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The repository principally contains the compiled products rather than the source for size reasons.

- ▶ Associated Python code (as Jupyter notebooks mostly) will be held on the same repository. The source data however might be big, so I am going to be naughty and possibly just refer you to where you might get the data if that is the case (e.g. JRA-55 data). I know I should make properly reproducible binders etc., but I didn't...
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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

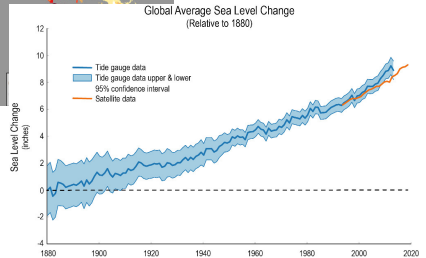
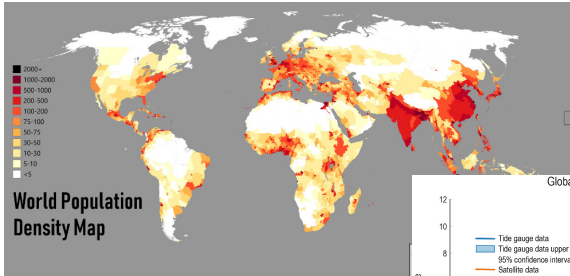
Key terms: (mean) sea level, (mean) sea level rise

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

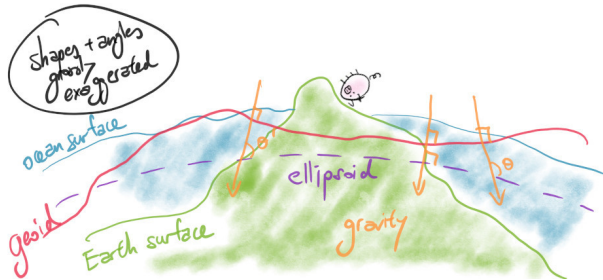
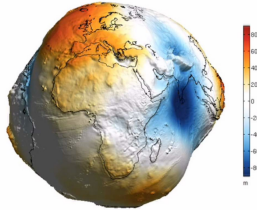
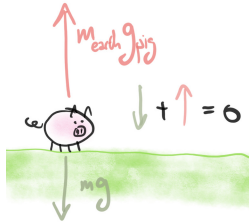


left: reddit user [some_dawid_guy](#); right: from USGCRP

Recap: impact of sea level rise



Relative to what though? (space)



Relative to what though? (time)

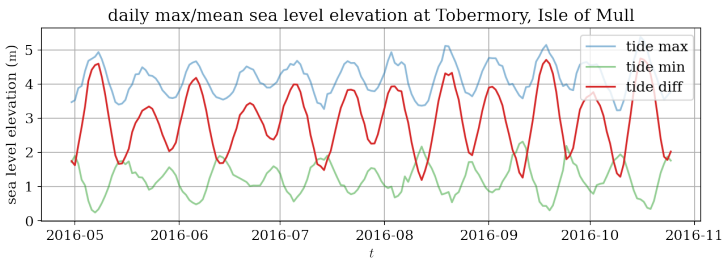


Figure: Daily maximum and minimum sea surface elevation (blue and green) and their difference (red) over a six month period. Data from BODC, see `tobermory_tides.ipynb`.

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

Summary figure

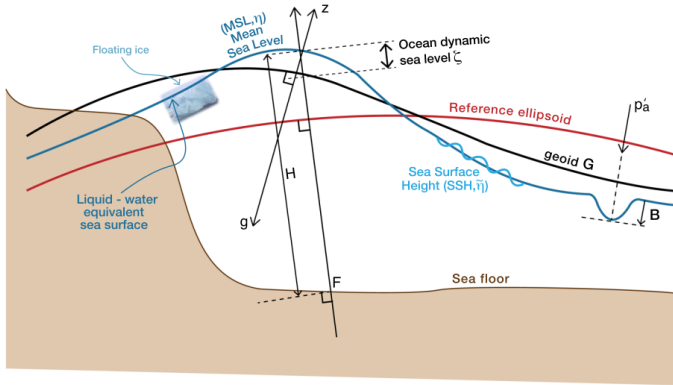
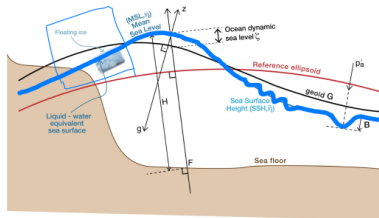


Figure: Schematic figure from Gregory *et al.* (2019), Fig. 2.

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

Sea surface

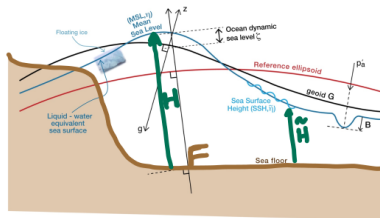


- ▶ sea surface $\tilde{\eta}$
→ **instantaneous**
- ▶ mean sea surface η
→ **time averaged**, but over how long?

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

- ▶ 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}

→ time-independent for reasonable time-scales

→ can move around though (e.g. VLM, GIA...)

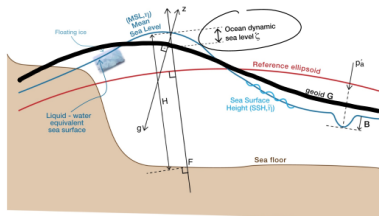
► water depth \tilde{H} and H

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

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

where $\tilde{F} \approx F$

Geoid



► geoid \tilde{G}

→ time-independent for reasonable time-scales

→ 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.

$$\iint G - F \, dA = \iint \eta - F \, dA$$

→ η and F can both evolve in time...

→ more useful definition (ocean is never at rest anyway...)

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

Variations in η (and ζ)

► tides

→ instantaneous response from astronomical forcing \Rightarrow
equilibrium tides (Lec 17)

→ wave propagation \Rightarrow **dynamical tide**

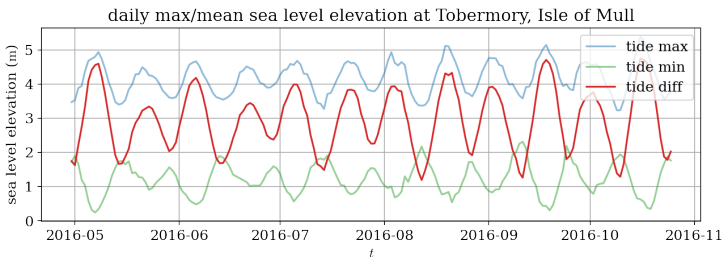


Figure: Daily maximum and minimum sea surface elevation (blue and green) and their difference (red) over a six month period. Data from BODC, see `tobermory.tides.ipynb`.

Variations in η (and ζ)



- ▶ wind driven waves (Lec 16)
 - distinguished from tidally forced waves
 - surface intensified, effect diminishing with depth (Lec 9, 10)

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

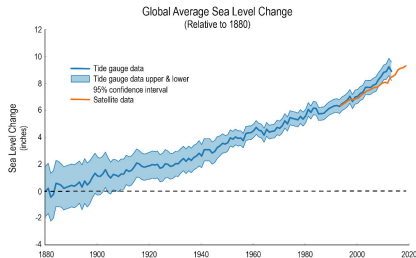
$$\sigma = \tilde{\eta} - \tilde{\eta}_{\text{tide}}$$

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

→ can lead to **extreme sea level**

→ 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

Contributions to sea level

- ▶ **dynamic** sea level change: $\Delta\zeta$
 - relative to **geoid**
 - average out to zero globally by definition (why?)

Contributions to sea level

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 - relative to **ellipsoid**

Contributions to sea level

- ▶ **dynamic** sea level change: $\Delta\zeta$
 - relative to **geoid**
 - average out to zero globally by definition (why?)
- ▶ **geocentric** sea level change: $\Delta\eta$
 - relative to **ellipsoid**
- ▶ **relative** sea level change (RSLC):

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

- relative to **sea floor** F (which can evolve in time)
- this is the one of practical interest

Contributions to sea level

- ▶ sea level affected by volume of sea water:
→ density of sea water (steric effects)

Contributions to sea level

- ▶ sea level affected by volume of sea water:
 - density of sea water (**steric** effects)
 - change in local mass distribution (**manometric** effects)

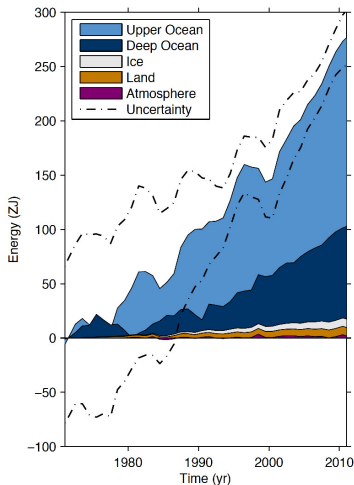
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 - change in overall mass (**barystatic** effects)

Contributions to sea level

- ▶ sea level affected by volume of sea water:
 - density of sea water (**steric** effects)
 - change in local mass distribution (**manometric** effects)
 - change in overall mass (**barystatic** effects)
 - 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)

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

(in-situ here!)

→ **halosteric** effects: $\Delta\rho$ from ΔS and $\beta = \beta(T, S, p)$

- ocean heat context increasing
⇒ thermosteric sea level rise

Contributions to sea level: steric effects

- ▶ note the use of **in-situ** temperature here
 - 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
 - some care regarding nonlinear EOS required (Lec 6)
 - contribution mostly from **thermosteric** effects
 - **halosteric** effects locally non-negligible, but averages out to zero globally (see HW question for why)

Contributions to sea level: manometric effects

- ▶ manometric \sim pressure
→ local mass changes (not addition)
→ e.g. atmospheric and circulation effects
- ▶ measured through **bottom pressure** (see Lec 20)
→ hydrostatic balance (Lec 5, 7) \sim weight \sim mass/volume

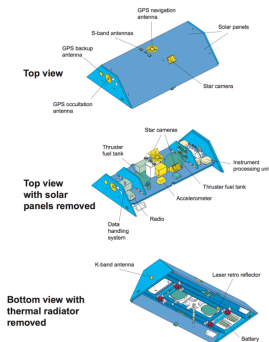


Figure: GRACE schematics. Modified image originally taken from NASA.

Contributions to sea level: barystatic contributions

- ▶ actual changes in mass
 - changes in hydrological cycle
 - **land** ice melting adding water to ocean
 - nothing really from **sea** ice
 - atmospheric contribution minimal?
- ▶ sometimes called **eustatic**, but **barystatic** been around since IPCC AR3



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

Contributions to sea level: VLM

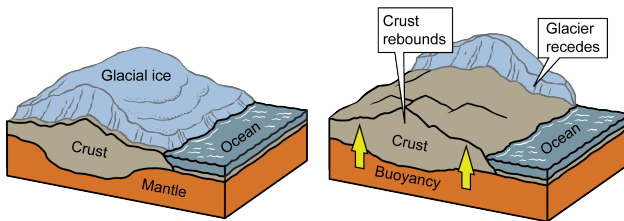


Figure: Image by Jim Houghton, modified for the EarthHome project.

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

Summary

- ▶ many different contributors to sea level
 - operating on different time-scales
 - importance varies regionally
 - important to distinguish these for **attribution** purposes
- ▶ observations (Lec 19, 20) are relative to **ellipsoid**, but dynamics are relative to **geoid**
 - conversion / comparison between observation and numerical model data not trivial
 - extra complication from multiple contributors evolving in time and interacting nonlinearly...
- ▶ observations later (Lec 20 in particular)