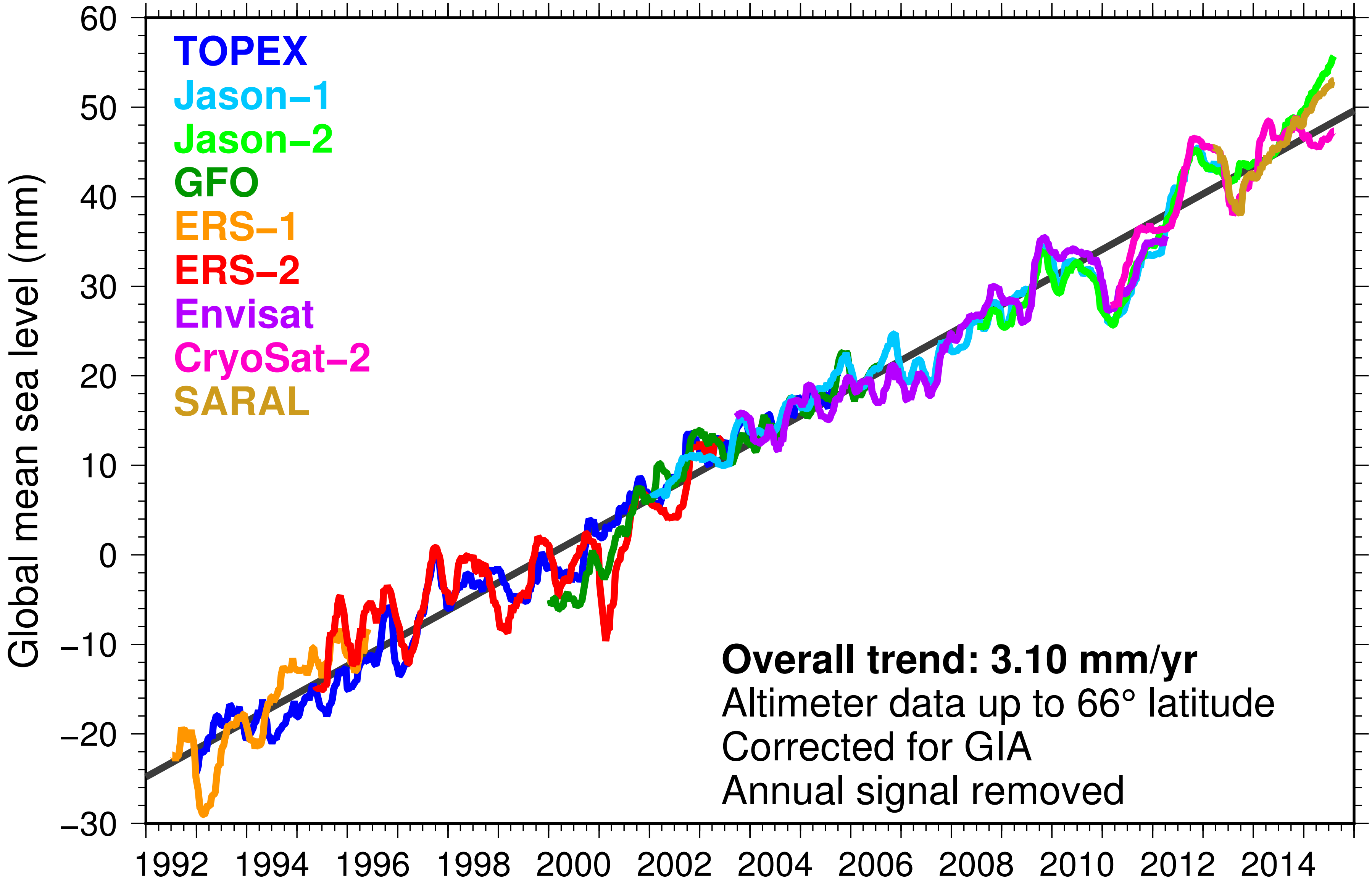
How do we “measure” global MSL?

Since 1992 we can obtain direct estimates of global MSL from satellite altimetry measurements.

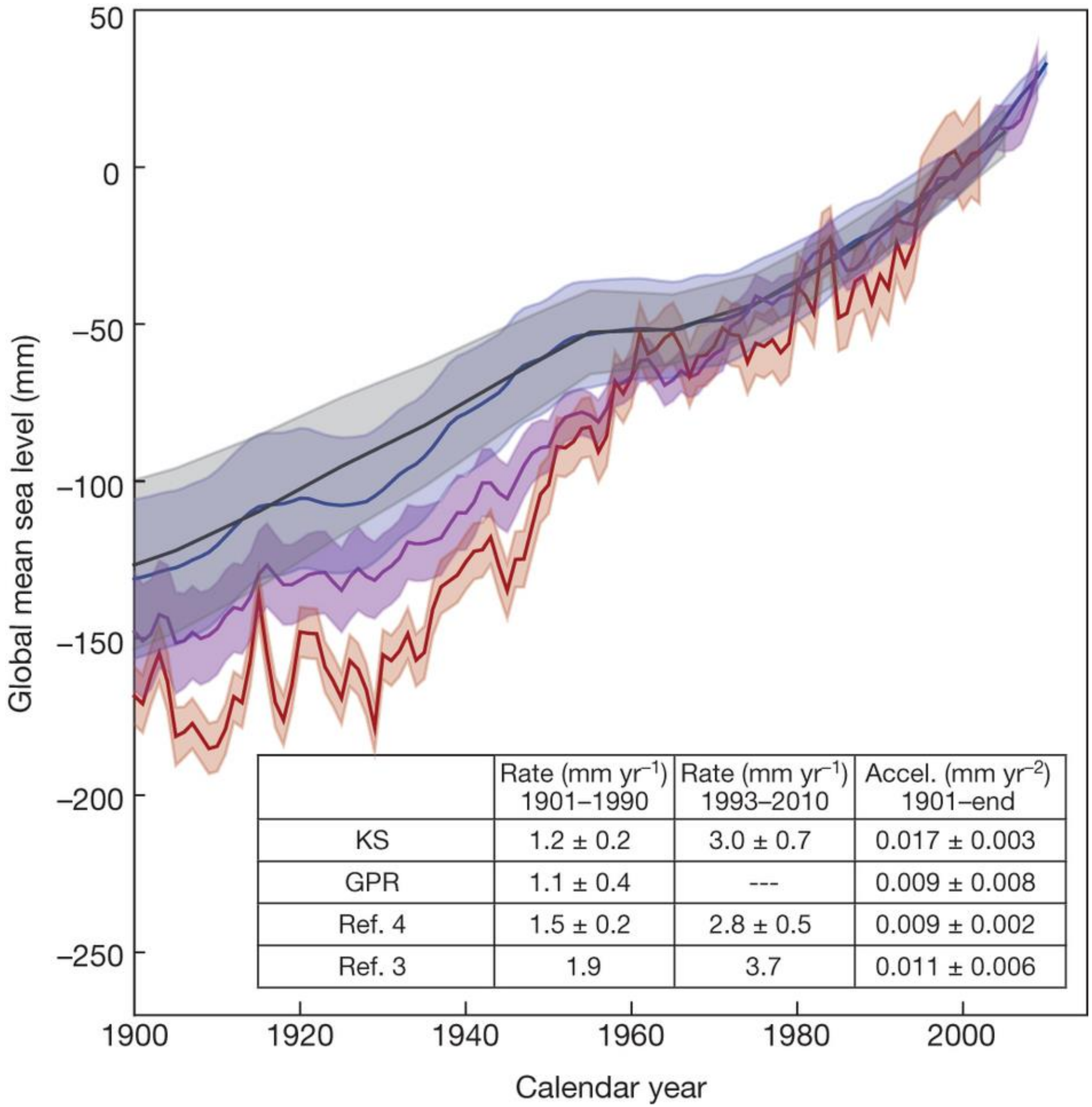
Prior to this, estimates of global MSL are derived from sea level reconstructions usually based on a combination of tide gauge and satellite altimetry observations.

Global MSL reconstructions can go as far back as 1700, but their uncertainty is large before 1950 and increases rapidly as we move backwards in time due to the decreasing number of tide gauge stations

Global MSL over the last 23 years as measured by satellite altimetry



Global MSL over the last 110 years



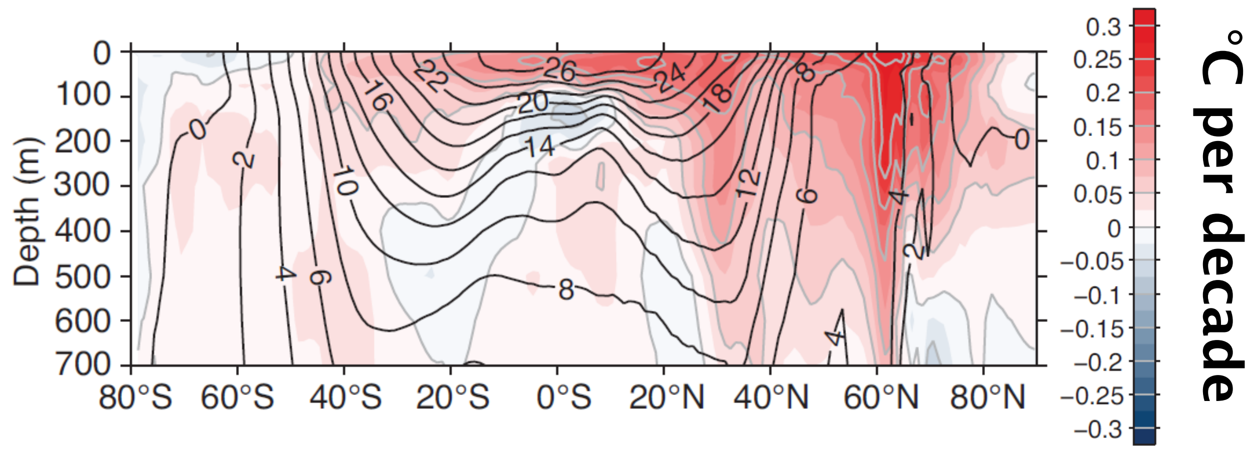
	Rate (mm yr^{-1}) 1901–1990	Rate (mm yr^{-1}) 1993–2010	Accel. (mm yr^{-2}) 1901–end
KS	1.2 ± 0.2	3.0 ± 0.7	0.017 ± 0.003
GPR	1.1 ± 0.4	---	0.009 ± 0.008
Ref. 4	1.5 ± 0.2	2.8 ± 0.5	0.009 ± 0.002
Ref. 3	1.9	3.7	0.011 ± 0.006

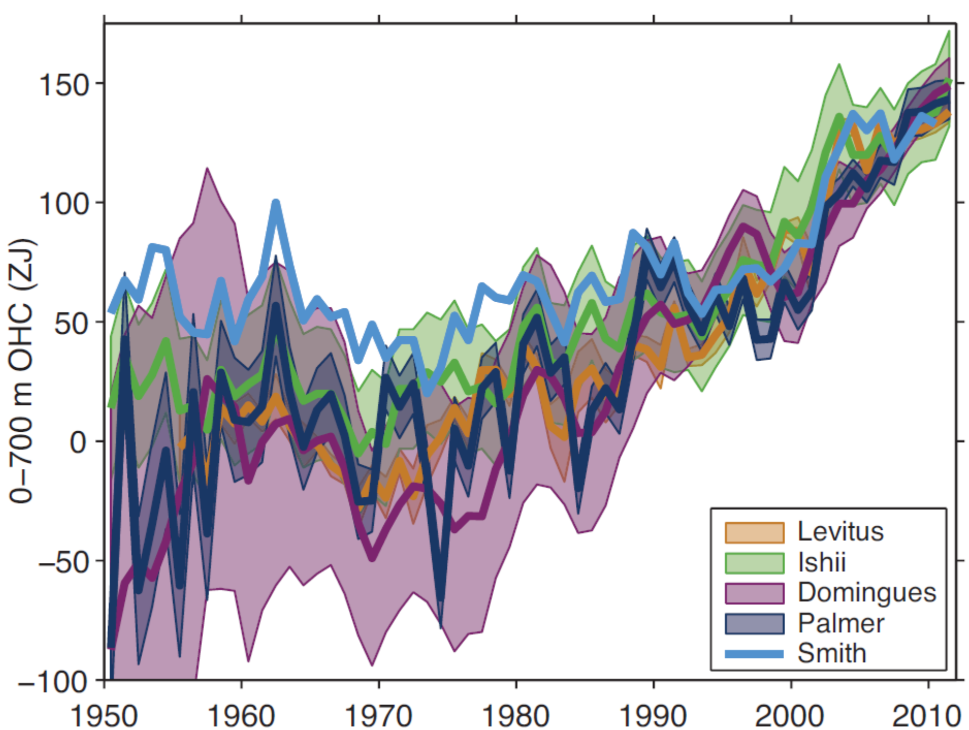
Reconstructions of global average sea level change from various authors

Hay et al. (2015)

Observed ocean temperature

Zonally averaged temperature trends in the ocean

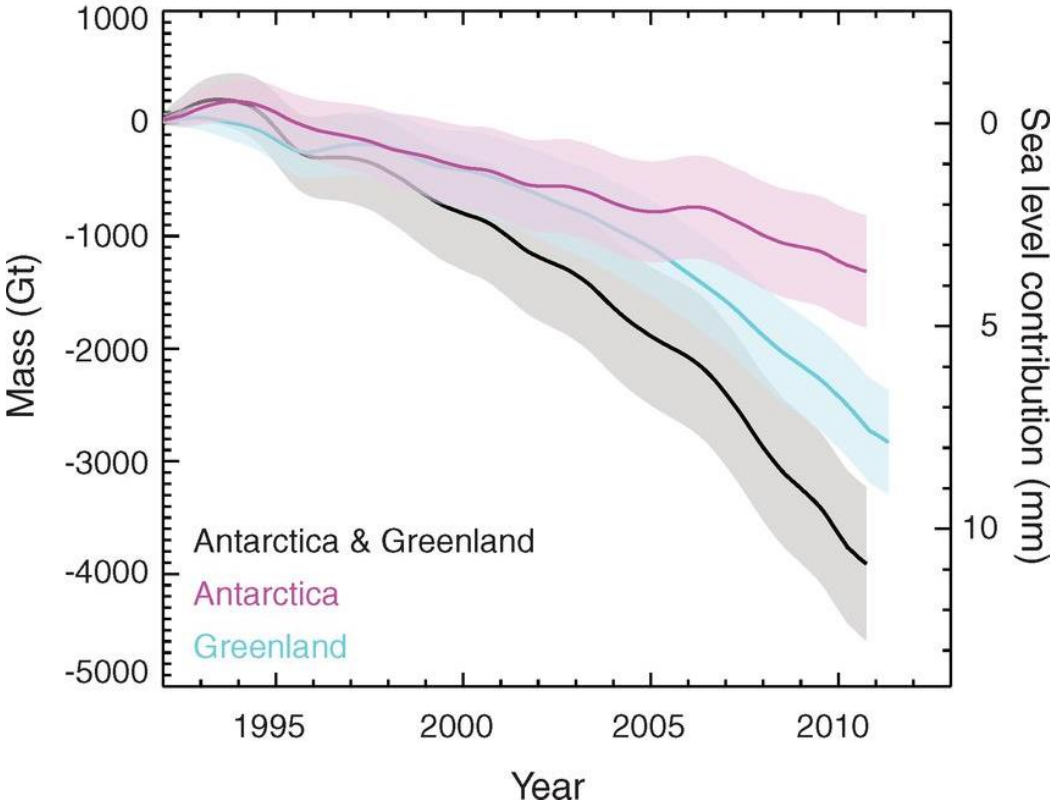




Global mean upper ocean heat content

Source: IPCC AR5

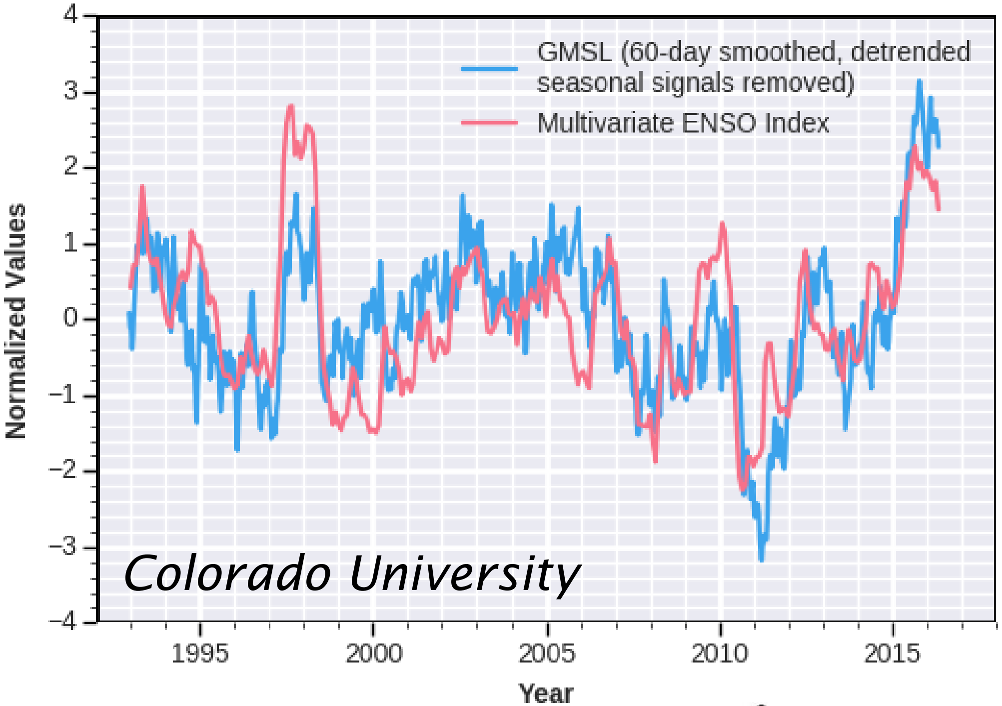
Observed ice mass changes



Cumulative changes in the mass of (left axis) the Greenland and Antarctic ice sheet, and the equivalent global sea level contribution (right axis)

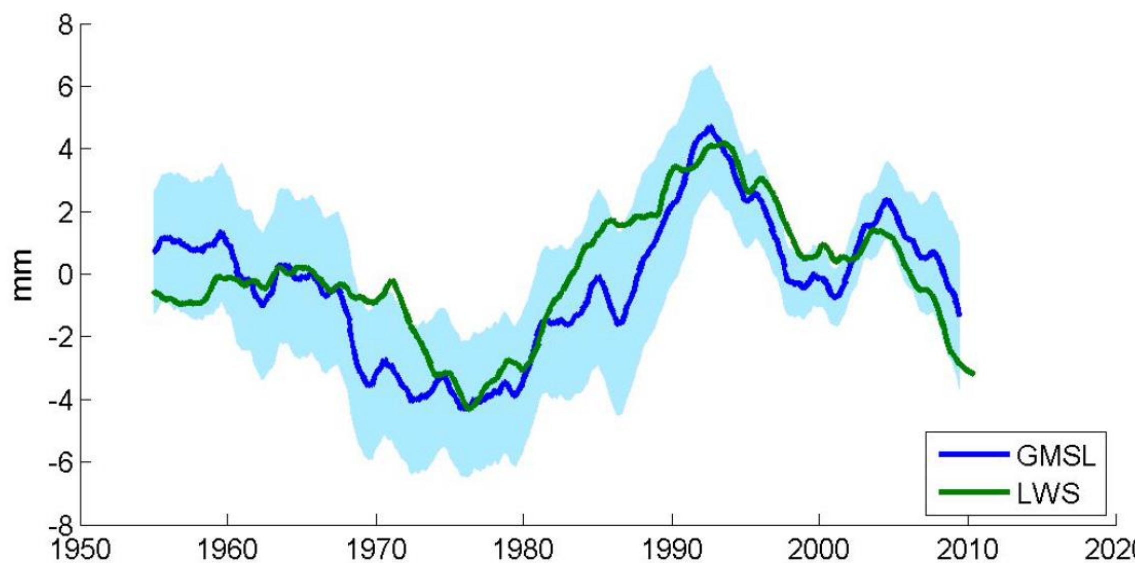
Shepherd et al. (2012)

Interannual variability in global MSL



Detrended Global MSL changes from altimetry are significantly correlated with the ENSO index

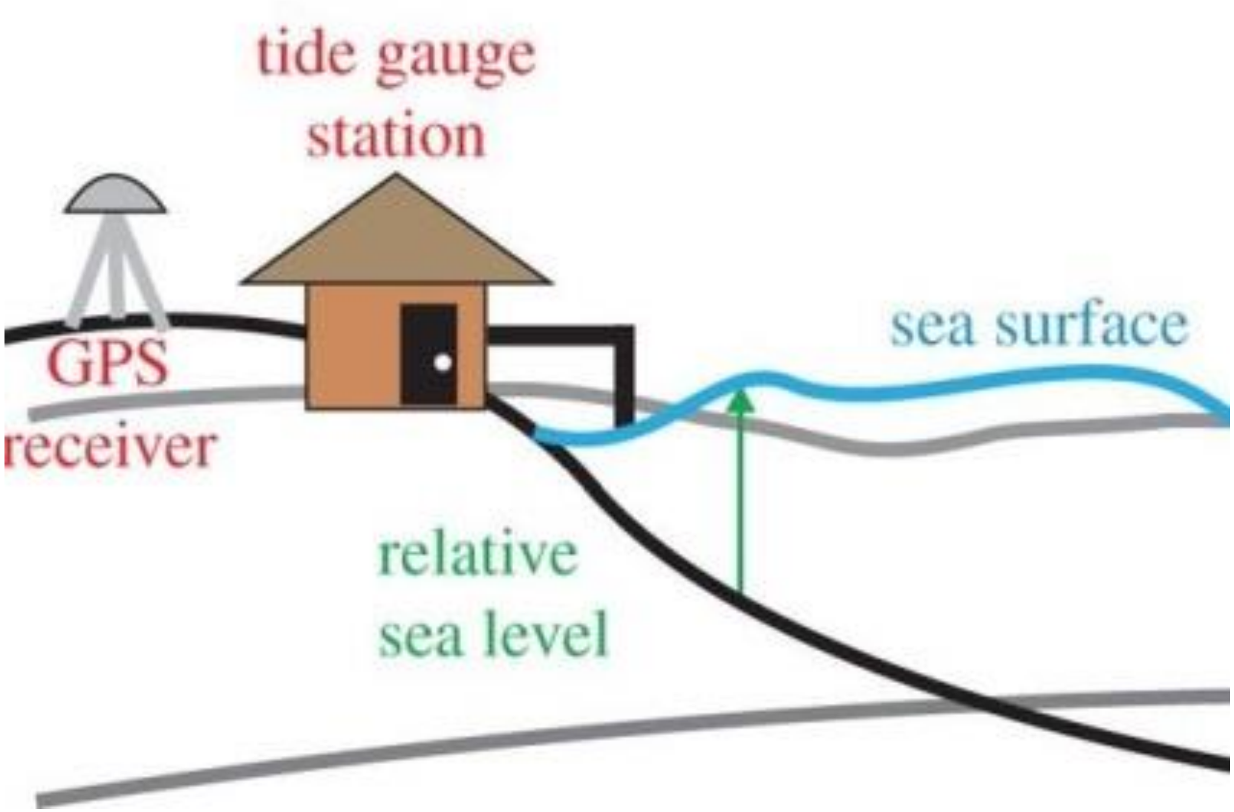
Detrended Global MSL changes from a sea level reconstruction (*Calafat et al., 2014*) compared with land water storage (LWS)



Regional MSL changes

Relative sea level changes

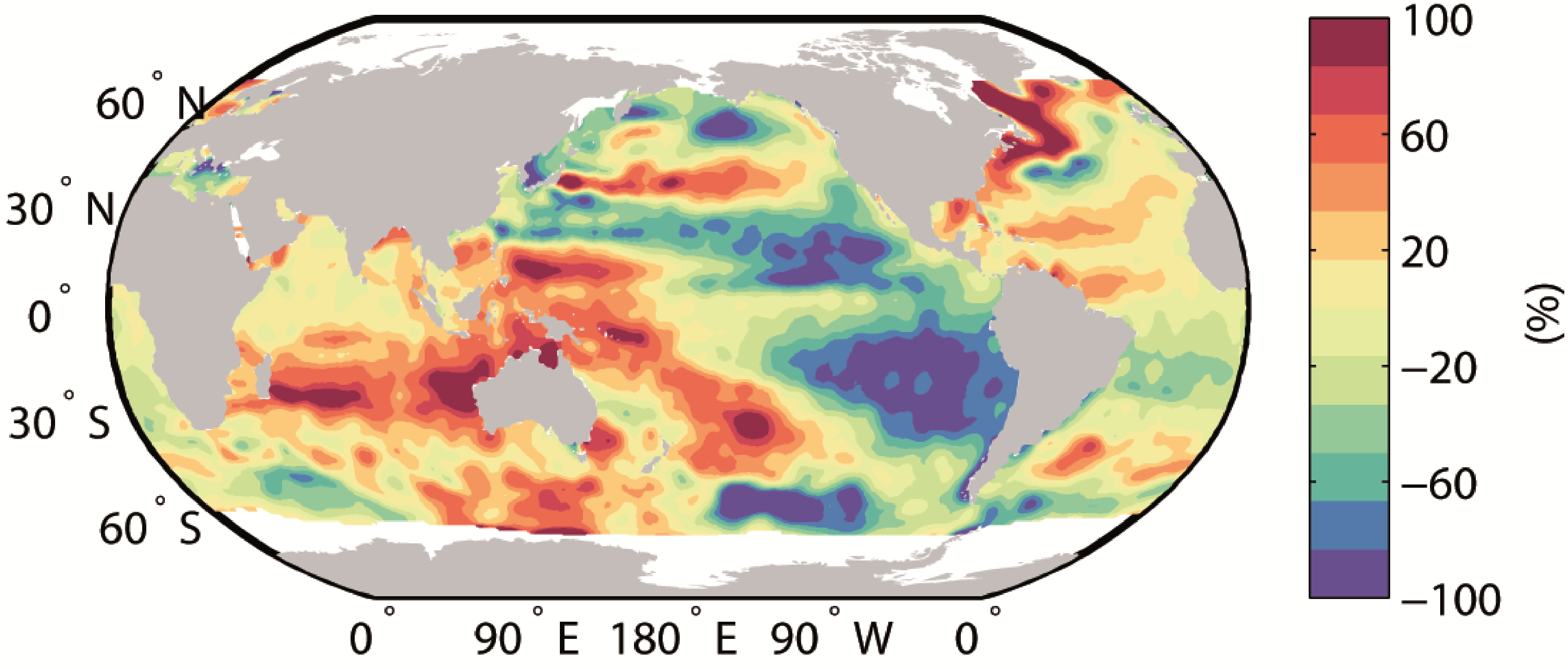
Tide gauge observations can be viewed as a measure of changes in the thickness of the ocean



Tamisiea et al. (2014)

Regional sea level deviates greatly from global MSL

Deviation of the relative sea level trend from the global mean trend as derived from satellite altimetry data (1993-2015)



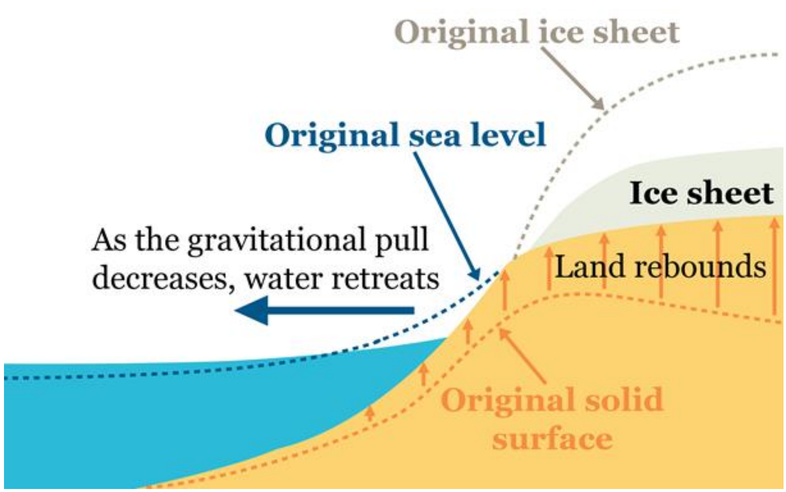
What causes regional variability in MSL?

Local MSL can deviate significantly from global MSL because:

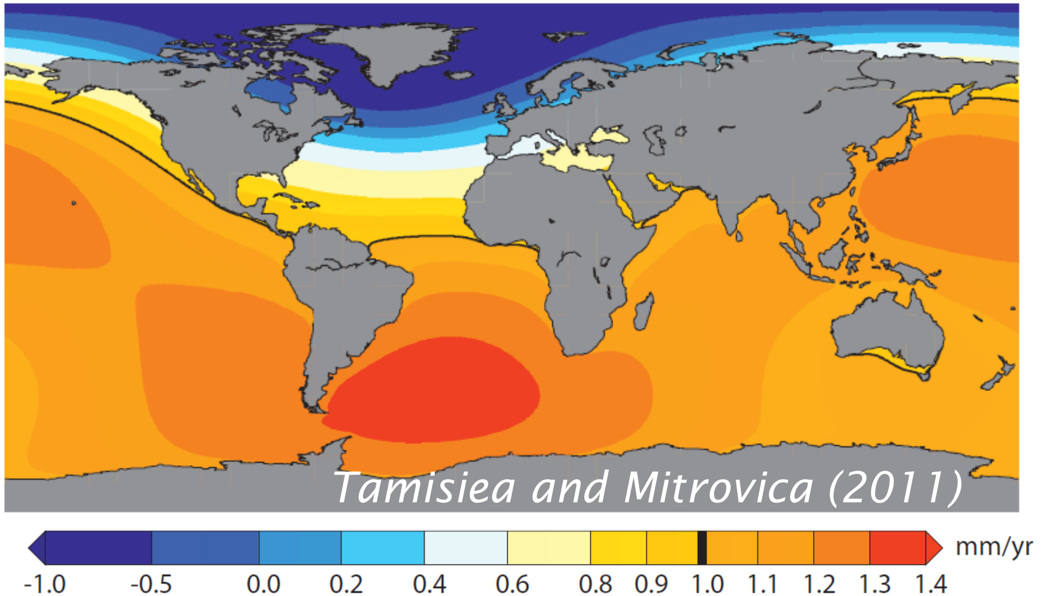
1) **Ice melting (or any mass redistribution) gives raise to highly non-uniform spatial patterns of sea level by perturbing both the Earth's gravity field and its crust.**

2) **Non-uniform changes in ocean dynamics**

Regional sea level response to land-based ice

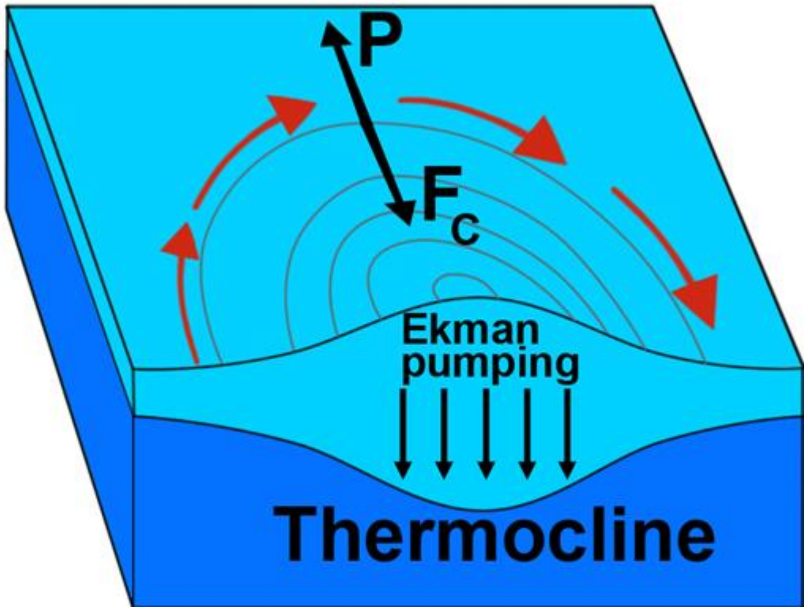


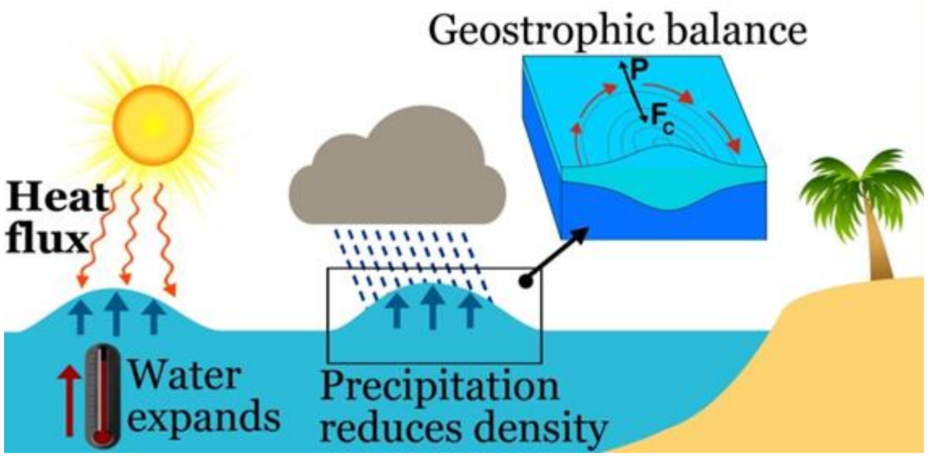
Static equilibrium response to meltwater from the Greenland ice sheet (so-called fingerprint)



What causes regional variability in MSL?

Changing winds and surface buoyancy fluxes cause changes in ocean circulation and thus in sea level



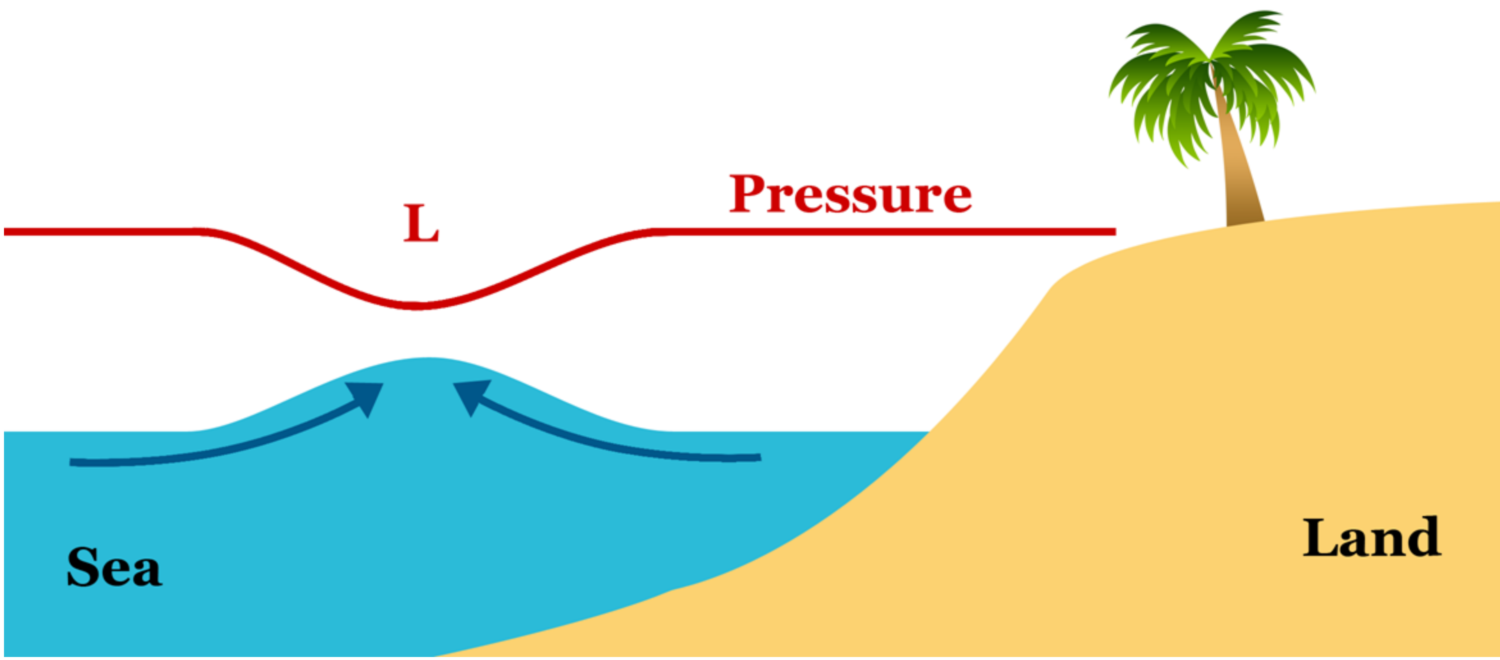


Ocean currents redistribute heat and mass non-uniformly in the ocean, which results in non-uniform sea level changes

What causes regional variability in MSL?

The inverse barometer effect

Variations in surface atmospheric pressure usually cause sea level to change at a rate of -1 cm/hPa. High (low) atmospheric pressure corresponds to low (high) sea level.

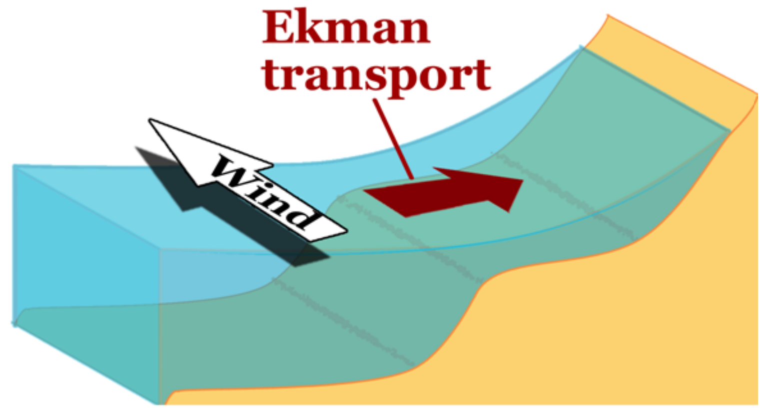


What causes regional variability in MSL?

Sea level response to alongshore wind

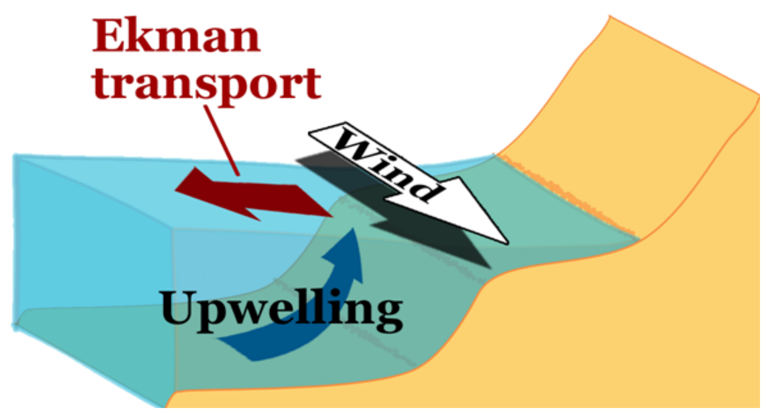
Coast on the right

Wind blowing alongshore with the coast on its right causes water to pile up against the coast with a consequent rise in sea level.

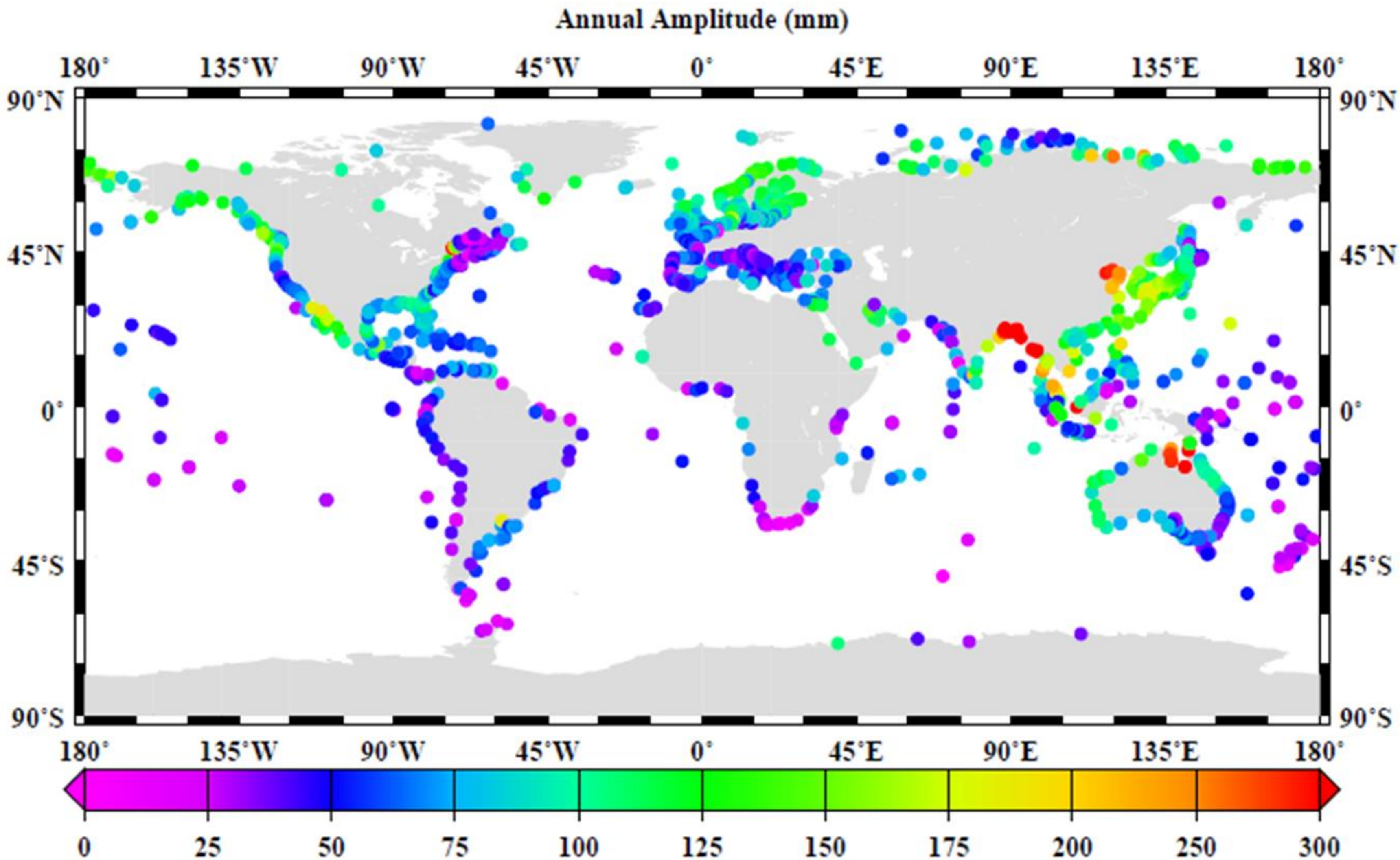


Coast on the left

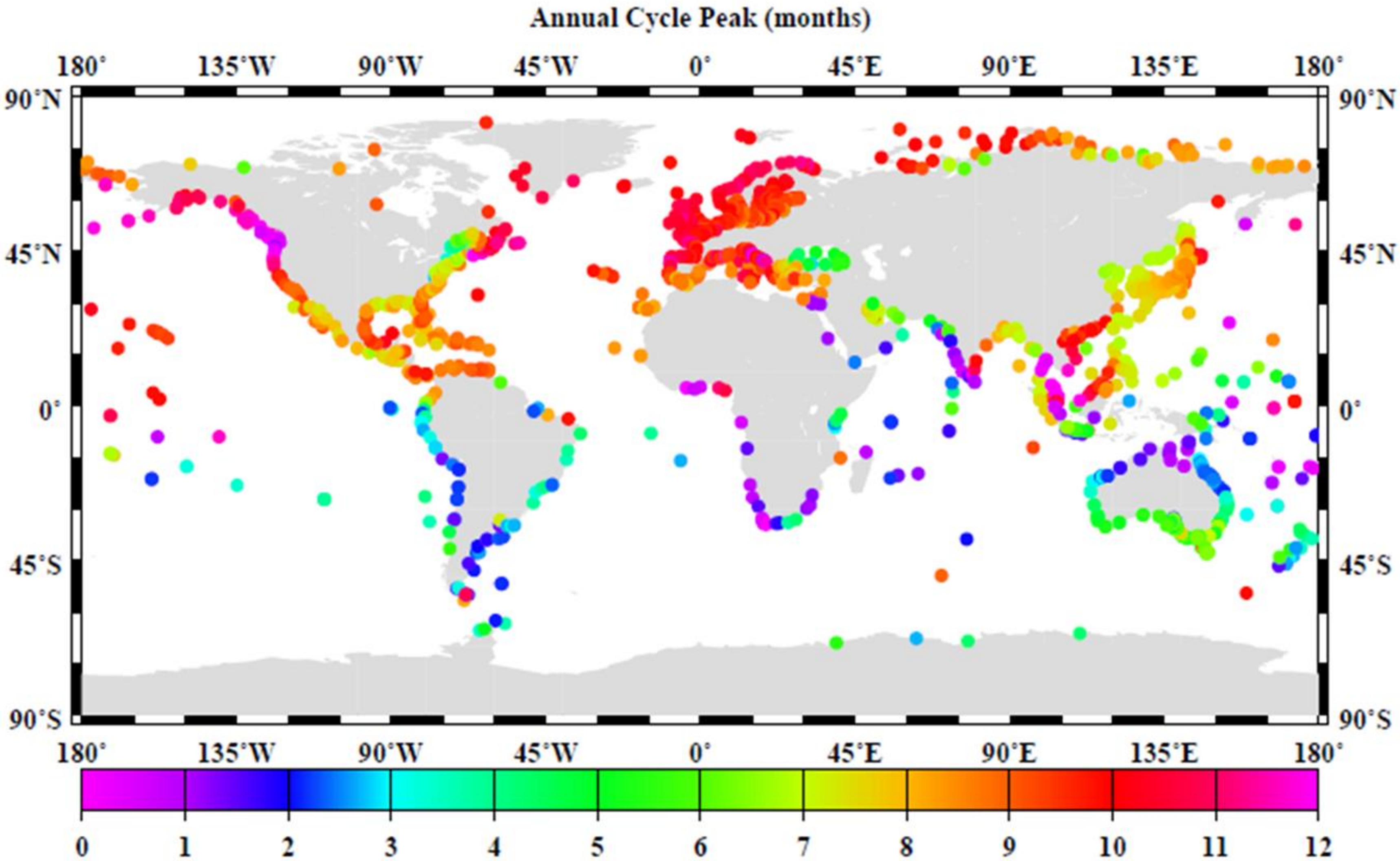
Wind blowing with the coast on its left causes surface water to be replaced by deep, cold water, which leads to a fall in sea level



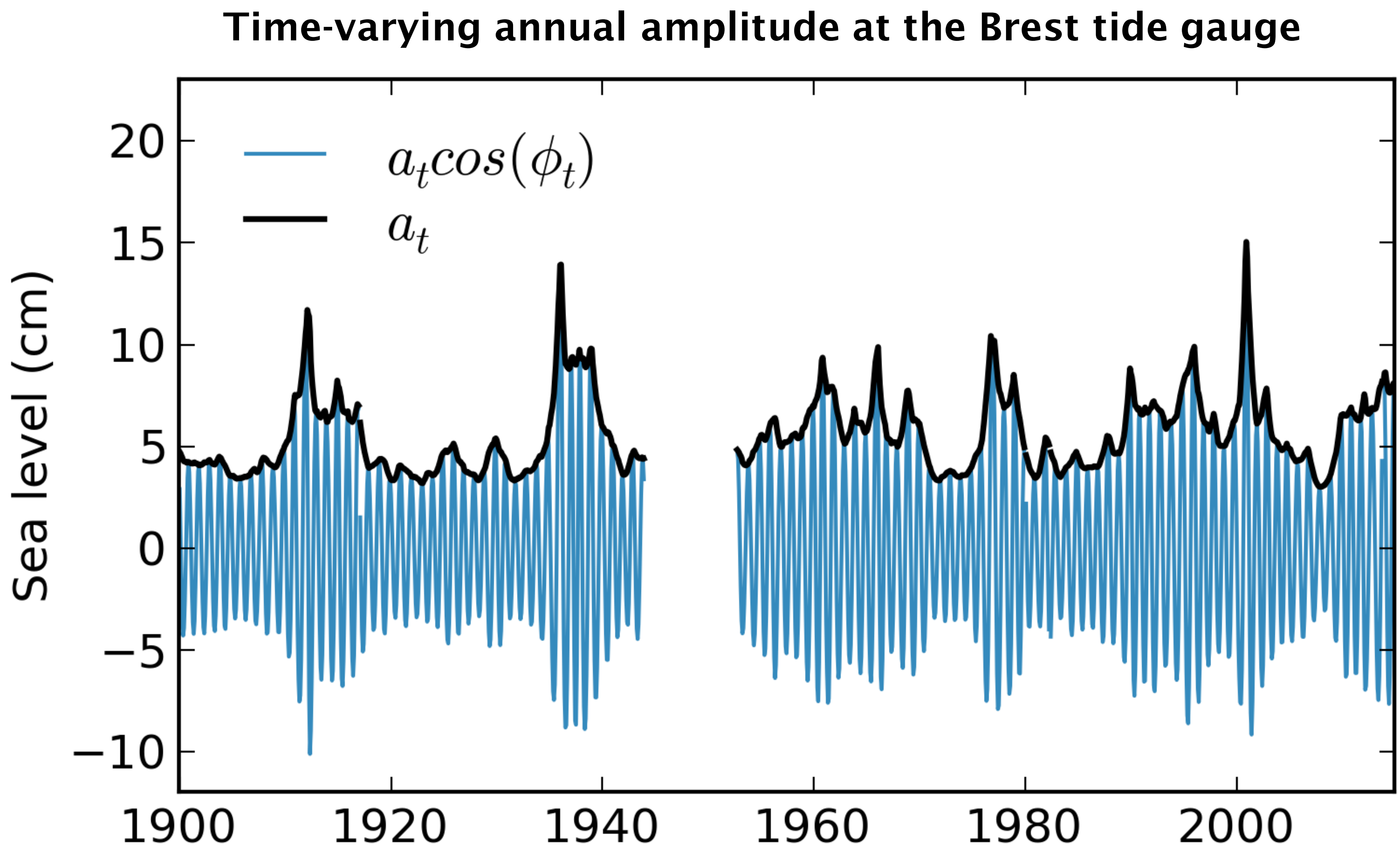
The seasonal cycle of MSL



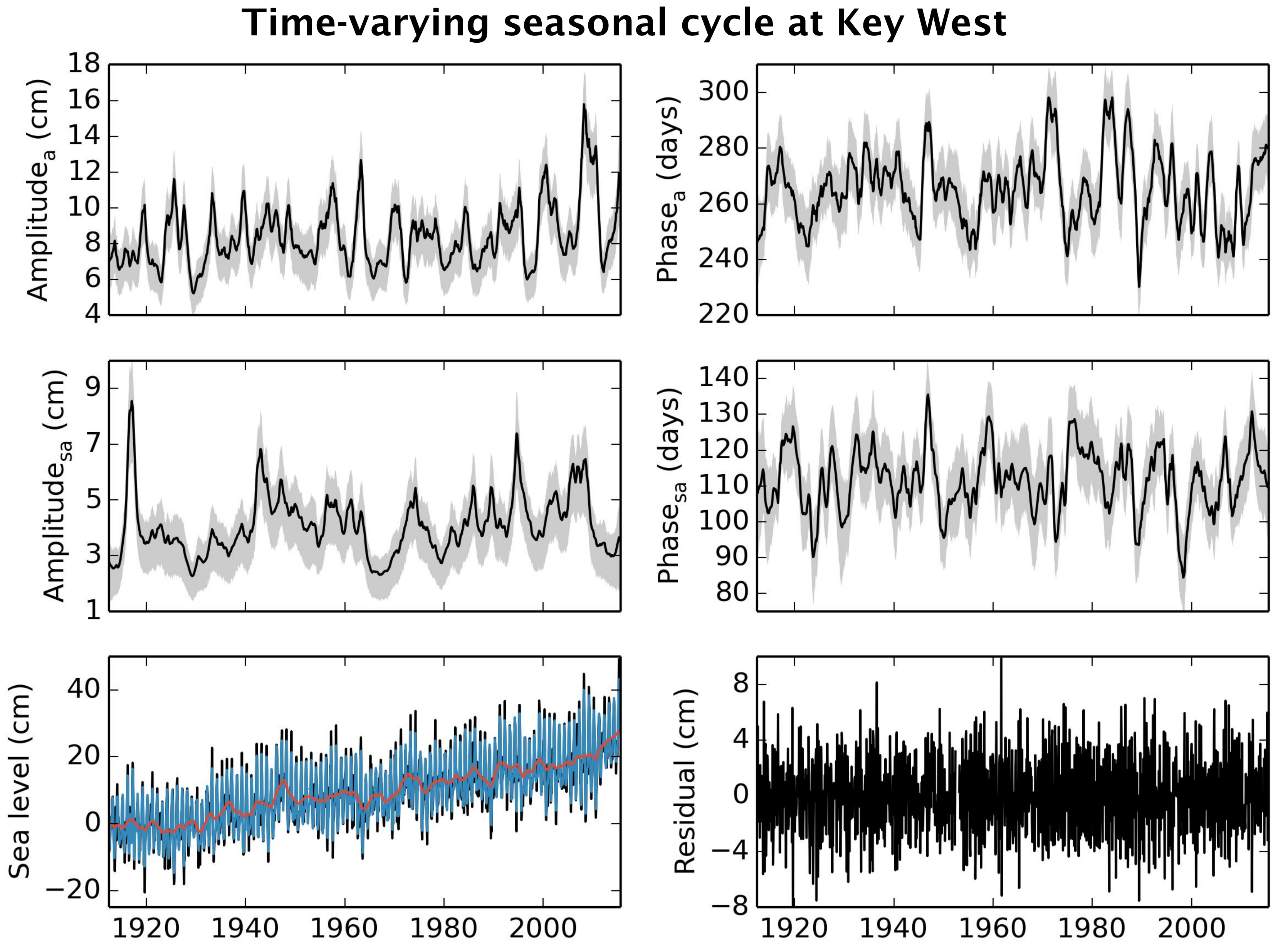
The seasonal cycle of MSL



The seasonal cycle of MSL

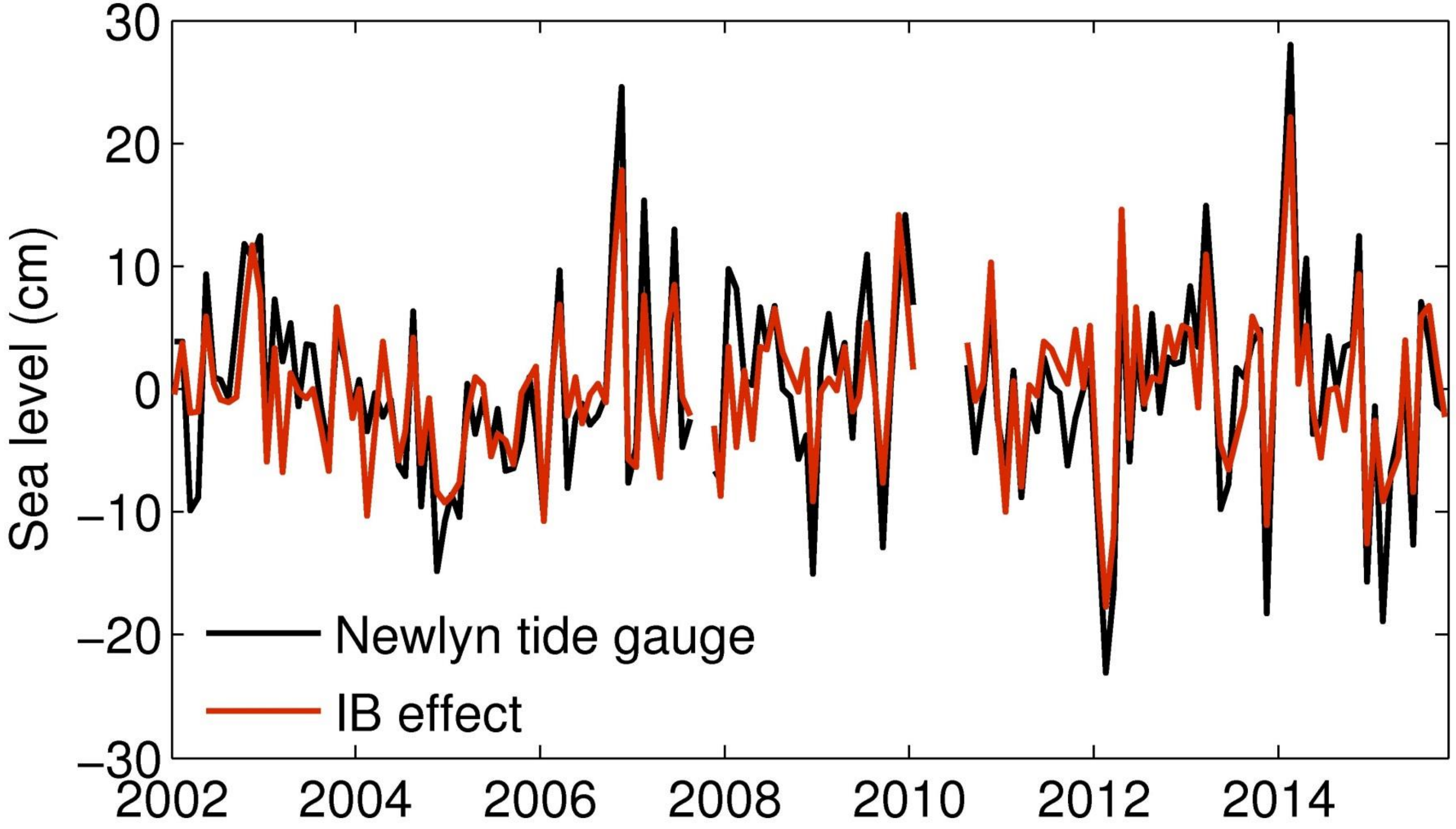


The seasonal cycle of MSL



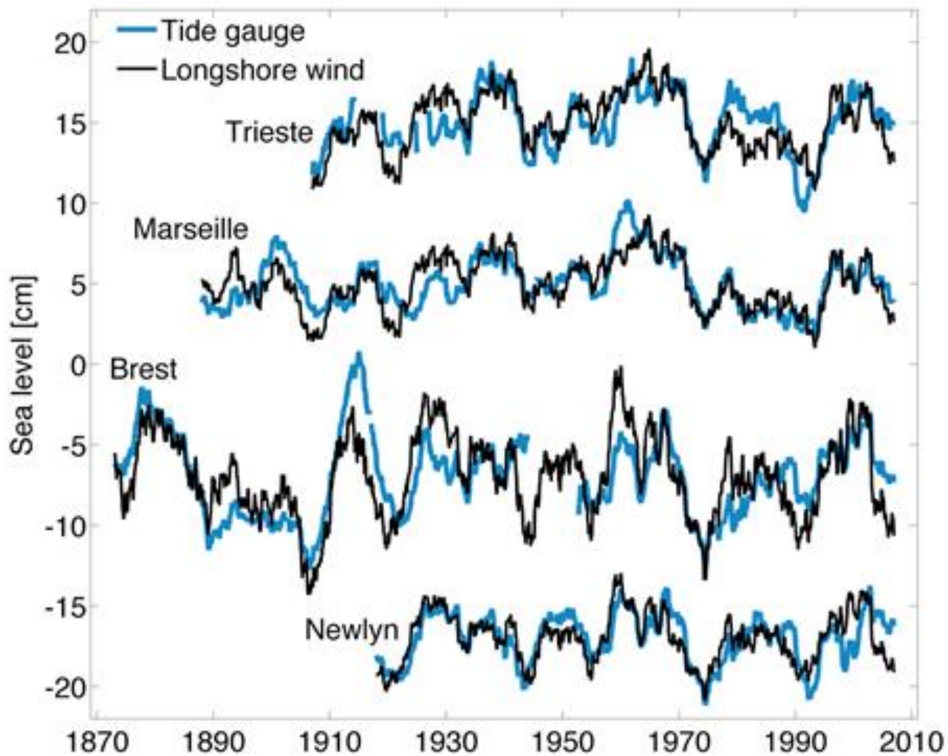
Interannual MSL changes: the response to atmospheric pressure variations

Detrended and deseasoned sea level from the Newlyn tide gauge (black) and the inverse barometer effect (red)



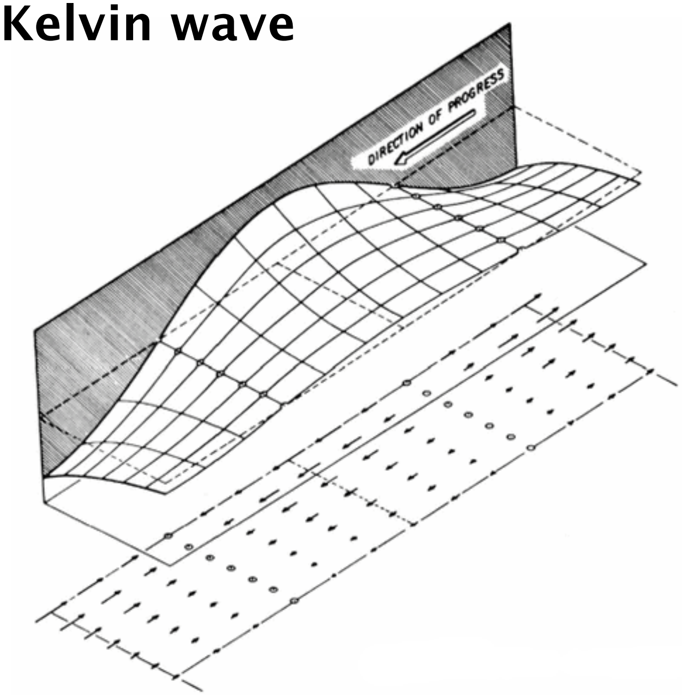
Decadal MSL changes: the response to alongshore wind forcing

Detrended sea level from tide gauges and the integrated alongshore wind



Calafat et al. (2012)

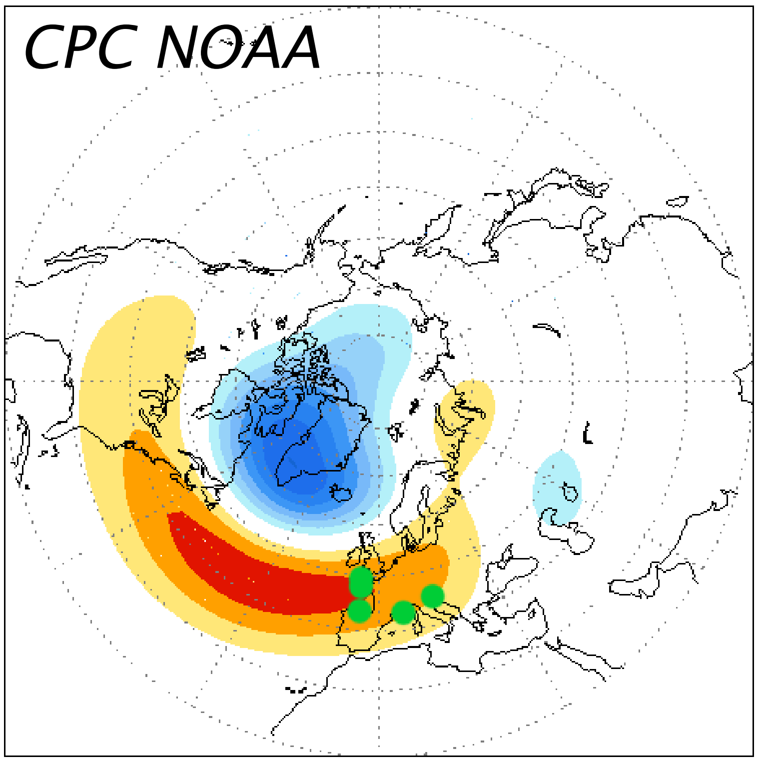
Northern Hemisphere Kelvin wave



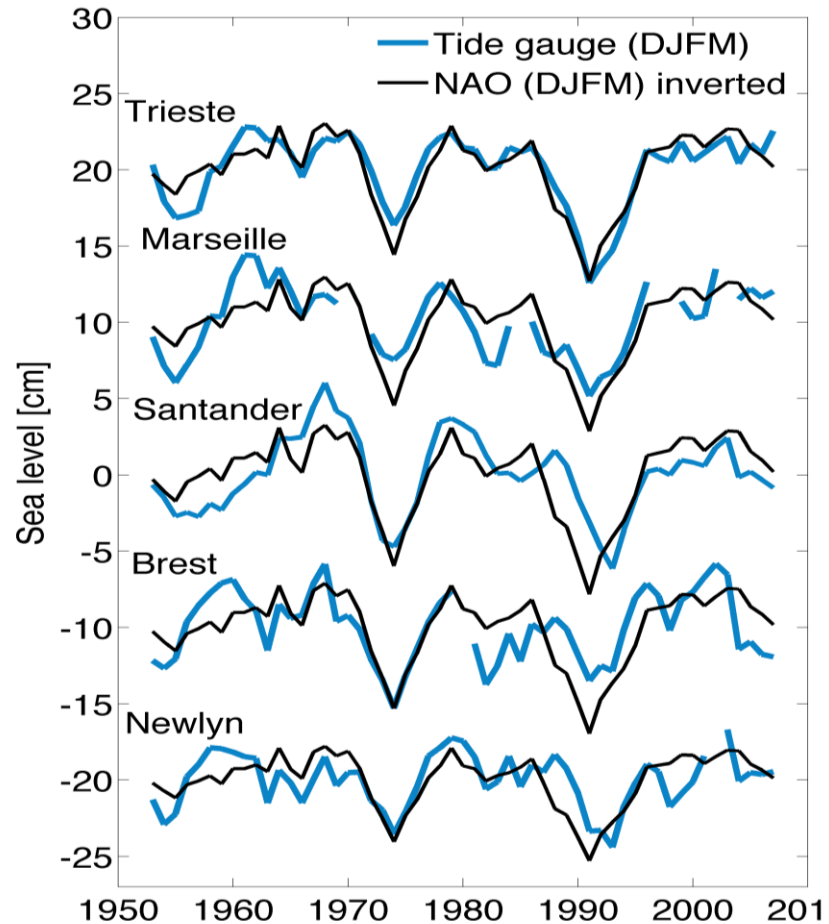
$$\frac{1}{c}\frac{\partial A}{\partial t} + \frac{\partial A}{\partial y} = B\tau^{y}(y,t) \quad \Longrightarrow \quad A(y,t) = \int_{Equator}^{y} B\tau^{y'}\left(y', t - \frac{y-y'}{c}\right)dy'$$

Decadal MSL changes: link to modes of natural variability

North Atlantic Oscillation (NAO)



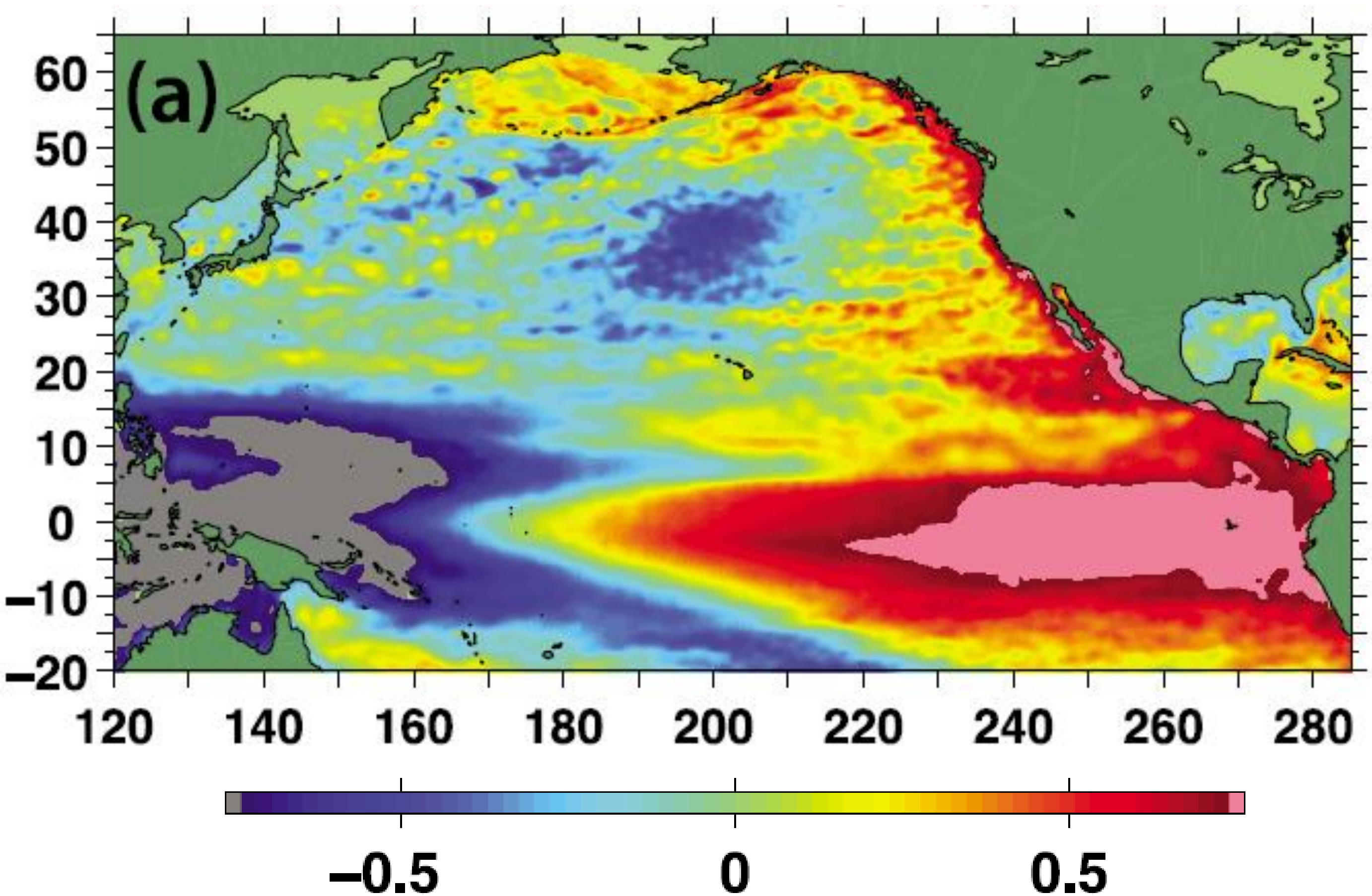
Sea level and the NAO index



Calafat et al. (2012)

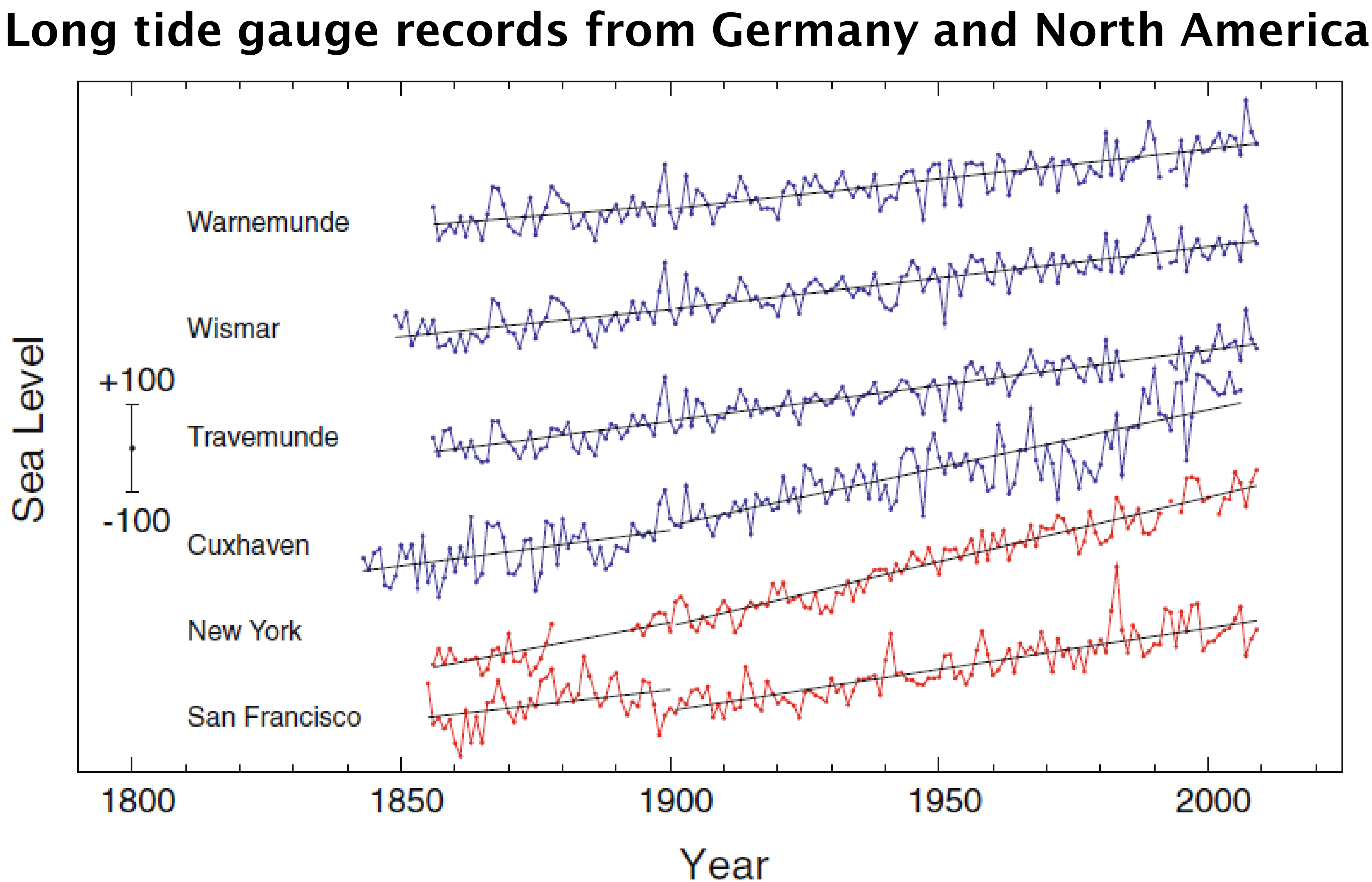
Decadal MSL changes: link to modes of natural variability

Correlation of satellite altimetry sea surface heights with the multivariate ENSO index



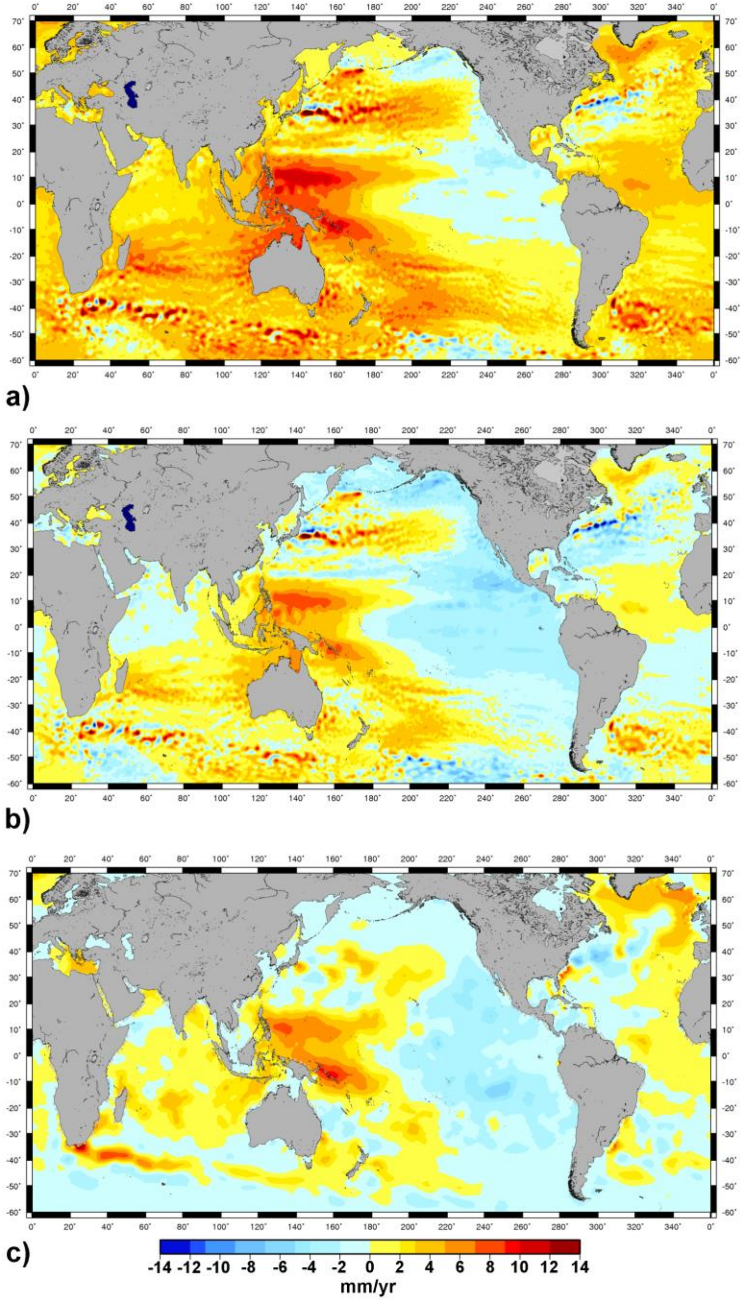
Bromirski et al. (2011)

Long-term changes in regional MSL



Woodworth et al. (2011)

Long-term changes in regional MSL



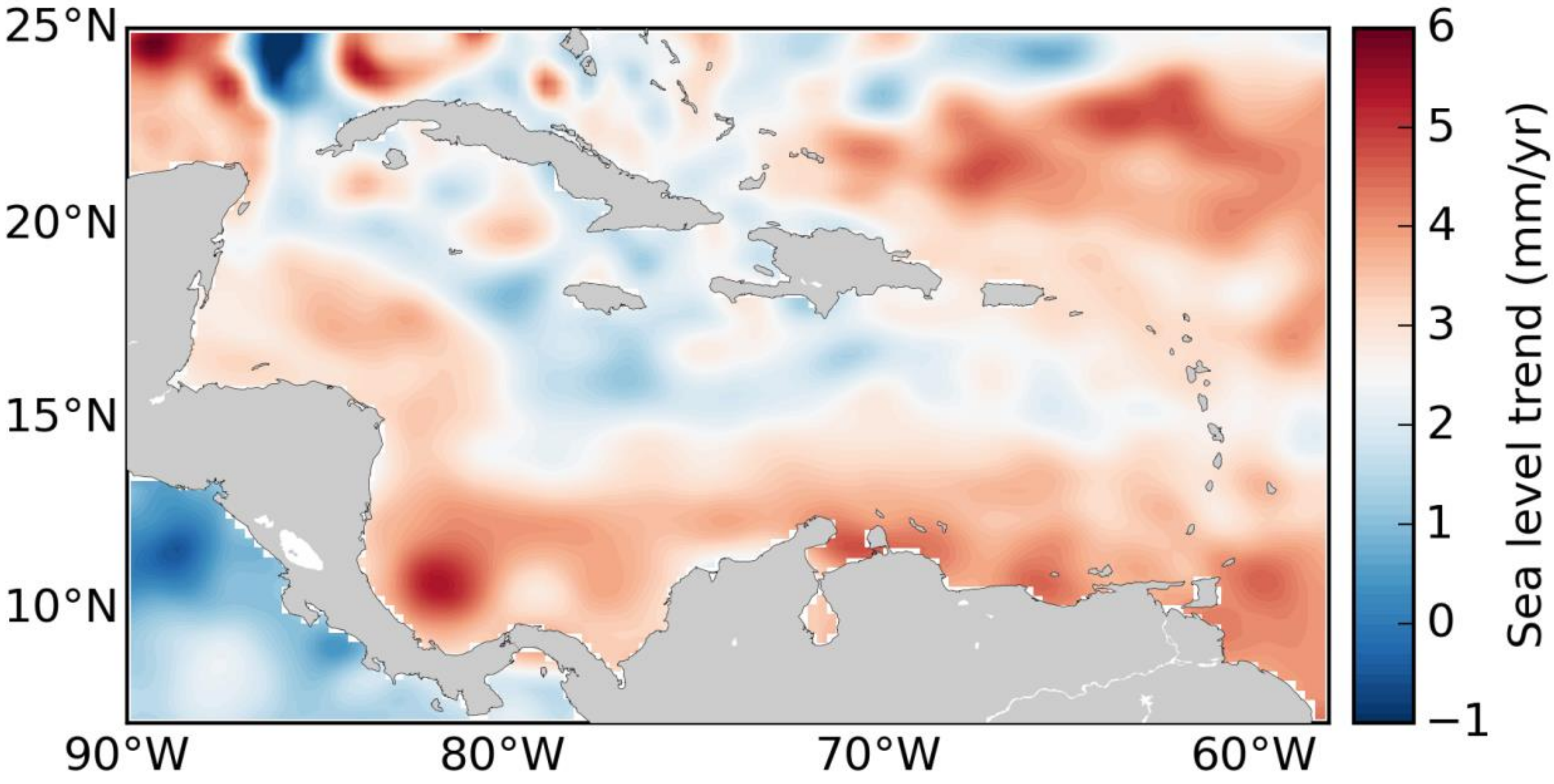
Sea level change during 1993-2009 obtained from satellite altimetry (max. in West Pacific ~15 mm/yr)

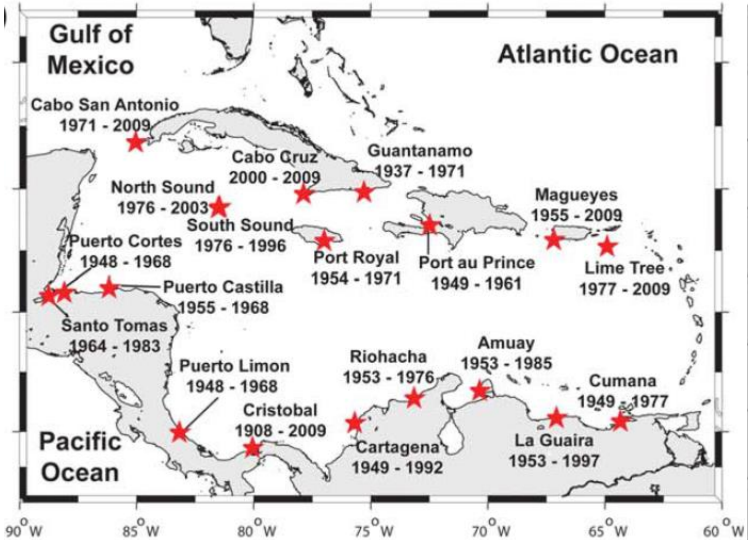
Pattern of change with the global-average removed

Thermosteric sea level change

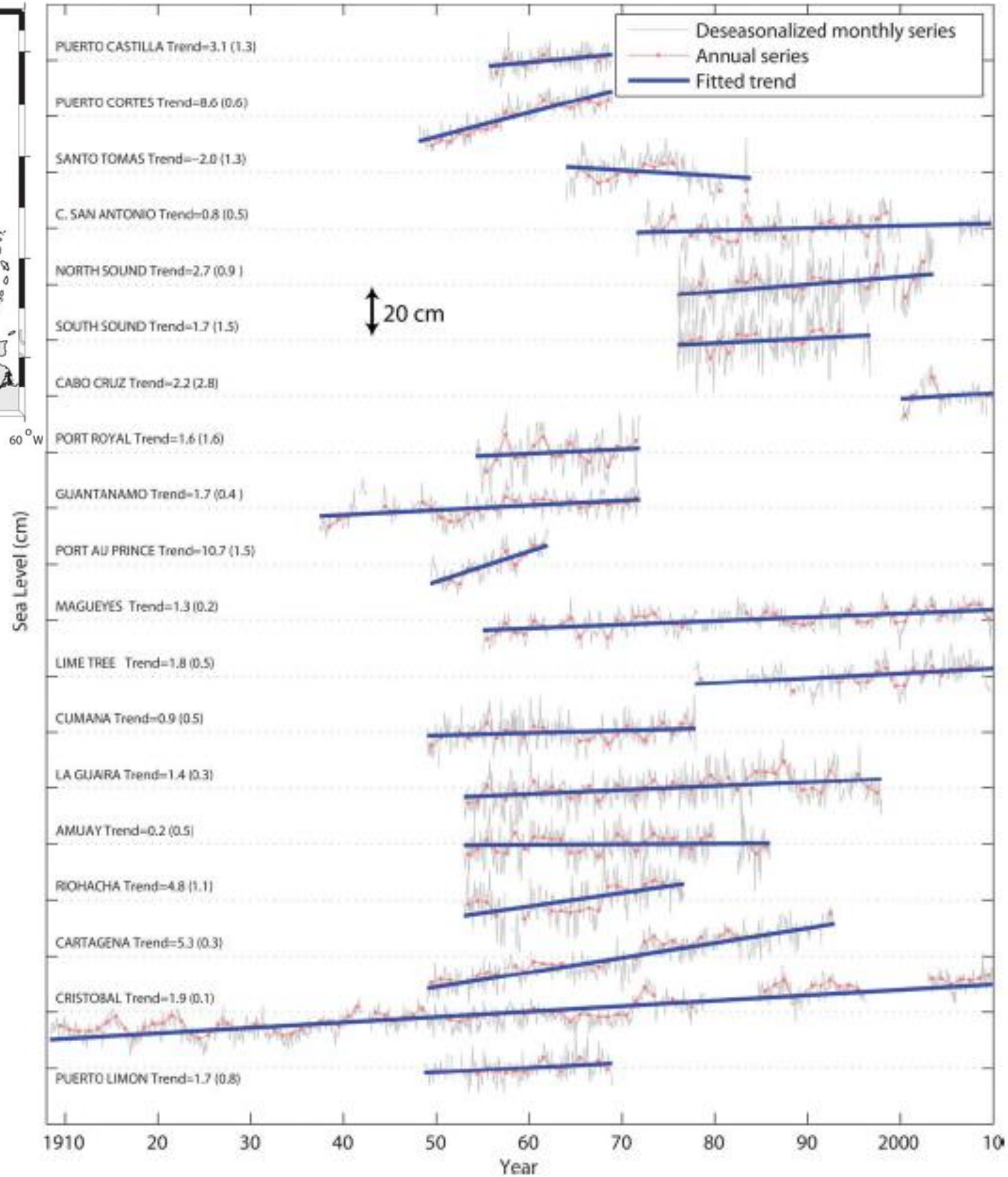
Long-term changes in regional MSL

Sea level trends derived from satellite altimetry for the period 1993-2015 in the Caribbean Sea





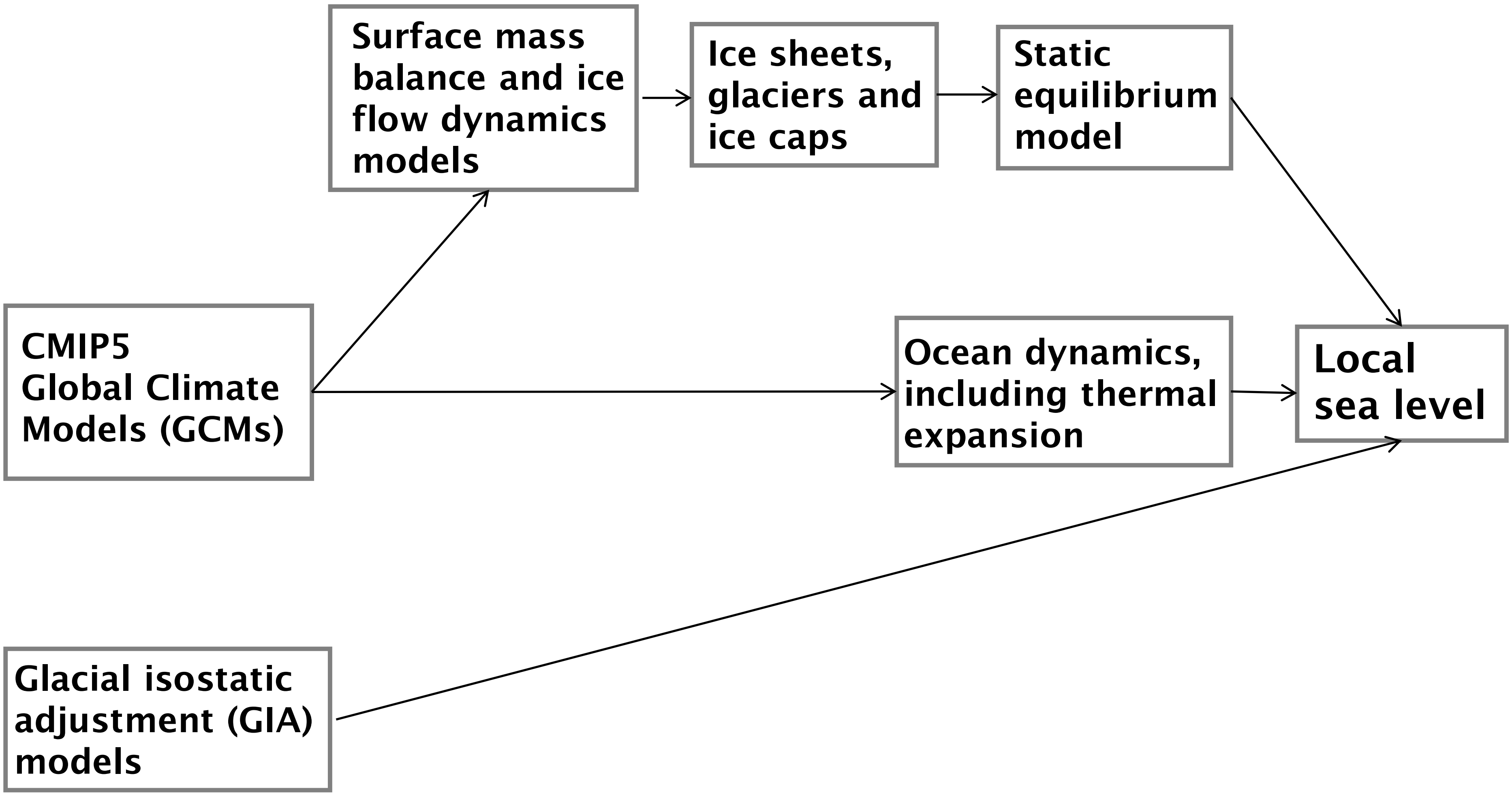
Torres and Tsimplis (2013)



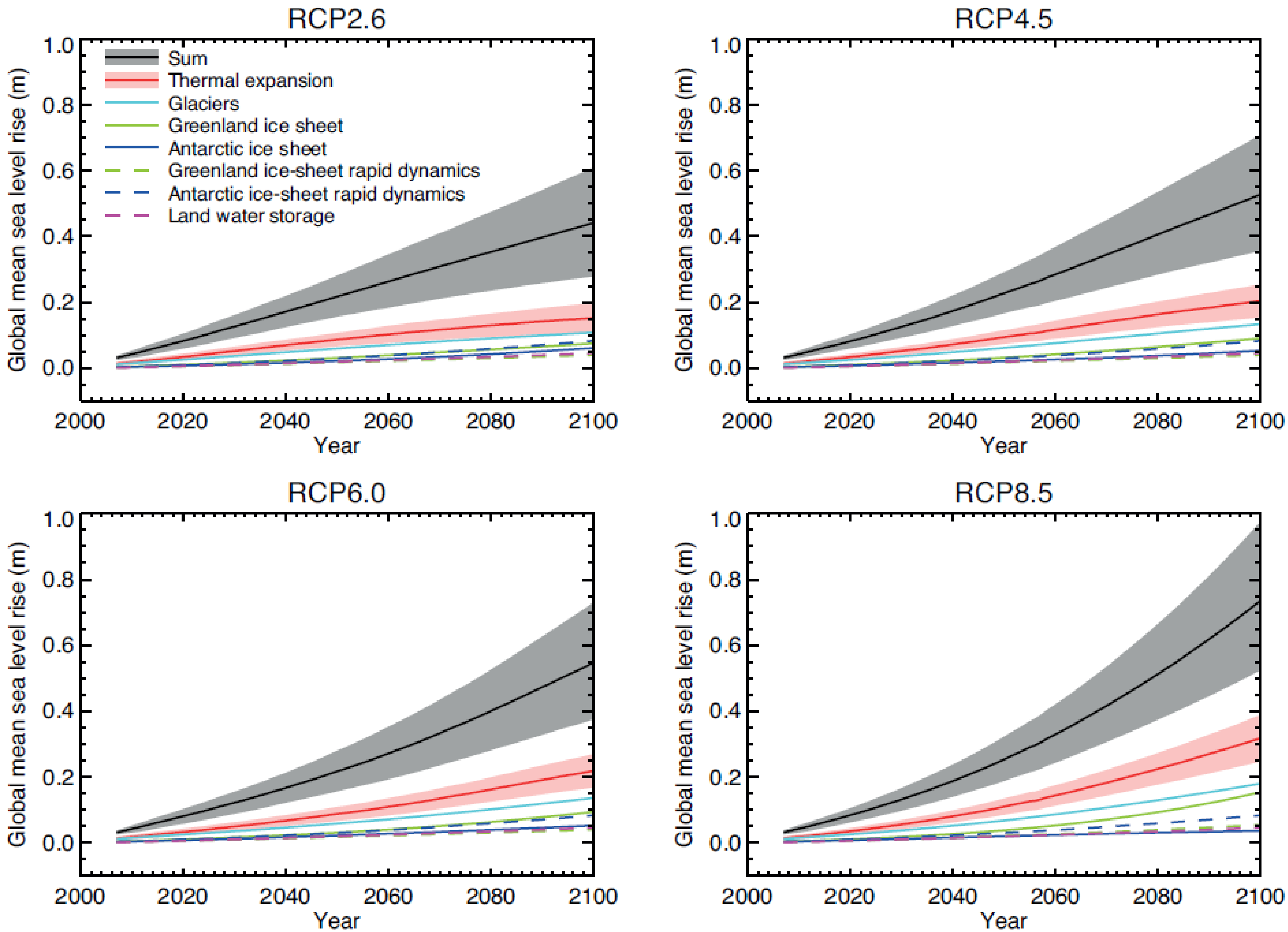
Observed sea level and trends from tide gauge records

Future MSL changes

How do we compute sea level projections?



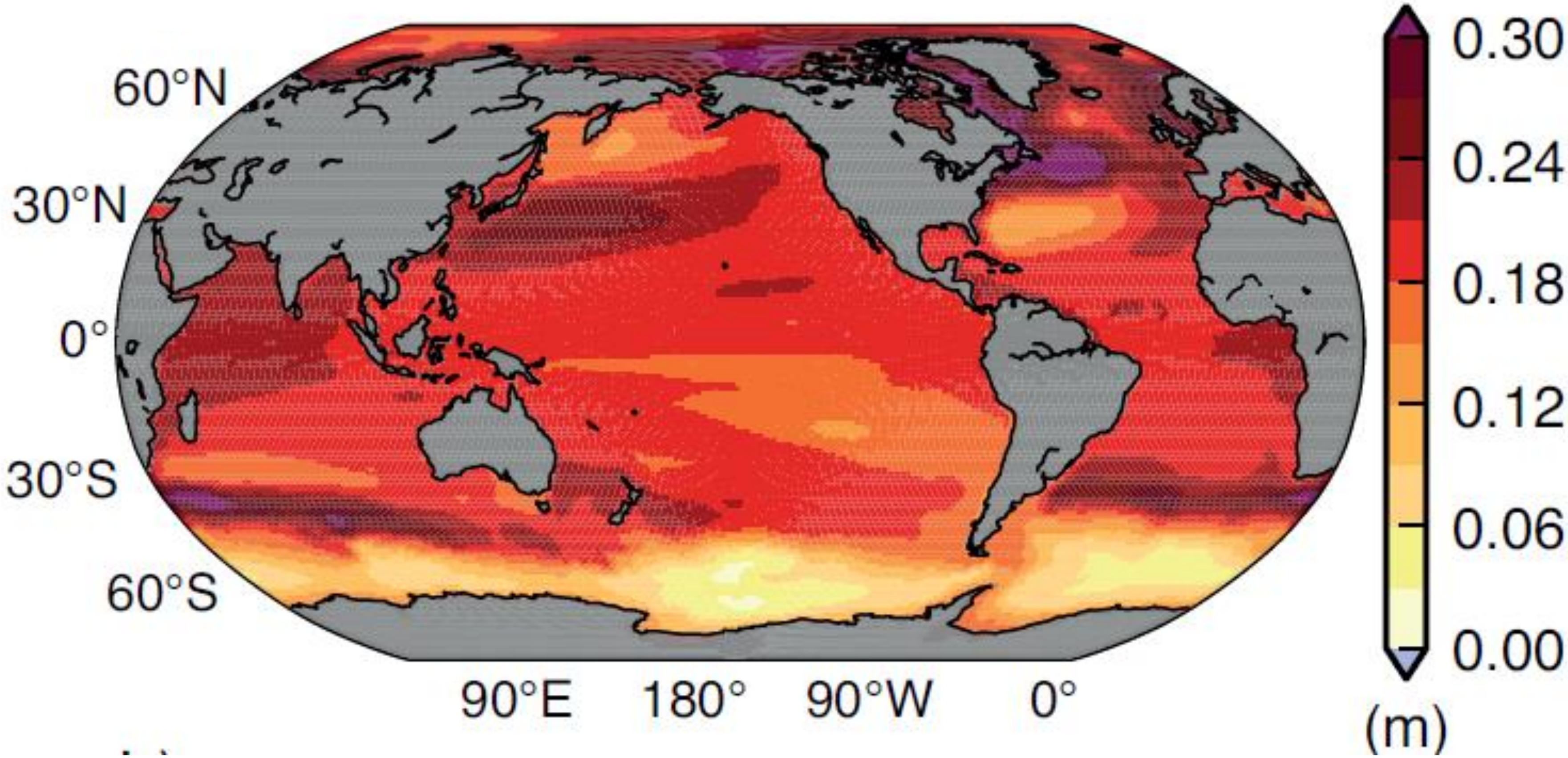
Projections of global MSL rise



IPCC AR5

Projection of regional MSL rise due to ocean dynamics and thermal expansion

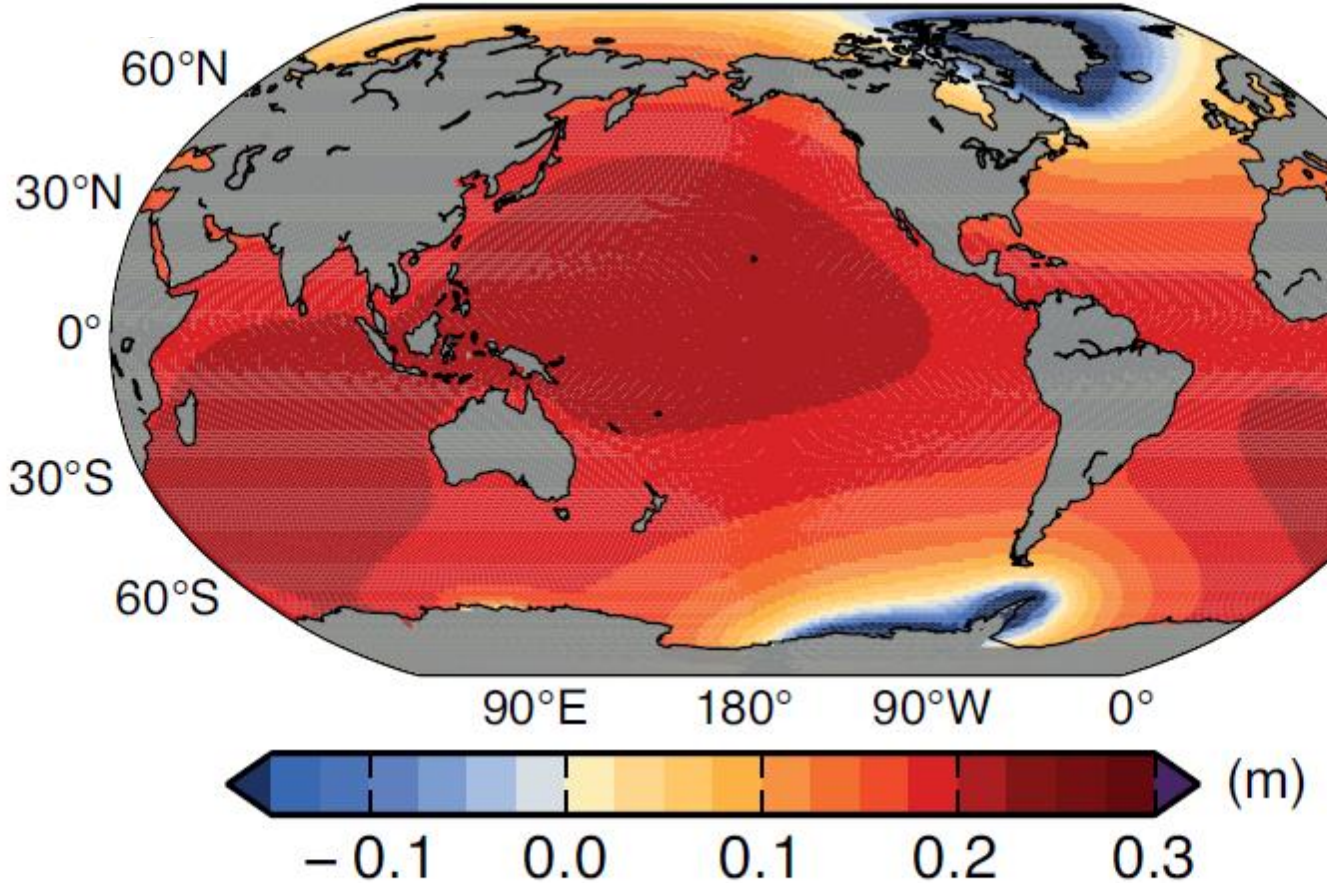
Sea level rise due to dynamics and thermal expansion for the period 2081-2100 relative to 1986-2005 based on scenario RCP 4.5



IPCC AR5

Projection of regional MSL rise due to meltwater from ice sheets

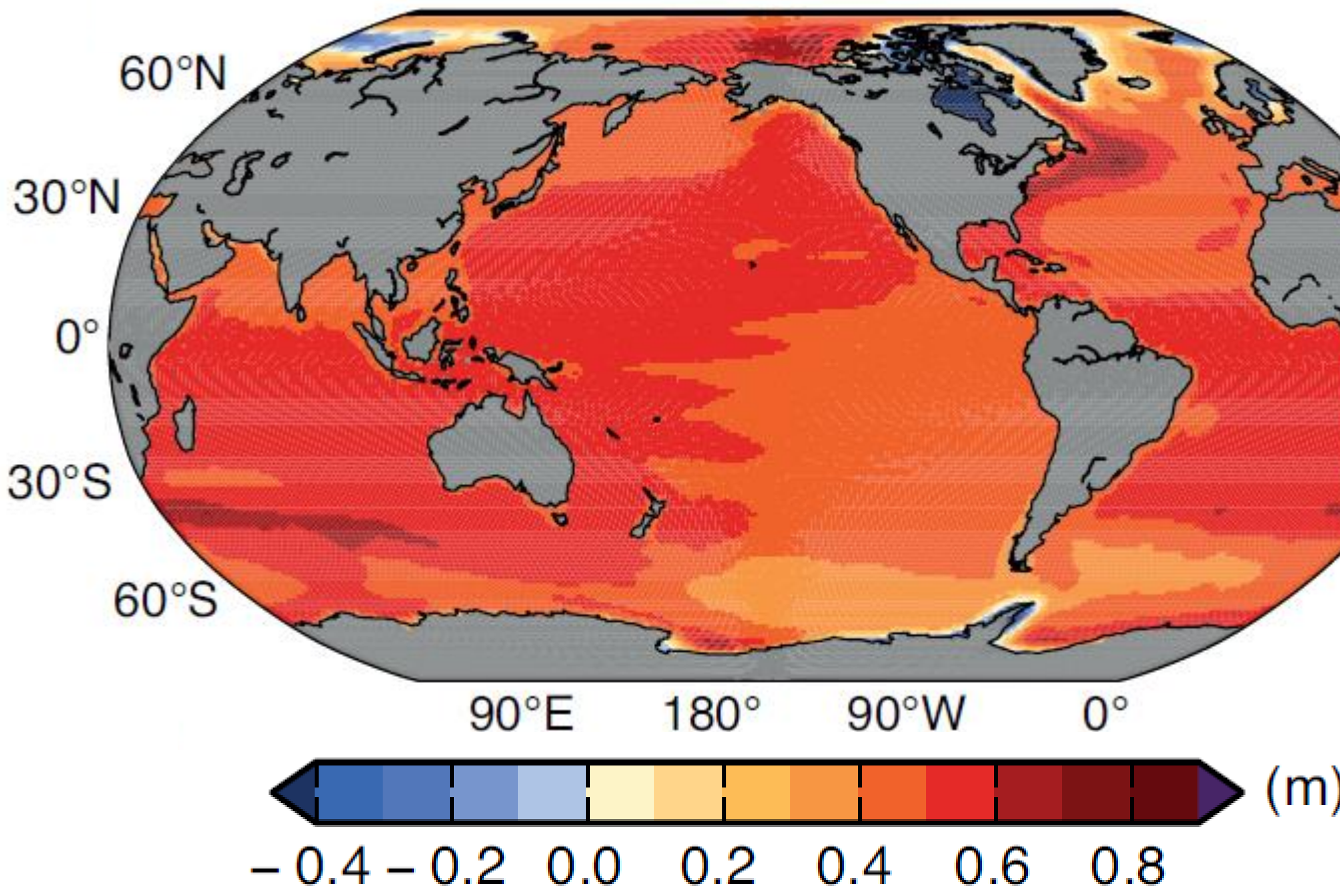
Sea level rise due to meltwater from the Greenland and Antarctic ice sheets for the period 2081-2100 relative to 1986-2005 based on scenario RCP 4.5



IPCC AR5

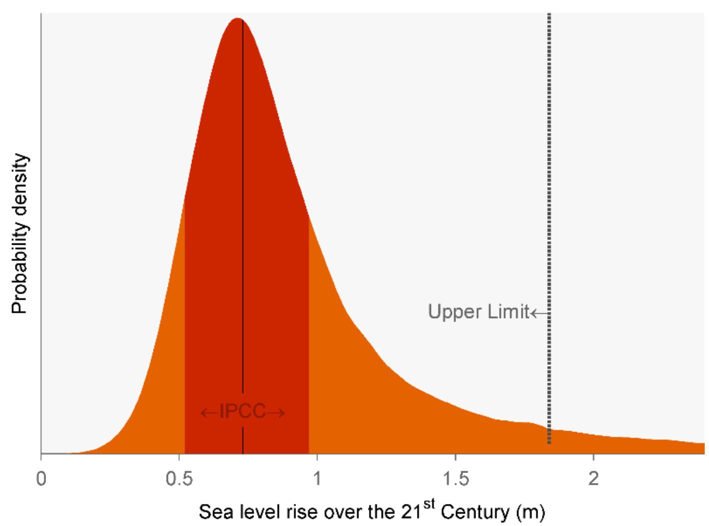
Projection of regional MSL rise due to all contributions

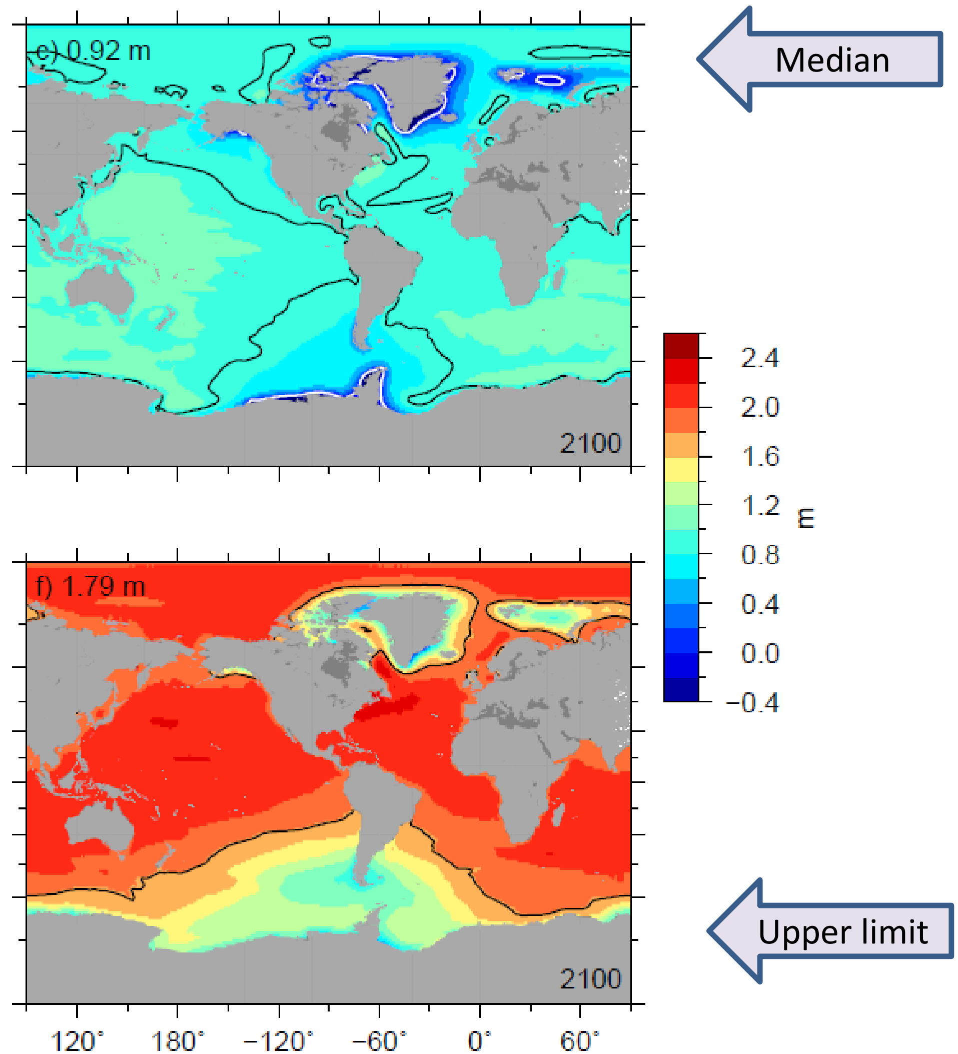
Sea level rise due to all contributions for the period 2081-2100 relative to 1986-2005 based on scenario RCP 4.5



IPCC AR5

Probabilistic sea level projections with RCP8.5 by 2100





RISES-AM- EU Research Project

Jevrejeva et al, 2016 (in review)

Conclusions

- Global MSL has been rising 2 times faster in the past two decades than in throughout most of the 20th century, and projections suggest even greater rates of rise for the 21st century

- This will significantly increase the risk of coastal flooding and erosion

- There is large geographic variability in sea level rise, implying that in many regions the increase in flood risk will be much larger than expected from the global average alone

- There is also significant decadal variability in regional MSL, which can cause a critical threshold to be crossed much earlier than expected from the long-term trend alone

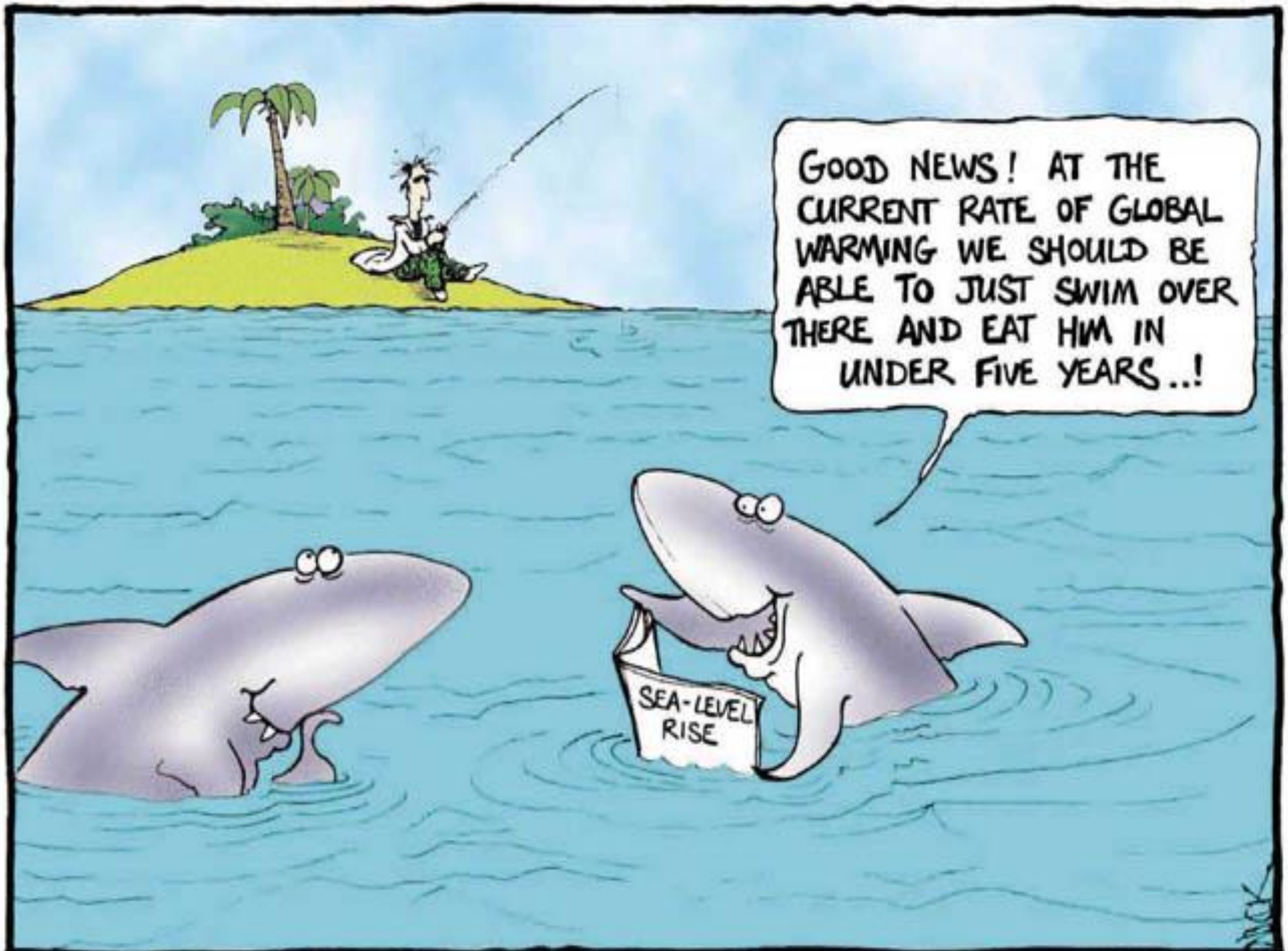
Conclusions

- **Although our understanding of MSL changes of the past has improved greatly in the last decades, future sea level projections are subject to huge uncertainty, especially on regional scales.**

- **It is clear that a good understanding of all the processes contributing to sea level changes is crucial to improve our predictive capability. And this requires:**

    1) **Continued access to all the necessary datasets**

    2) **Global networks of tide gauges to address many of the scientific issues. In particular, we need to maintain sea level monitoring in the GLOSS network, and the international cooperation that it implies.**


GOOD NEWS! AT THE CURRENT RATE OF GLOBAL WARMING WE SHOULD BE ABLE TO JUST SWIM OVER THERE AND EAT HIM IN UNDER FIVE YEARS..!
SEA-LEVEL RISE