Other techniques for measuring sea level

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What we will cover

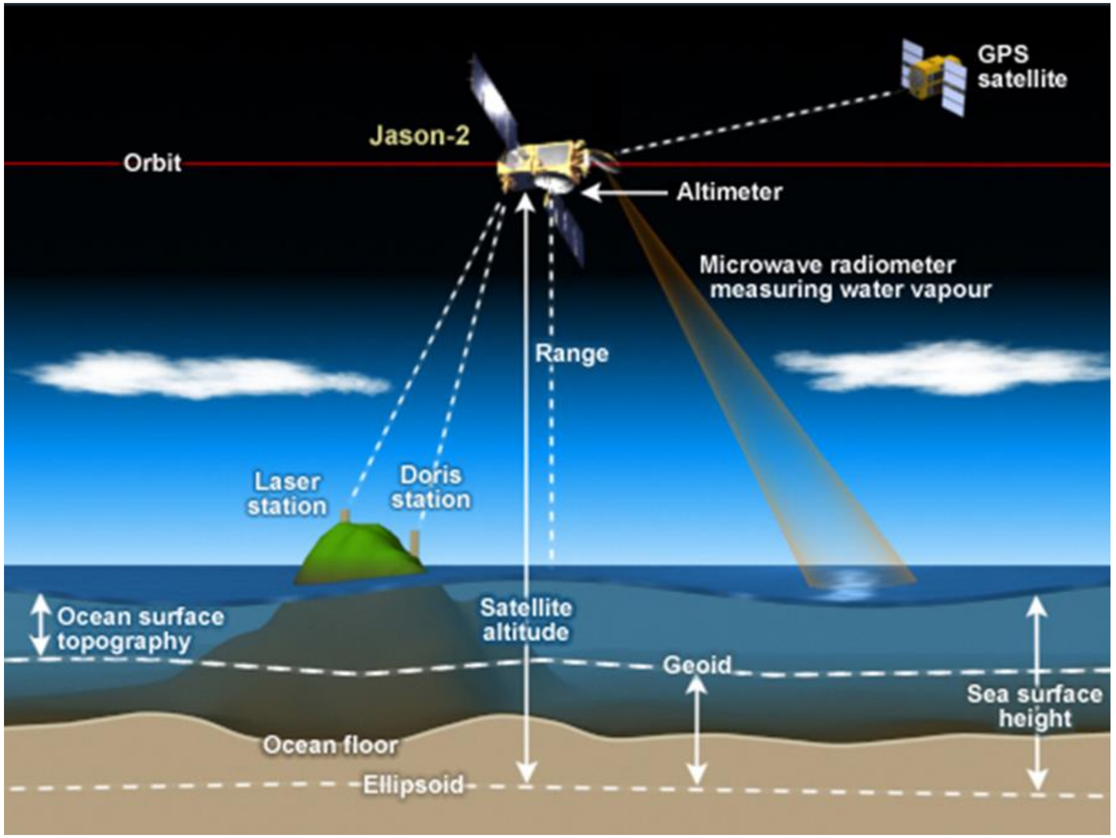
- Satellite altimetry
- Satellite gravimetry and the Argo float network
- Some geological techniques for obtaining 'proxy' measurements of sea level (landforms, fossils, etc.)

Satellite altimetry

Basic principles of satellite altimetry

- Radar altimeters transmit signals at high frequency to Earth, and receive the echo from the surface
- By timing it, we measure the distance between satellite and sea (**range**)
- We know the position of satellite (precise **orbit**) from models and measurements
- Hence determine **height** of sea surface w.r.t. reference ellipsoid
- altimeters also measure **waves** and **wind**

Conceptually simple
Technically challenging!!
(required accuracy ~1 cm from ~1000km)



Atmospheric corrections

- Ionospheric correction: 2-20 cm [+/- 3 cm]

  Caused by the presence of free electrons in the ionosphere

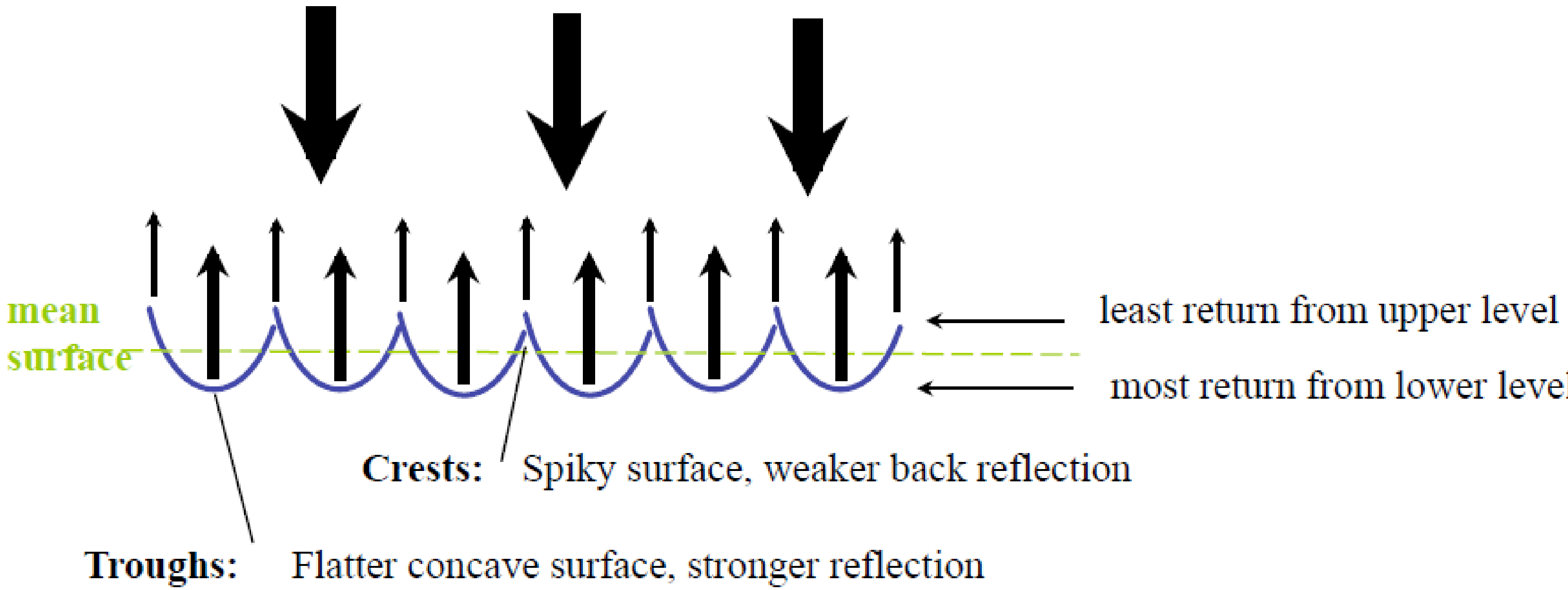
- Dry tropospheric correction: 2.3 m [+/- 2 cm]

  Caused by oxygen molecules

- Wet tropospheric correction: 5-35 cm [+/- 3-6 cm]

  Caused by clouds and rain

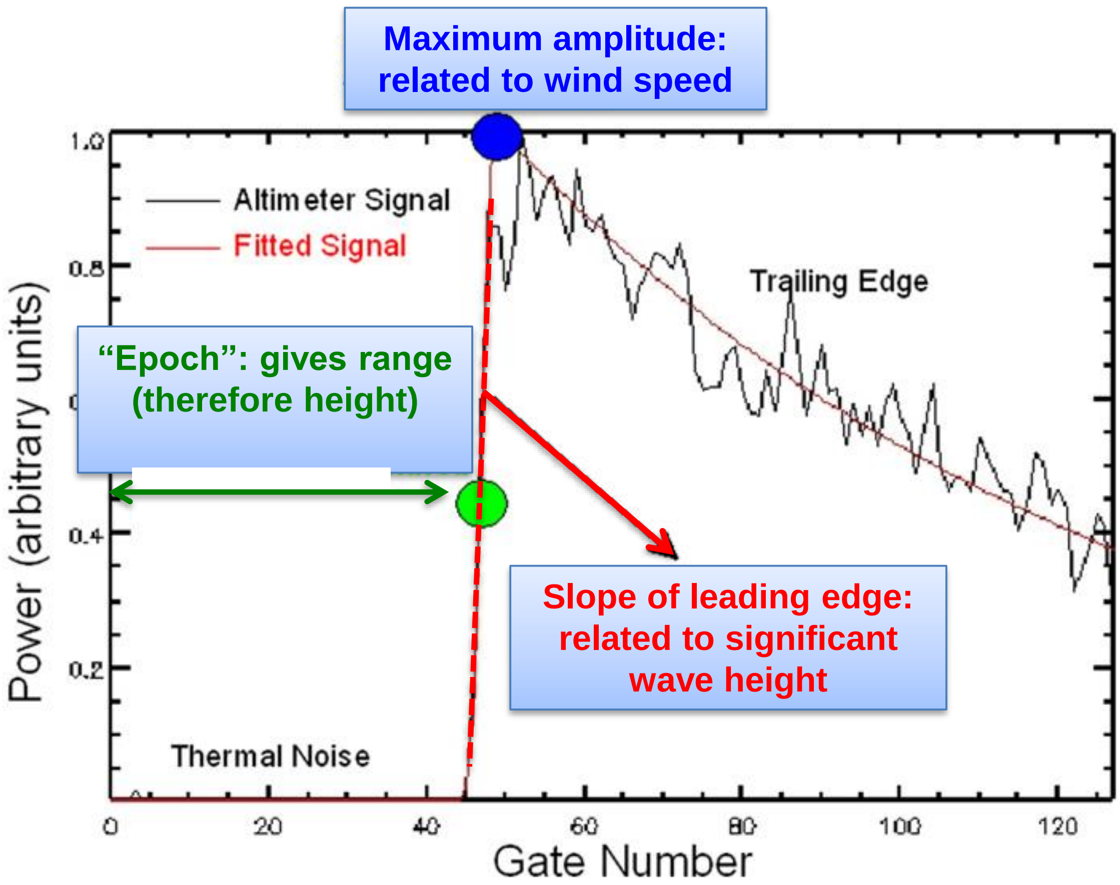
Sea state bias correction



- The bias is typically 2% to 5% of the significant wave height
- There is no theoretical method for estimating the sea state bias, hence we use empirical methods.

Retracking of the radar waveforms

= fitting the radar echoes (waveforms) with a waveform model,
→ we estimate the three fundamental parameters



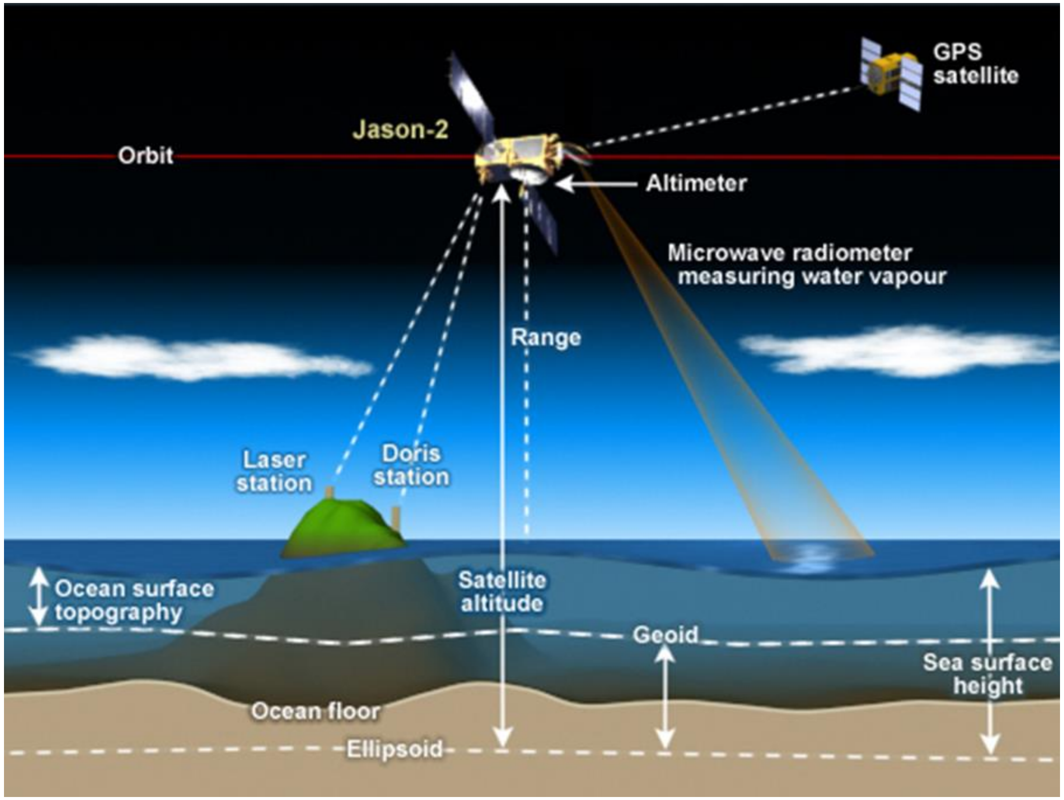
Normally done at 18-20 Hz (~350 m along-track) and then averaged at 1-Hz (~7km) to improve precision

Figure from J Gomez-Enri et al. (2009)

Open-ocean waveform model: Brown, 1977

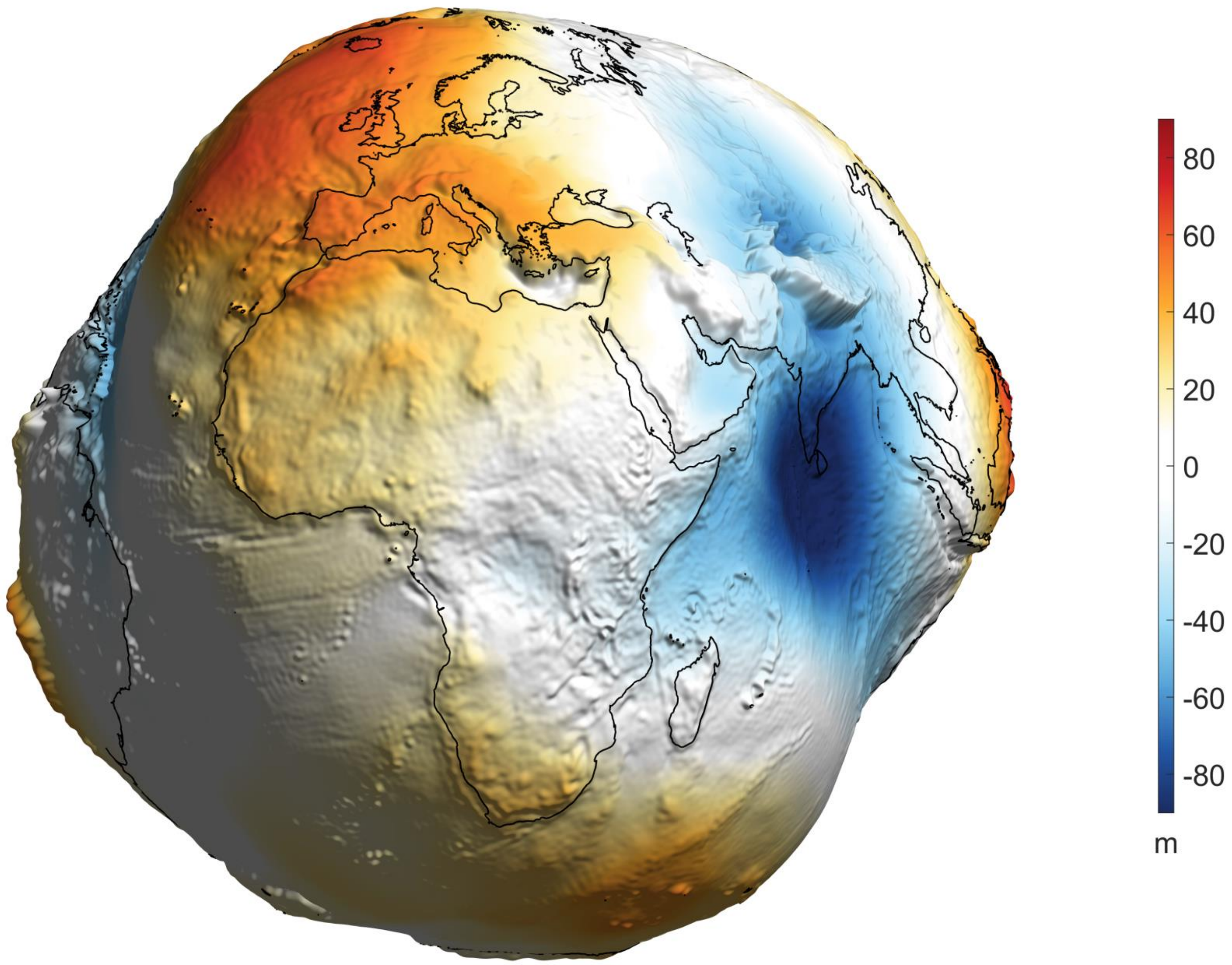
Reference surfaces

- The **reference ellipsoid** is a rough approximation of the Earth's shape
- The **geoid** is an equipotential surface that coincides with the shape that the sea surface would take in the absence of perturbing forces (currents, wind, etc.)



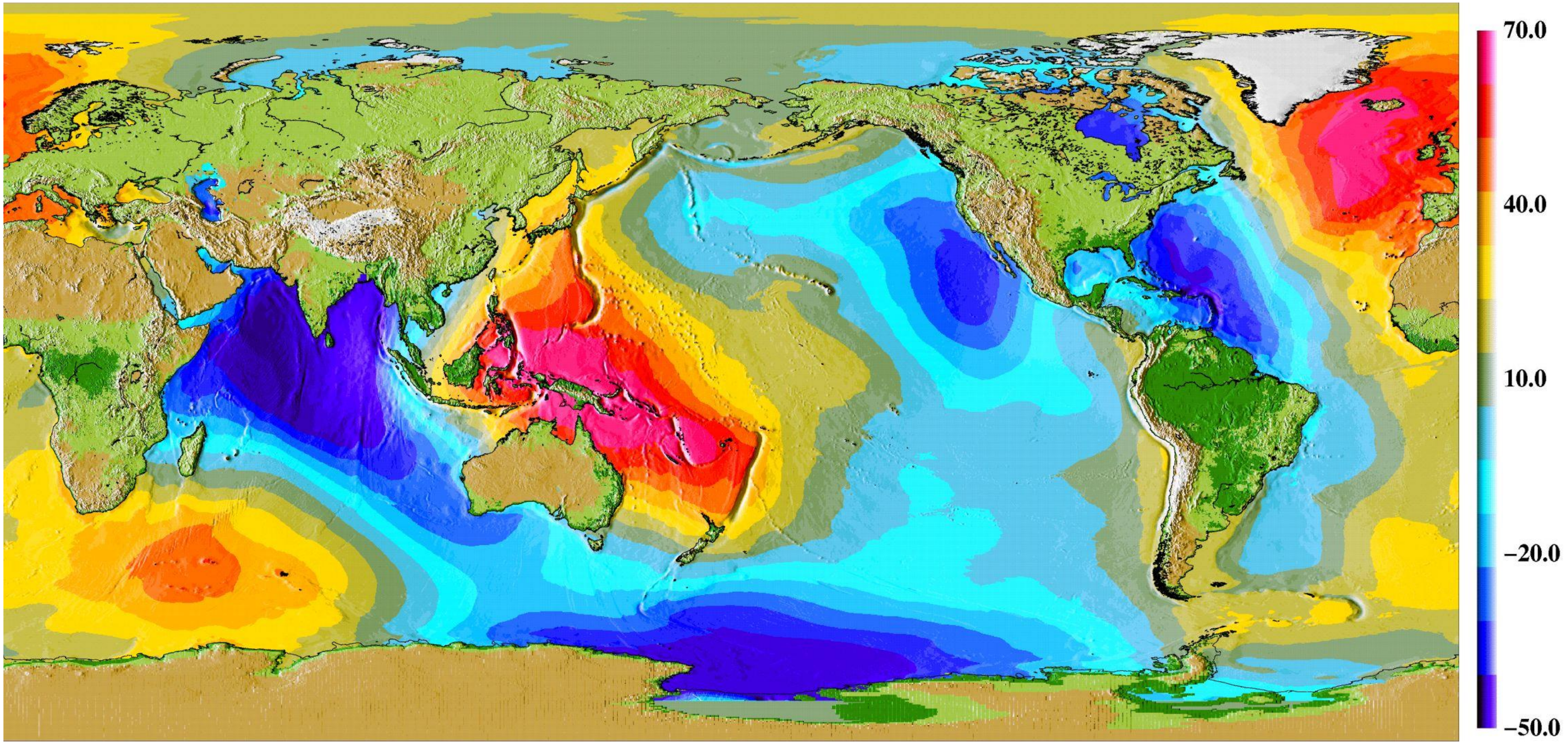
- The **mean dynamic topography (MDT)** is the stationary component of the ocean dynamic topography (not given by altimetry)
- The **mean sea surface (MSS)** is the sum of the geoid and the MDT
- The **sea surface height** is the sea surface height wrt the reference ellipsoid.
- The **sea level anomaly** (SLA) is the sea surface height wrt the MSS

The geoid



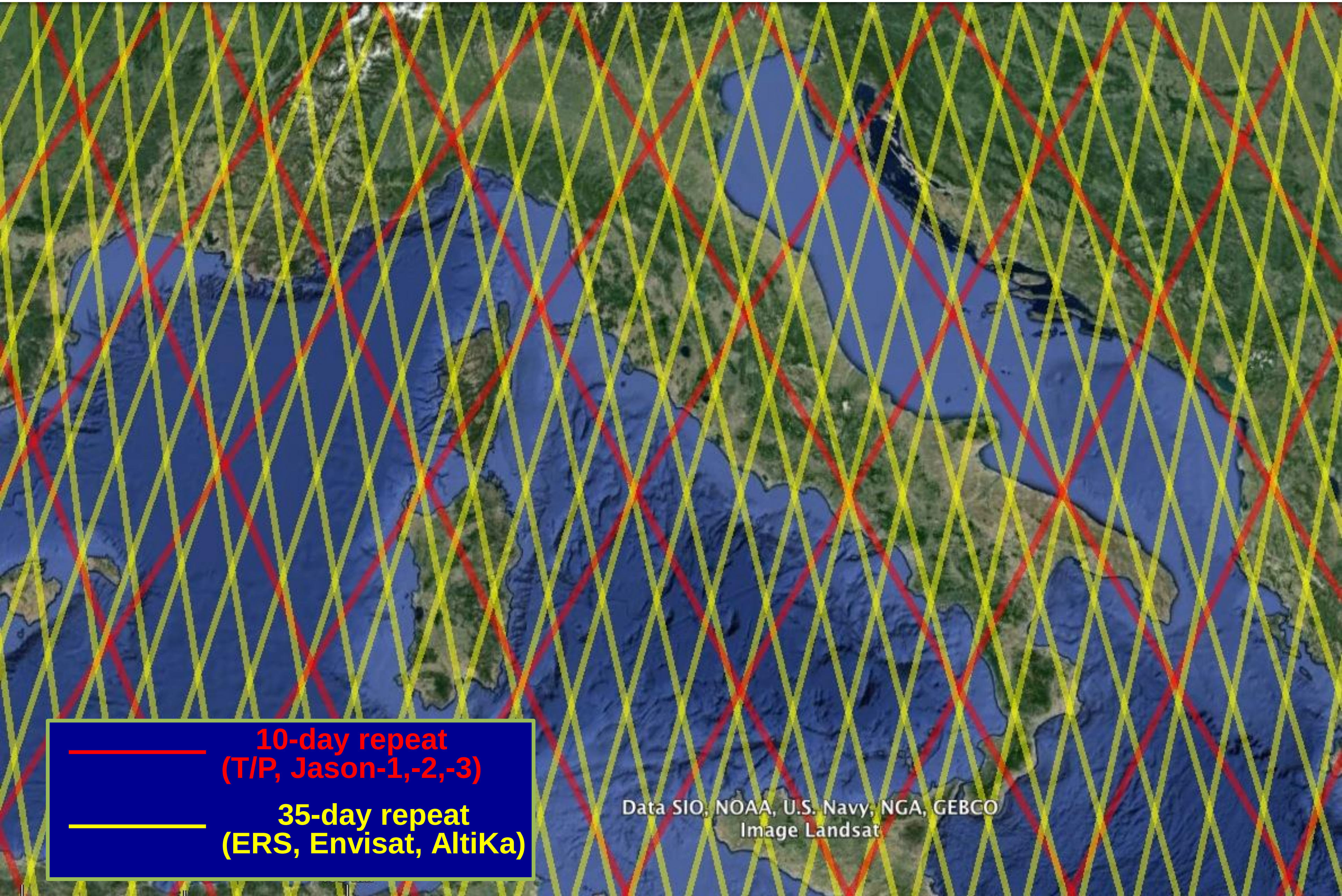
Geoid height (EGM2008, nmax=1000)

The mean sea surface (with respect to the reference ellipsoid)



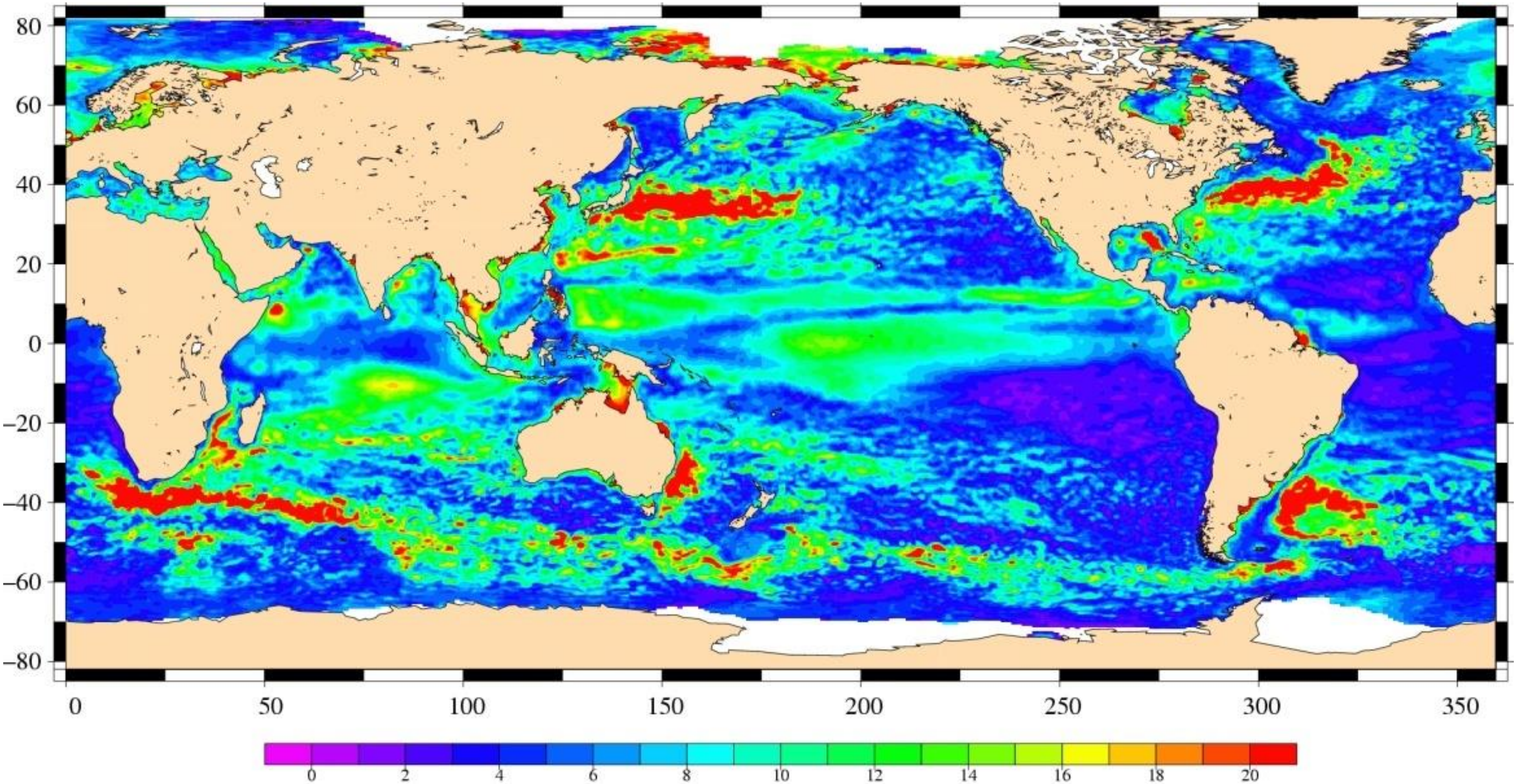
The MSS departs from the standard ellipsoid by ± 100 metres because of the density composition of the solid Earth

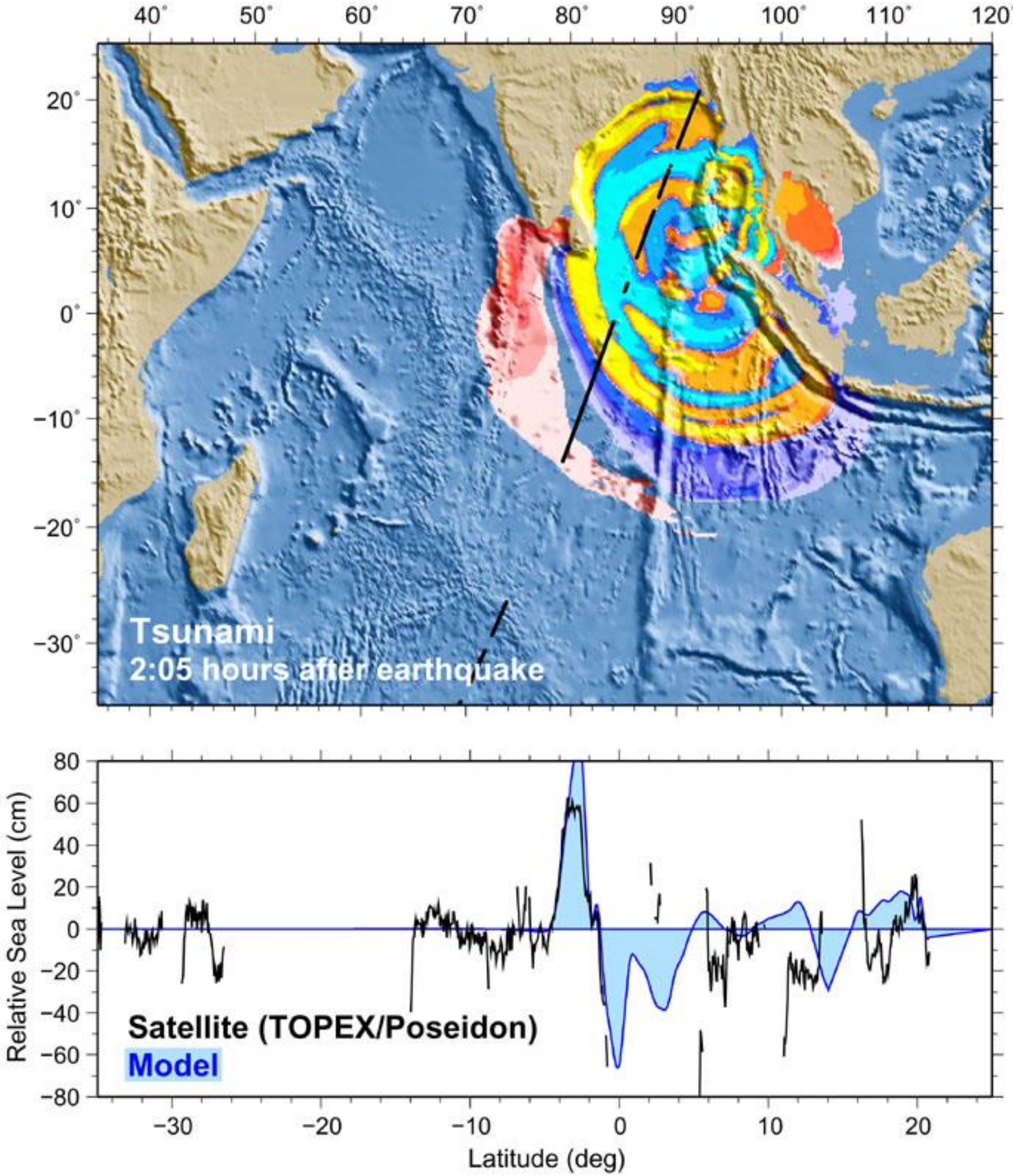
Altimetry is "along-track"



Mesoscale variability from altimetry

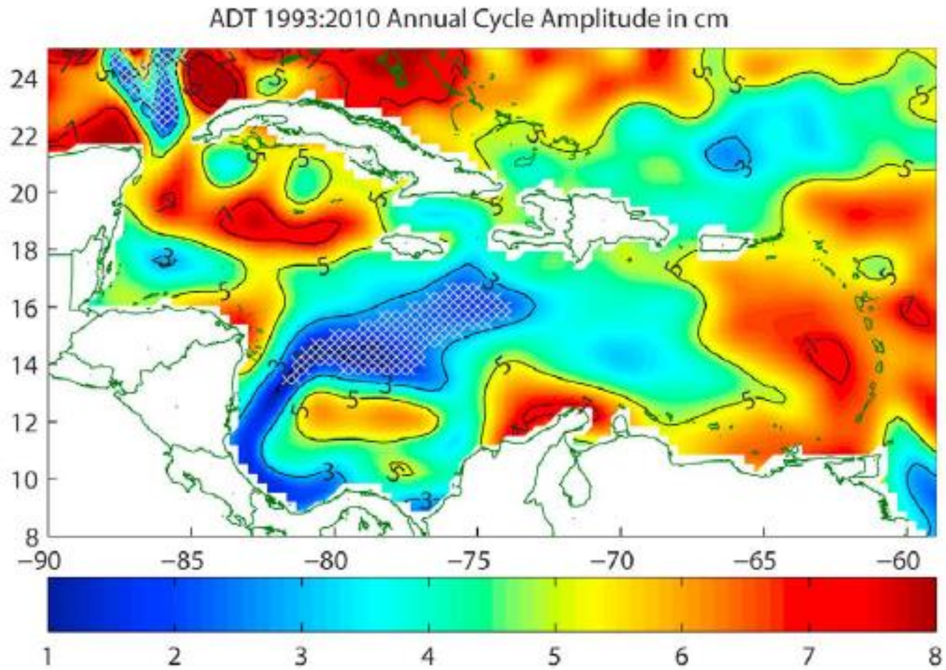
Mesoscale variability due to eddies and instabilities in ocean currents



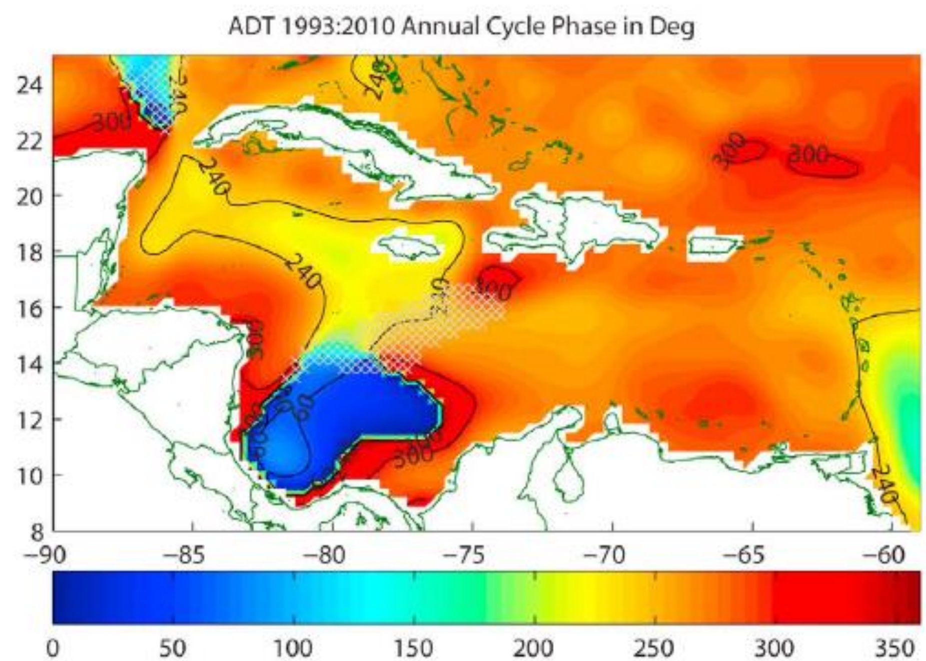


The Tsunami of 26 Dec 2004

Credit: NOAA



Amplitude of the annual cycle from satellite altimetry

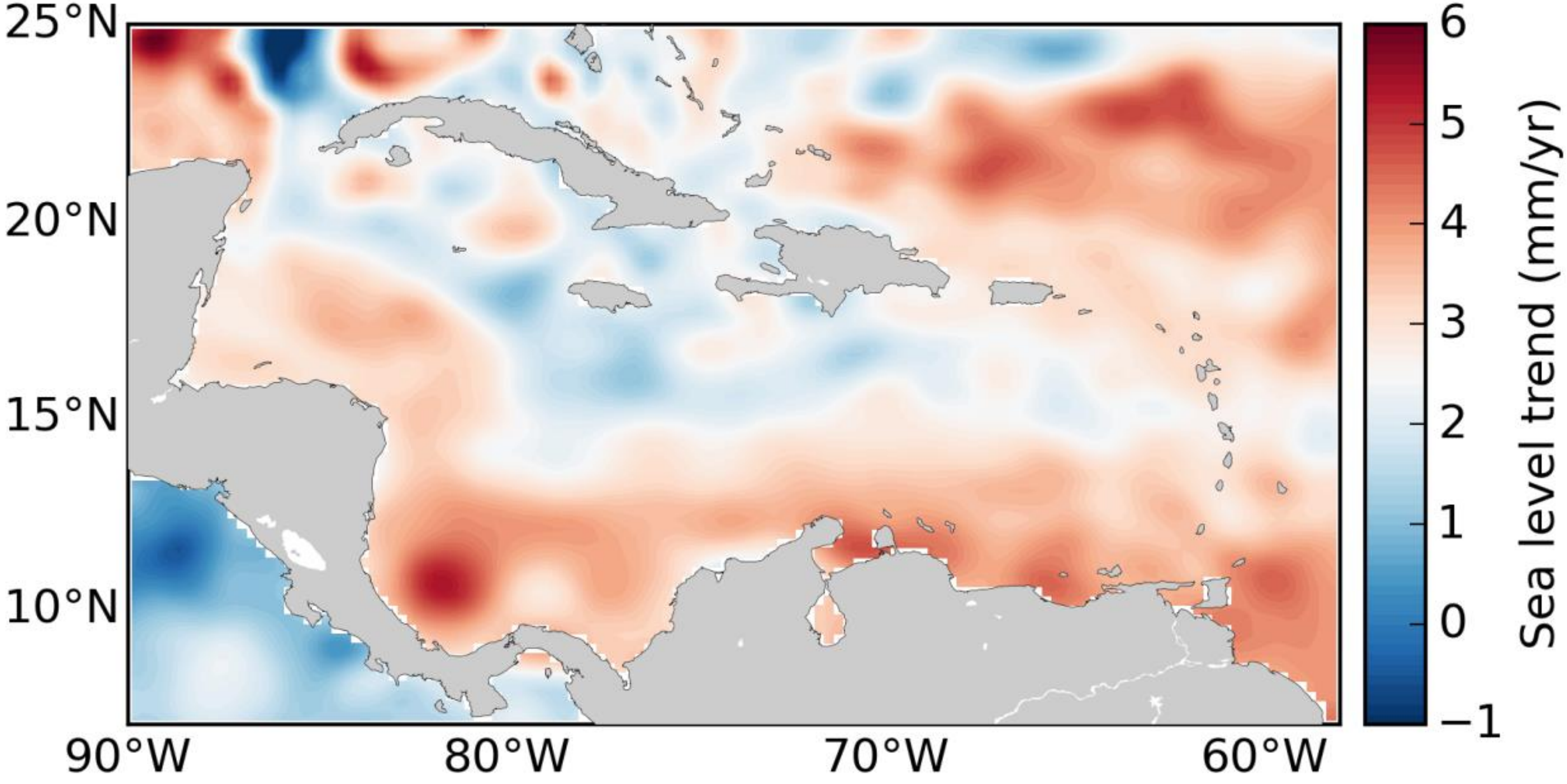


Phase of the annual cycle from satellite altimetry

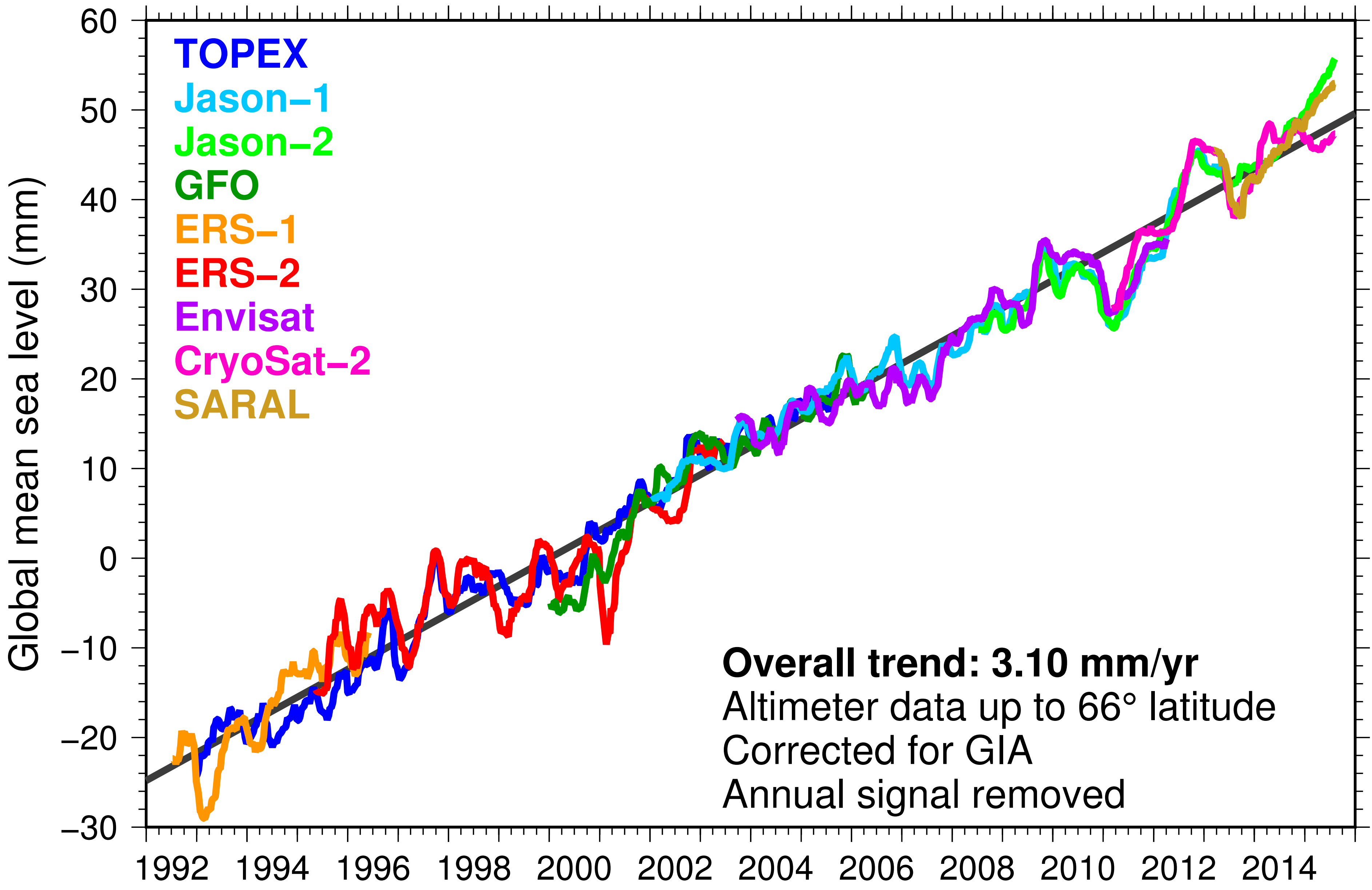
Torres and Tsimplis, 2012

Regional sea level trends from altimetry

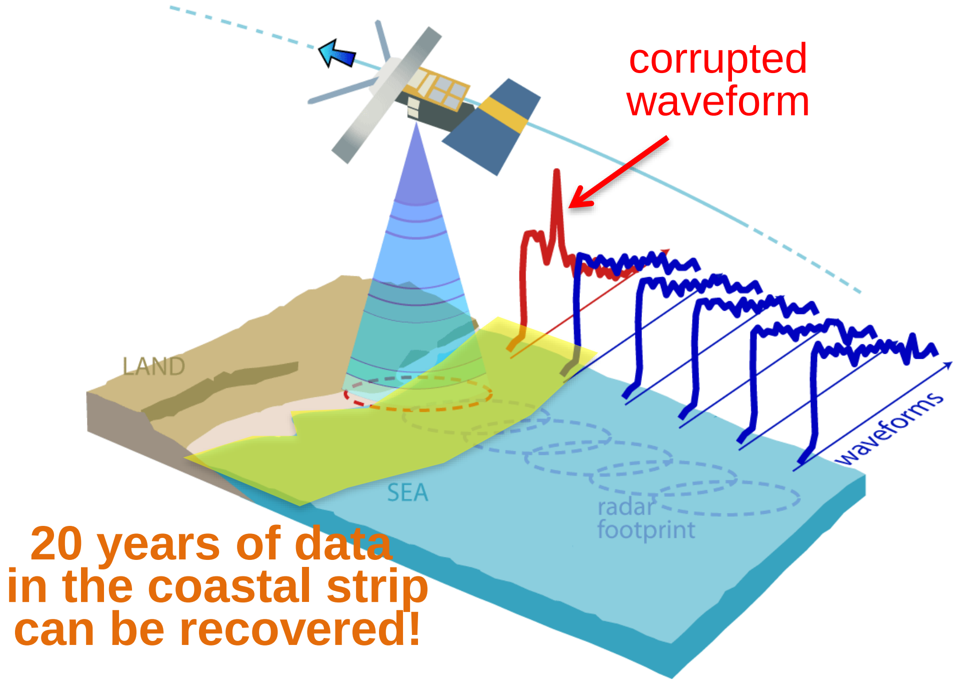
Sea level trends derived from satellite altimetry for the period 1993-2015 in the Caribbean Sea



Global mean sea level from altimetry



Altimetry in the coastal zone



Traditionally, data in the **coastal zone** are flagged as bad and left unused

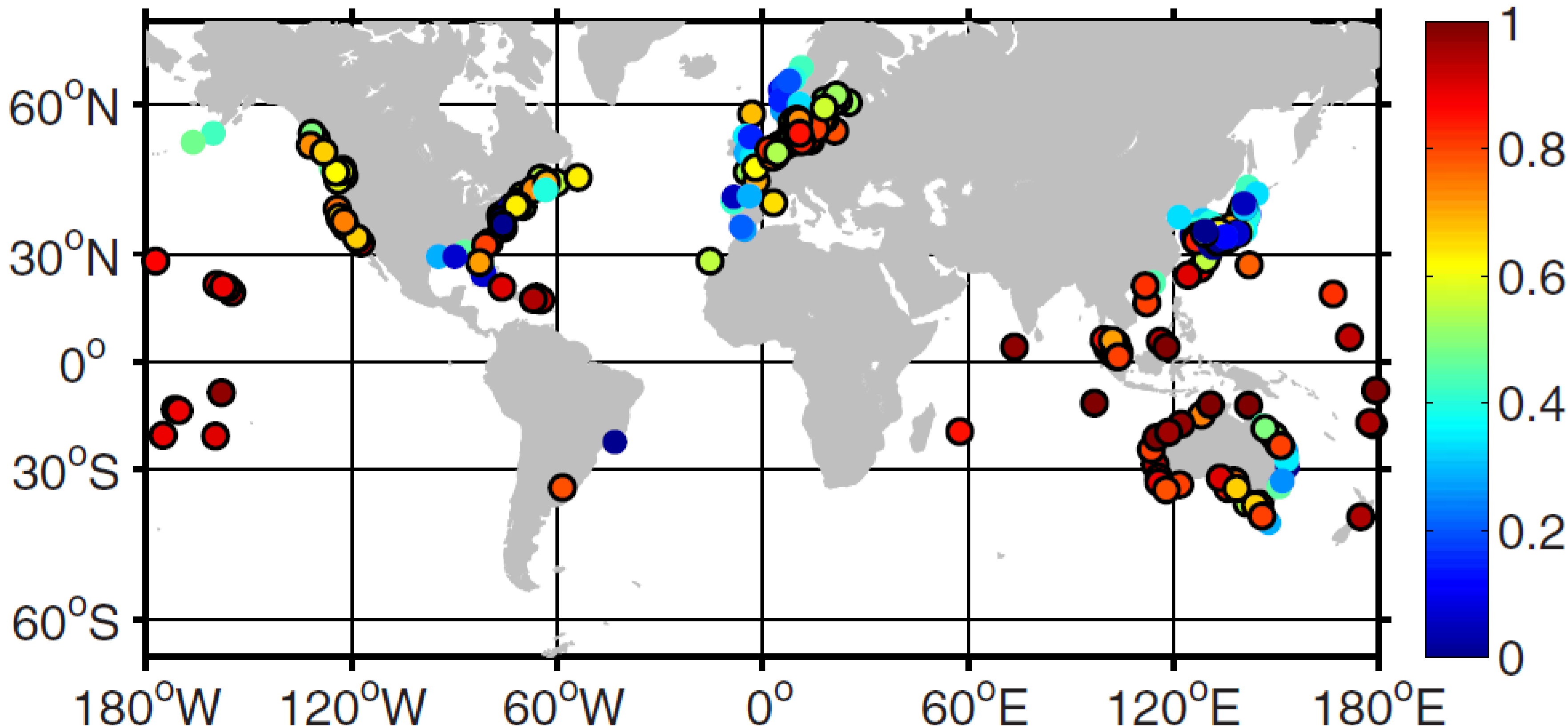
(coastal zone: as a rule of thumb 0-50 km from coastline, but in practice, **any place where standard altimetry gets into trouble** as waveforms are non-Brown and/or corrections become inaccurate)

In recent years a vibrant community of researchers has started to believe that most of those coastal data can be recovered

http://www.coastalt.eu/community

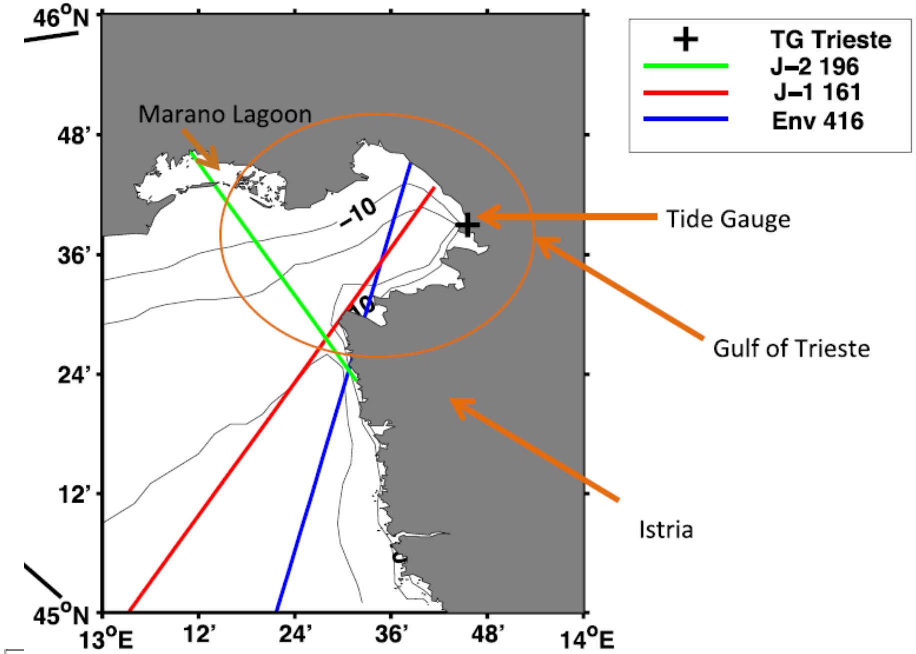
Altimetry in the coastal zone

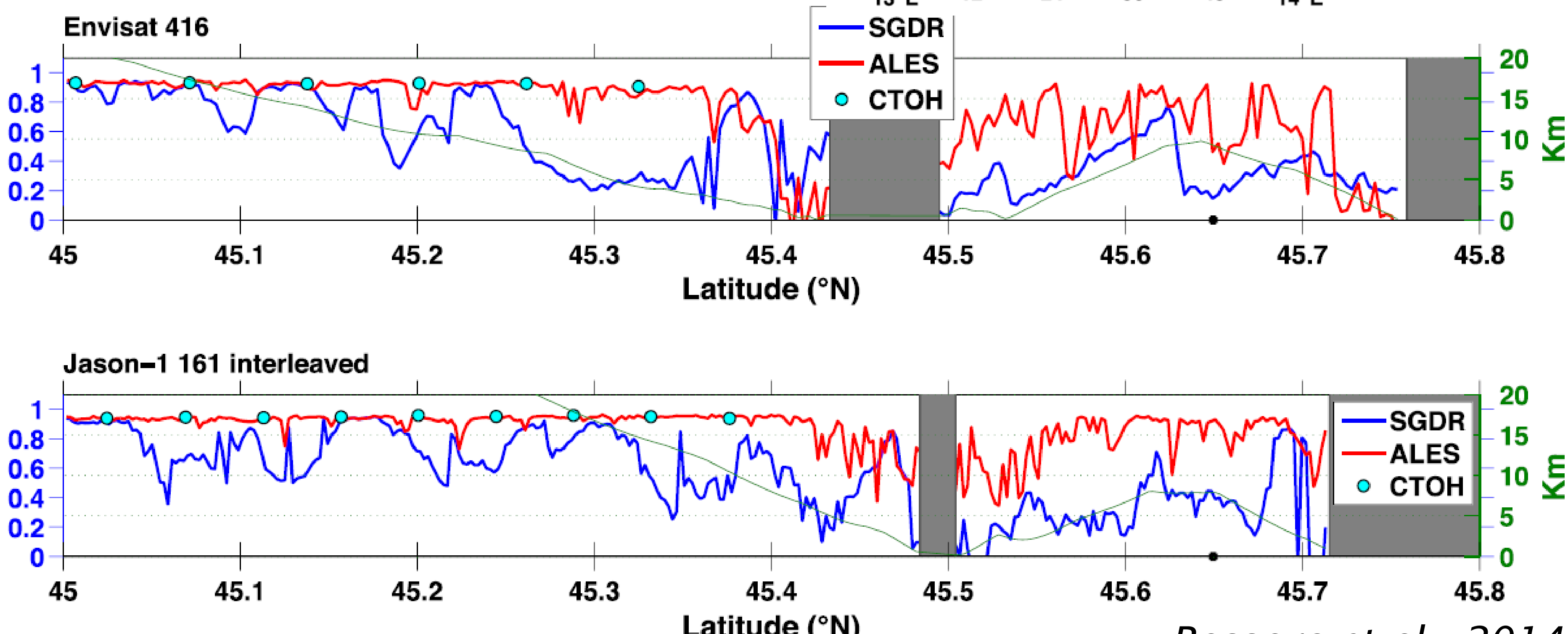
Correlation between tide gauge data and satellite altimetry observations



Calafat et al., 2014

Correlation between conventional and coastal (as reprocessed by ALES) altimetry data and the Trieste tide gauge record





Passaro et al., 2014

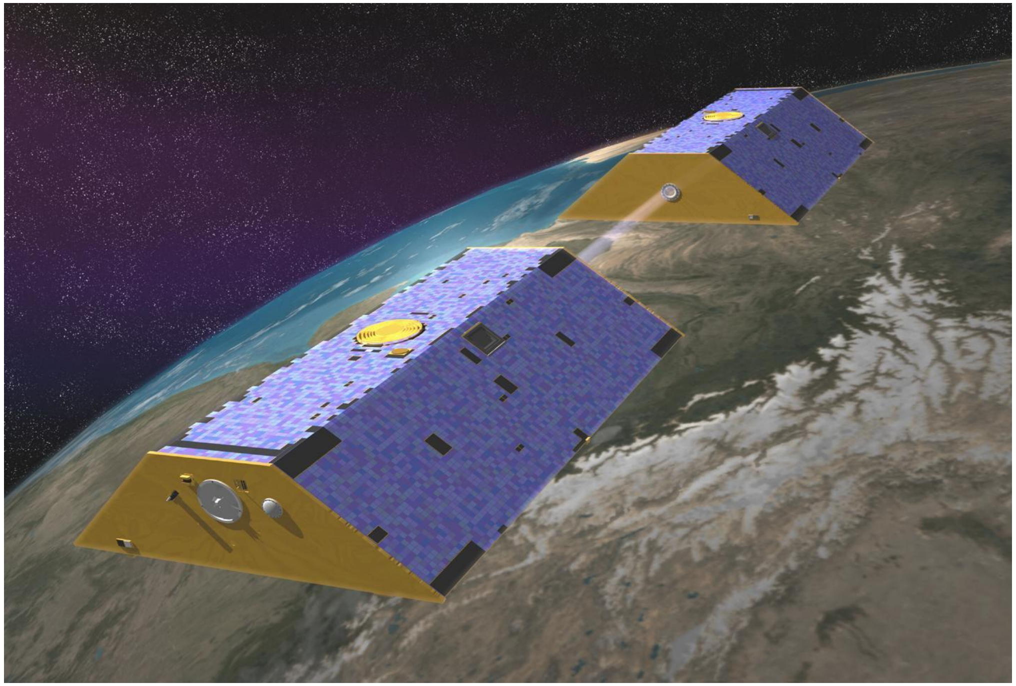
Satellite gravimetry and the Argo float network

The Gravity Recovery and Climate Experiment (GRACE)

GRACE consists of two satellites separated by a few hundred kilometers

Changes in their separation are used to infer the gravity field

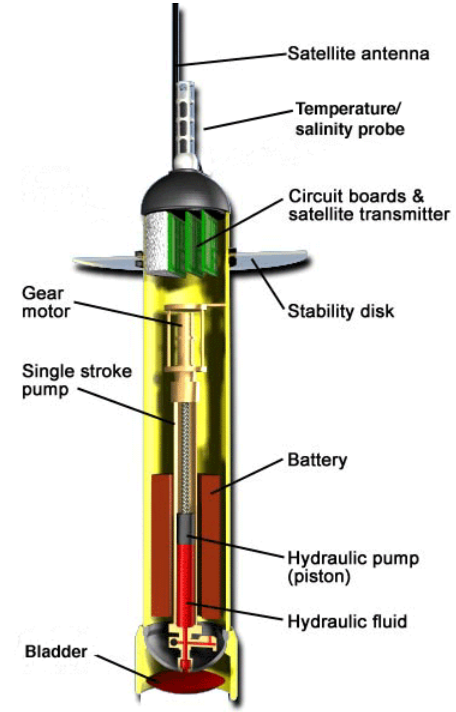
GRACE provides a horizontal resolution of about 500 km



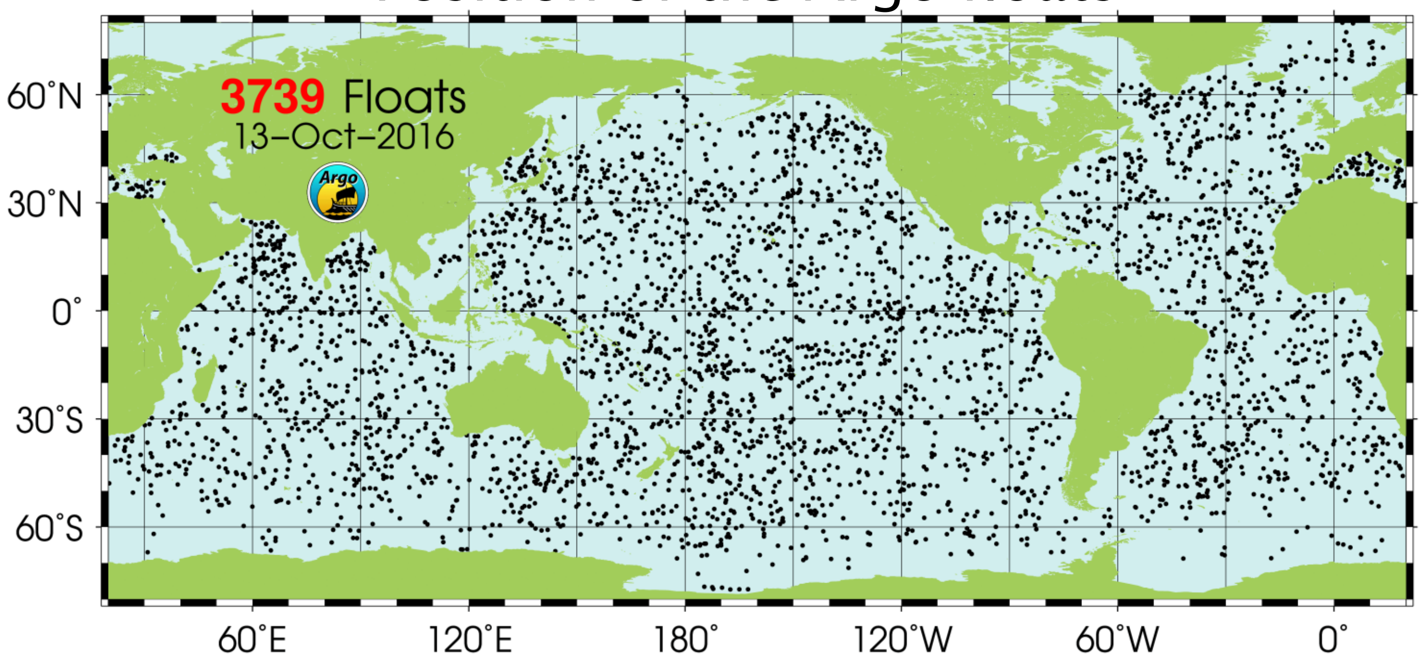
The temporal gravity variations measured by GRACE can be used to monitor changes in water storage on continents, **ocean bottom pressure** (i.e., mass changes), mass loss of ice sheets, etc.

The Argo float network

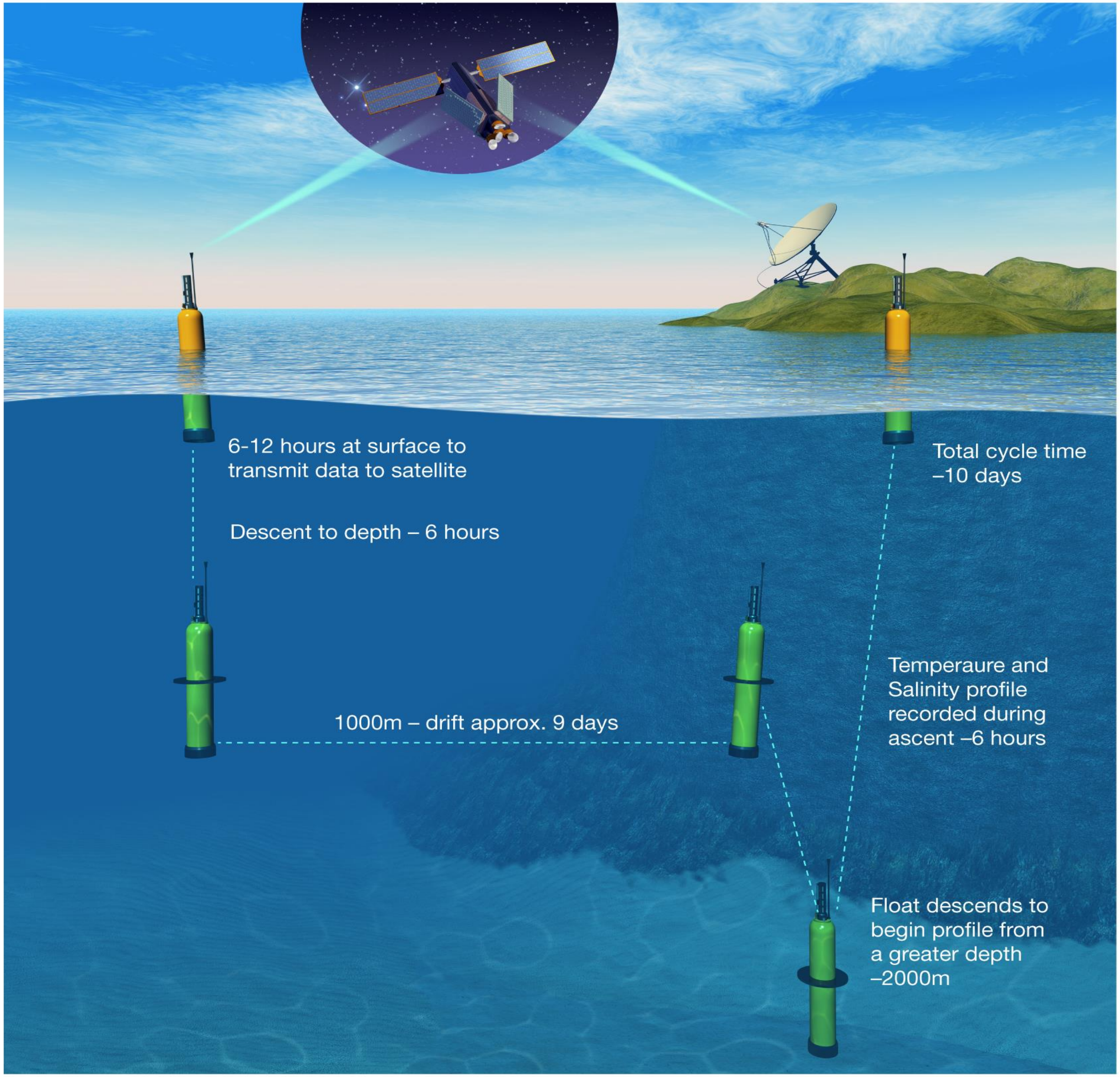
Argo floats measure the temperature and salinity of the upper 2000 m of the ocean as they freely drift with the ocean currents



Position of the Argo floats



How do Argo floats work?



How do we use gravimetry and Argo float observations for sea level?

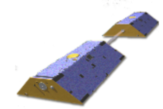
The sea surface height anomalies observed by an altimeter can be viewed as the sum of two terms (after removal of atmospheric pressure effects):

$$h' = h'_{steric} + \frac{P'_{bottom}}{g\rho_0}$$

Satellite altimetry

Argo

H < 2000 m



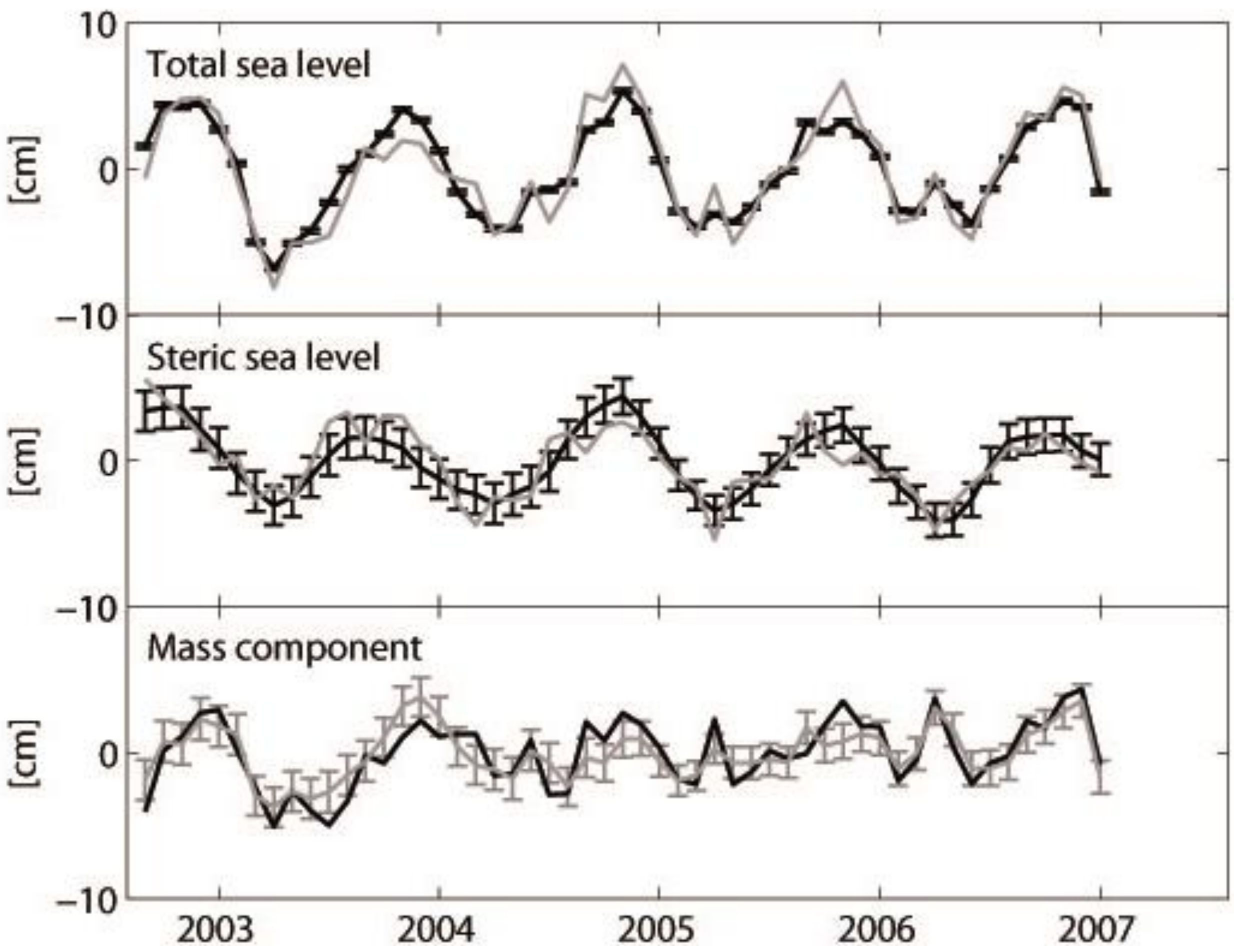
GRACE

h'_{steric} represents expansion/contraction of the seawater associated with T/S changes

The second term represents sea level variations associated with mass addition or redistribution

An example of using GRACE/Argo data for regional sea level

Mediterranean Sea mean sea level and its components

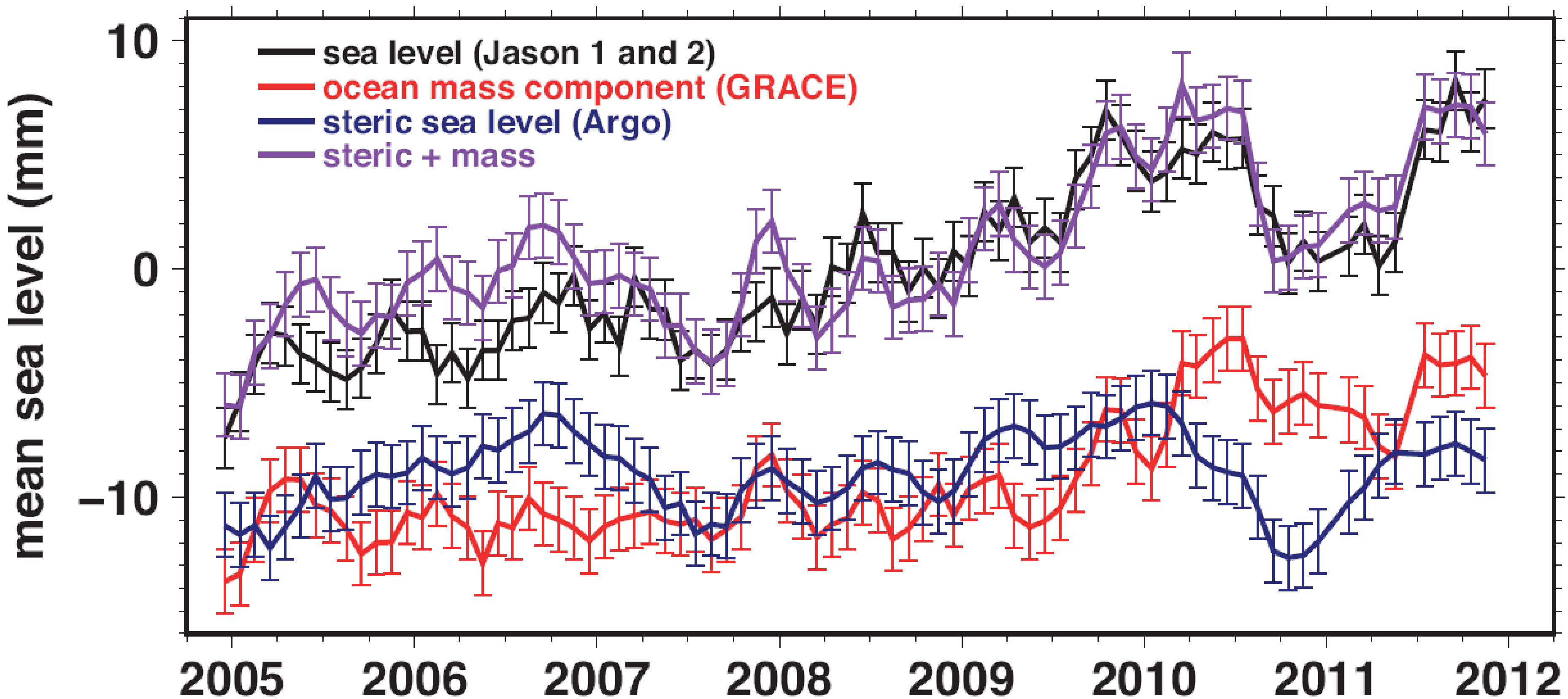


Observed estimates from altimetry, Argo, and GRACE in **black.**

Grey curves represent estimates obtained by adding or subtracting the other two observational components.

Calafat et al., 2010

An example of using GRACE/Argo data for global mean sea level



Geological techniques

Three important points to start

1. Sea level has changed throughout the geological record, is changing now and will change in the future
2. The many timescales and rates of change imply many different measurement techniques
3. All the 'sea level' we discuss using geological techniques is what we call <u>Relative Sea Level</u>

<u>Relative</u> means sea level relative to the height of the nearby land (like for tide gauge data).

‘Proxy’ geological data

‘Proxy’ means non-instrumental. We have tide gauges and altimetry for studying sea level changes over years to centuries. But for longer timescales we have to make use of ‘proxy’ techniques involving study of:

- Landforms
- Stratigraphy
- Fossils

Beach ridges above present-day sea level

- Beach ridges are wave-swept or wave-deposited ridges running parallel to a coastline
- They essentially record the height of storm wave run-up
- Beach ridges above present position could suggest MSL change
- They can be carbon dated using entrapped material (e.g. driftwood, mollusc shells)

Present-day beach ridges, north coast of Estonia (Many beach ridges in Scandinavian beach mapped extensively by N-A. Mörner and others)

Wave cut notches

- Prolonged wave action causes a notch in a cliff to be eroded.
- A displaced notch (above or below present water level) is an indication of a former sea level, often due to tectonic change
- Dated by inference, or sometimes barnacles, or using nearby corals if available

- Any significant rising or falling trend doesn't have sufficient residence at a given elevation to produce a notch

Corals

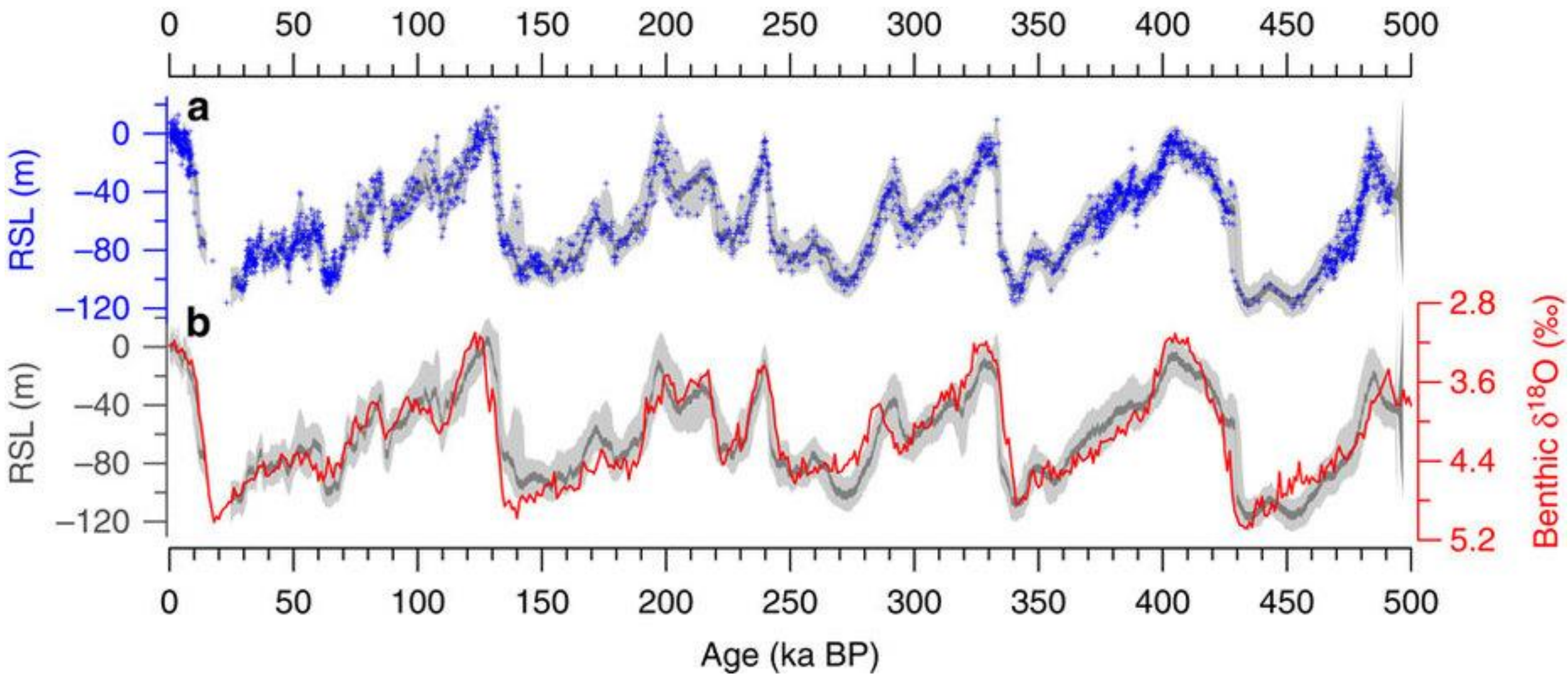
A micro-atoll forms when the top of a coral head breaks water (e.g. due to sea level fall) and becomes visible at low tide. The top dies but growth continues laterally. Micro-atolls are primarily Porites. (Photo. Maui Nui Marine Resource Council, Hawaii).

Oxygen Isotope Analysis

- **Many of the methods we have discussed so far apply only to study of sea level since the LGM.**
- **To go further back, one can use landforms or other technique such as oxygen isotope analysis of shells of tiny marine organisms (foraminifera or 'forams').**
- **During extended Warm Periods, when ice sheets small or absent (e.g. Cretaceous to Pliocene), the $^{18}0$ variations in benthic forams largely reflect temperature (the forams take up less $^{18}0$ when they are warmer).**
- **$^{18}0$ in a sample can be readily measured using a mass spectrometer**

Oxygen ^{18}O and sea level

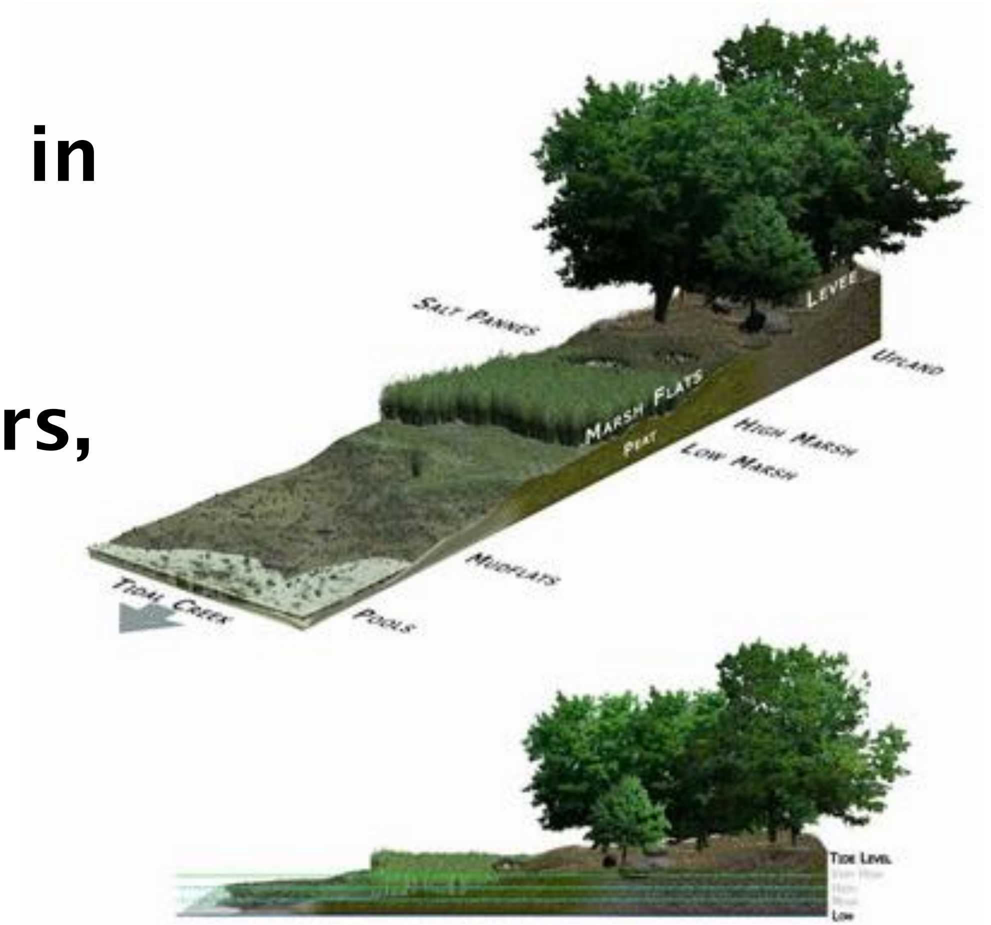
Sea level variability over 5 glacial cycles



Grant et al., 2014

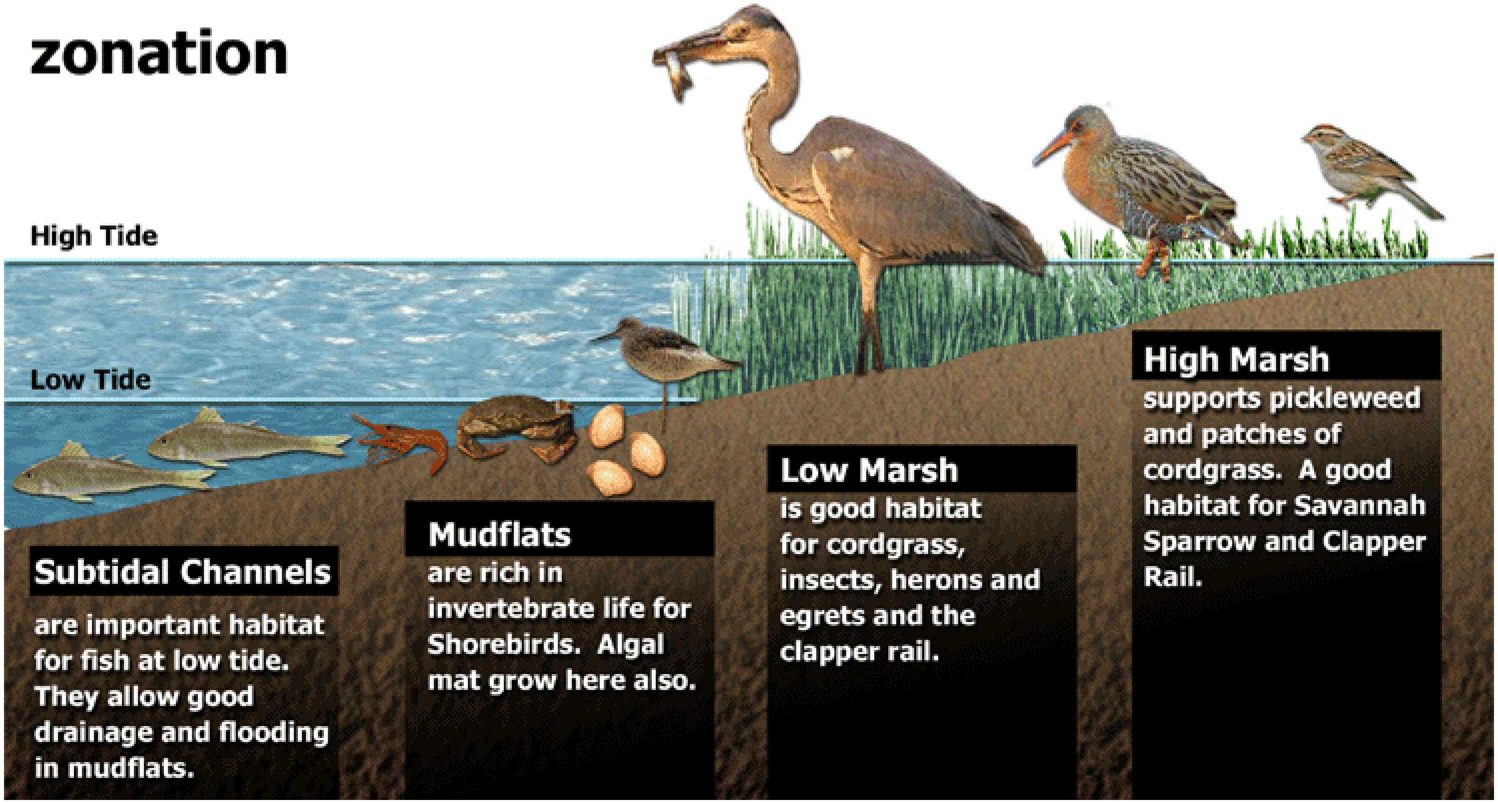
Salt marshes

- Salt marshes develop in the intertidal zone in sheltered lagoons behind coastal barriers, river estuaries etc.



- Upward growth of the marsh and of peat largely follows sea level as long as sediment supply sufficient

Salt marshes



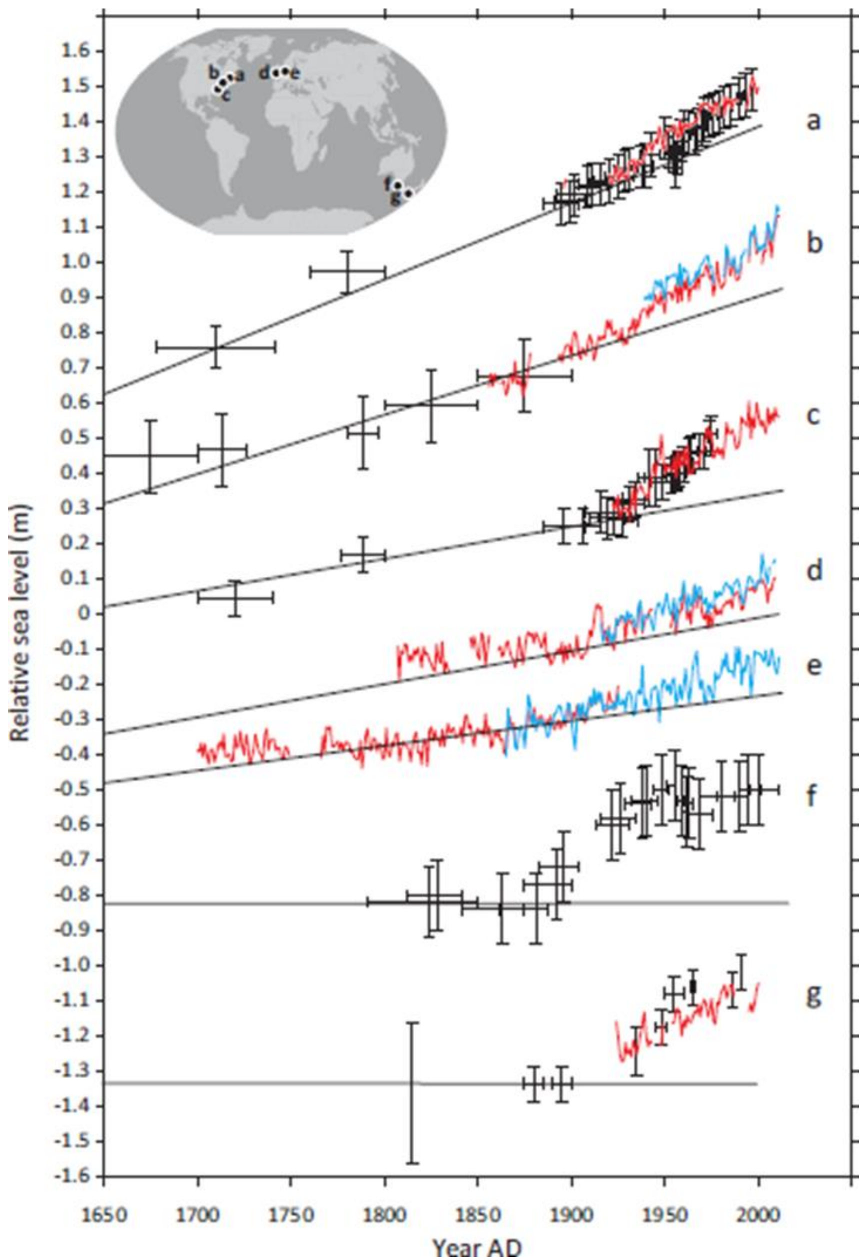
Salt Marsh Zonation

- The differing frequency of salt water inundation leads to differing plants (and foraminifera) at different heights on the marsh

Salt marshes and the transfer function

- A ‘transfer function’ expresses the heights of forams on the present marsh surface as heights above Mean Tide Level. These heights are obtained from a set of surface samples whose heights are measured by levelling and with the use of a temporary tide gauge to determine MTL
- Accuracy typically 10-20% of the local tidal range
- Assumption then is that the marsh environment has not changed, such that a particular mix of forams at a certain height above MTL now will tell us what the height above MTL was for a sample in a core

Salt marshes and sea level



Salt marsh data (black crosses) and corresponding tide gauge information (coloured lines)

Thank you for listening!

Questions?