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  `https://github.com/julianmak/academic-notes`

  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...
- I do not claim the compiled products and/or code are completely mistake free (e.g. I know I don't write Pythonic code). Use the material however you like, but use it at your own risk.
- As said on the repository, I have tried to honestly use as content that is self made, open source or explicitly open for fair use, and citations should be there. If however you are the copyright holder and you want the material taken down, please flag up the issue accordingly and I will happily try and swap out the relevant material.

OCES 2003 : Descriptive Physical Oceanography

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

Lecture 20: Observation 2 (remote)

Tue 27^{th} Apr

Outline

- remote sensing: acoustics and satellites

  → sonar, doppler effect, ADCPs

  → TOPEX/Poseidon, JASON, QuikSCAT, GRACE, Sentinel...
- example applications

  → geostrophic currents from SSH (recall Lec. 8, 9, 13)

  → data assimilation + reanalyses

  → acoustic tomography
- datasets and repositories

Key terms: remote sensing, satellites, reanalyses

Recap: geoid (Lec. 7, 18)

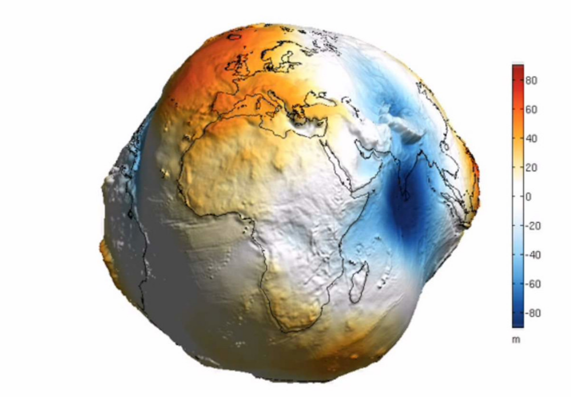

Figure: The "lumpy potato" Earth, variations in the geoid height magnified by several orders of magnitude to highlight difference. From Earth Gravitational Model 2008.

How do we get this...?

Recap: SSH (Lec. 7, 8)

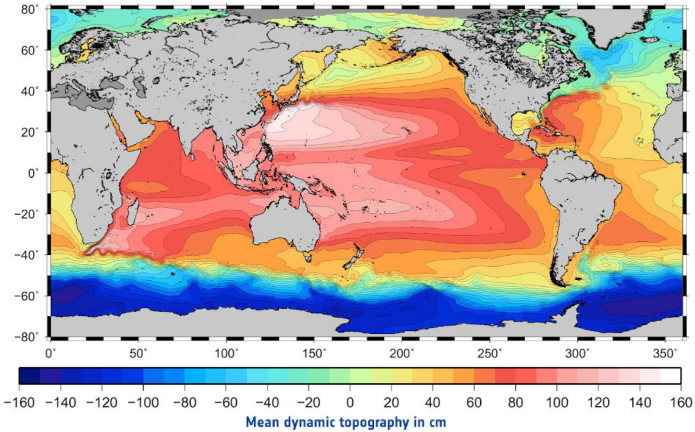

Figure: Time-mean global SSH (also called mean dynamic topography), with time-mean currents drawn on (notice the orientation around high/low SSH regions). Modified from Rio *et al.* (2011), J. Geophys. Res: Oceans.

Or this...?

Remote sensing

- in-situ observation is sampling of location at the location
- remote sensing is observing from somewhere else
  $\rightarrow$ relies on reflected/emitted signals

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waves!!! (Lec 15)

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waves!!! (Lec 15)

- some sort of detector to 'sense' perturbations
  $\rightarrow$ sound (acoustics), electromagnetic (EM) radiation (cf. Lec. 5)

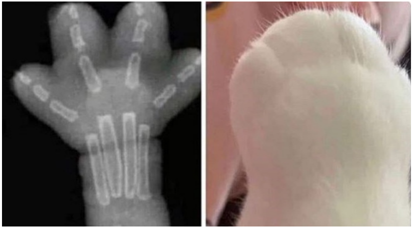

Figure: Probably a kitten paw X-ray? (Bones may appear detached in very young animals in X-rays; see `veteriankey.com`.) Image taken from `cheezburger.com`, source Twitter account appears suspended.

Recap: EM spectrum (see also Lec. 5)

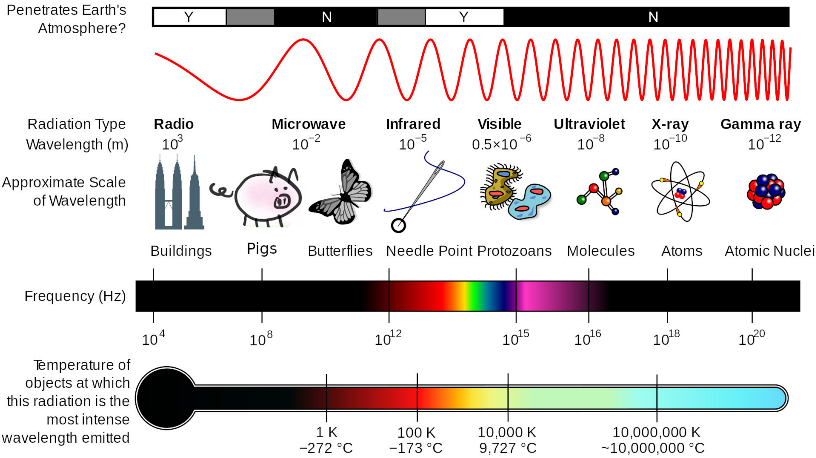

Figure: The electromagnetic spectrum by wavelength and frequency. Image from Wikipedia, adapted from an image form NASA.

Remote sensing

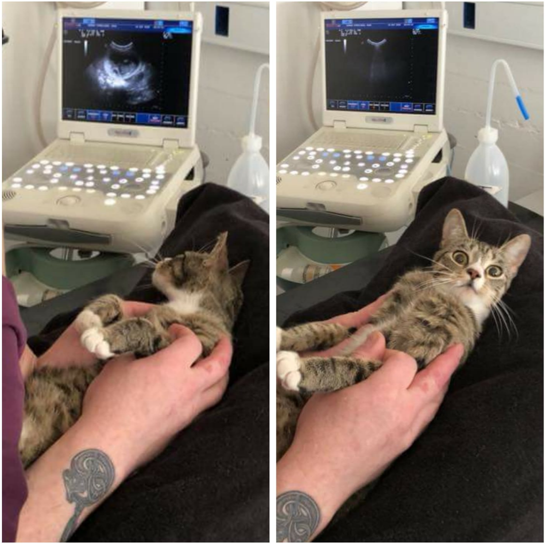

Figure: Ulla shocked (?) at finding out she is pregnant from the ultrasound. From Dyrenes Venner Greenland's facebook page.

Recall: wave propagation (Lec. 15)

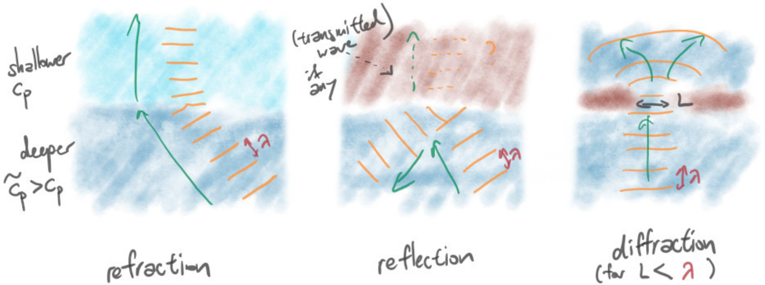

Figure: Schematic of refraction, reflection (and transmission), and diffraction, nominally using **monochromatic** (i.e. one choice of k) surface gravity wave as an example. The orange lines are phase lines (e.g. think wave crests).

- propagation properties depends on
  $\rightarrow$ medium + type of wave (e.g. sound vs. EM)

Acoustics

- recall that ocean is opaque
  → EM waves of limited use in ocean, but sound waves ok?

- e.g. **SO**und **NA**vigation and **R**anging
  → bats + dolphins, ultrasound example above
  → navigation, mapping the sea floor, etc.
  → choice of receivers?

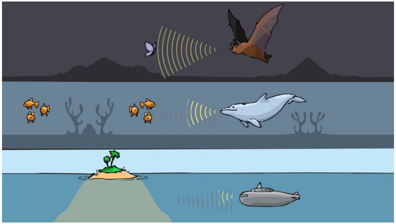

Figure: Schematic of Sonar. Image from the Smithsonian National Museum of Natural History.

- essentially application of $U = L/T$
  → U determined by wave type and medium, T you measure, get L out of it (devil is in the details though...)

What if the target moves?

- Doppler shifting, i.e. change in frequency + wavelength
  → e.g. ambulance pitch changing relative to pedestrian

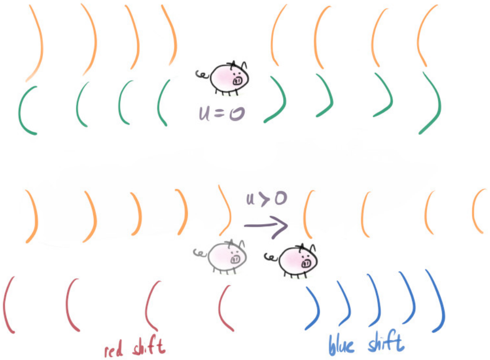

Figure: Schematic of Doppler shifting. Red/blue shift (decrease/increase in frequency) if target is moving away/towards observer. Principles apply generically for waves (e.g. similar principles are used to detect universe expansion).

Acoustic Doppler Current Profiler (ADCP)

- (better) alternative to current meters

  → fewer moving parts = good thing usually!

  → still need to control biofouling
- dependent on things in water to rebound from

  → not as good if water quality is good (!)

- high freq = more precise

  → sample smaller scales
- low freq = travel further

  → less scattering etc.
- multibeams to sample velocity components

Figure: An ADCP mounted on a frame. Image from Wikipedia, user DopplerMusic.

Satellites

Satellite = object in space that orbits a bigger object

- the moon a **natural** satellite of the Earth
  $\rightarrow$ interested here in **artificial** satellites for observing

- principles similar: shoot some stuff out, see what reflects
  $\rightarrow$ use EM waves here (atmosphere is only a bit opaque)
  $\rightarrow$ much better horizontal coverage, limited somewhat to **surface**

the devil is in the details that we are going to skip here

Satellite orbits

- Low Earth Orbit (LEO)
  - → altitude about 1/3 of the Earth's radius ($\approx$ 2000 km)
  - → orbital period of less than 128 minutes (how many orbits a day then?)
  - ✓ high bandwidth, less latency/lag
  - × restricted 'vision', space debris?
- others above this (MEO, geostationary, HEO etc.)
  - → e.g. Global Positioning System (GPS)
  - → more latency, wider 'vision' etc.

Figure: To scale diagram of sample orbital ranges of Earth. Counting from the upper limit of the MEO, the moon is about ten lots of MEO away to the right of the diagram (not shown). Image taken from Wikipedia, user Rrakanishu.

Satellites: TOPEX/Poseidon

- one of the first satellite altimeters

  → from 1992 to 2006
- measure SSH (relative to **ellipsoid**)

  → want it relative to the **geoid**? (see GRACE later)

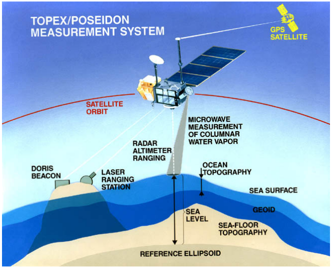

Figure: Brief schematic of TOPEX/Poseidon.

- measure ocean topography by rebounds

  → again, $U = L/T$ really, but need careful calibrating to get it accurate enough
- measure (on global scales) sea level, tides, large-scale waves, etc.

Satellites: Jason

Figure: The Jason series of satellite altimeters. Image from the European Space Agency.

- successor to TOPEX/Poseidon
  $\rightarrow$ three of them
- measures SSH
- from Jason and the Argonauts in Greek mythology

- uses multiple navigation systems to determine position
  $\rightarrow$ GPS, DORIS, LRA
  $\rightarrow$ needed for accuracy, $O(1\text{ cm})$, but flying $O(1000\text{ km})$ above Earth's surface!

Satellites: GRACE

- measure anomalies in g from changes in **mass**

  $\rightarrow$ e.g. ice loss
- two of them chasing the other in low-ish orbit

  $\rightarrow$ 'Tom' and 'Jerry'

  $\rightarrow$ about 220 km apart, 500 km above Earth in polar orbit
- measure mutual distance by Doppler shifts + geolocation (e.g. GPS, and others)

  $\rightarrow$ advertised accuracy of 10 μm (1/10 of width of human hair!)

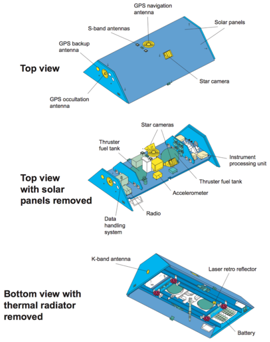

Figure: GRACE schematics. Modified image originally taken from NASA.

Satellites: GRACE brief rationale

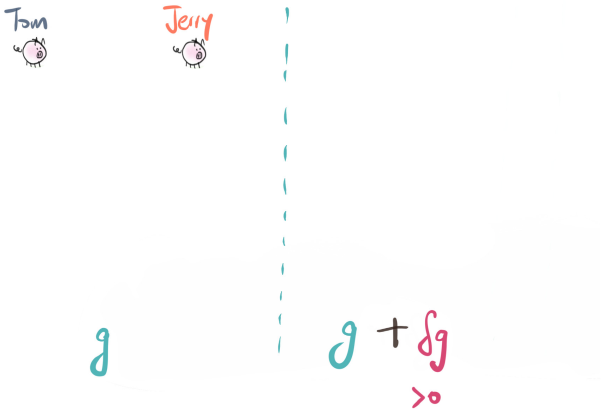

Figure: Rough schematic of idea behind GRACE. Satellites travelling through gravitational field anomalies accelerate and decelerate, and one can get the relative changes in the distances via Doppler shifts between the satellites. Together with pinpointing the location of the satellite relative to Earth, changes in the gravitational attraction can be inferred accordingly.

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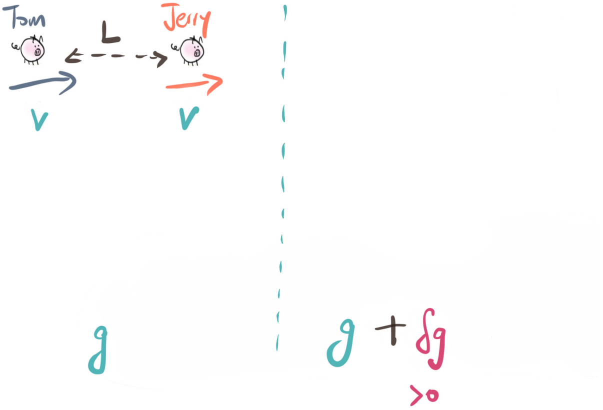

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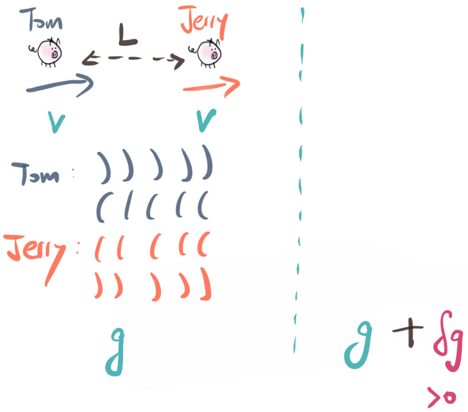

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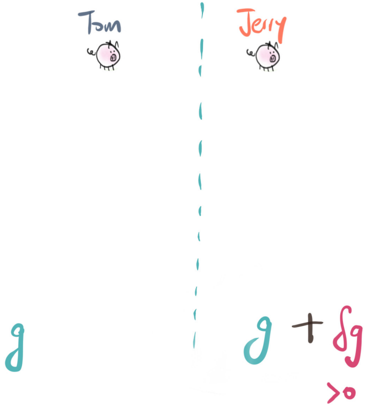

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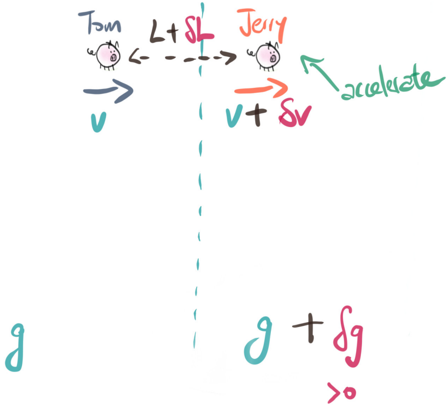

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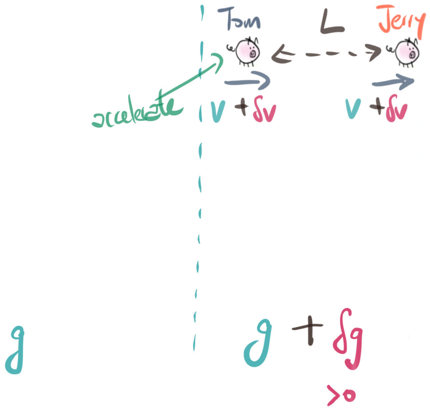

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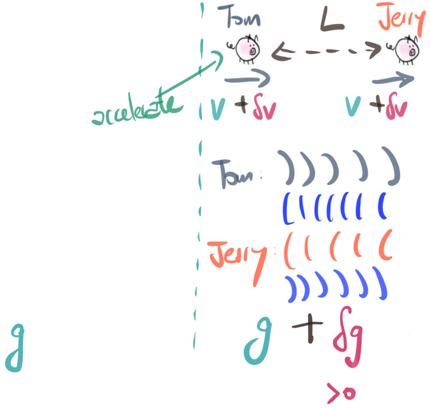

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Satellites: QuikSCAT

- measure scattering of emitted microwaves to get **wind speed** and **direction**

  $\rightarrow$ scattering depends on surface roughness

  $\rightarrow$ roughness depends on **surface waves** (cf. Lec 16)

  $\rightarrow$ waves depends on wind profile
- important for atmosphere forecasting (initialise state) + ocean forcing

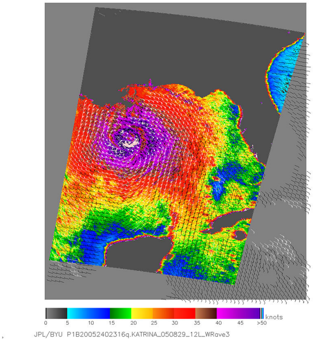

Figure: QuikSCAT image of Hurricane Katrina in 2005. Image from NASA / JPL.

Satellites: Sentinel

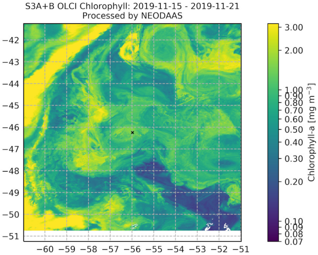

Figure: Inferred Chlorophyll-*a* from Sentinel 3a and 3b OLCl data. Image from UK NERC NEODAAS.

- run by the EU Copernicus programme
- various bands in the visible to infra-red spectrum

  $\rightarrow$ e.g. infra-red to infer for **SST**

  $\rightarrow$ e.g. green to infer for **chlorophyll-*a***
- various resolutions
- whole load of these, each of them do 'look' at different things

Sample usage: geostrophic currents from SSH

- want: $\boldsymbol{u}_g$

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- thermal wind ($\nabla\rho \sim \partial\boldsymbol{u}_g/\partial z$) to get some sort of depth profile

  $\rightarrow$ **in-situ measurements** to get T, S and p

  $\rightarrow$ feed into EOS to get a relevant density

  $\rightarrow$ need to assume a value of $\boldsymbol{u}_g$ at some z

Sample usage: geostrophic currents from SSH

- e.g. **eddy kinetic energy** (EKE) (cf. KE = $0.5mv^2$)

$$\frac{1}{2}\rho\,\overline{\boldsymbol{u}'_g\boldsymbol{u}'_g}, \qquad \boldsymbol{u}_g = \overline{\boldsymbol{u}_g} + \boldsymbol{u}'_g$$

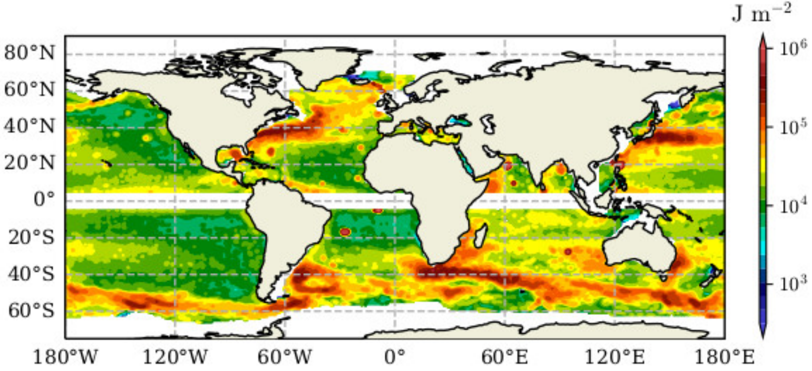

Figure: Depth-integrated eddy kinetic energy of geostrophic flow from satellite altimetry, extended down in depth using the first baroclinic mode. Data product provided by Xiaoming Zhai (University of East Anglia).

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  $\rightarrow \ldots$

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  $\rightarrow$ ...

constrain the numerical model with observational data

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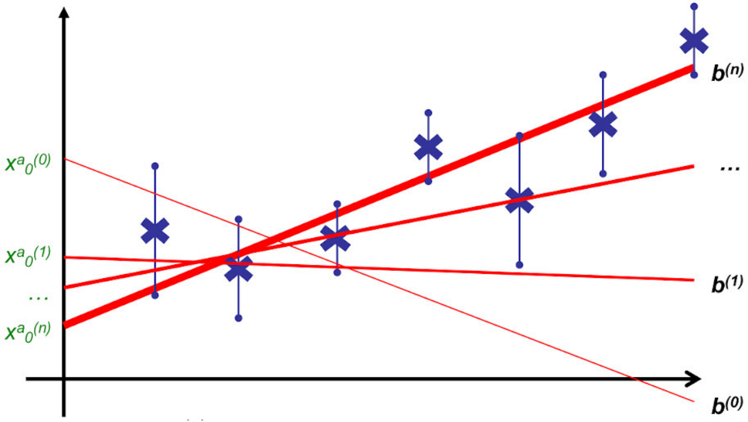

Figure: Illustration of an adjoint model adjustment, for a linear model $y = ax + b$. Adjust the parameter a and the starting value $y(x = 0) = b$ until the line is "close' to the data points (whatever "close" means). You may know this better as linear regression. Figure from Patrick Heimback (University of Texas).

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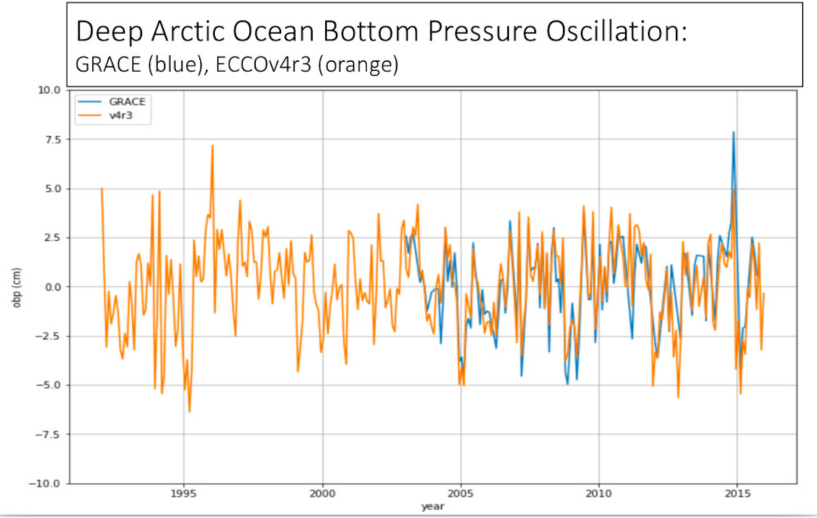

Figure: Bottom pressure in the Arctic Ocean as measured by GRACE (blue) and from the ECCO v4r3 state estimate. Figure from Ian Fenty (NASA JPL).

Sample usage: sea level reanalysis (Lec. 18)

eye candy

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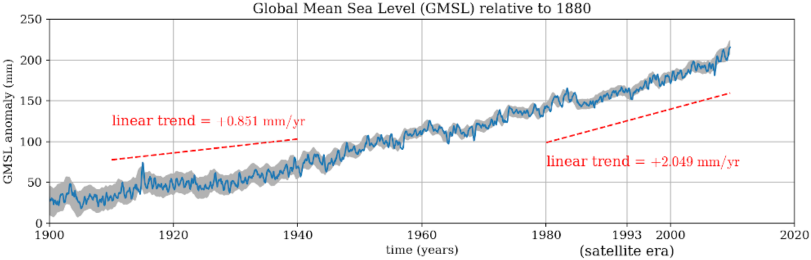

Figure: Global mean sea level over a hundred years or so. Data from Church & White (2011). See `tobermory_tides.ipynb` and `historical_sea_level_plot.ipynb`.

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- got heavily lobbied by animal rights group (see Wikipedia article), but recent renewed interest (e.g. Wu *et al.*, 2020, *Science*)

Data acquisition + analysis (more in OCES 3301)

- most commonly accessible are slightly processed data
  $\rightarrow$ time series, gridded data
  $\rightarrow$ e.g. SST, winds, g
  $\rightarrow$ further analysis them as required

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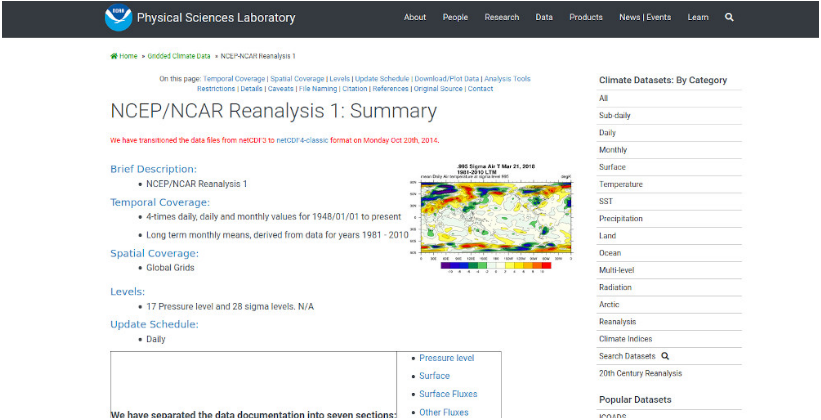
- skipping here completely on techniques in data analysis...

Data acquisition

NCEP: atmospheric data



https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html

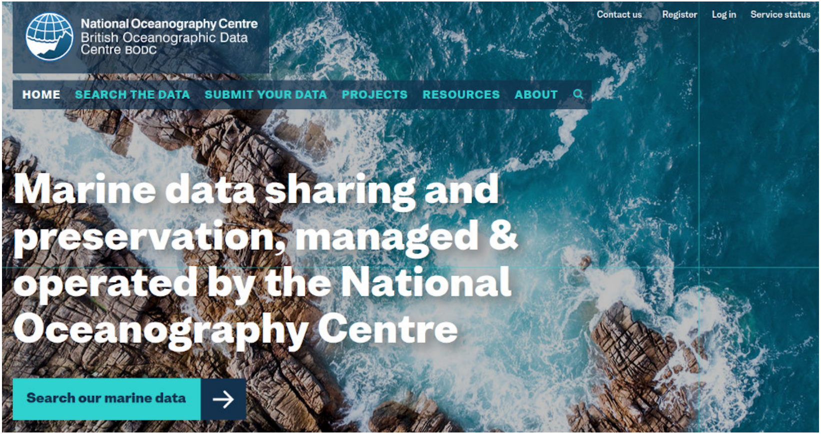
Data acquisition

NASA PO.DAAC: physical oceanography data

https://podaac.jpl.nasa.gov/

Data acquisition

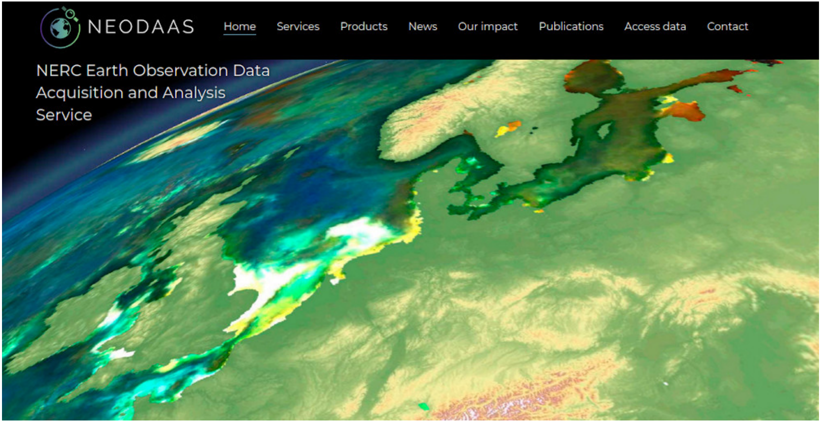
BODC: marine related data



https://www.bodc.ac.uk/

Data acquisition

NERC NEODAAS: Earth observation data



https://www.neodaas.ac.uk/Home

Data acquisition

GEBCO: bathymetry and topography

https://www.gebco.net/

Summary

- highlighted a few (!) ideas, equipment and applications

  → Doppler shifts

  → how to use acoustic + EM waves to do remote sensing

  → applications, e.g. altimetry to get $\boldsymbol{u}_g$

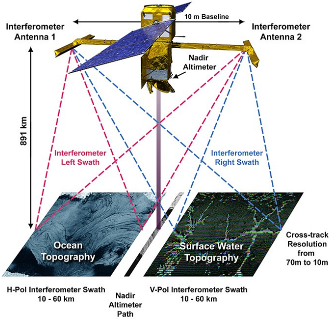


Figure: Schematic of SWOT. Image from NASA JPL.

quantitative principles in examples class (altimetry and $\boldsymbol{u}_g$) + assignment 4 (GRACE)

The devil is in the details...

- how to do the data analysis? (OCES 3301)

  → methods, soft/hardware, presentation, management etc.
- uncertainty quantification

  → error bars
- attribution

  → data gives you correlation, how to get causation?

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- more quantitative theories? (OCES 3203)

  → OCES 2003 is descriptive + ideas + some terminology

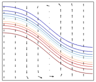
  → scientific statements need quantification

What is physical oceanography (recall Lec 1)

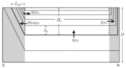
$\varepsilon \equiv \nu \langle \|\nabla \boldsymbol{u}\|^2 \rangle < \kappa H^{-1} b_{\max}.$

Paparella & Young (2002)
cf. Sanstrom (1908)

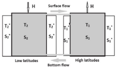
Orr (1907)
Harnik & Heifetz (2007)



Gent et al. (1995)

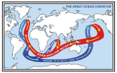


D. Marshall & Zanna (2014)

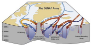


Stommel (1961)

Theory



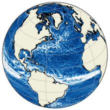
Ocean conveyor belt
e.g. Broecker (2010)



O-SNAP
e.g. Lozier et al. (2019)

Physical Oceanography

NEMO *Madec (2008)*



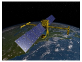
Jason-3

Observations

Modelling

Jet Propulsion Laboratory, California Institute of Technology | ECCO

https://ecco.jpl.nasa.gov/, *e.g. Forget et al (2015)*



SWOT

Boaty McBoatface

Argo

http://www.argo.ucsd.edu/

MEOP, e.g. Roquet et al (2013)

MITgcm *J. Marshall et al (1997a, b)*

understanding the ocean require
interdisciplinary + complementary approaches