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  The repository principally contains the compiled products rather than the source for size reasons.
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OCES 2003 :
Descriptive Physical Oceanography

(a.k.a. physical oceanography by drawing pictures)

Lecture 18: intro to sea level

Outline

Surveys in Geophysics (2019) 40:1251–1289
https://doi.org/10.1007/s10712-019-09525-z

Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global

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- descriptive outline of some content in this paper

Outline

- sea level

  → but relative to what?

  → sea level **rise**, but also relative to what?

- contributions to sea level (a collection of definitions)

  → thermosteric, halosteric, inverse barometer,
- solid earth contributions

  → GIA
- storm surges

  →

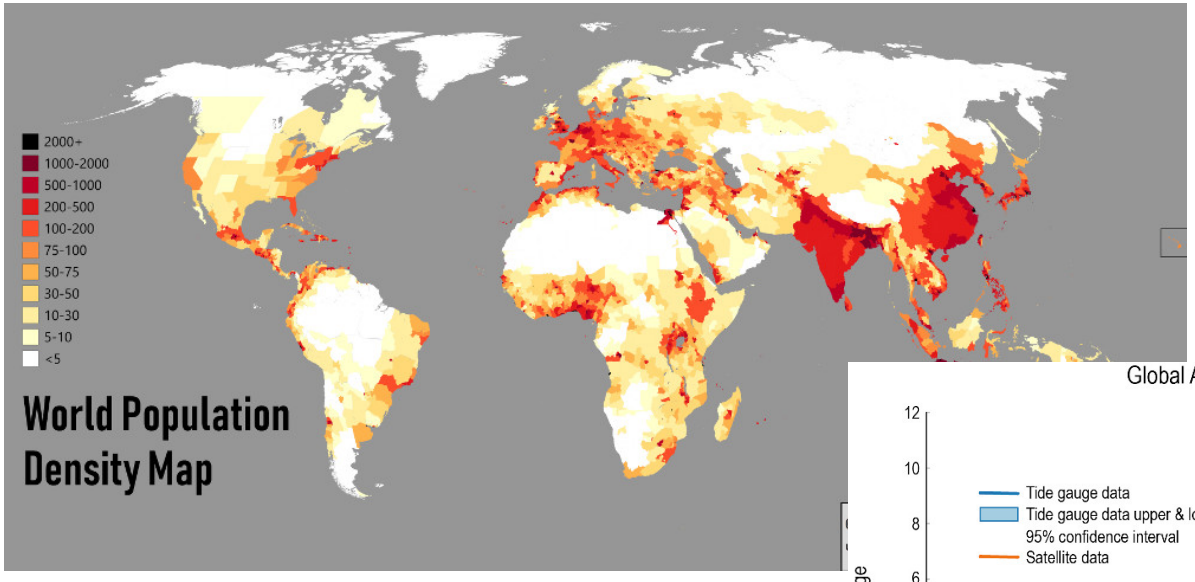
Key terms: (mean) sea level, (mean) sea level rise

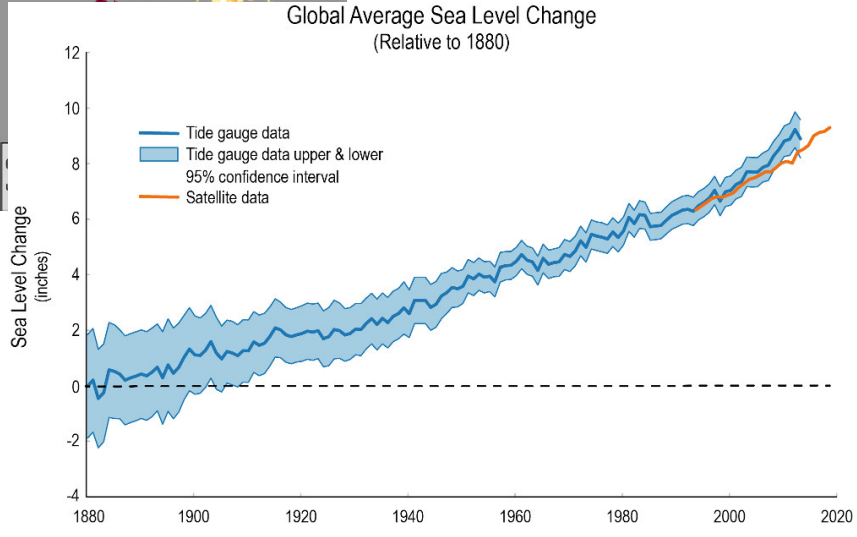
Recap: observational data

sea level spiral

Historical reconstruction of Global Mean Sea Level (GMSL) data of Church & White (2011), relative to 1880.

Recap: impact of sea level rise

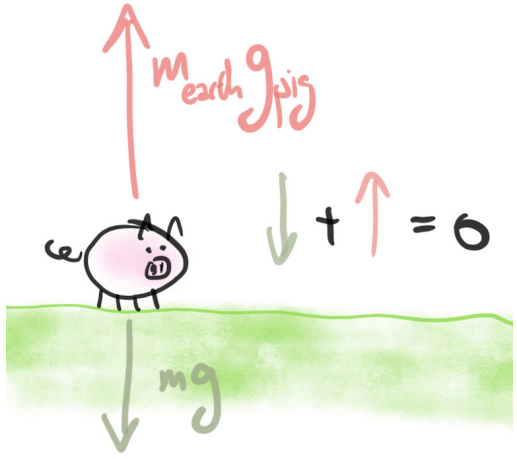


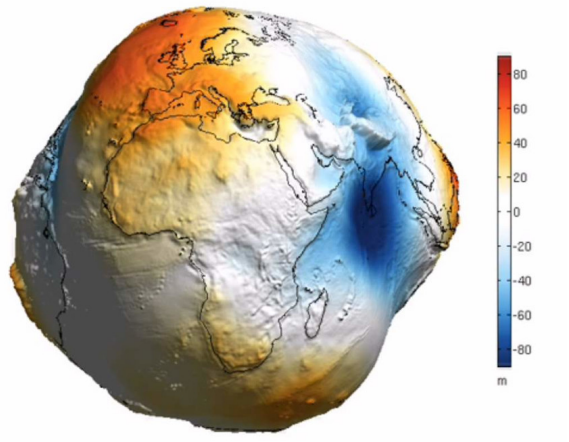


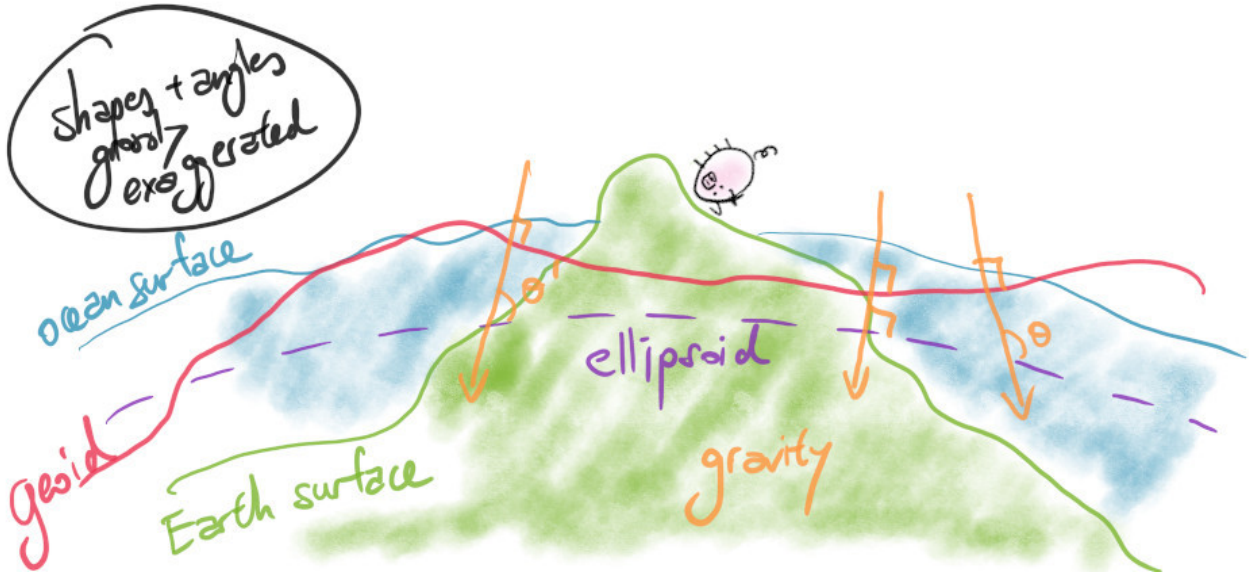
left: reddit user `some_dawid_guy`; right: from USGCRP

Recap: impact of sea level rise

Relative to what though? (space)







Relative to what though? (time)

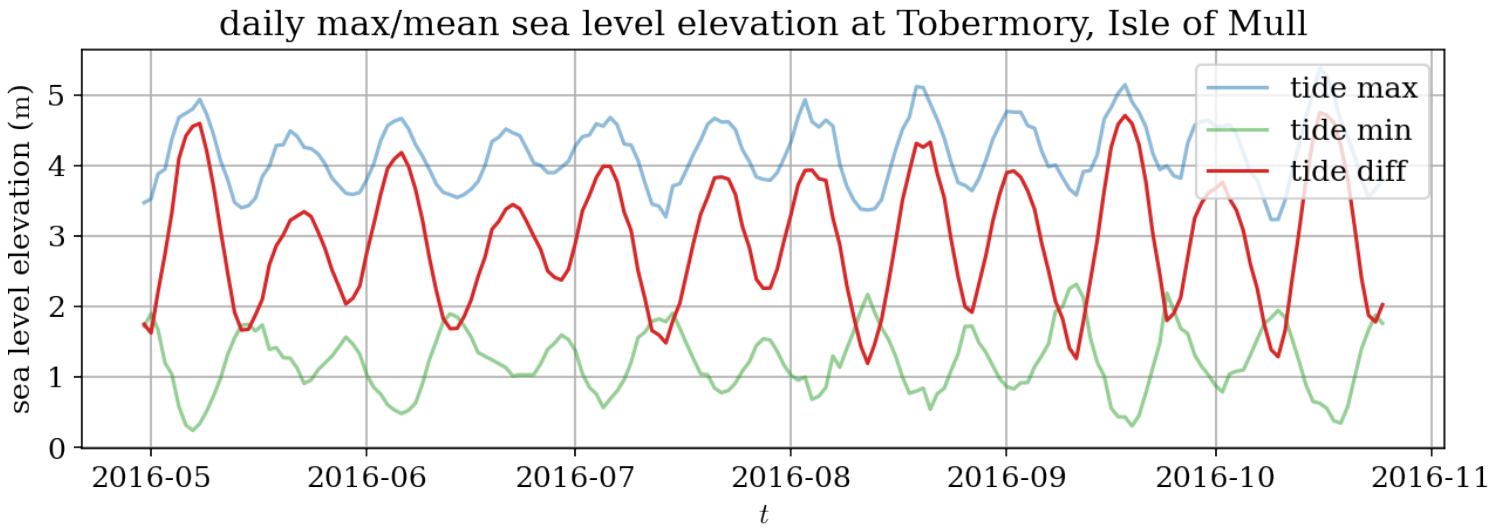


Figure: Daily maximum and minimum sea surface elevation (blue and green) and their difference (red) over a six month period. Data from BODC, see `tobermory_tides.ipynb`.

- how to define a (useful) **reference/mean**?

Summary figure

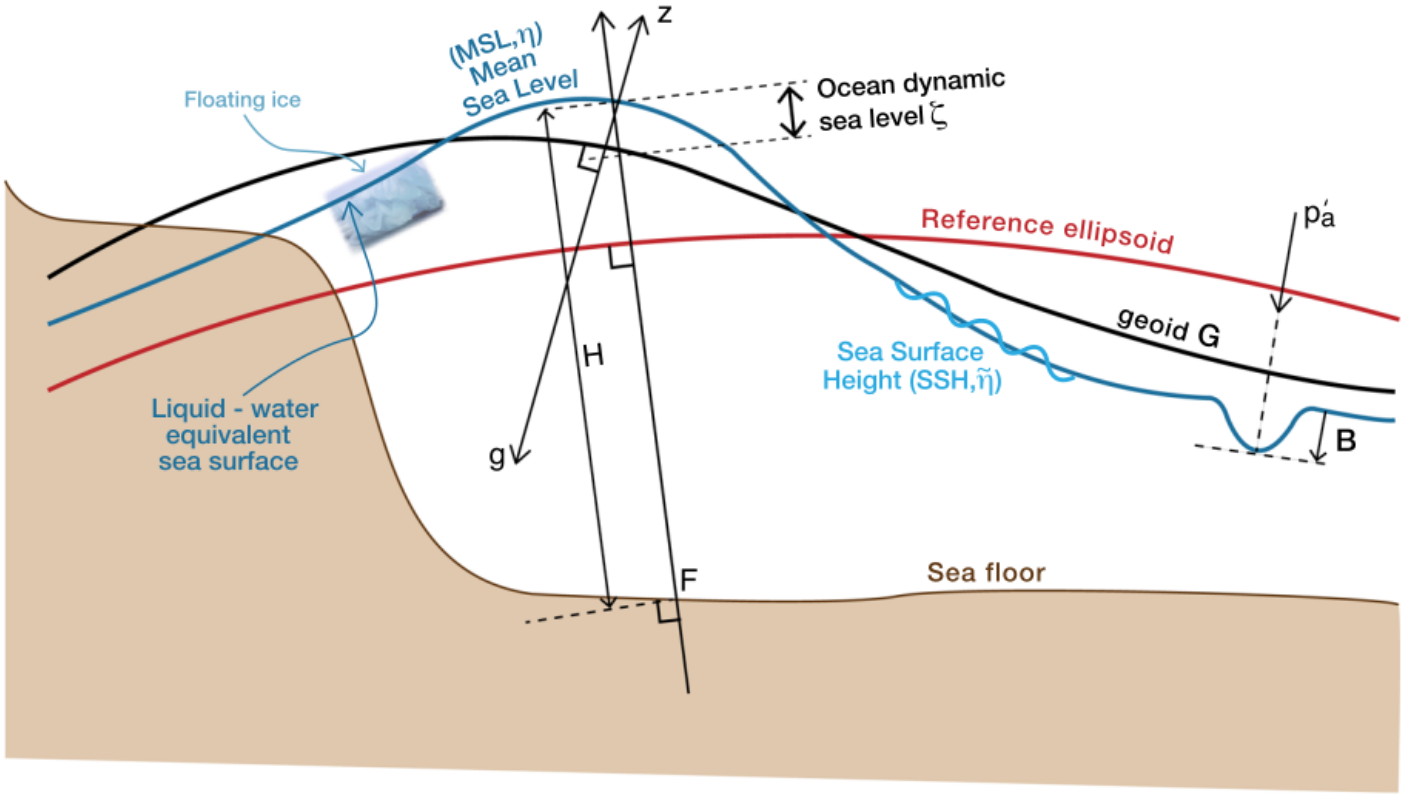
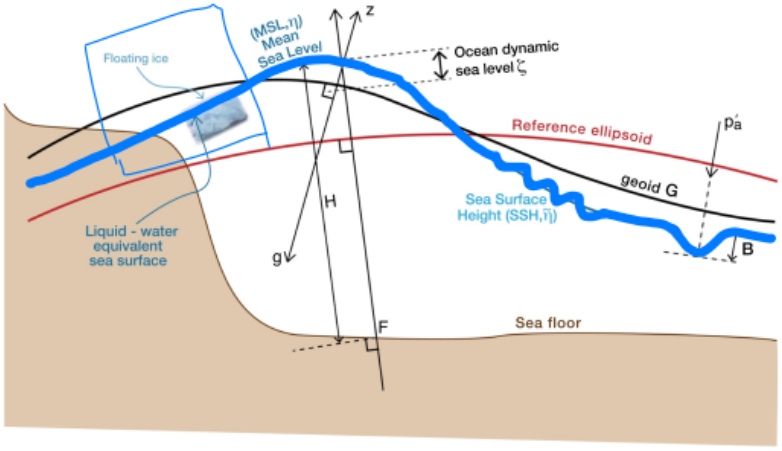


Figure: Schematic figure from Gregory *et al.* (2019), Fig. 2.

- observations are relative to **ellipsoid**, dynamics relative to **geoid**, can differ quite a bit ($O(100\ \mathrm{m})$)

Sea surface



- sea surface $\tilde{\eta}$

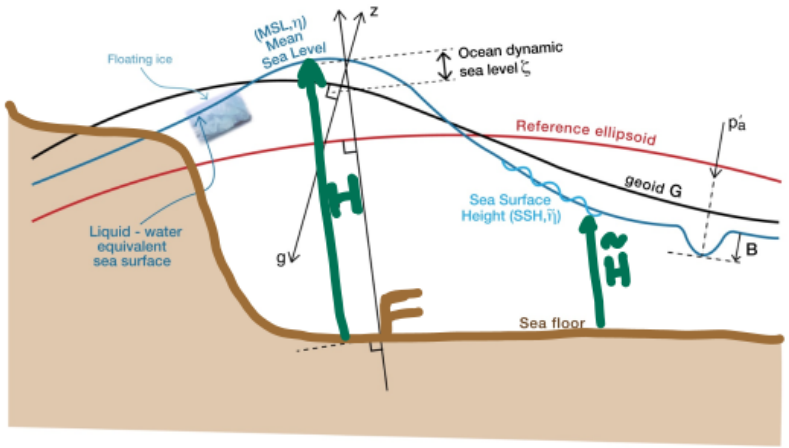
  $\rightarrow$ **instantaneous**
- mean sea surface η

  $\rightarrow$ **time averaged**, but over how long?

$$\tilde{\eta}(\boldsymbol{x}, t) = \eta(\boldsymbol{x}) + \eta'(\boldsymbol{x}, t)$$

- subtlety: η could be time-dependent...
- when **sea**-ice is present, convert ice to equivalent water and then add it on (cf. inverse barometer later)

Sea floor and water depth



- sea floor $\tilde{F}$

  $\rightarrow$ time-independent for reasonable time-scales

  $\rightarrow$ can move around though (e.g. VLM, GIA...)

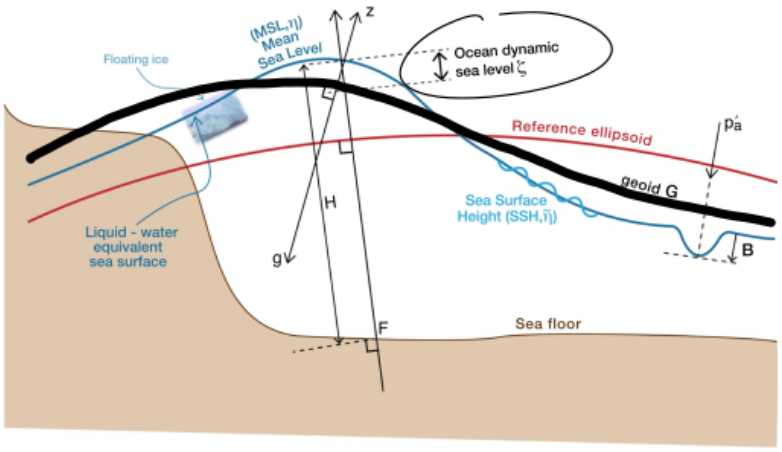
- water depth $\tilde{H}$ and H

$$\tilde{H} = \tilde{\eta} - \tilde{F} \geq 0,$$

$$H = \eta - F \geq 0$$

where $\tilde{F} \approx F$

Geoid



- **geoid $\tilde{G}$**

  $\rightarrow$ time-independent for reasonable time-scales

  $\rightarrow$ can move around (e.g. GRD...)

- G is where it is the geopotential that bounds the same volume of the ocean between η and F, i.e.

$$\iint G - F \, \mathrm{d}A = \iint \eta - F \, \mathrm{d}A$$

  $\rightarrow$ η and F can both evolve in time...

  $\rightarrow$ more useful definition (ocean is never at rest anyway...)

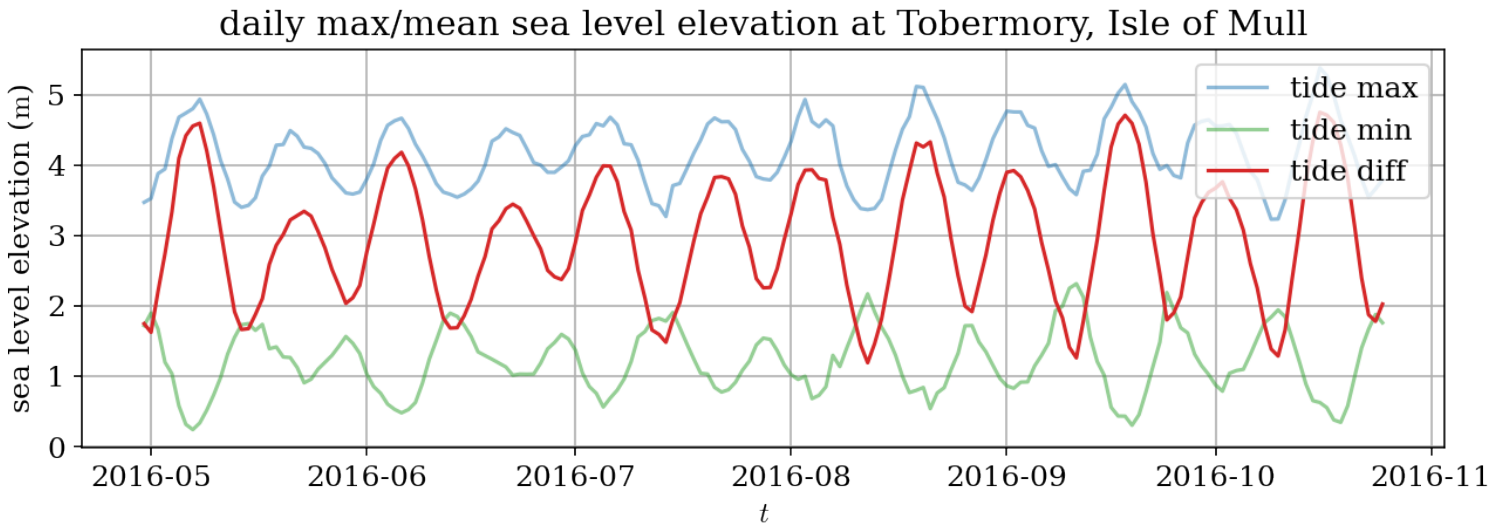
  $\rightarrow$ associated with it the dynamic sea level $\tilde{\zeta}$

Variations in η (and ζ)

- tides

  $\rightarrow$ instantaneous response from astronomical forcing $\Rightarrow$ **equilibrium tides** (Lec 17)

  $\rightarrow$ wave propagation $\Rightarrow$ **dynamical tide**



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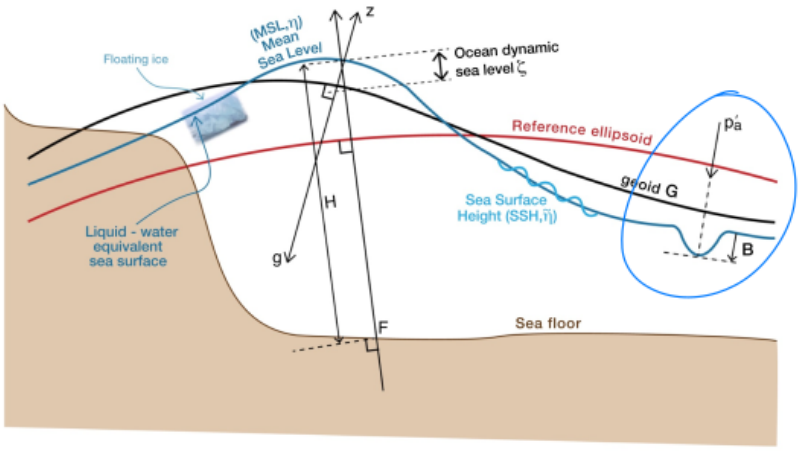
Variations in η (and ζ)



- inverse barometer effect

  $\rightarrow$ atmosphere presses down on the ocean

  $\rightarrow$ low atmospheric pressure $\Leftrightarrow$ rise in sea surface

- 10 hPa $\Leftrightarrow$ about 10 cm change

  $\rightarrow$ only really get this level with **storms** (cyclones, low pressure; Lec 7, 8)

- global mean contribution is **zero**

  $\rightarrow$ local pressure variations moves the ocean around though, affecting $\tilde{\eta}$ (and $\tilde{\zeta}$)

Variations in η (and ζ)

- wind driven waves (Lec 16)

  $\rightarrow$ distinguished from tidally forced waves

  $\rightarrow$ surface intensified, effect diminishing with depth (Lec 9, 10)

- storm surge the sea level **with respect to predicted tidal sea level**

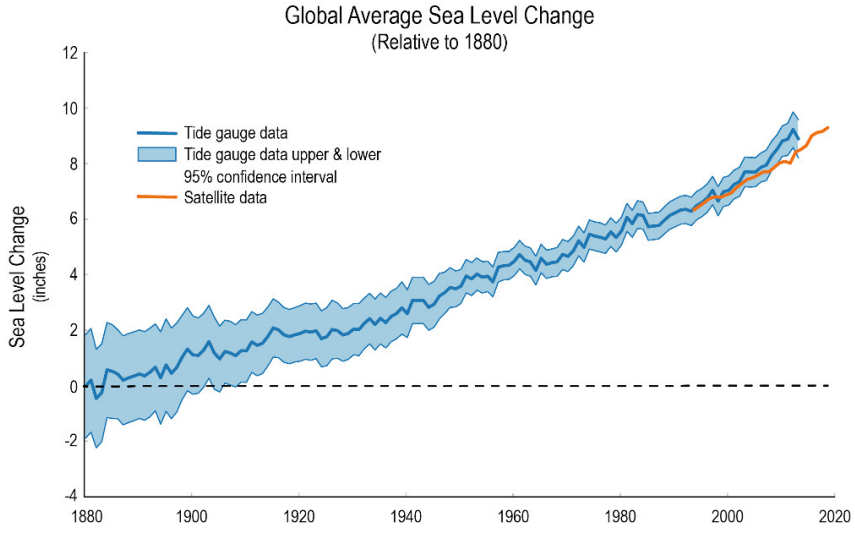
$$\sigma = \tilde{\eta} - \tilde{\eta}_{\text{tide}}$$

where $\tilde{\eta}$ is the observed sea level, $\tilde{\eta}_{\text{tide}}$ the predicted sea level with tides, and σ the surge residual

$\rightarrow$ can lead to extreme sea level

$\rightarrow$ distinguish from tsunami, which is triggered by **earthquakes** (sometimes **tidal wave**, but possibly confusing naming)

Contributions to sea level



- GMSL: Global Mean Sea Level
  → averaged in space, globally
  → averaged over some time window
- distinguished from **regional** mean sea level
  → different choices of averaging

from USGCRP

Contributions to sea level

- dynamic sea level change: $\Delta\zeta$

  $\rightarrow$ relative to **geoid**

  $\rightarrow$ average out to zero globally by definition (why?)

Contributions to sea level

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  $\rightarrow$ relative to **ellipsoid**

Contributions to sea level

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  $\rightarrow$ relative to **geoid**

  $\rightarrow$ average out to zero globally by definition (why?)

- geocentric sea level change: $\Delta\eta$

  $\rightarrow$ relative to **ellipsoid**

- relative sea level change (RSLC):

$$\Delta R = \Delta\eta - \Delta F$$

  $\rightarrow$ relative to **sea floor** F (which can evolve in time)

  $\rightarrow$ this is the one of practical interest

Contributions to sea level

- sea level affected by volume of sea water:
  $\rightarrow$ density of sea water (steric effects)

Contributions to sea level

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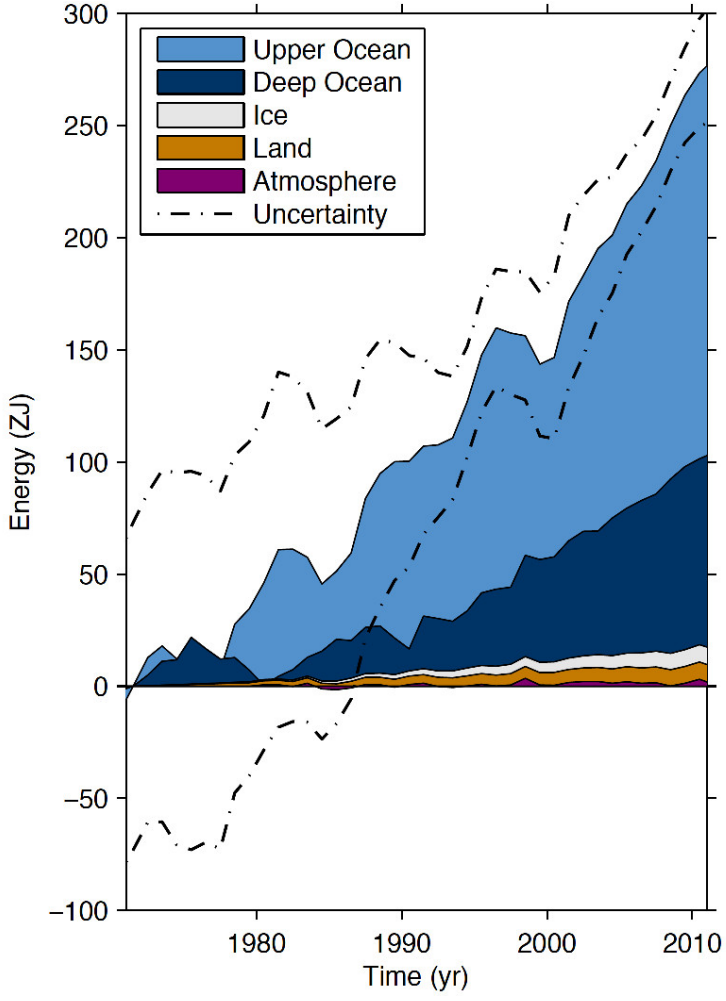
Contributions to sea level

- sea level affected by volume of sea water:
  - $\rightarrow$ density of sea water (steric effects)
  - $\rightarrow$ change in local mass distribution (manometric effects)
  - $\rightarrow$ change in overall mass (barystatic effects)
  - $\rightarrow$ change in containing volume (e.g. isostatic adjustments)

Contributions to sea level: steric effects



- density affected by temperature and salinity through EOS (see Lec 5)

  $\rightarrow$ thermosteric effects: $\Delta\rho$ from ΔT and $\alpha = \alpha(T, S, p)$

  (in-situ here!)

  $\rightarrow$ halosteric effects: $\Delta\rho$ from ΔS and $\beta = \beta(T, S, p)$
- ocean heat context increasing $\Rightarrow$ thermosteric sea level rise

left: IPCC AR5 (2014)

Contributions to sea level: steric effects

- note the use of **in-situ** temperature here

  $\rightarrow$ not contradictory: for **dynamics** you almost never care about in-situ temperature (Lec 6)

- global mean steric sea level would be contribution to GMSL by steric effects

  $\rightarrow$ some care regarding nonlinear EOS required (Lec 6)

  $\rightarrow$ contribution mostly from **thermo**steric effects

  $\rightarrow$ **halo**steric effects locally non-negligible, but averages out to zero globally (see HW question for why)

Contributions to sea level: manometric effects

- manometric $\sim$ pressure

  $\rightarrow$ local mass changes (not addition)

  $\rightarrow$ e.g. atmospheric and circulation effects

- measured through **bottom pressure** (see Lec 20)

  $\rightarrow$ hydrostatic balance (Lec 5, 7) $\sim$ weight $\sim$ mass/volume

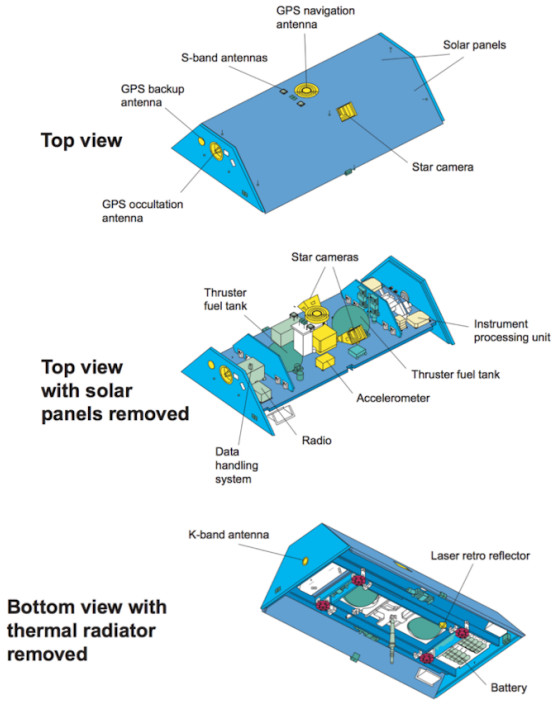


Figure: GRACE schematics. Modified image originally taken from NASA.

Contributions to sea level: barystatic contributions

- actual changes in mass

  $\rightarrow$ changes in hydrological cycle

  $\rightarrow$ **land** ice melting adding water to ocean

  $\rightarrow$ nothing really from **sea** ice

  $\rightarrow$ atmospheric contribution minimal?

Figure: Ice calving off the Perito Moreno Glacier in Patagonia, Argentina. Image of user durktalsma on VistaCreate.

- sometimes called **eustatic**, but barystatic been around since IPCC AR3

Contributions to sea level: VLM

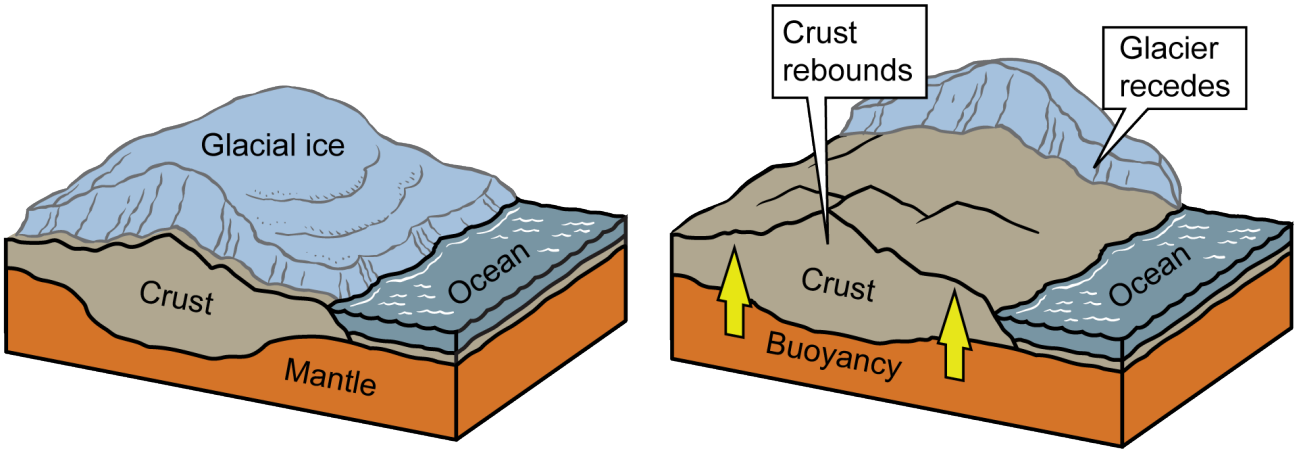


Figure: Image by Jim Houghton, modified for the EarthHome project.

- sea floor F can change (vertical land movement, VLM)
  $\rightarrow$ sedimentation, land reclamation, landslides / erosion, ...
  $\rightarrow$ crustal movements
  $\rightarrow$ rebounds from loading (elastic earth)
  $\rightarrow$ Glacial Isostatic Adjustment (GIA) (research at PolyU)

Summary

- many different contributors to sea level

  $\rightarrow$ operating on different time-scales

  $\rightarrow$ importance varies regionally

  $\rightarrow$ important to distinguish these for **attribution** purposes

- observations (Lec 19, 20) are relative to **ellipsoid**, but dynamics are relative to **geoid**

  $\rightarrow$ conversion / comparison between observation and numerical model data not trivial

  $\rightarrow$ extra complication from multiple contributors evolving in time and interacting nonlinearly...

- observations later (Lec 20 in particular)