Introduction to physical oceanography & climate

EPS/ESE 131, Dept of Earth and Planetary Sciences, Harvard University
Eli Tziperman

Perpetual Ocean, NASA https://www.youtube.com/watch?v=JQaEKk569Ew&t=2s

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Times: Tuesday, Thursday 10:30–11:45

Location: University Museum, 24 Oxford – classroom 375

Instructor: Eli Tziperman

Office: Museum building 456, 24 Oxford St

Email: eli@eps.harvard.edu

Office hours: Mon, Wed 1–2, unless otherwise noted on Canvas

TF: Kirstin Koepnick, kirstinkoepnick@g.harvard.edu

Tel, office, office hours: please see Canvas.

➡ *Please feel free to write and come to office hours!*

EPS131 logistics

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Course requirements: homework every week and a half (40% of grade, lowest grade dropped); 2 in-class 10 min presentations & a group video project (30%); Final (a take home, 30%). Woods Hole field trip.

Needed preparation: Math 21b; Physics 15a/12a/AP50a; no programming preparation expected; Matlab/Python will be introduced and used.

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Detailed syllabus with links to online sources for lectures:
http://www.seas.harvard.edu/climate/eli/Courses/EPS131/2026spring/syllabus-EPS131.pdf

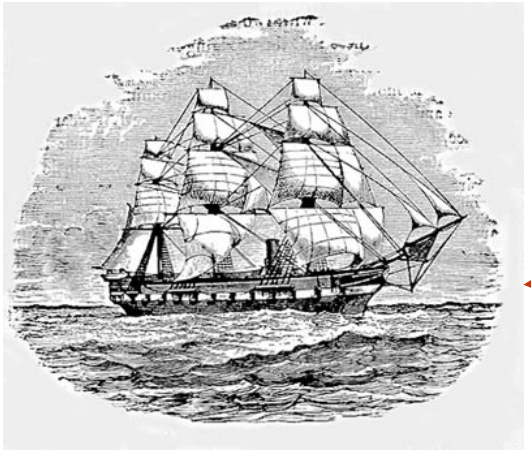
Origins… and today

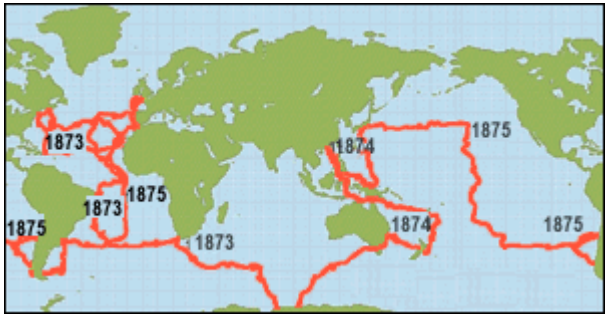
The first oceanographic expedition:

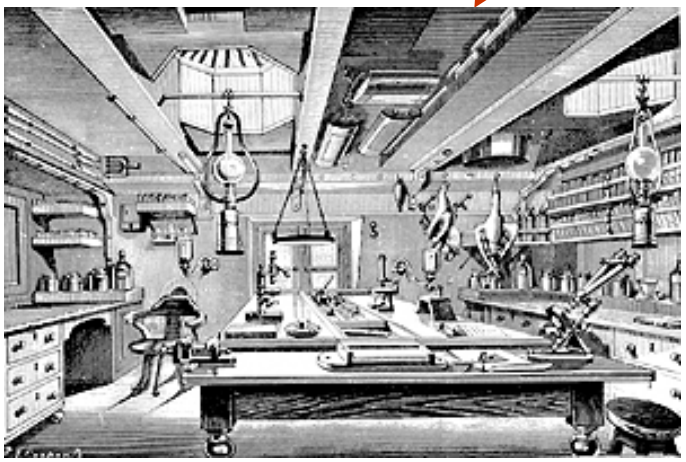
H.M.S. Challenger 1872–6

250 crew (incl. fifty 15-yr old);

30 miles of sounding line (ropes)







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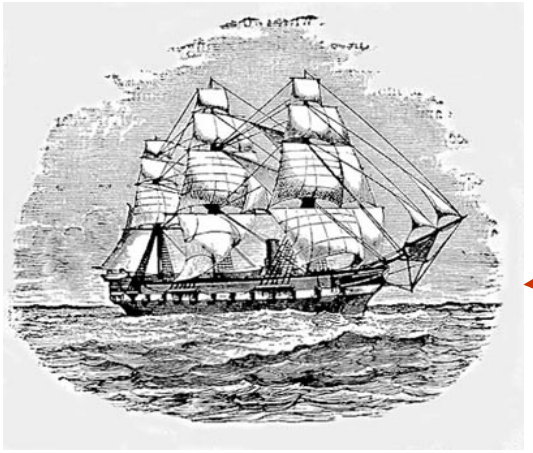

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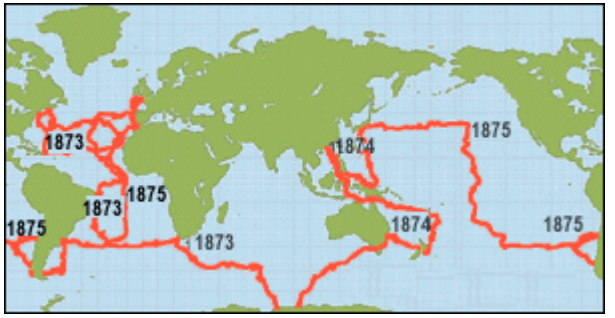
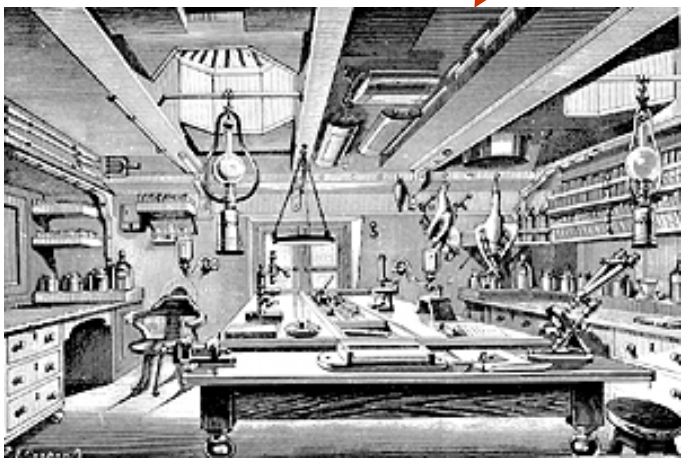
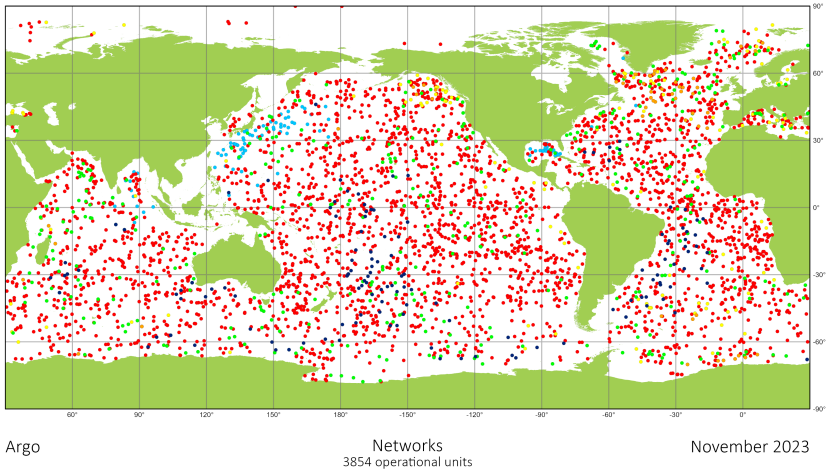




ARGO: 3M profiles. 20C ships: 0.5 M



Today: Autonomous ARGO floats continuously sampling the upper ocean since 2000; satellites; super computers

Outline

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- Oceans and climate:
  - The ocean's role in future global warming.
  - El Niño.
  - The Meridional Overturning Circulation, abrupt climate change, climate tipping points.

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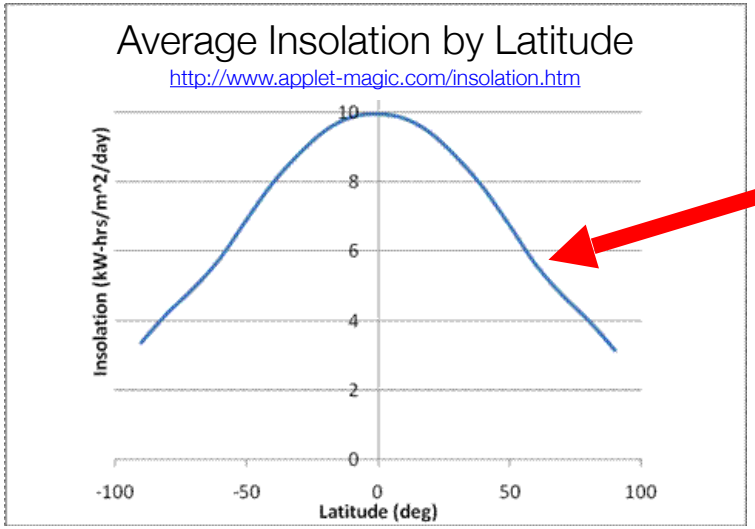
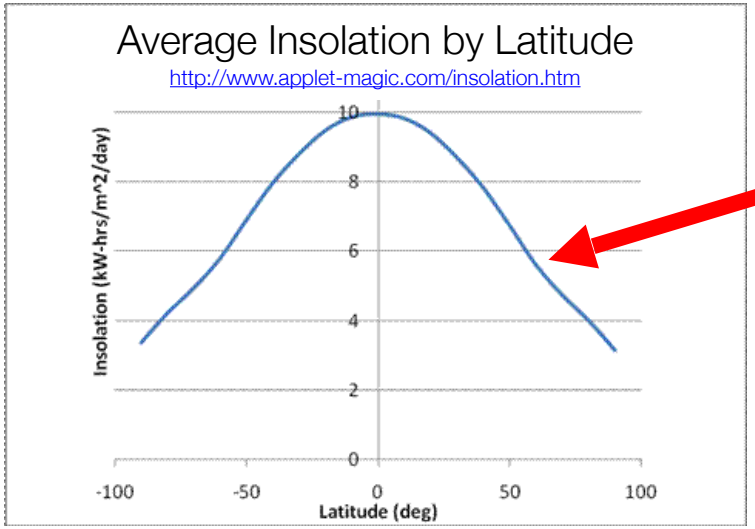
- How we observe:
  - Ships, satellites, airplanes, moorings, current meters, buoys, floats.

Temperature



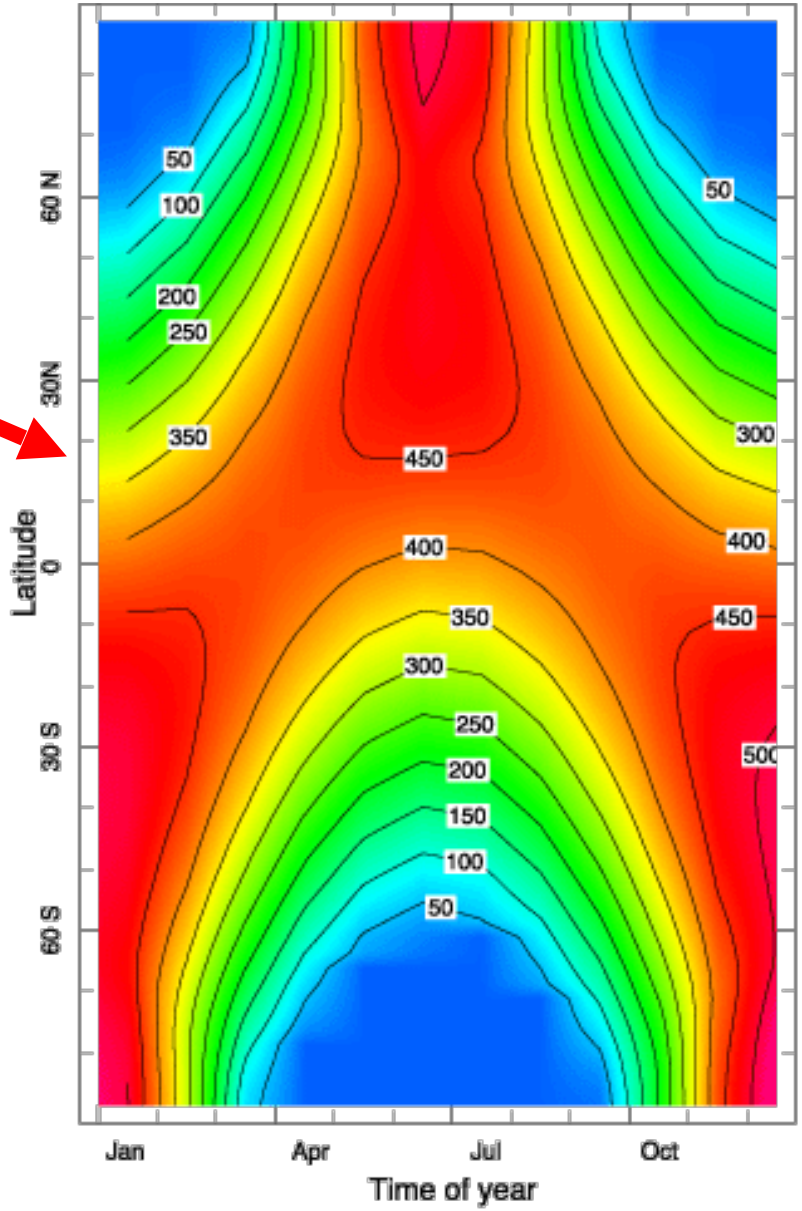
Solar radiation as a function of latitude and month…

Temperature



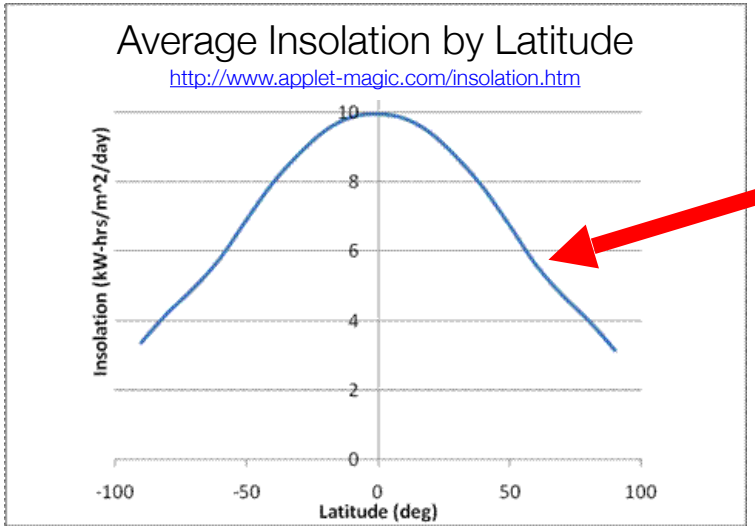
Solar radiation as a function of latitude and month…

Latitude-Time Distribution of Incoming Solar Radiation at the Top of the Atmosphere



Based on ERBE data. Units are W/m²

Temperature



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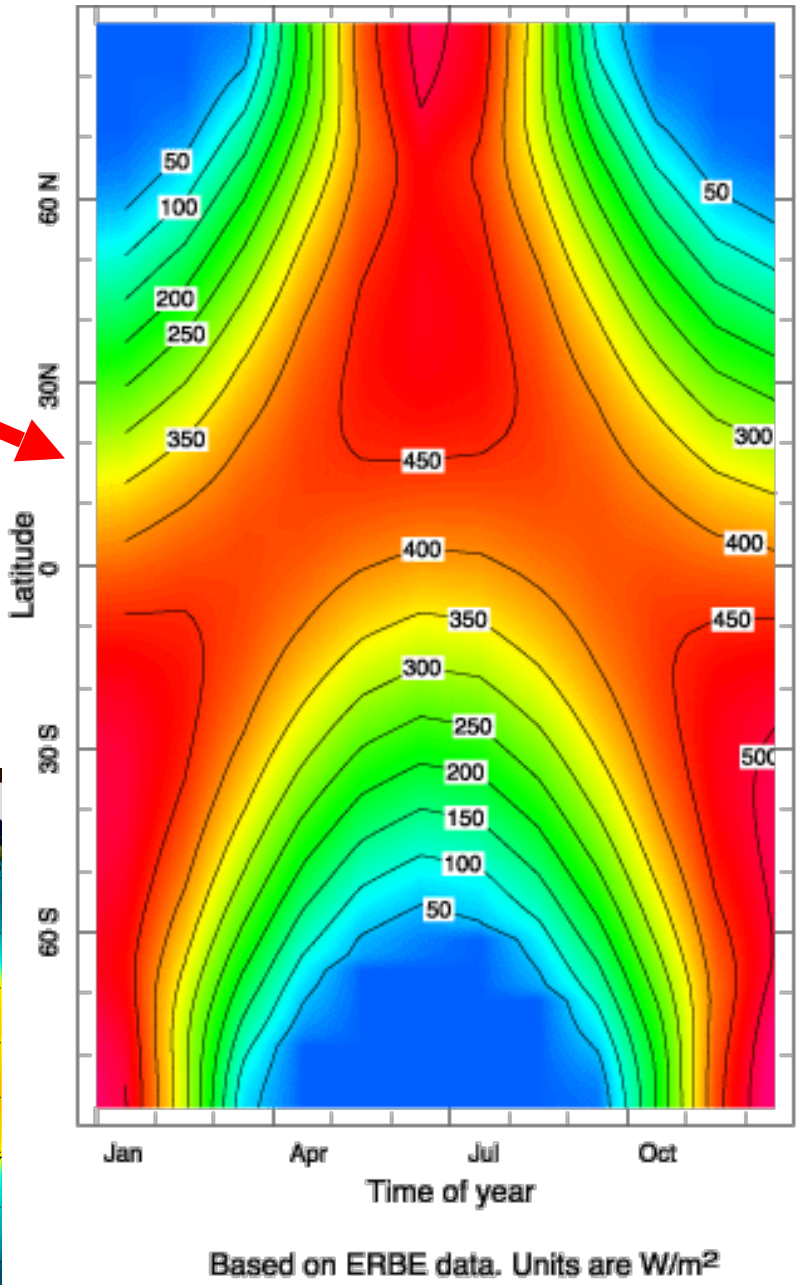
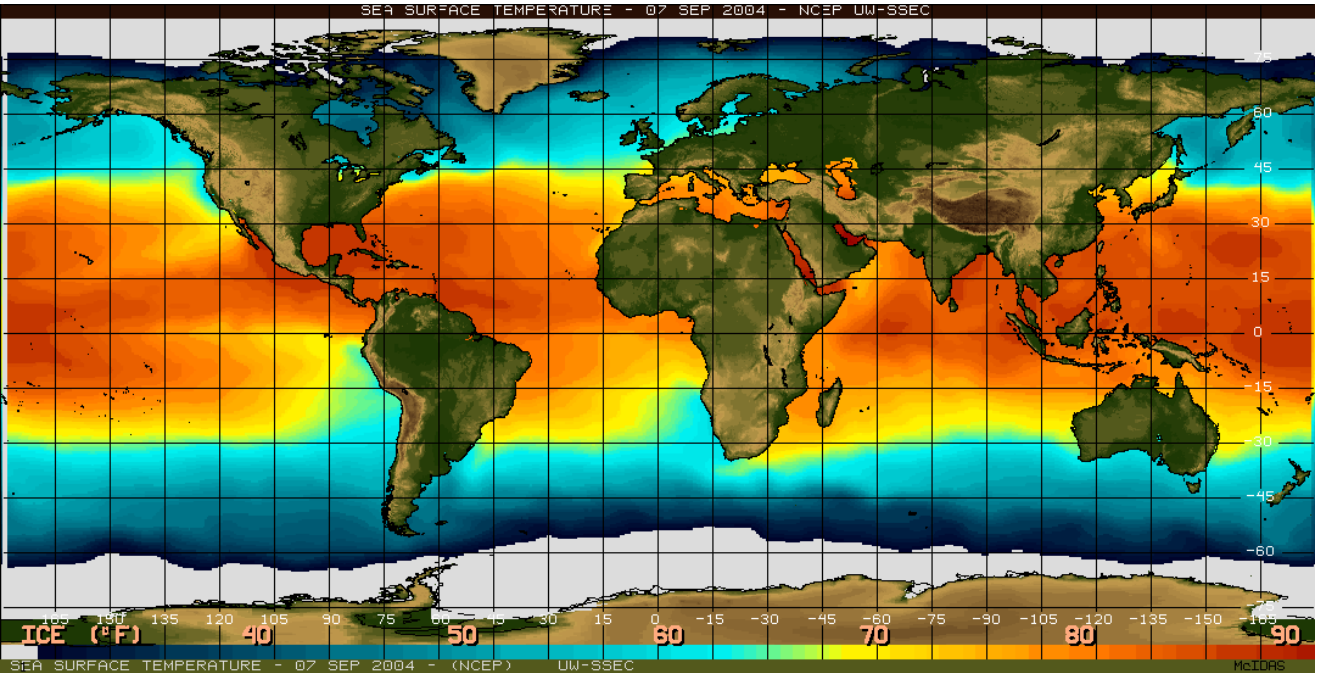


… Leads to cold high latitudes, warm tropics:
Horizontal map of sea surface temperature



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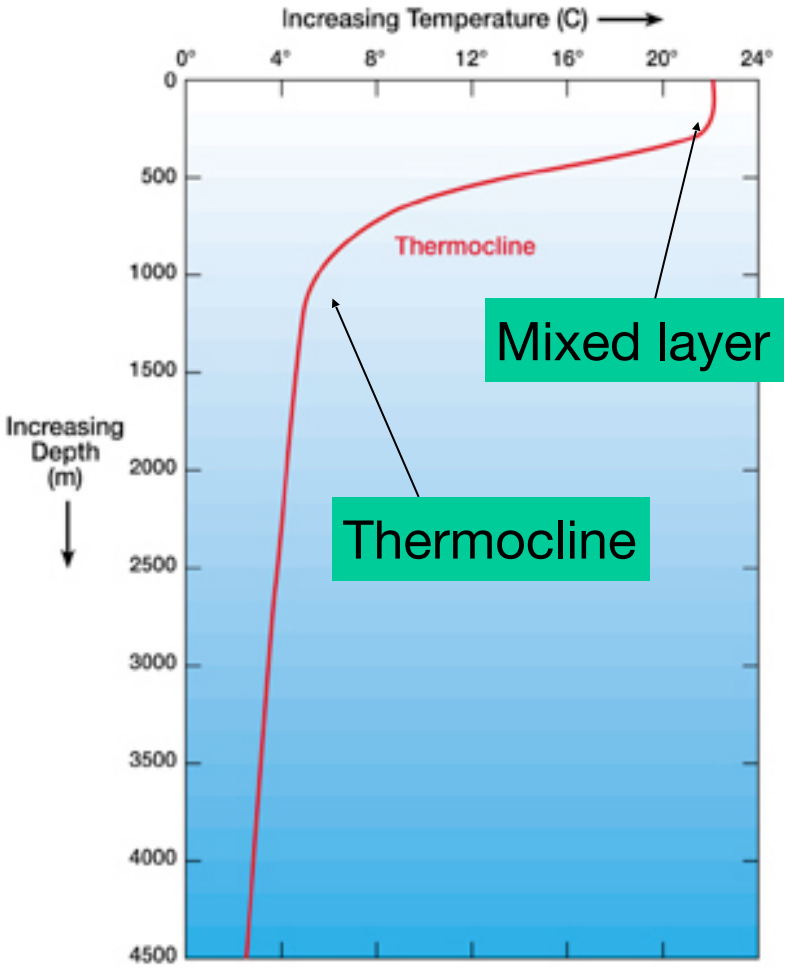
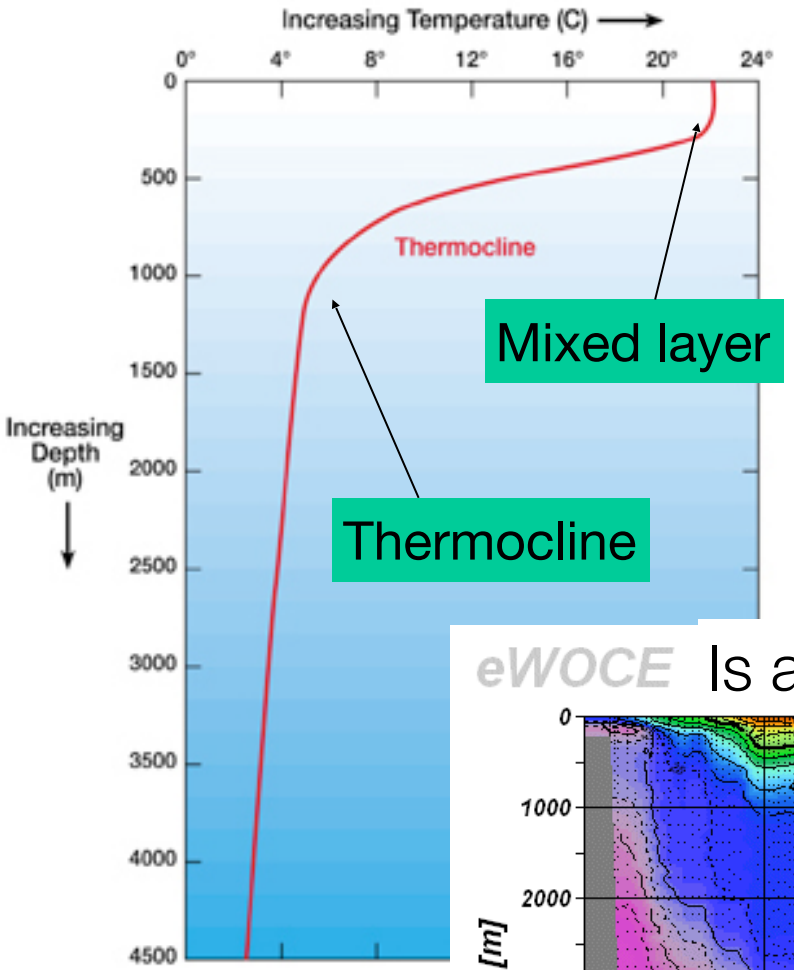


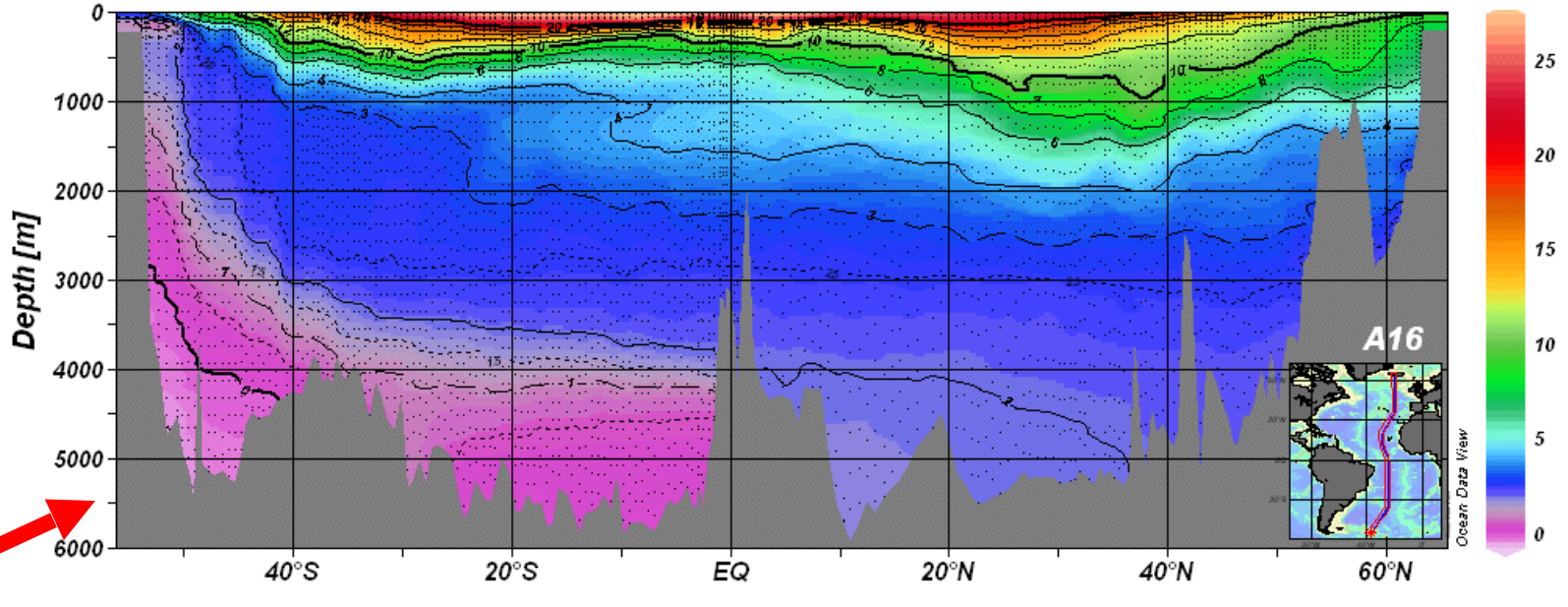
Vertical temperature profile

Temperature



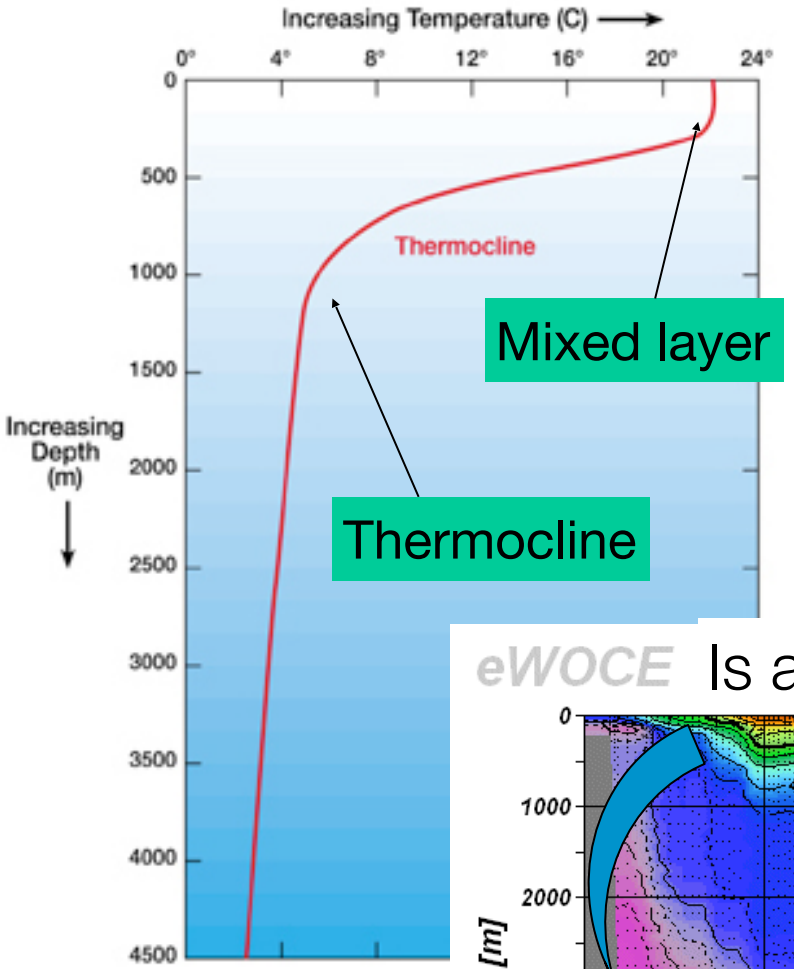
Vertical temperature profile

eWOCE Is an evidence for a meridional circulation



North-South Section. Bottom temperature is near 0 deg even at Equator

Temperature



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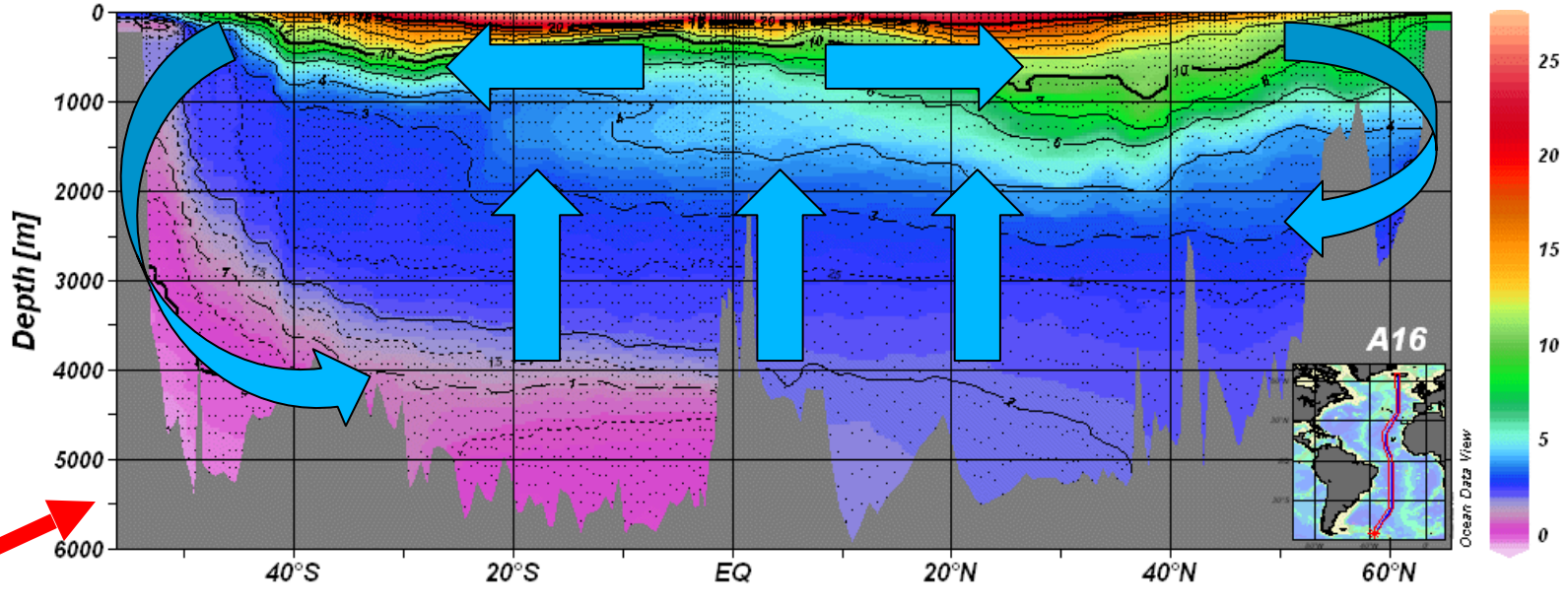


North-South Section. Bottom temperature is near 0 deg even at Equator

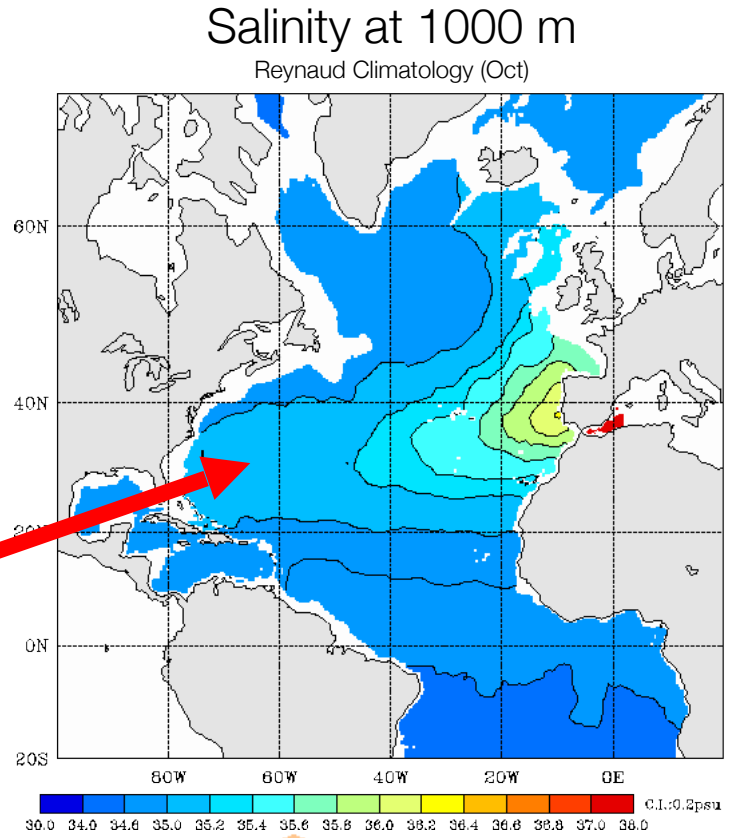
Salinity

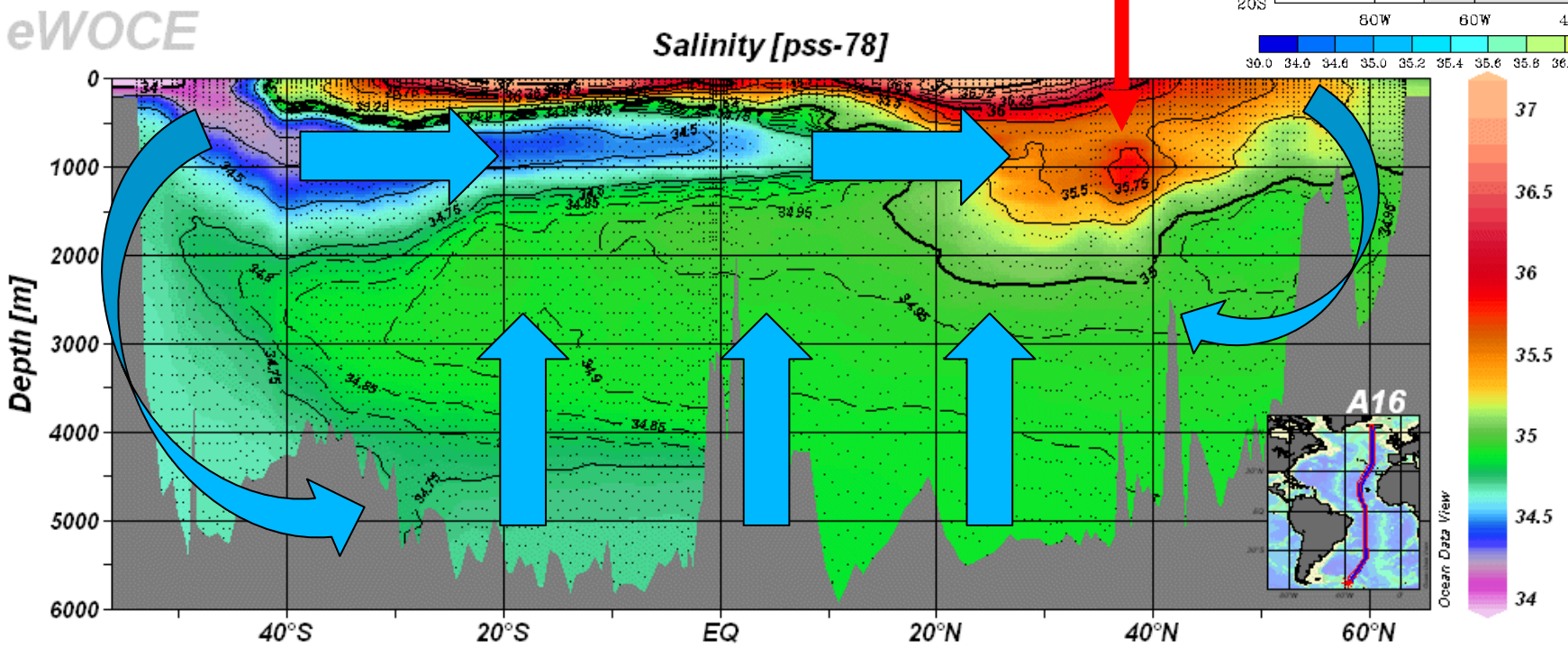
?? kg salt/meter cubed

Evaporation, precipitation, ice melt…

lead to salinity variations in space and time:

And also indicates the presence of a large-scale meridional circulation:

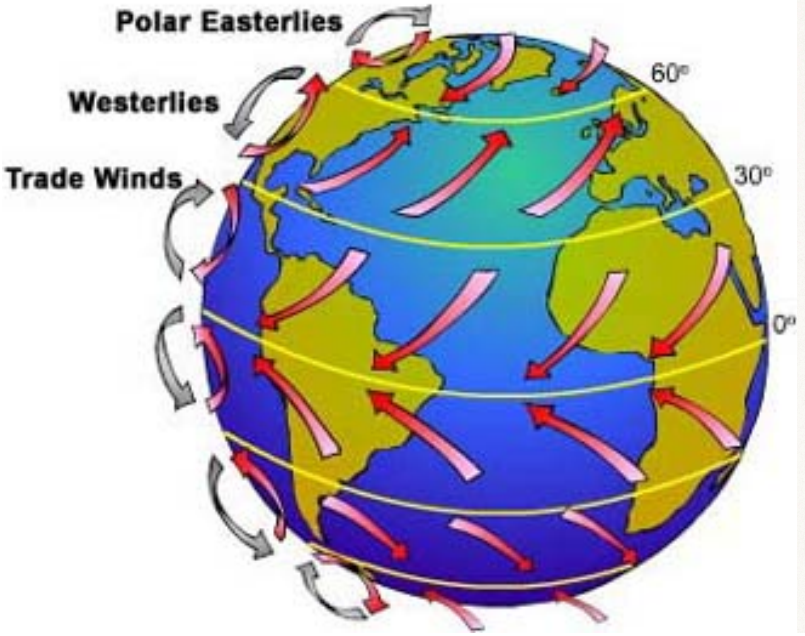




Salinity along Atlantic ocean, vertical axis exaggerated by x1000s

The sun also drives winds, forcing a *horizontal* ocean circulation (gyres)

Global winds…



…drive global circulation circulation

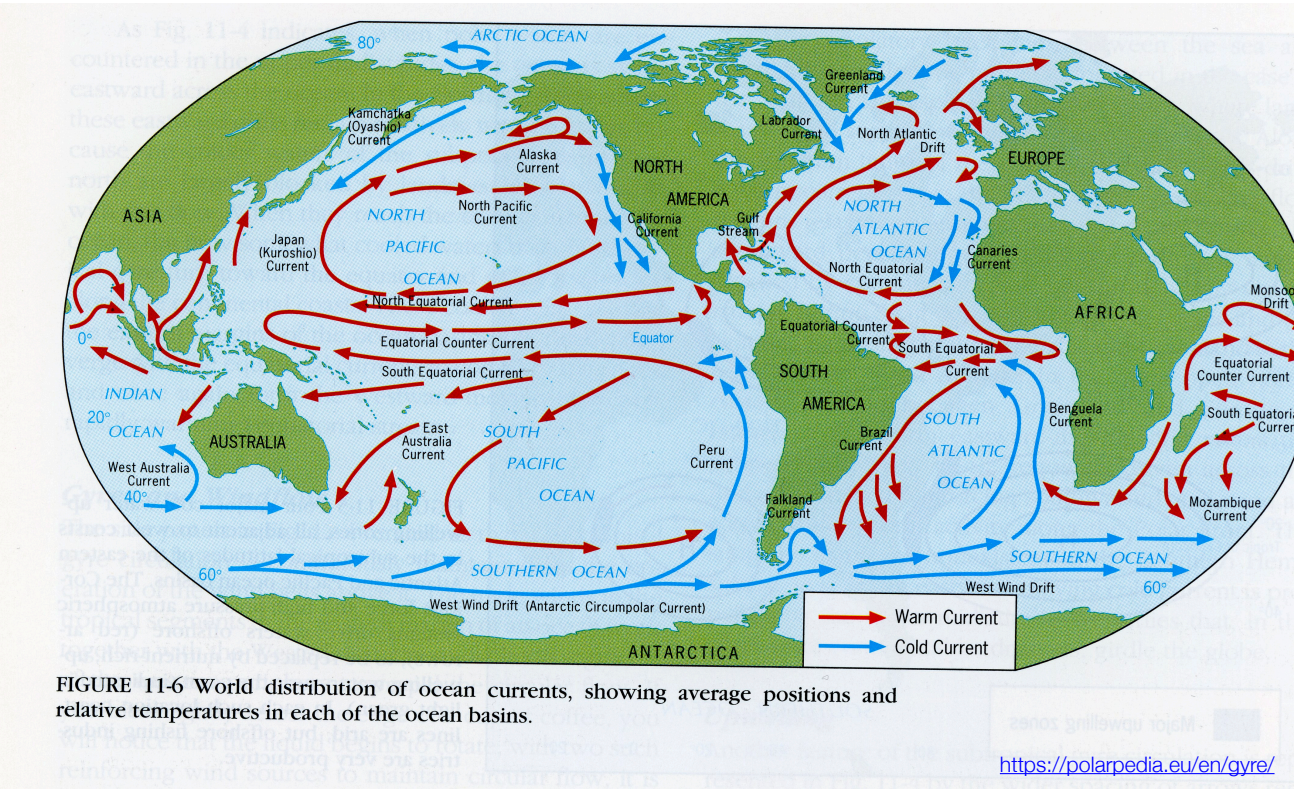
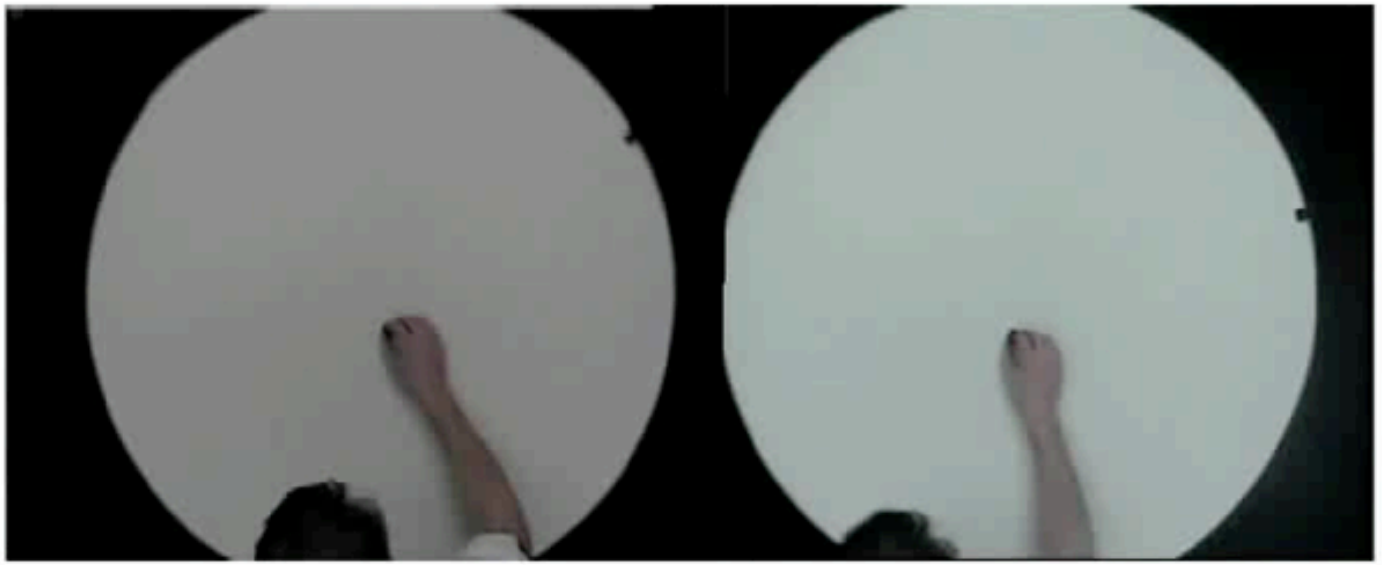


FIGURE 11-6 World distribution of ocean currents, showing average positions and relative temperatures in each of the ocean basins.

https://polarpedia.eu/en/gyre/

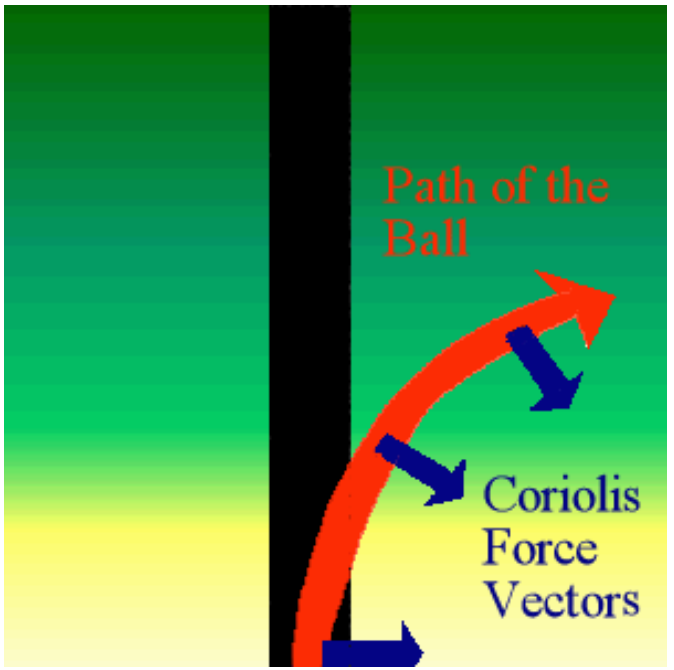
schematic of wind-driven ocean gyres

The Coriolis force



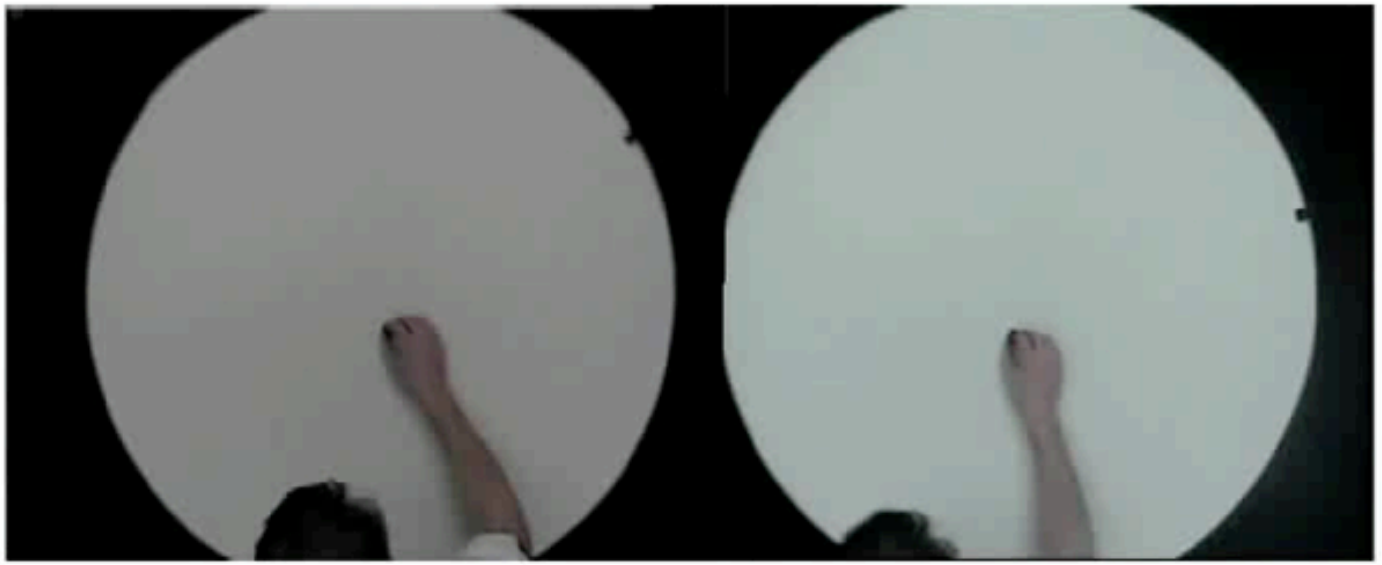
(https://www.youtube.com/watch?v=RrWKSOvqV-0 J. Marshall, MIT)

Ocean currents are driven by Earth rotation & resulting Coriolis force



Coriolis force is to right of motion in north hemisphere; left in south

The Coriolis force



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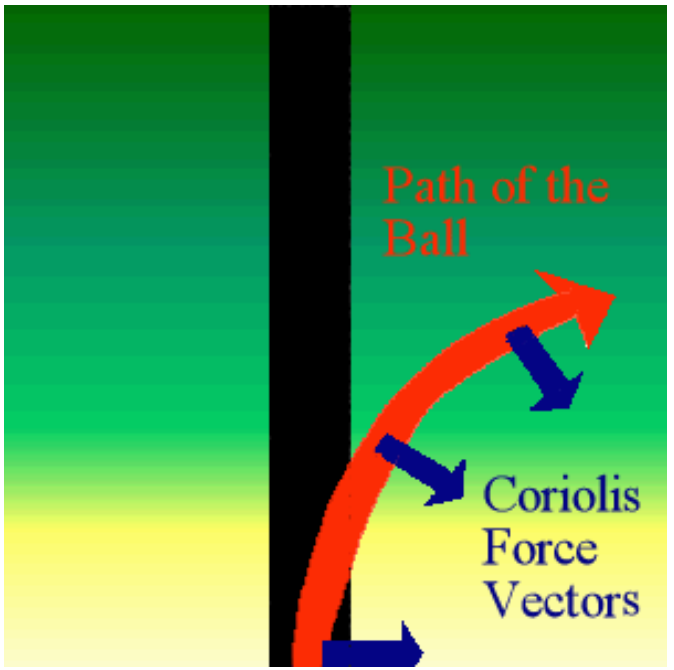

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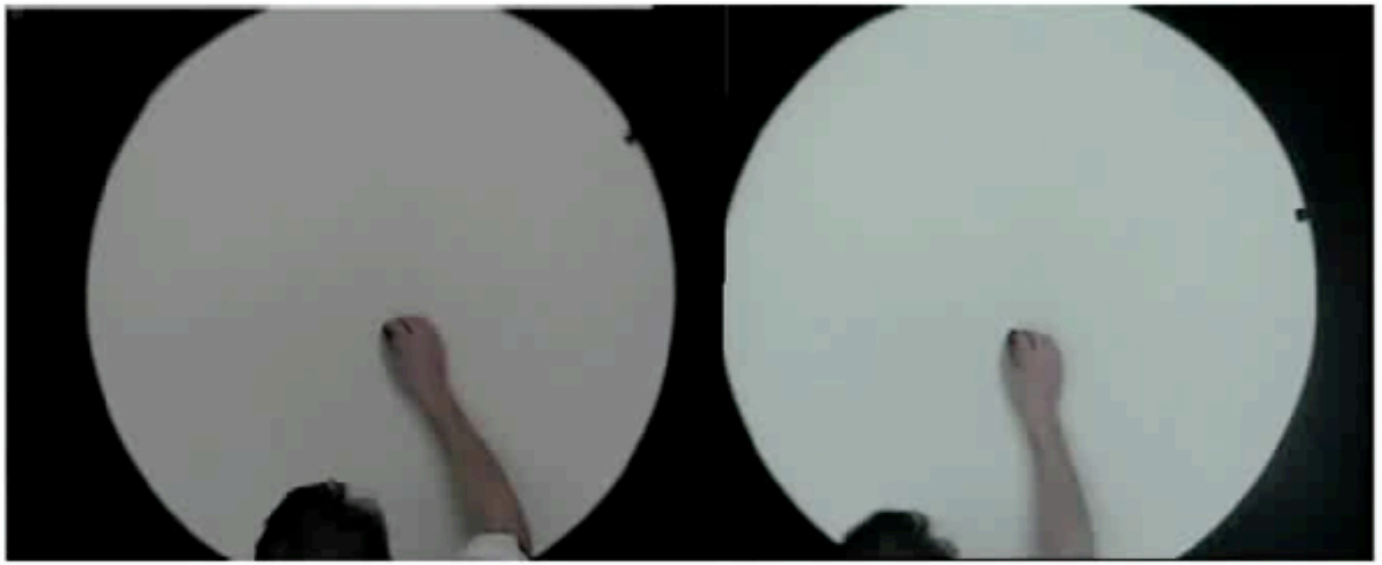

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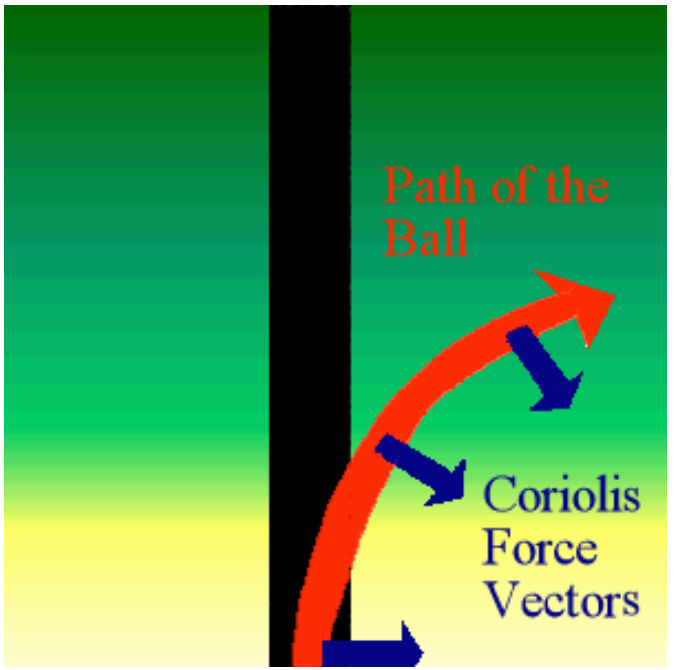

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Sink/toilet bowl water swirls clockwise?

It's *not* the Coriolis force…

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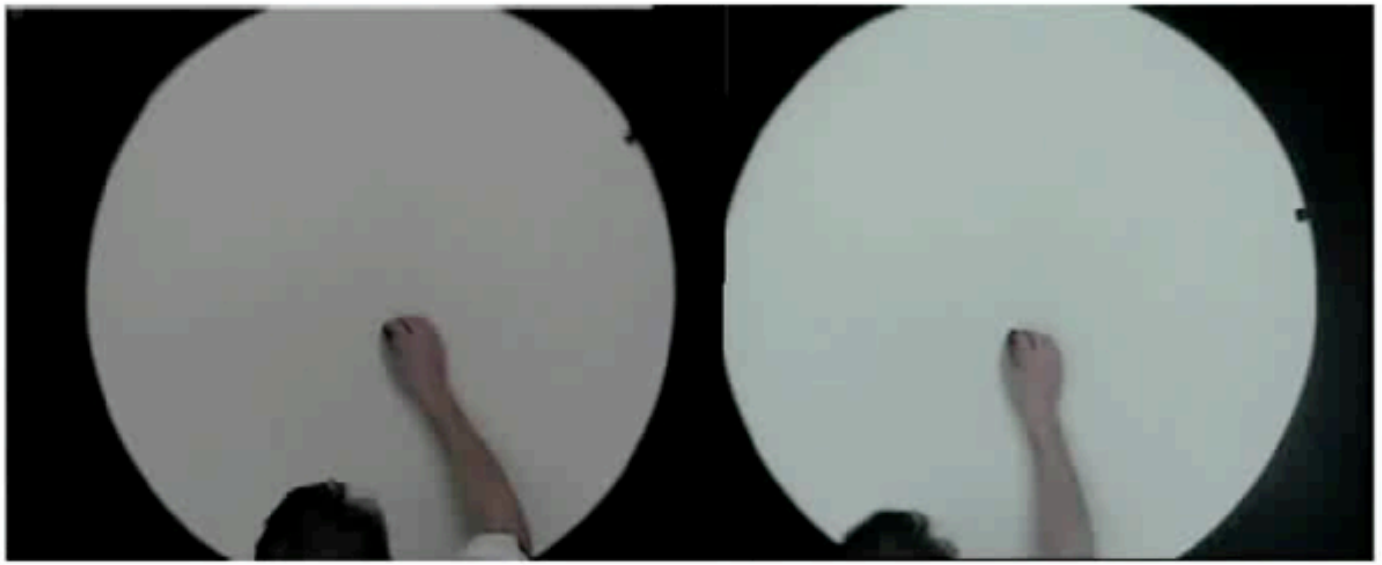

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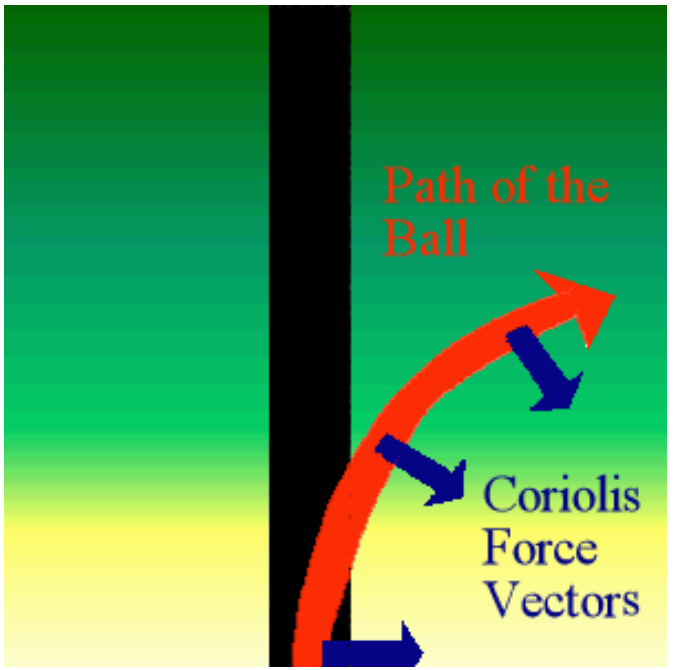

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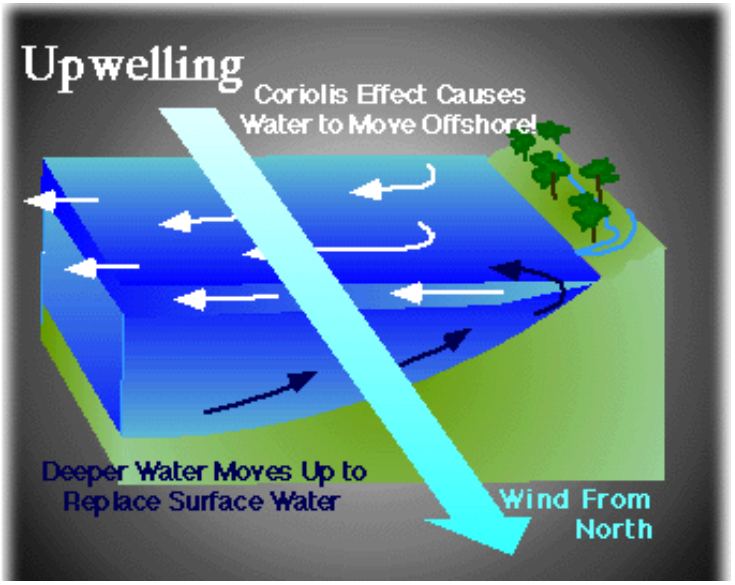
Coriolis force, Coastal Upwelling and fisheries

Currents driven by winds & diverted by Coriolis force, transport water away from shore. Deep, cold water upwells to compensate.



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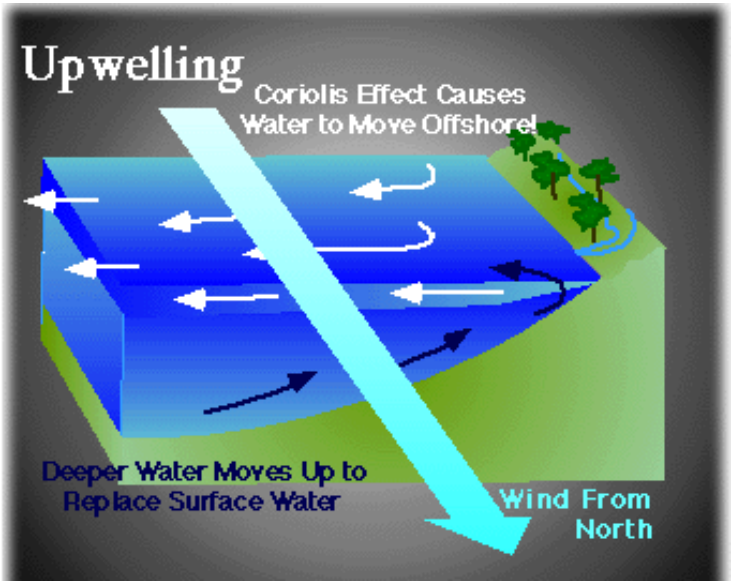
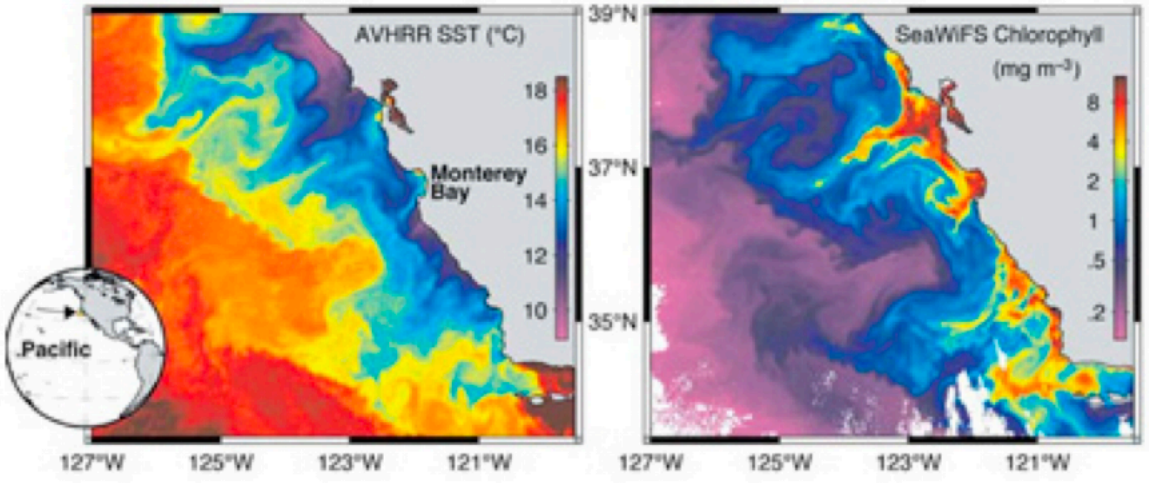


The rising cold water is rich in nutrients, attracts plankton & creates rich fisheries:

(Ryan et al. 2005).



Temperature and chlorophyll concentrations along the California coast

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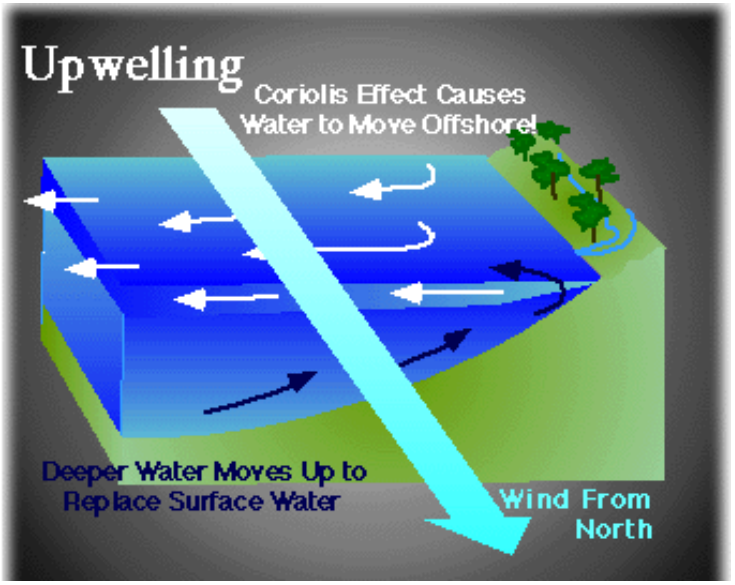

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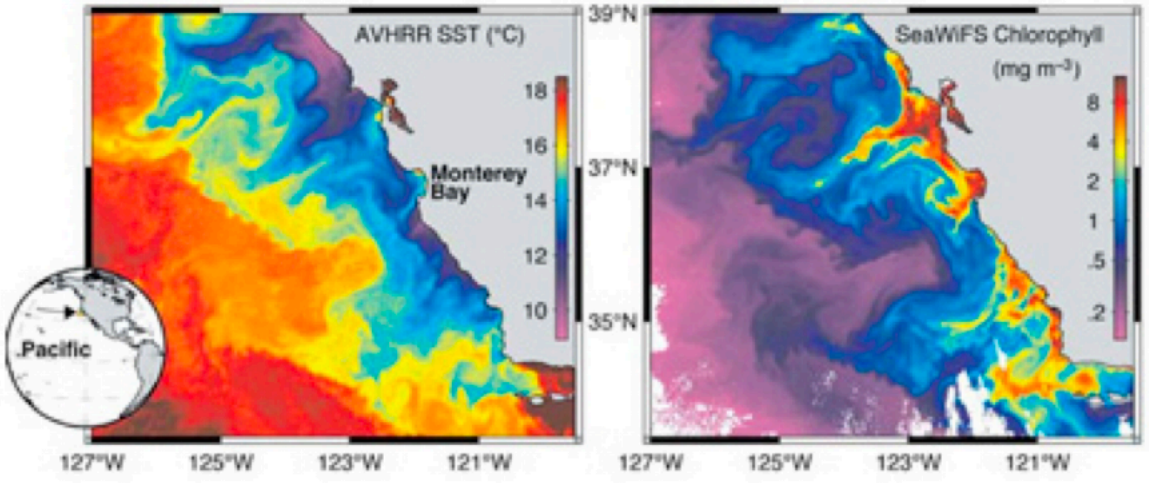
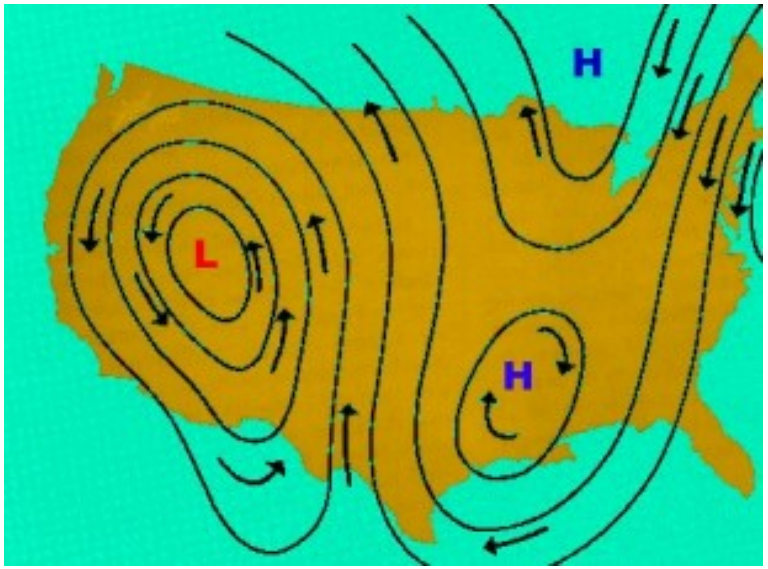
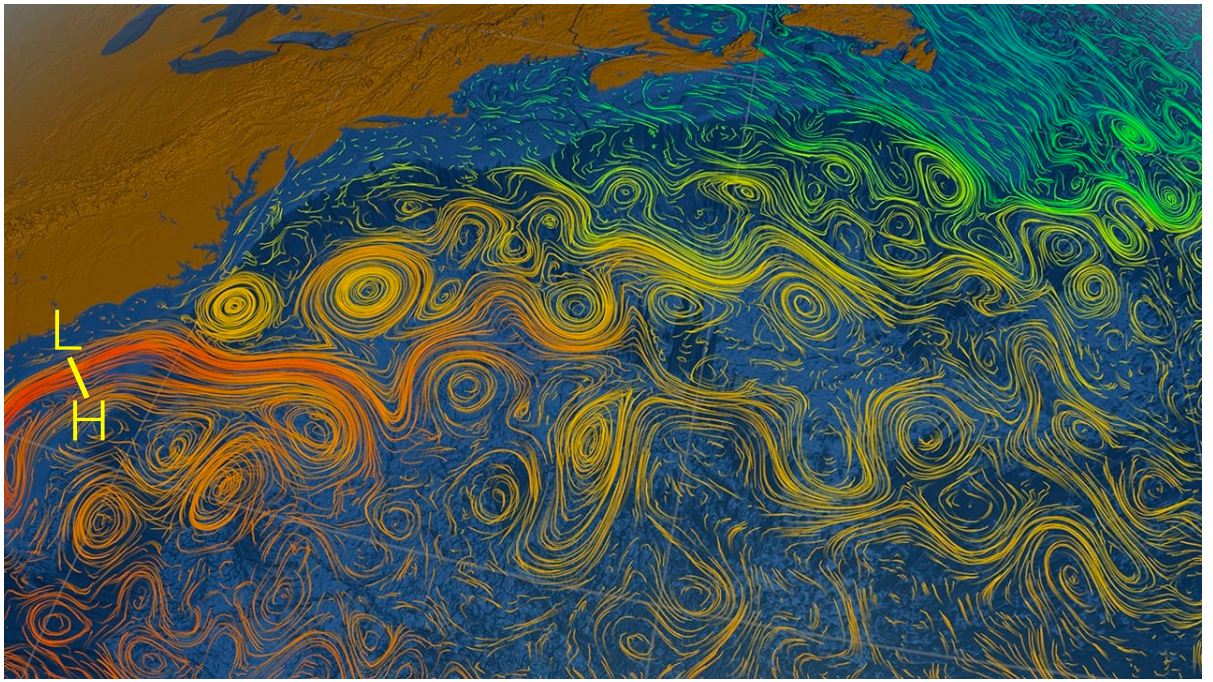


Temperature and chlorophyll concentrations along the California coast

Fishing boats, Ecuador due to El Niño's effect on upwelling

Coriolis force, highs/lows, ocean surface “topography”





https://www.whoi.edu/know-your-ocean/ocean-topics/how-the-ocean-works/ocean-circulation/currents-gyres-eddies/

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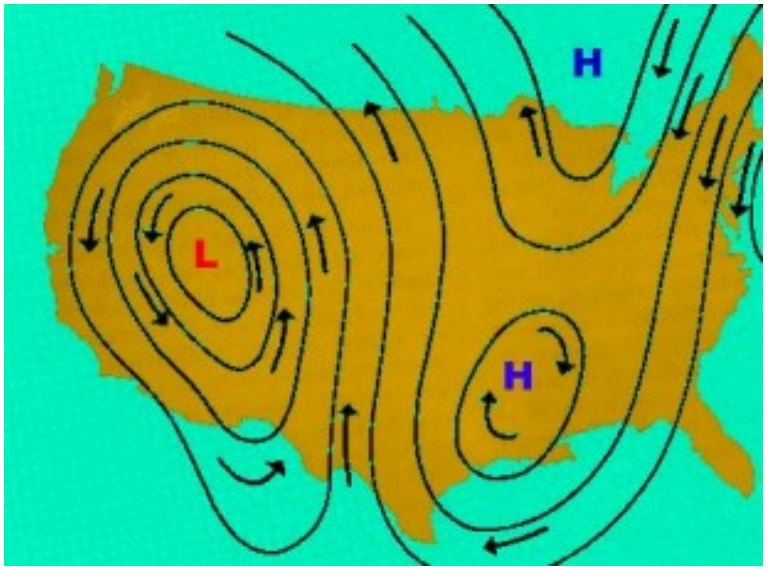

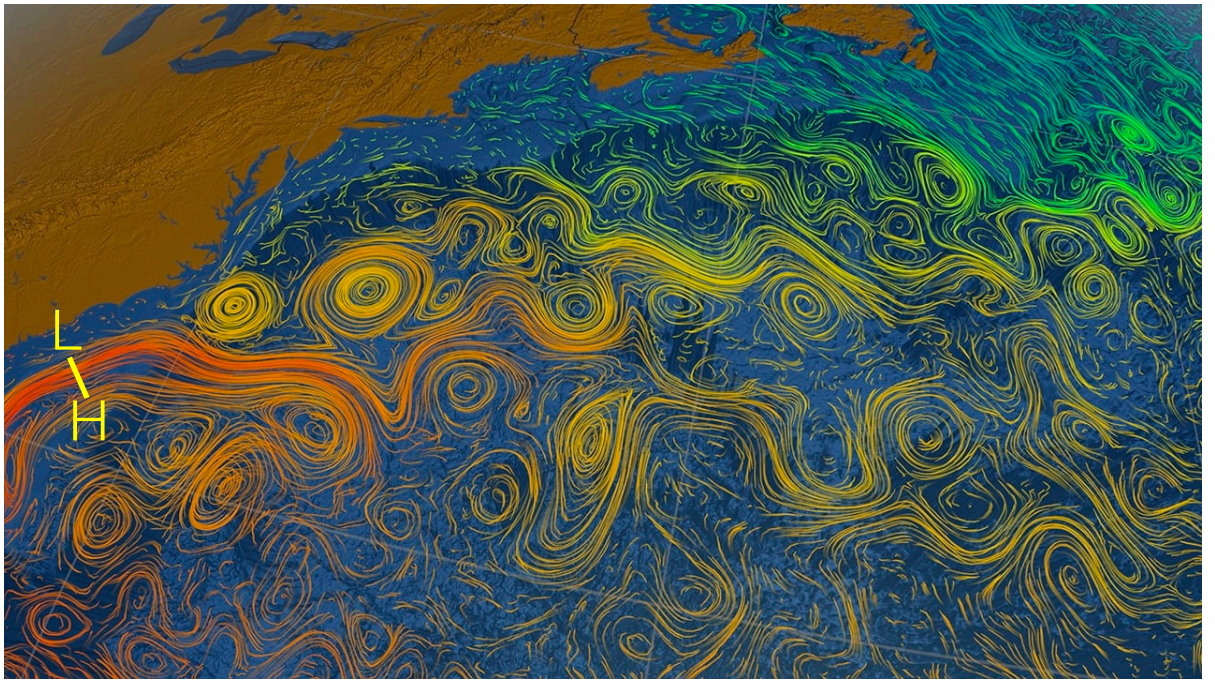

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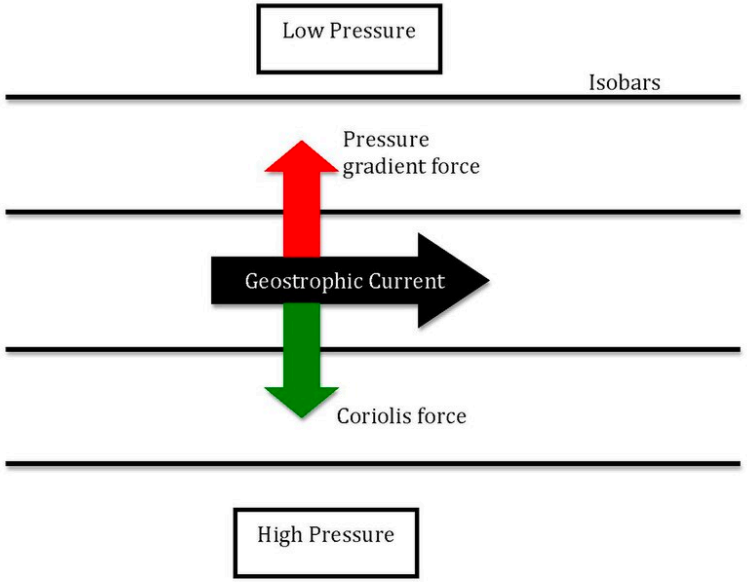
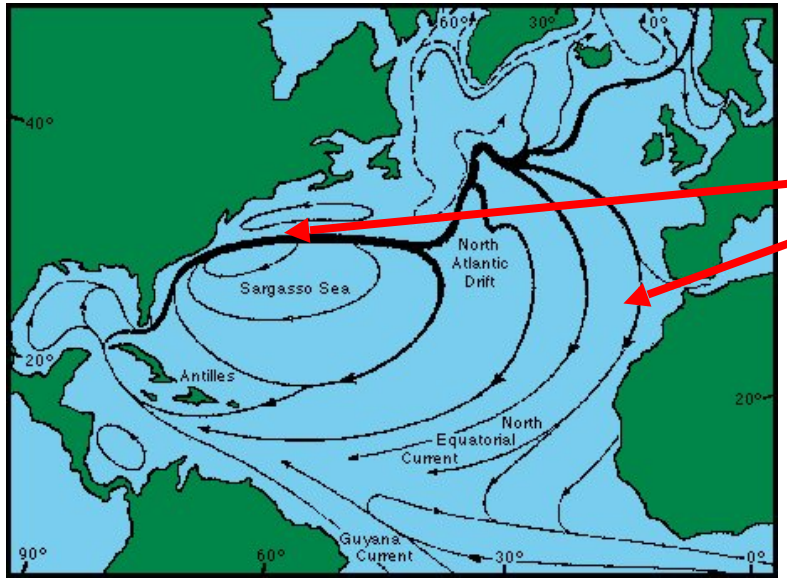
- Air/water *do not flow* from high to low pressure…
- Instead, the Coriolis force causes *flow along* equal pressure lines
- The surface height difference across the Gulf Stream (50 km) is about one meter(!)



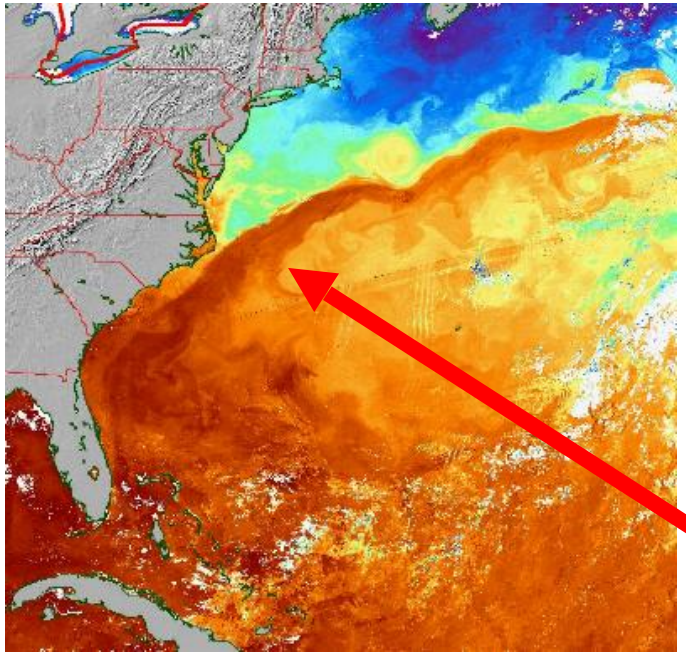
https://en.wikipedia.org/wiki/Geostrophic_current

Gulf Stream/ Kuroshio: western boundary currents

(Strong western vs. weaker eastern boundary currents)



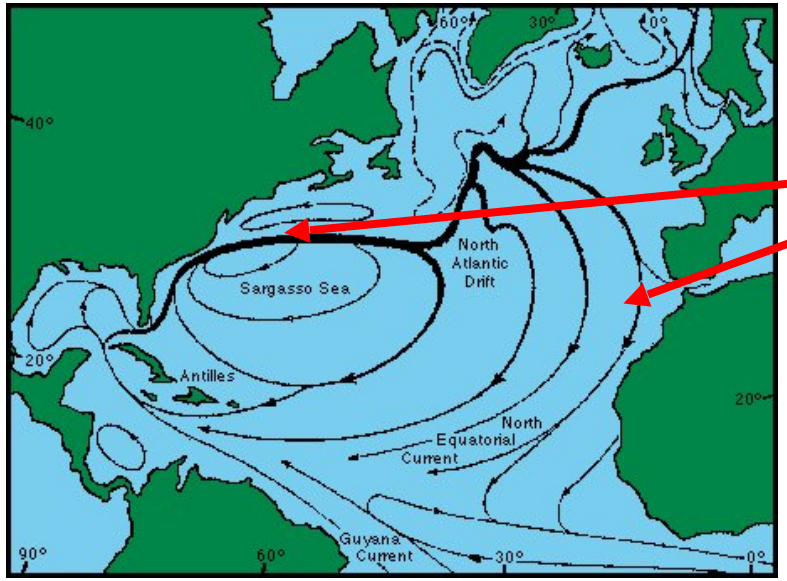
Note east-west
Asymmetry!



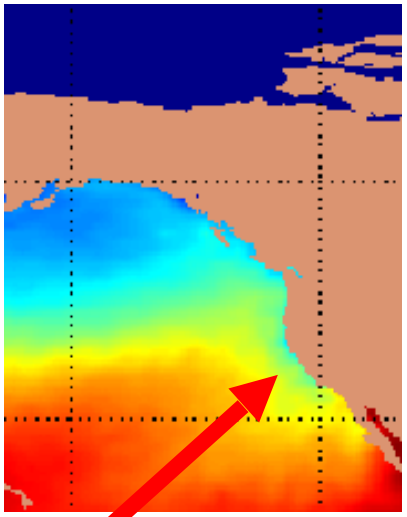
Warm Gulf Stream:
150M m^3/sec,
1–2 m/sec

Gulf Stream/ Kuroshio: western boundary currents

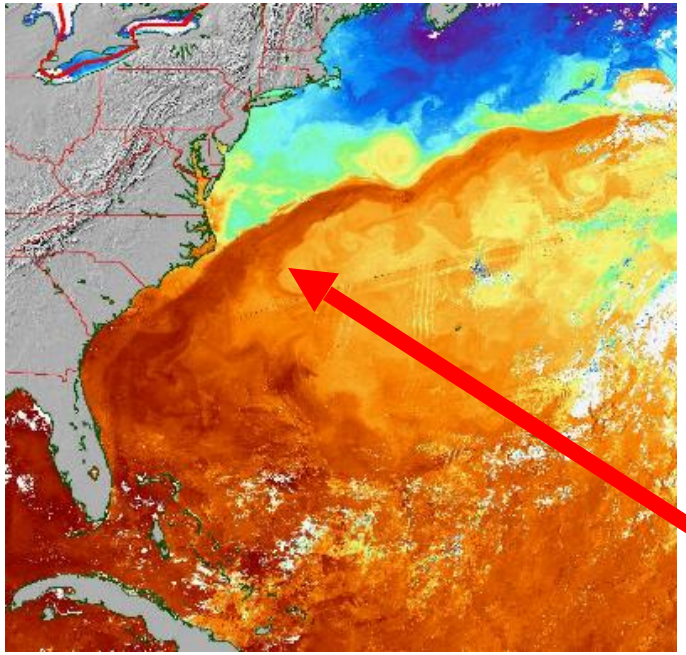
(Strong western vs. weaker eastern boundary currents)



Note east-west Asymmetry!



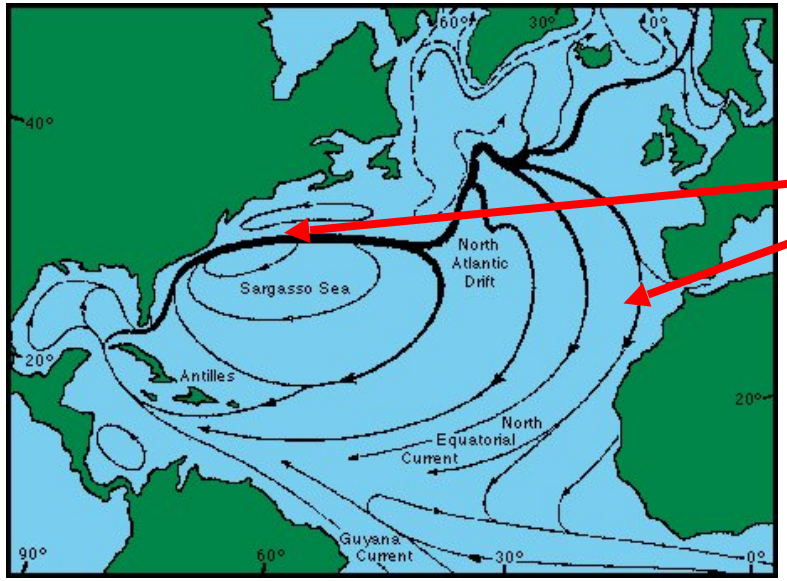
Cold California Current: 2M m^3/sec; 0.1m/s



Warm Gulf Stream: 150M m^3/sec, 1–2 m/sec

Gulf Stream/ Kuroshio: western boundary currents

(Strong western vs. weaker eastern boundary currents)



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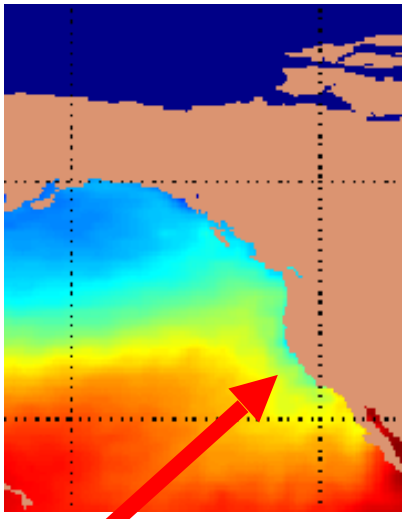

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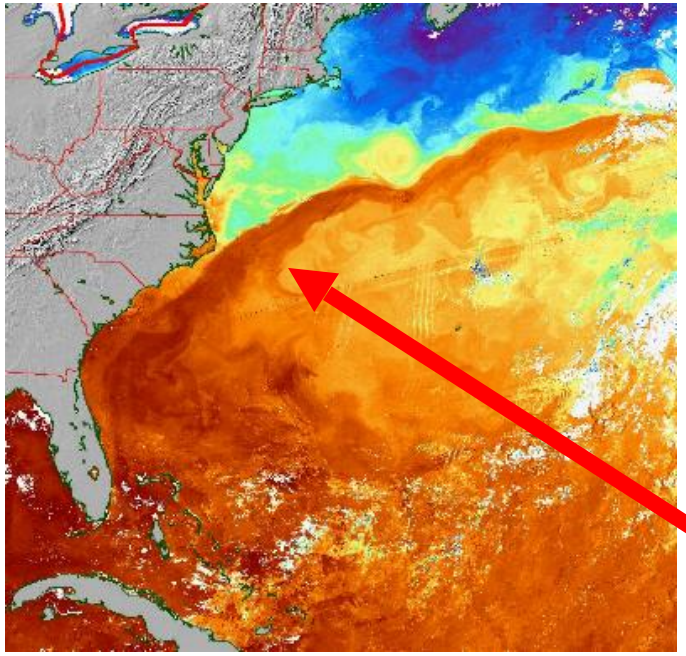


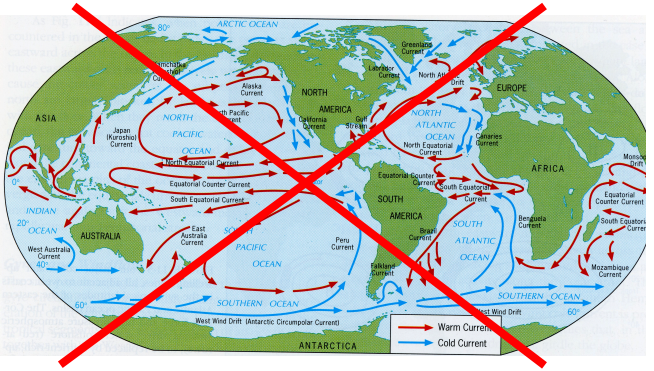
Warm Gulf Stream: 150M m^3/sec, 1–2 m/sec

Benjamin Franklin, deputy postmaster general, North America 1753–1774

His cousin's map of a feature known for 250 yr

Ocean Eddies

- 1970s: ocean is continuously changing
- Ocean turbulence: from mm to 100s of km “eddies”
- Similar to weather systems, but X10 smaller & slower



Eddies in the Southern ocean, NCI Australia
https://www.youtube.com/watch?v=t-FqF6PFDP0

NATIONAL COMPUTATIONAL INFRASTRUCTURE

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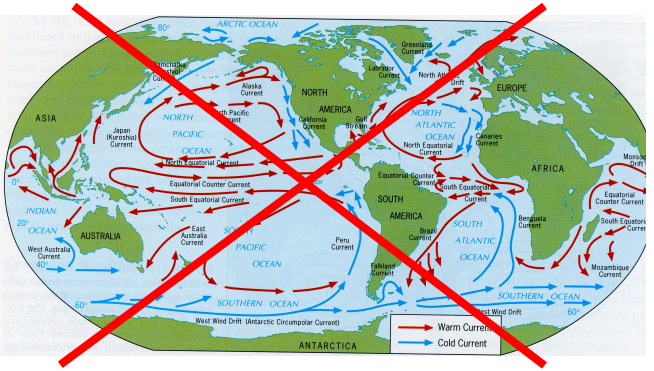

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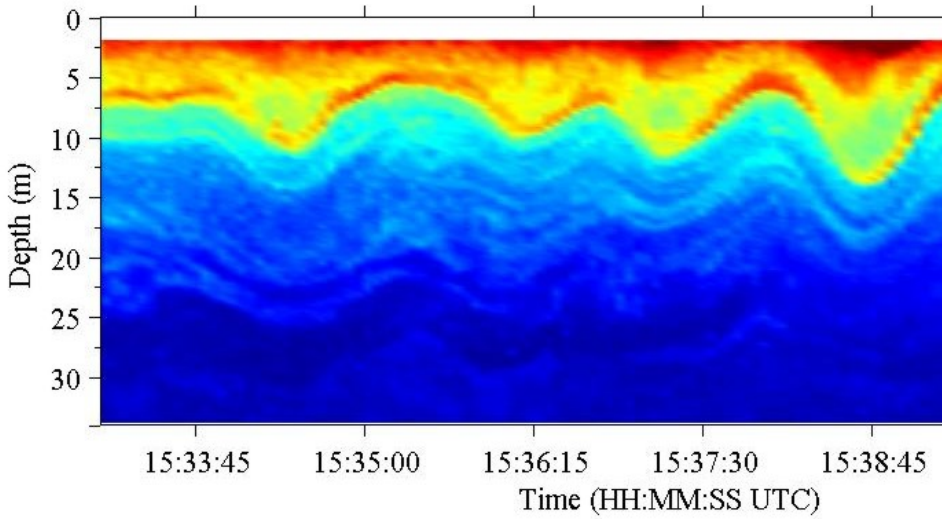
NATIONAL COMPUTATIONAL INFRASTRUCTURE

Waves, Tides, Tsunami

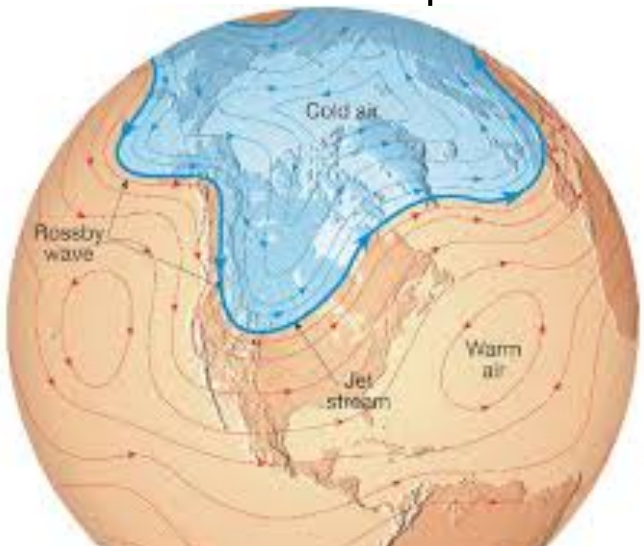
surface waves

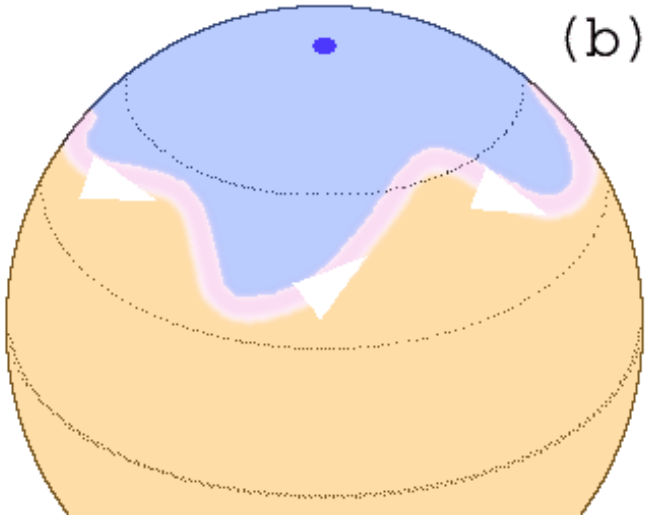
https://www.youtube.com/watch?v=-nbnnFzk0bA

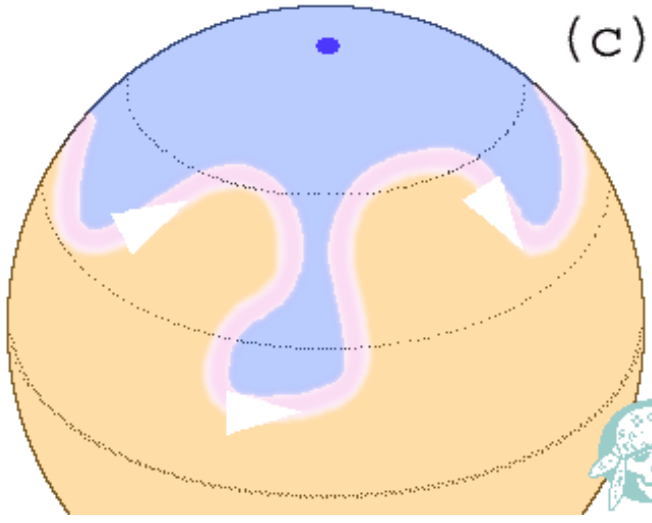
internal waves



“planetary” waves (of atmospheric jet stream)







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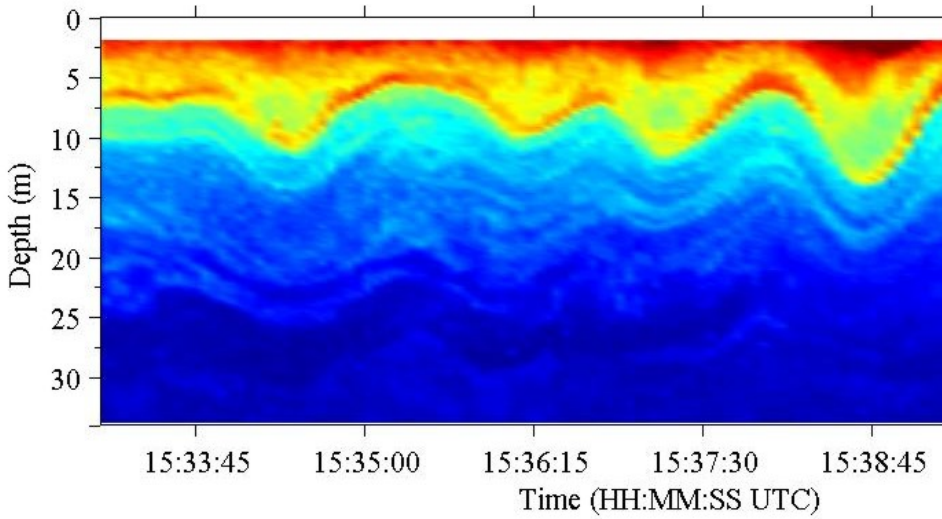

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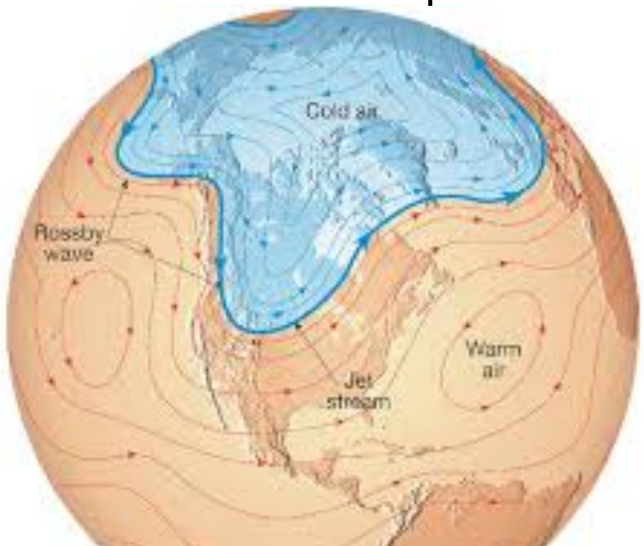
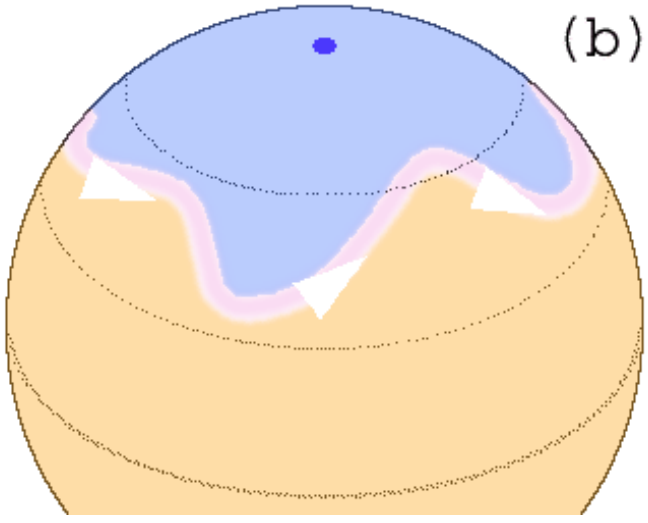
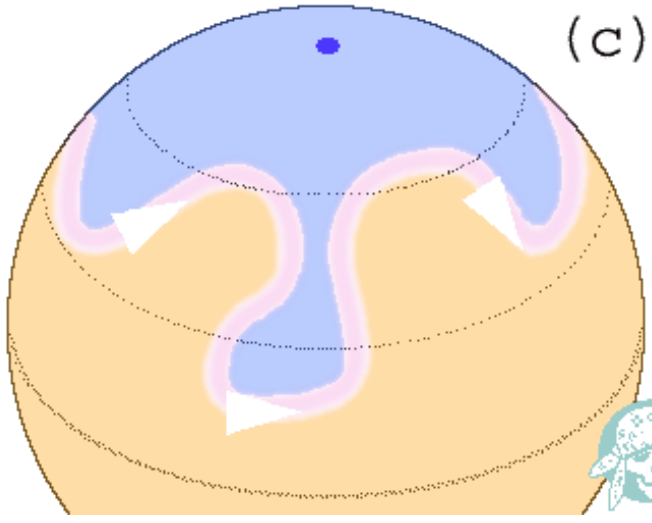
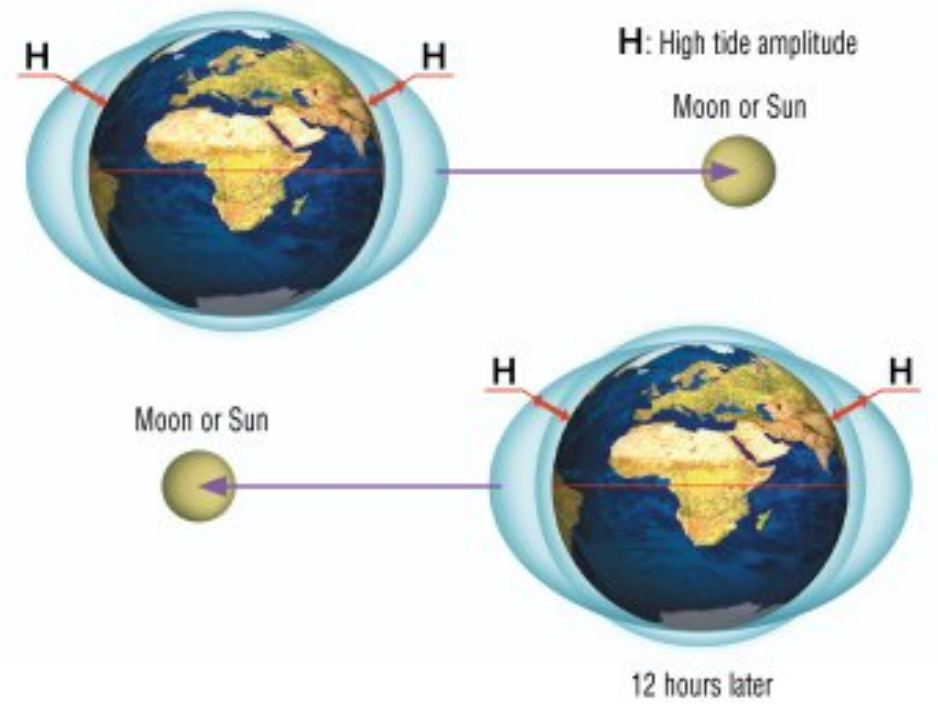






Waves, Tides, Tsunami

- Causes?
- Why two a day?
- Why large in some places & and small in others?

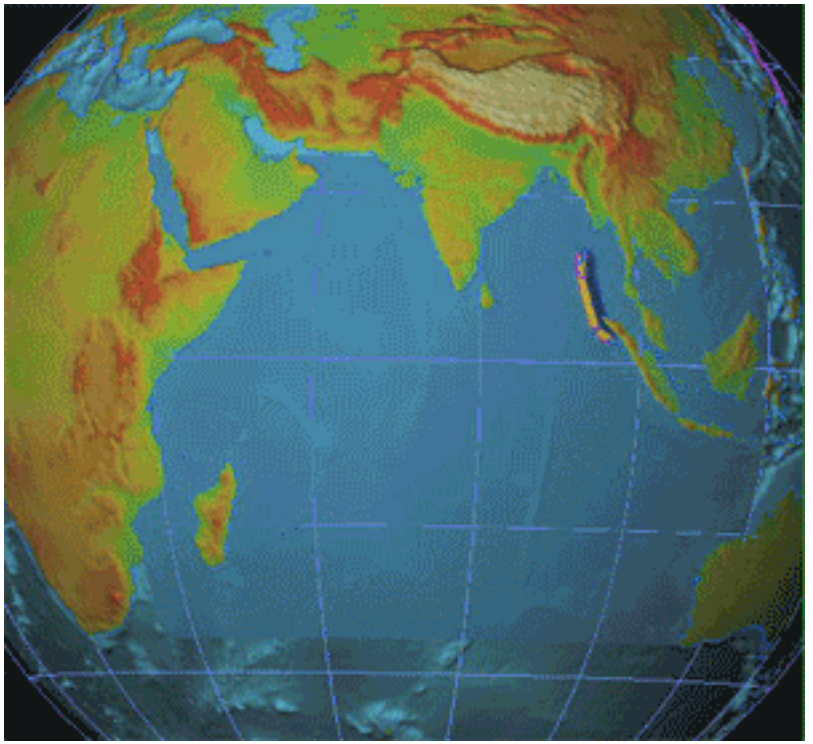


Mont-Saint-Michel (town of Normandy — France)

Waves, Tides, Tsunami

- caused by undersea earthquakes, landfalls
- propagate as undetectable low-amplitude surface waves
- speed = $\sqrt{gH} \approx 200m/\sec \approx 400mph$
- slow down and height increases to 10s m when approaching shallow coast.

1992, Indonesia, 3–4m waves



Sumatra, 2004, www.thelivingmoon.com/

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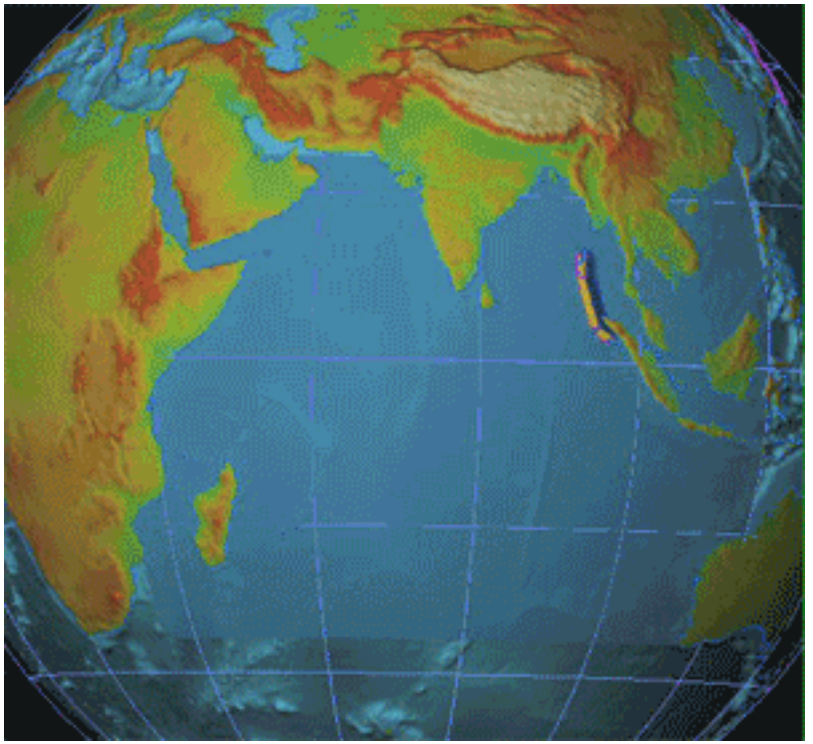
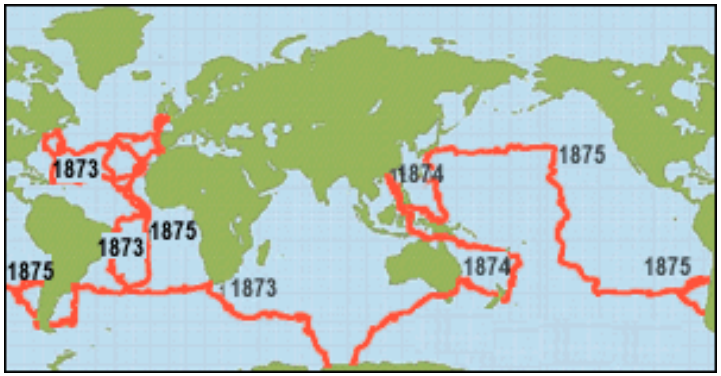


Sumatra, 2004, www.thelivingmoon.com/

Observing the oceans

Ships, satellites, moorings, floats

Challenger, 1870s

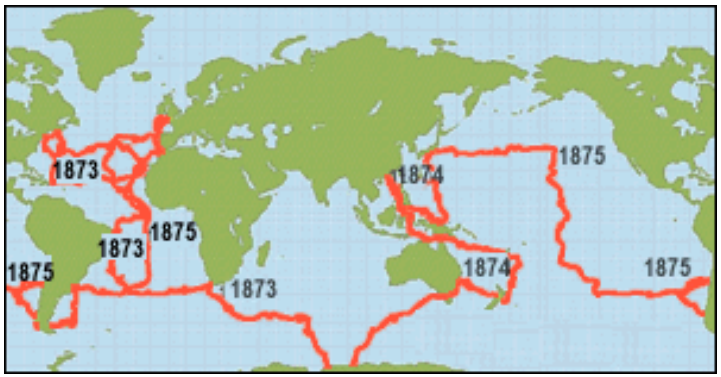


H.M.S. Challenger under Sail, 1874.

(EPS/ESE 131 field trip to WHOI @ Cape Cod will take place during the term…)

Ships, satellites, moorings, floats

Challenger, 1870s



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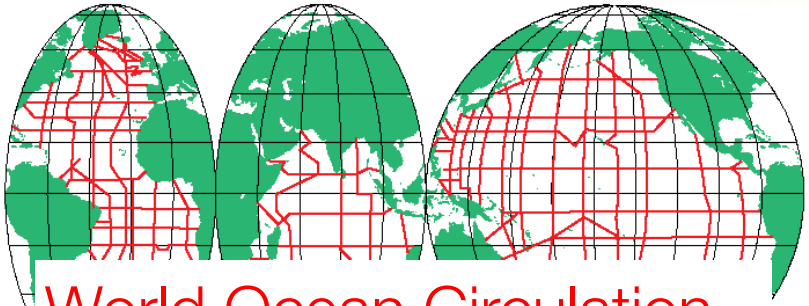

World Ocean Circulation Experiment, 1990s

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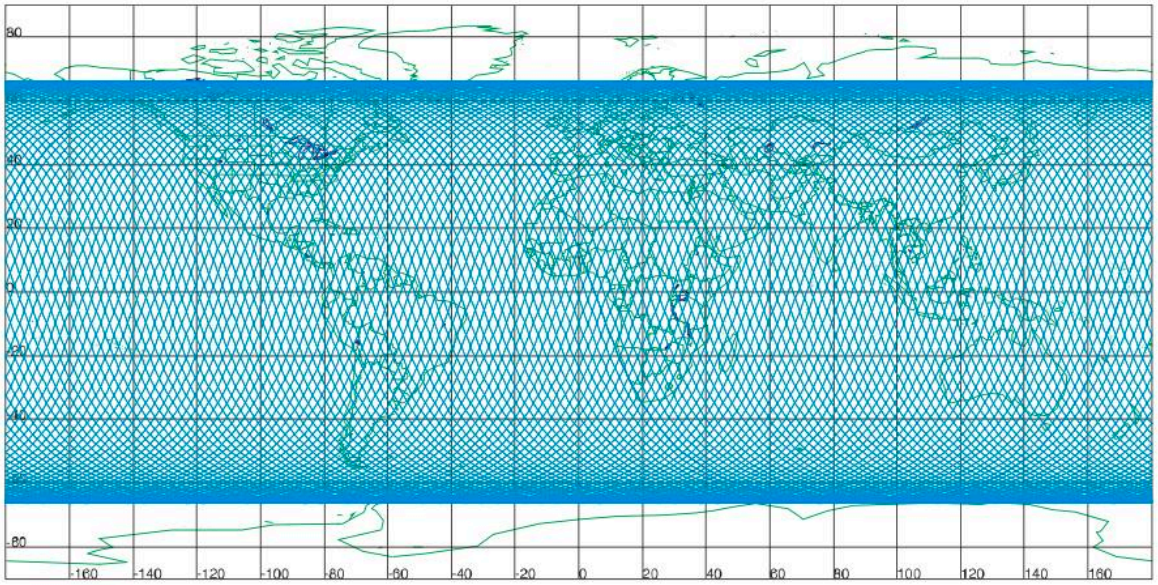
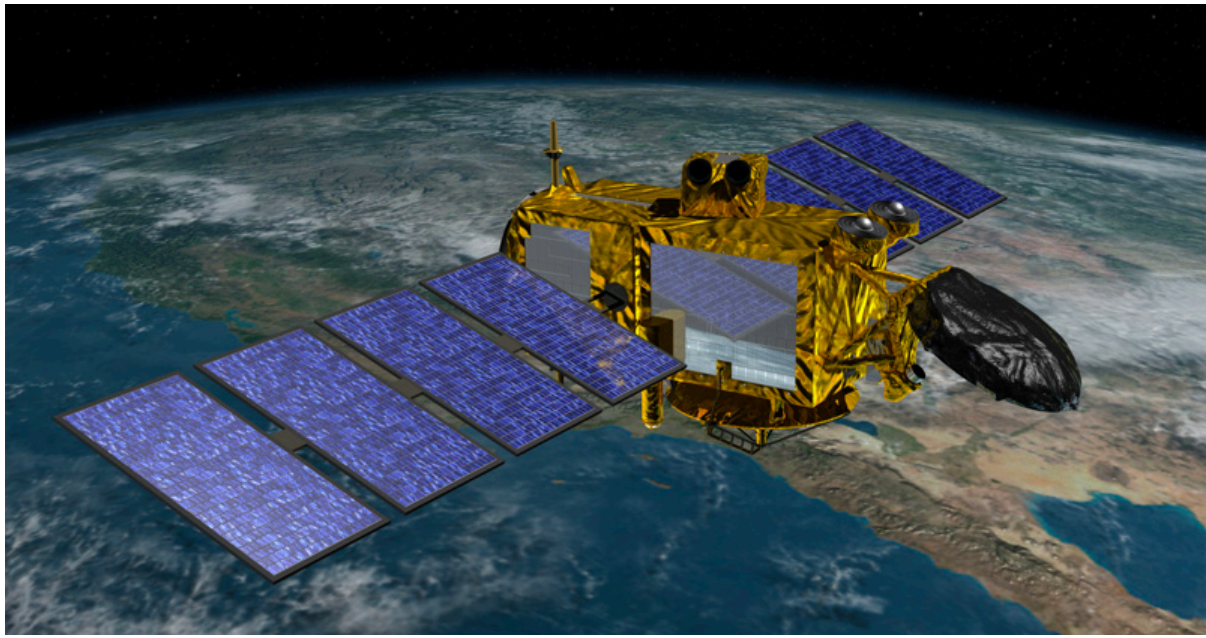
Ships, satellites, moorings, floats



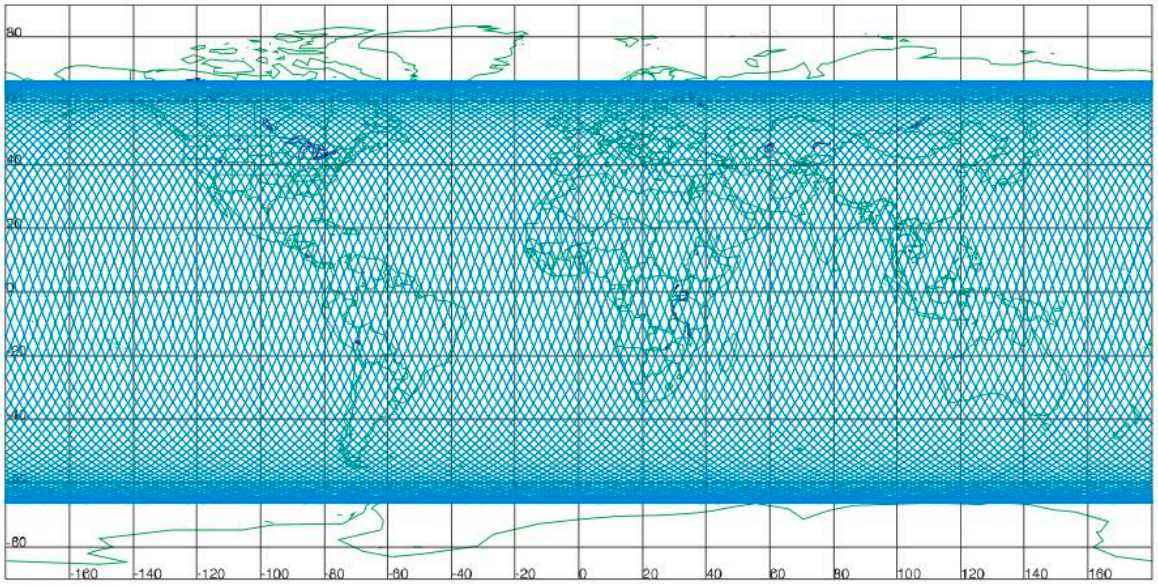
TOPEX/POSEIDON altimeter satellite (1995–2005); now: Sentinel 6 (2020–). Repeat the same ground track every 10 days (127 revolutions). Orbital period: 112 minutes. NASA/ESA.

Altimeter: radar measuring ocean surface height



https://sealevel.jpl.nasa.gov/missions/topex-poseidon/summary/

Ships, satellites, moorings, floats



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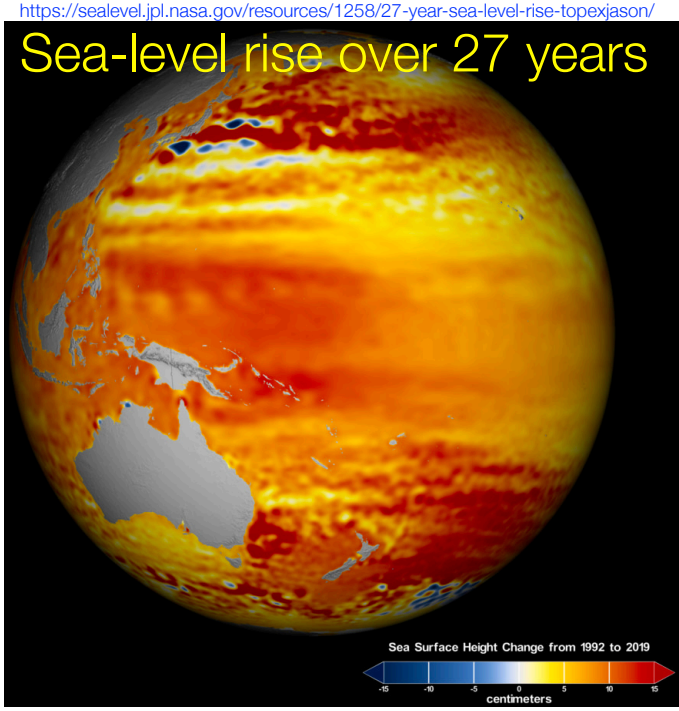

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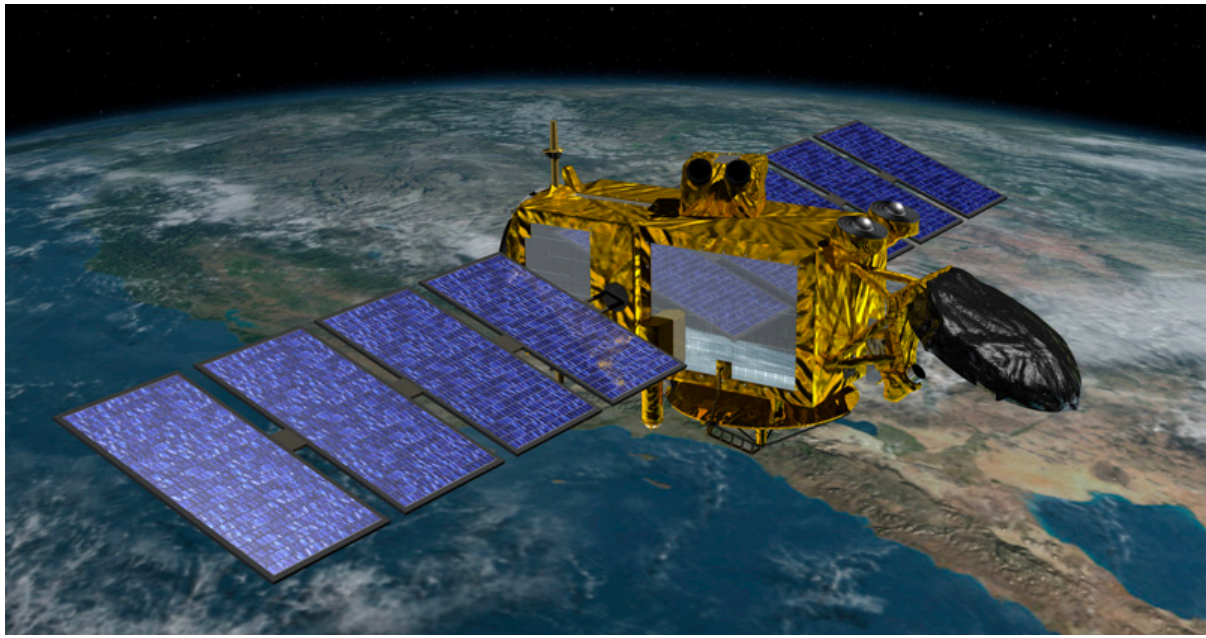

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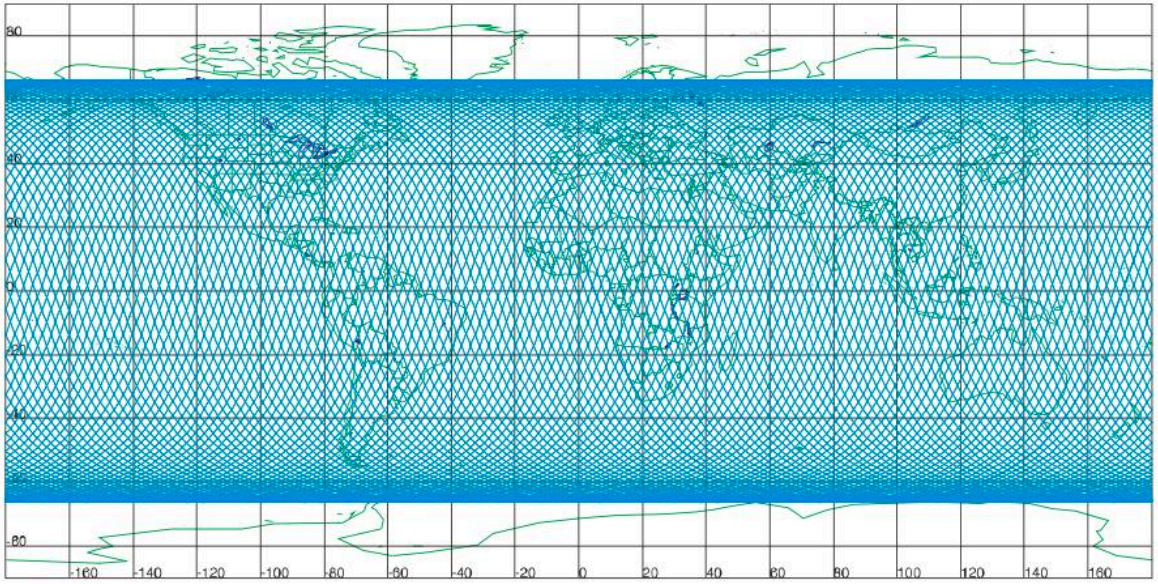

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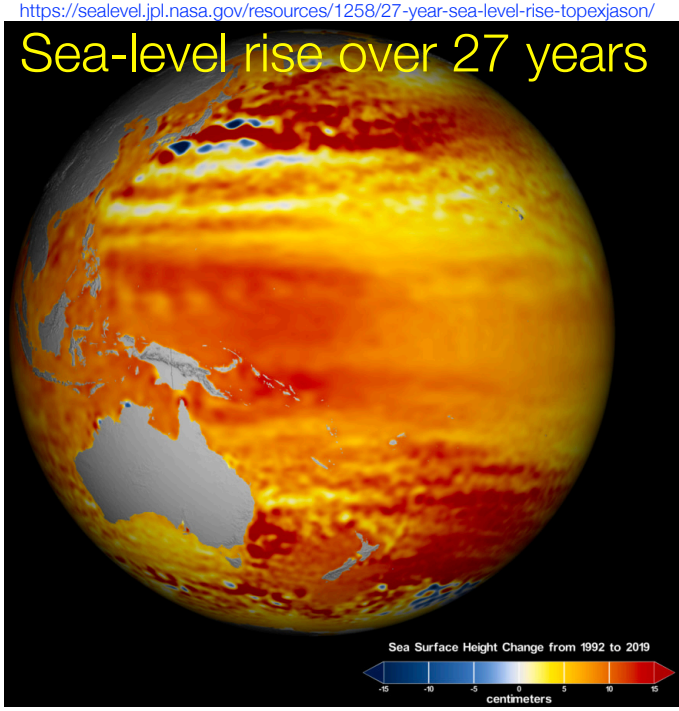
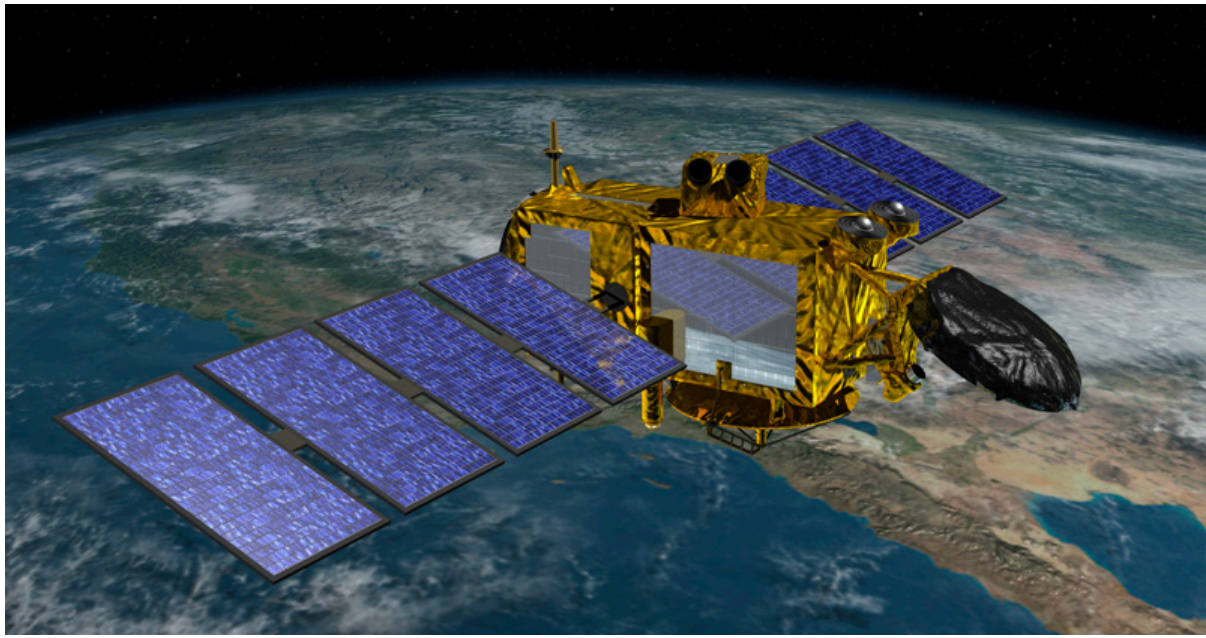


Altimeter: radar measuring ocean surface height

Satellites observe surface temperature, salinity, height, winds, waves, ice, chlorophyll…
but not the ocean interior…



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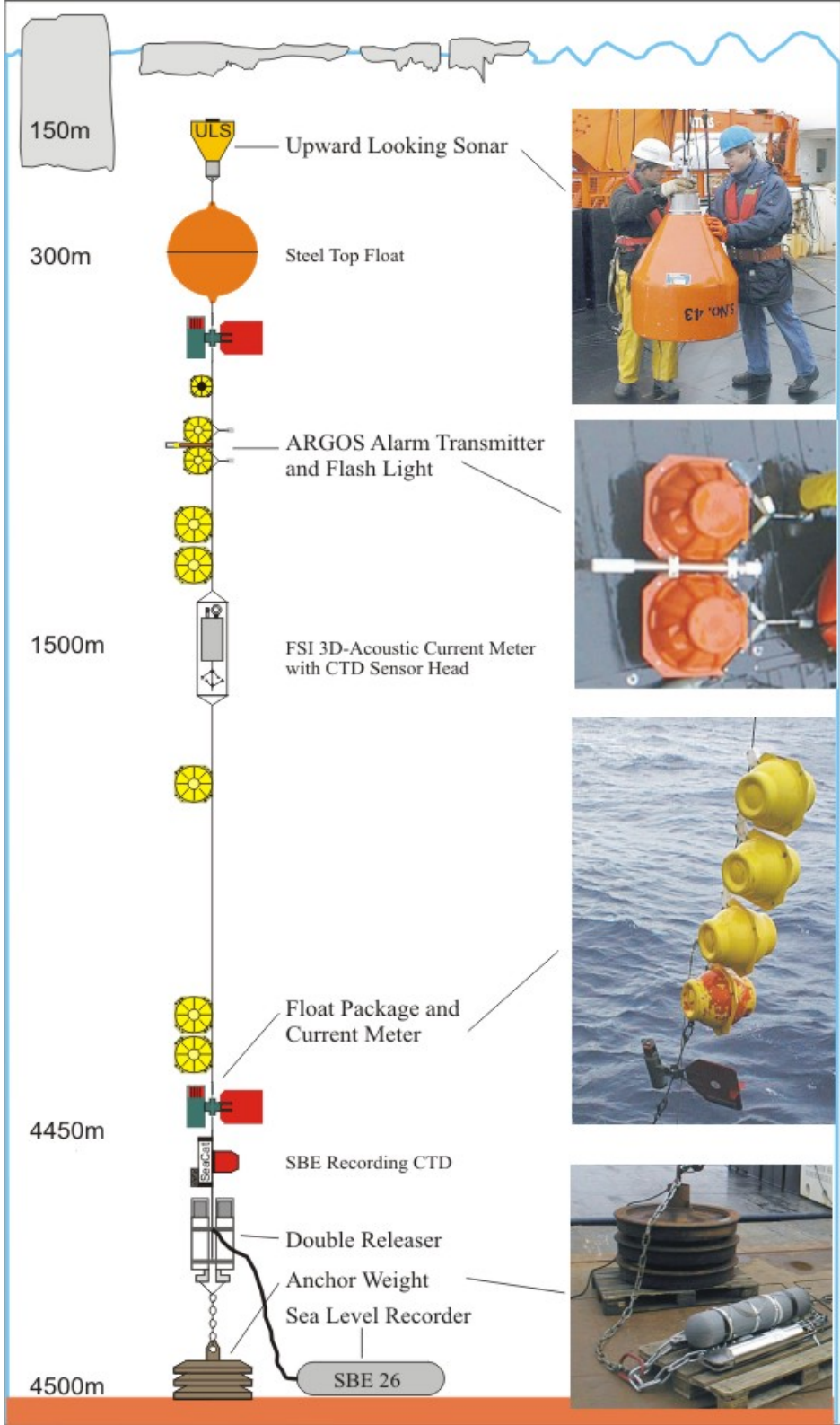
Ships, satellites, moorings, floats

https://education.nationalgeoraphic.org/resource/el-nino/



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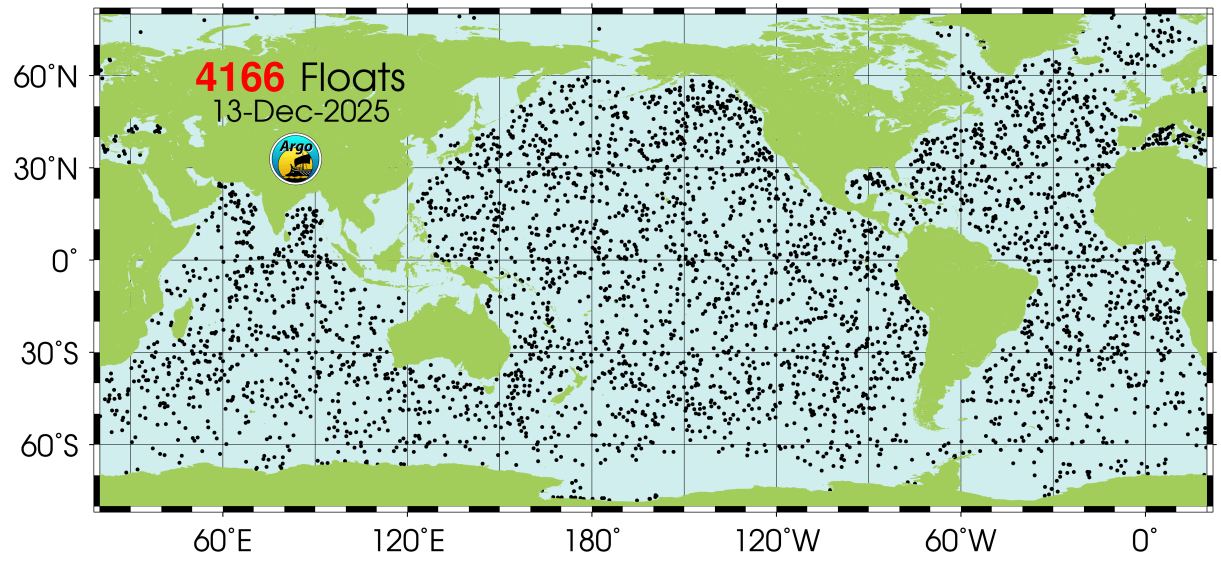
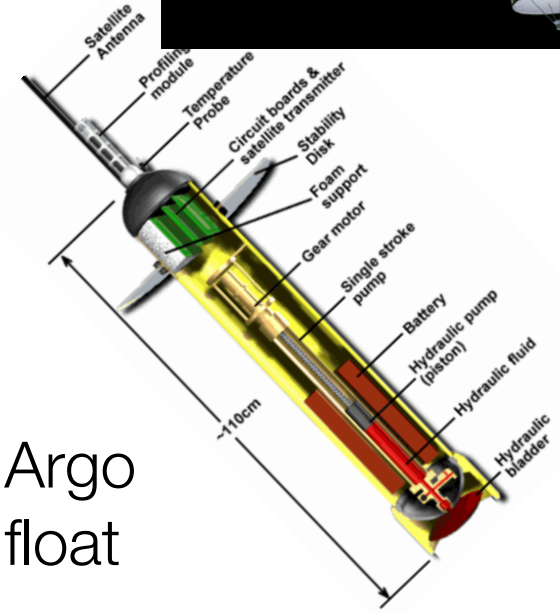
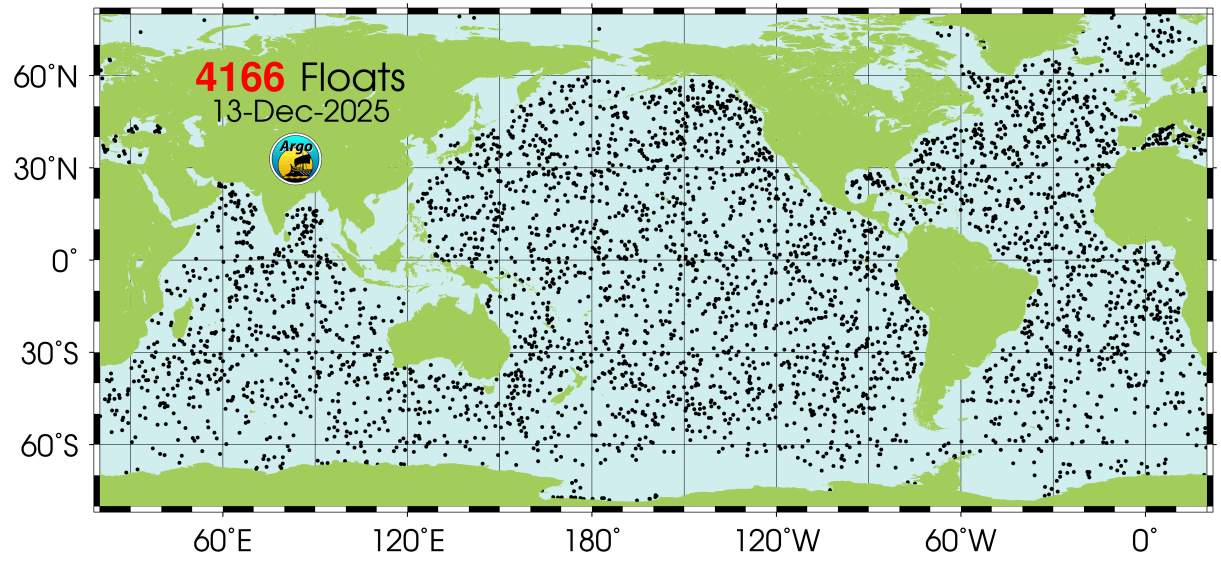


Argo floats that delivered data during past 30 days
https://argo.ucsd.edu/about/status/



Argo float

Ships, satellites, moorings, floats



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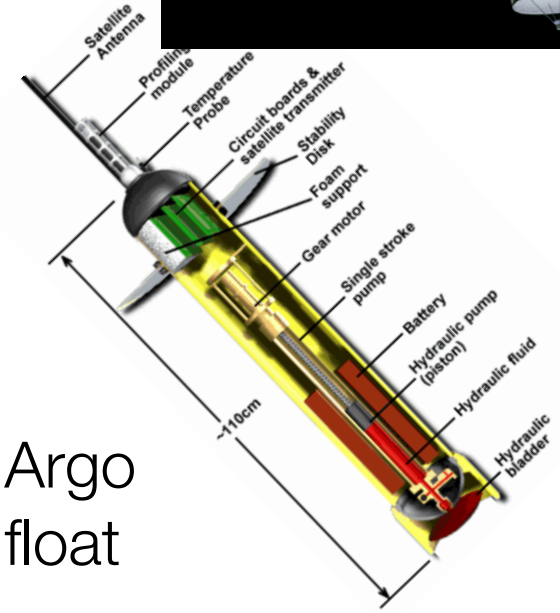

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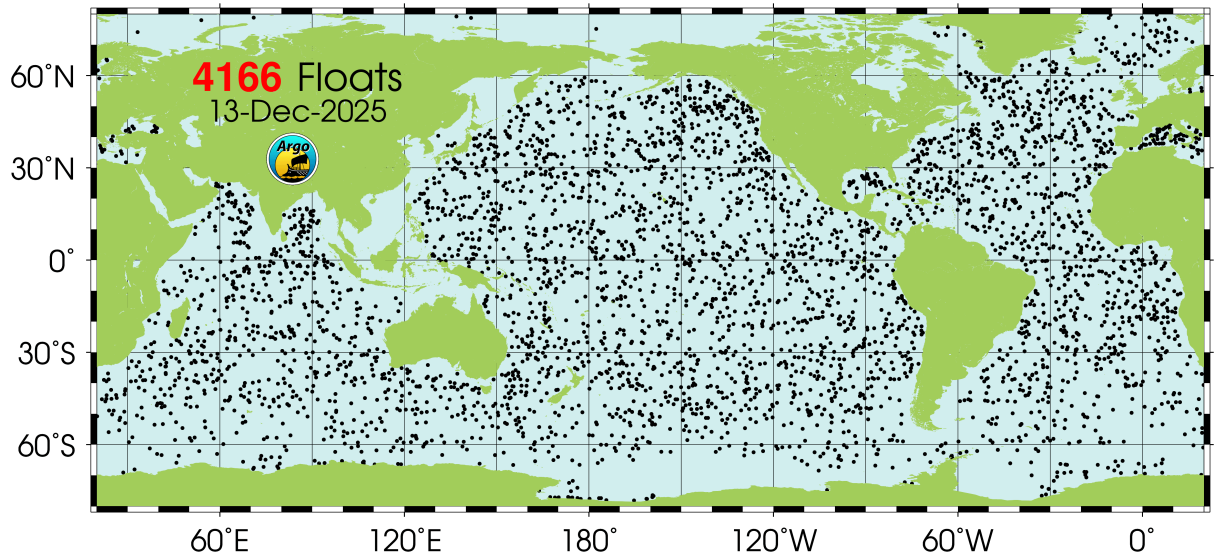

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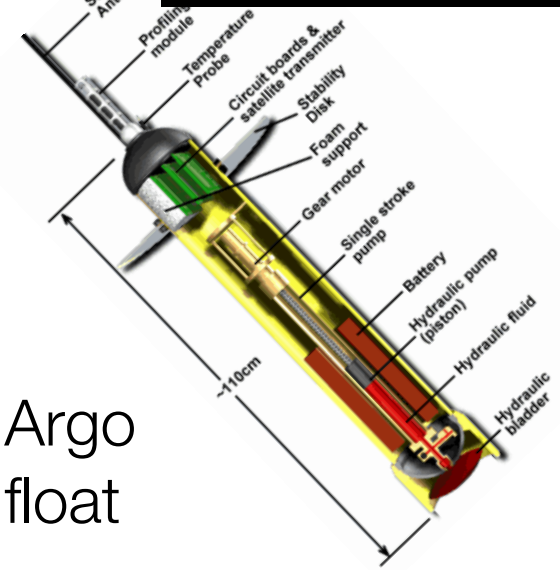
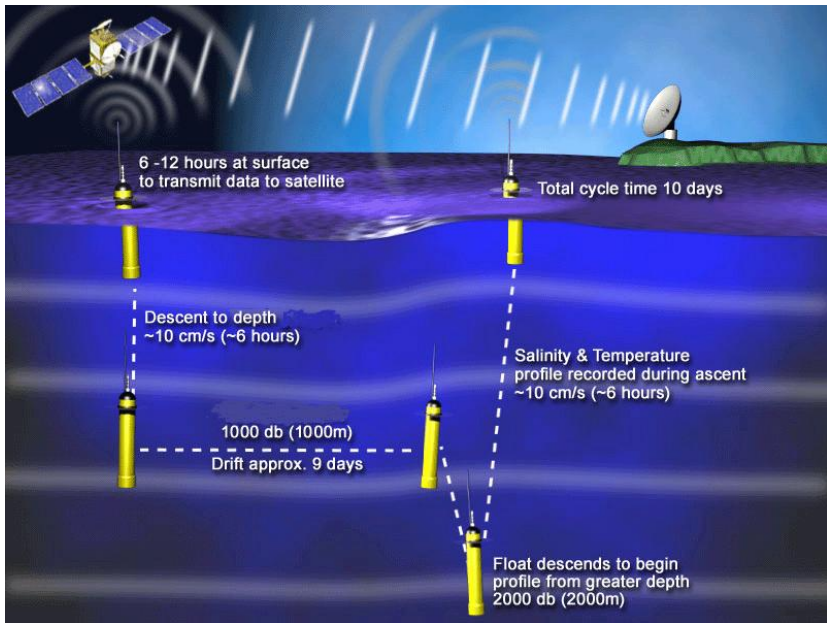


Argo float

Argo floats cycle between 2000 m and the surface every 10 days & drift with currents



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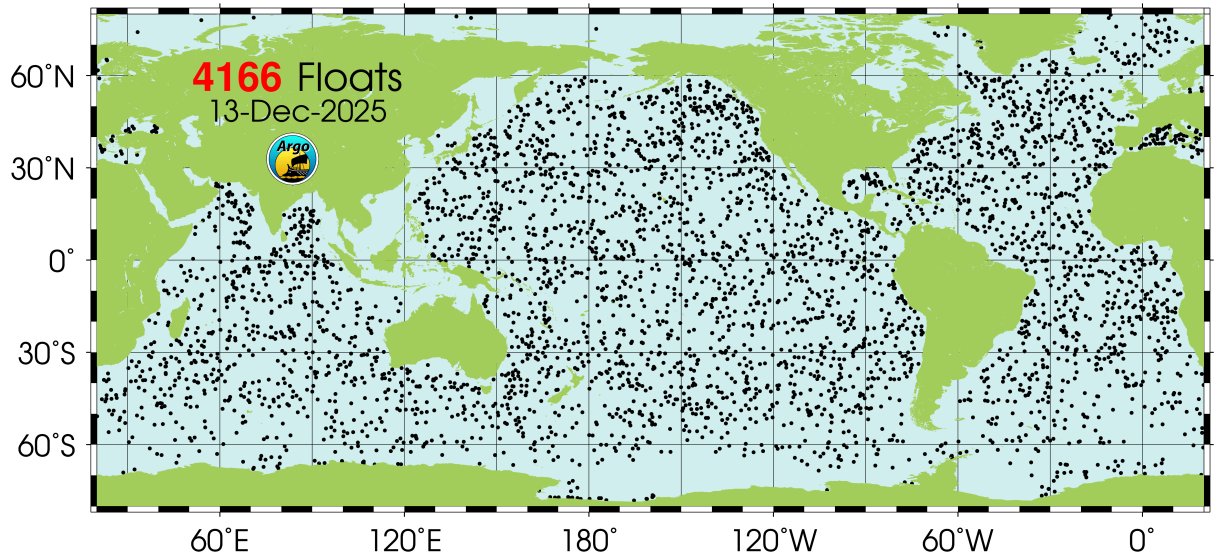

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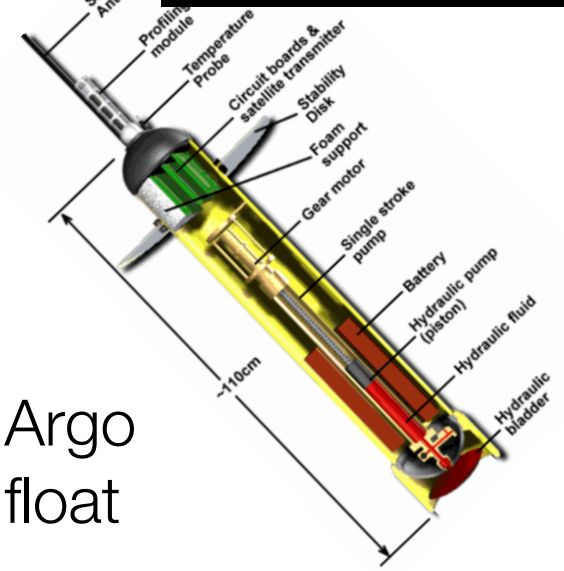

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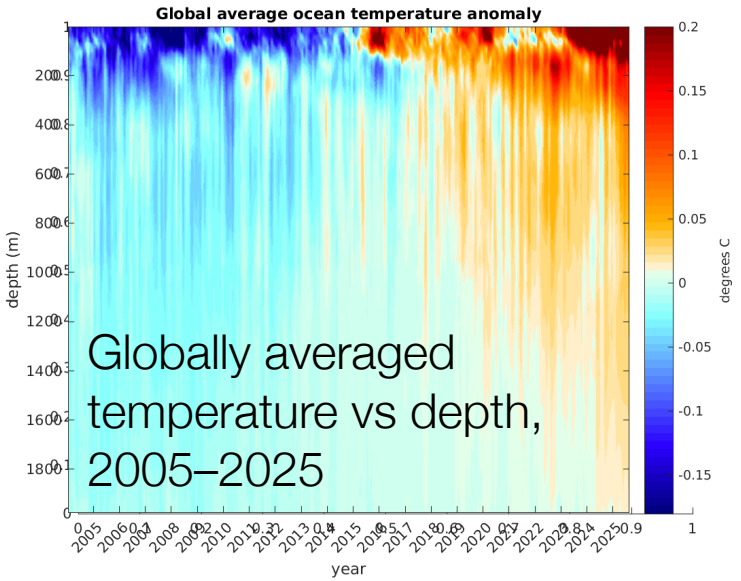

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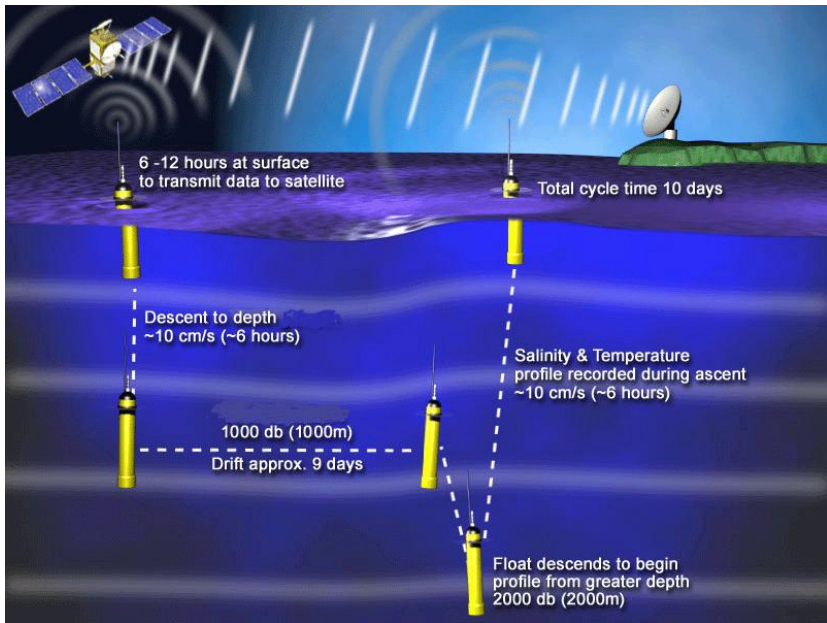
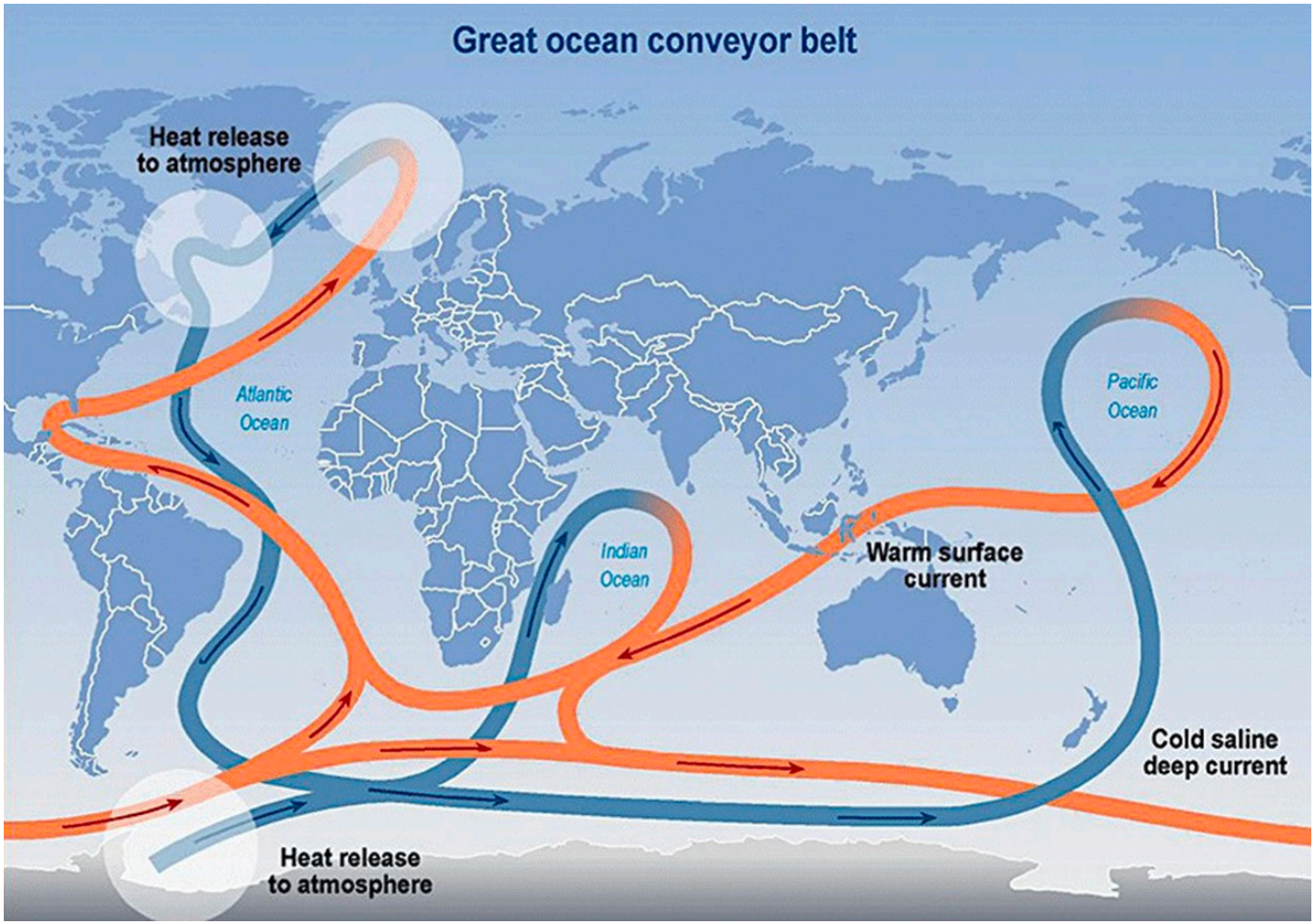


Climate!

- Atlantic Meridional Overturning Circulation
- Abrupt climate change due to AMOC/sea ice changes
- Climate tipping points
- El Niño

Meridional Overturning circulation & Global climate

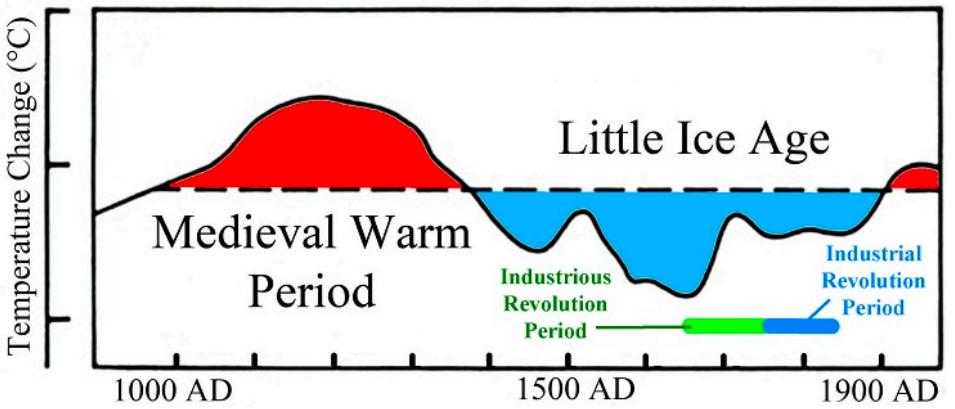
- 20 M ton per second (all world's rivers combined: 1 M)
- Carries a significant part of the heat transport from the equator to the pole
- Its past variations may have caused abrupt climate change.



https://phys.org/news/2018-04-atlantic-ocean-circulation-weakest-years.html

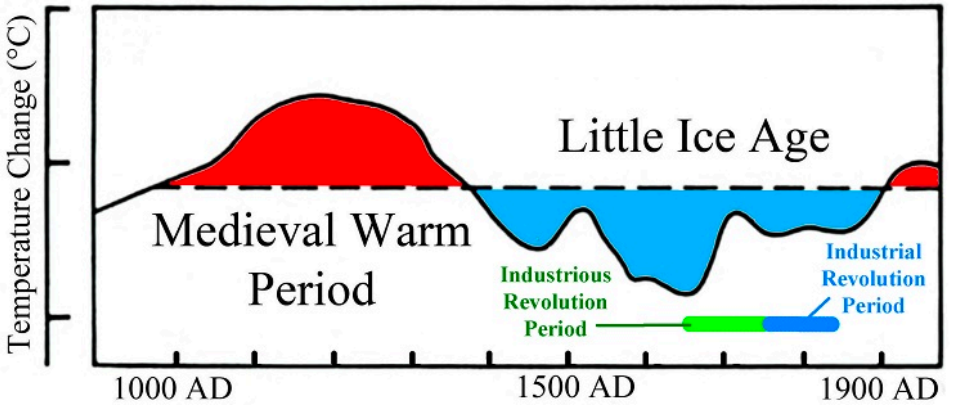
The AMOC and past climate

Europe's Little Ice Age, 14th Century;
Pieter Breugel the Elder.



https://www.gould.com.au/genealogy-and-the-little-ice-age/utp0151/

The AMOC and past climate



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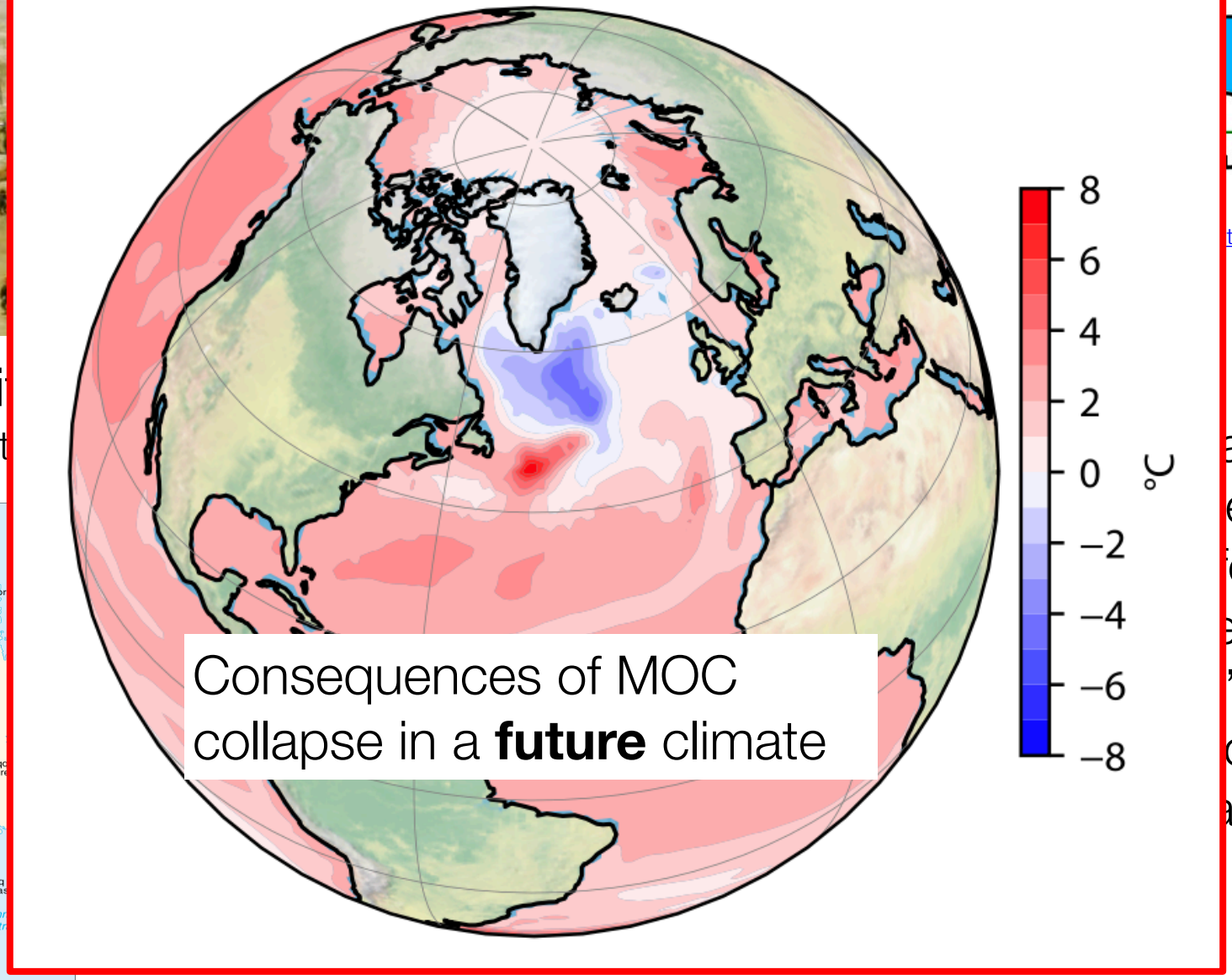
Europe's Little Ice Age, 14th Century;
Pieter Breugel the Elder.

Norse ruins from Brattahlid, Greenland. "Eirik the Red," exiled from Iceland for his crimes, 980 A.D., set sail and spotted "Greenland". ~1,000 Scandinavians lasted until 1480 A.D., suffered starvation due to nasty winters.

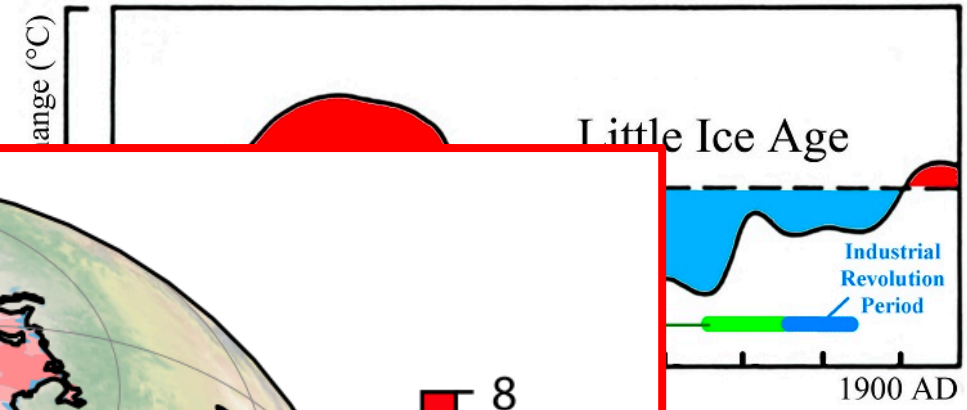
The AMOC and past climate

Europe's Li

Pieter Breugel t



Consequences of MOC collapse in a **future** climate



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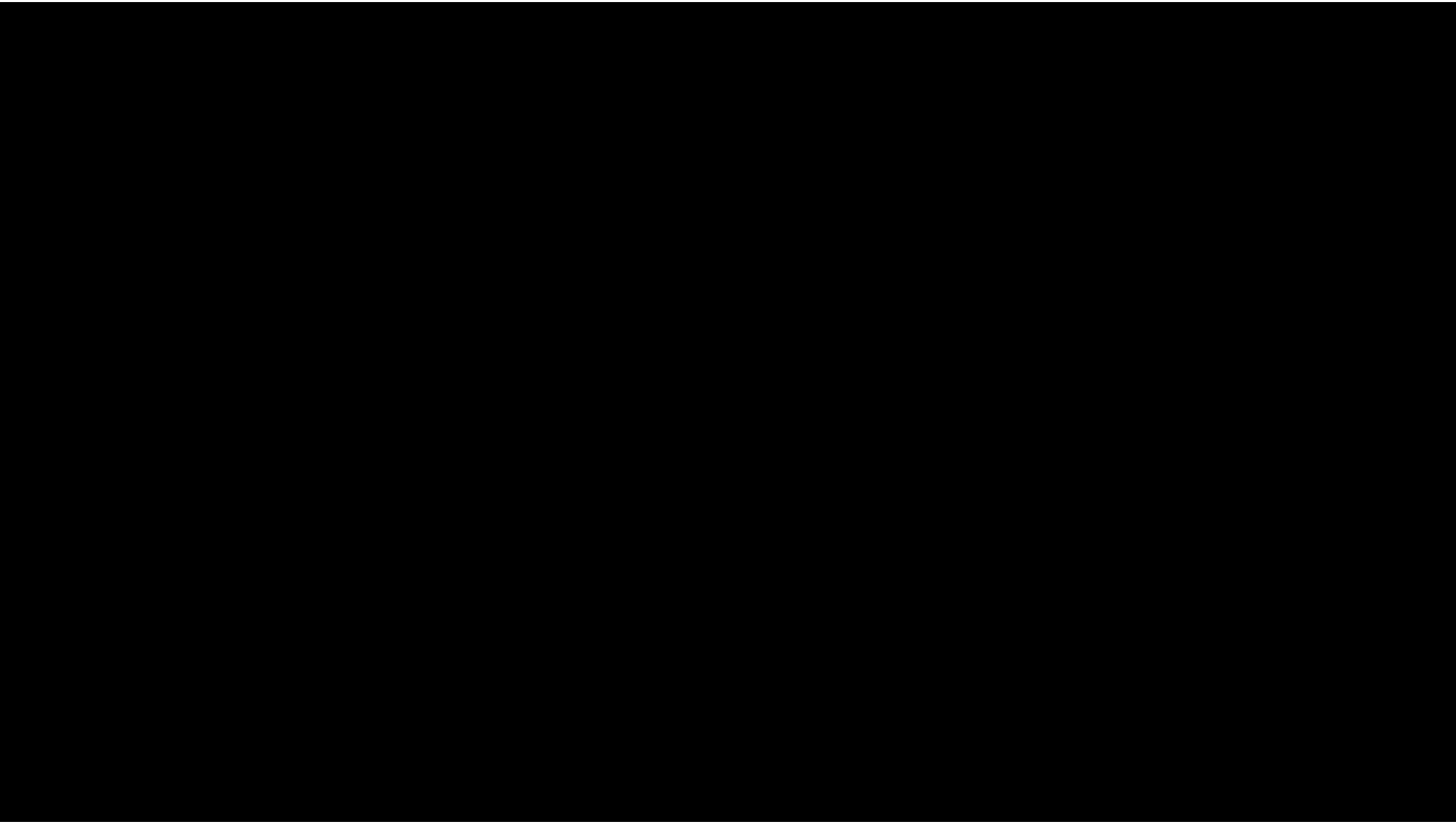
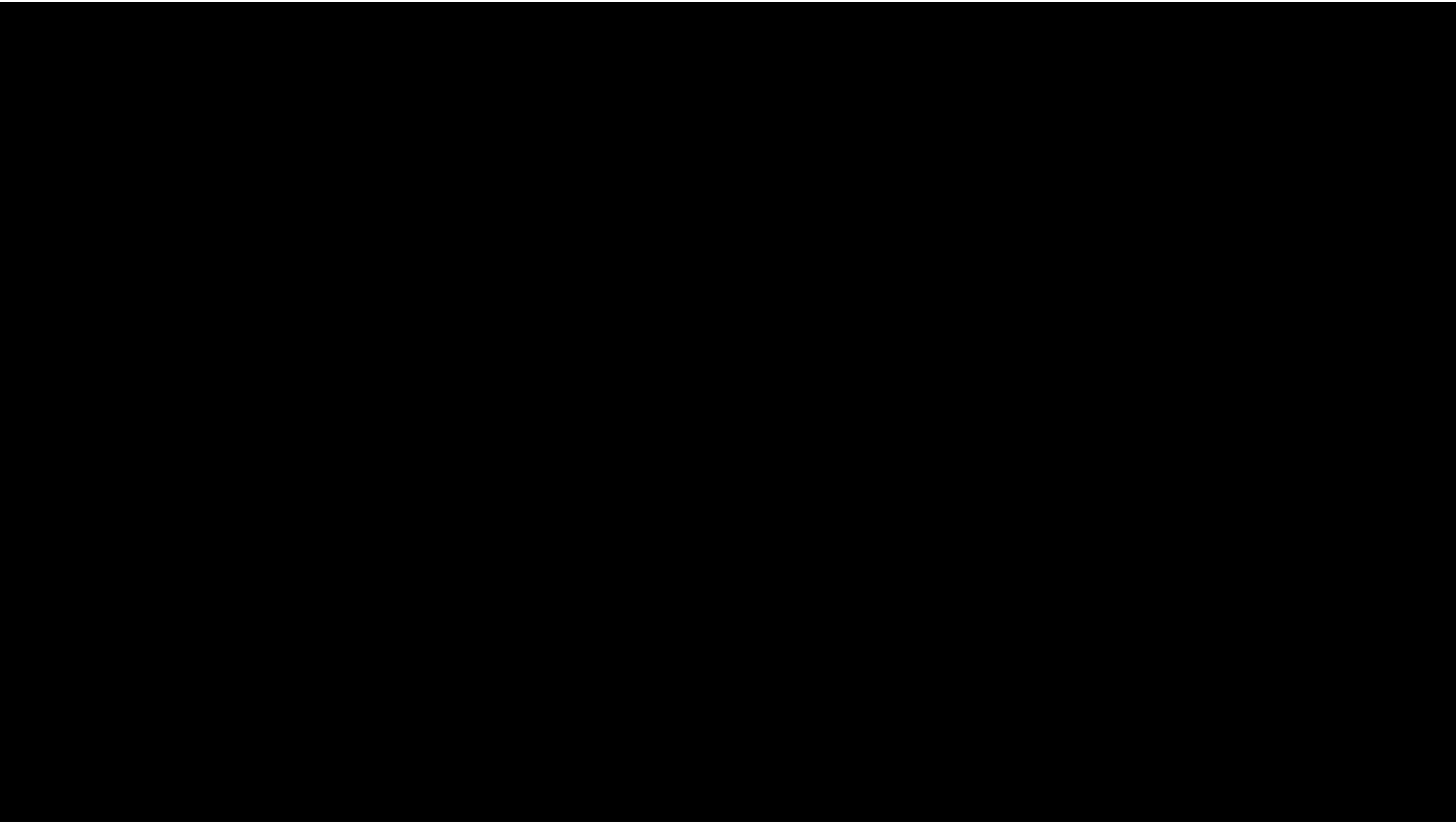
The day after tomorrow



https://www.youtube.com/watch?v=Ku_IseK3xTc

The day after tomorrow



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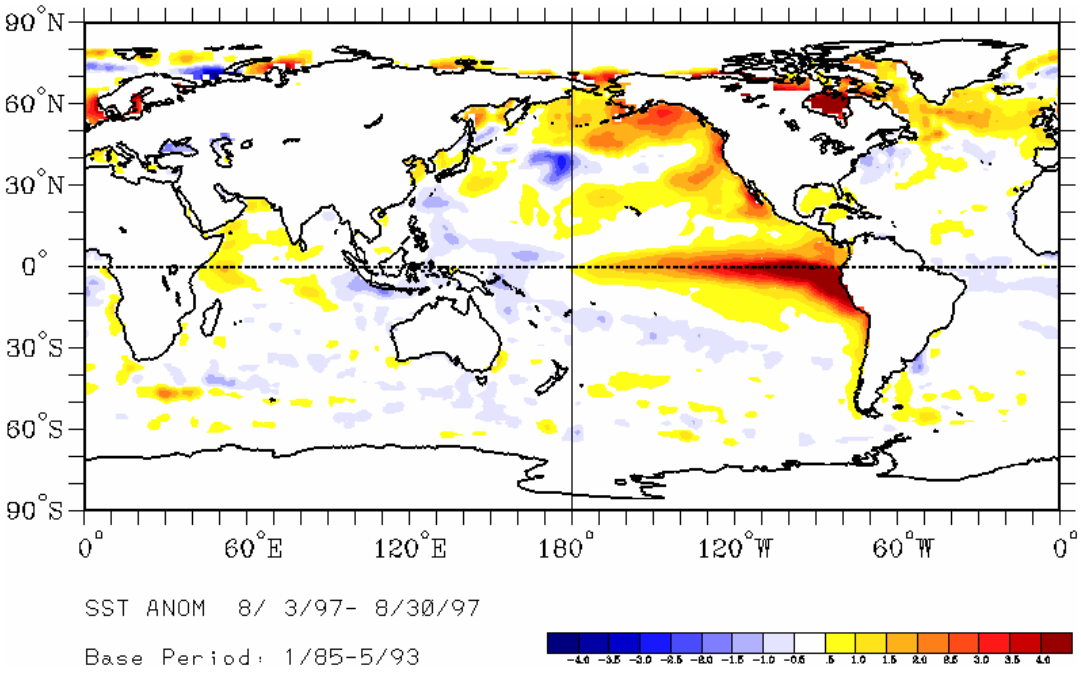
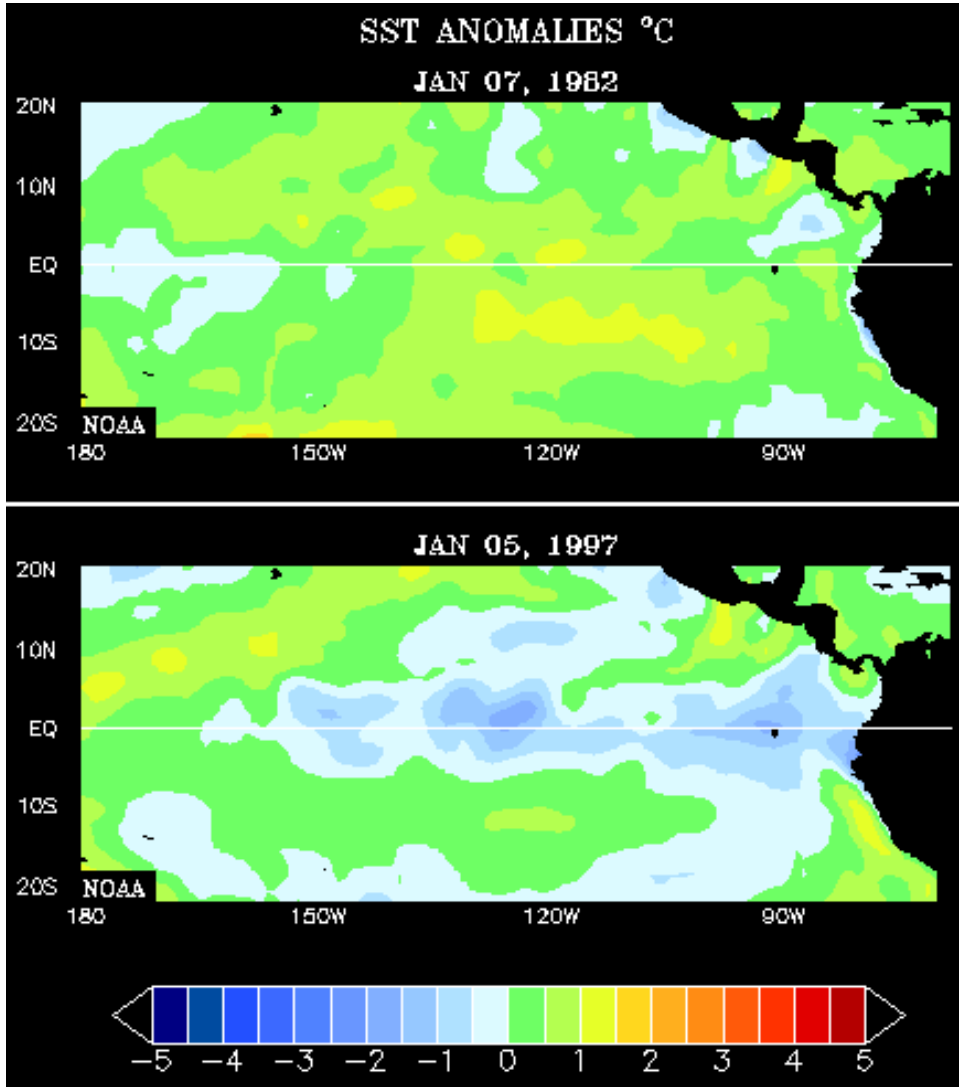
El Niño

El Niño events:

- Ocean waves play a dominant role.
- Occurs every 2–7 years.
- Irregular cycle, difficult to predict.



Observed sea surface temperature anomaly during 1997 event



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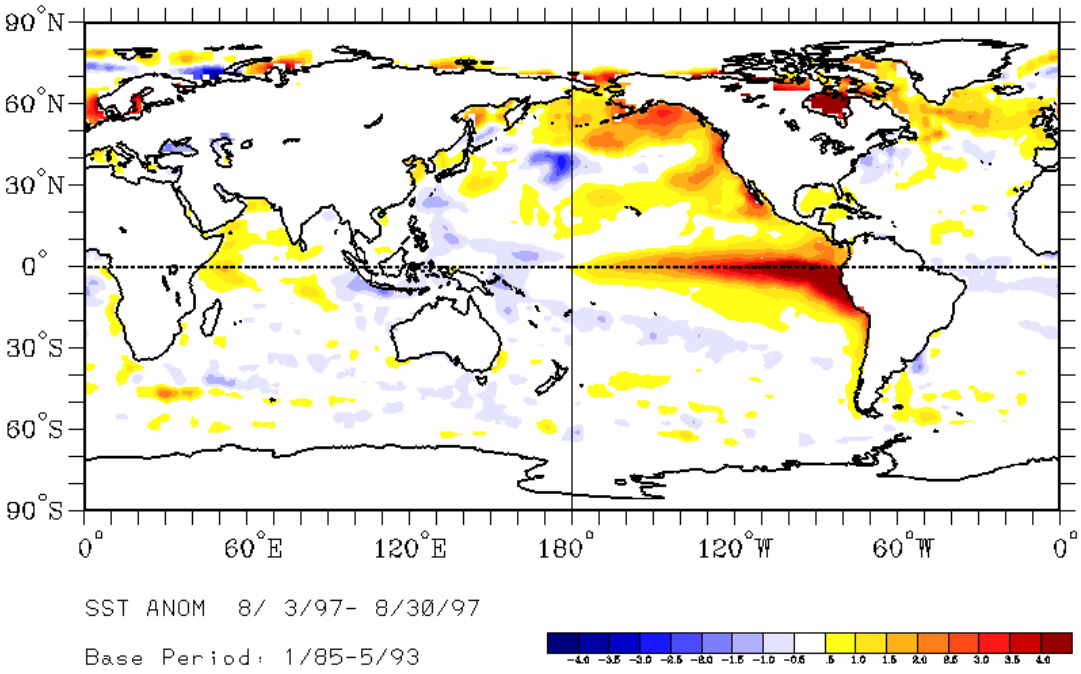

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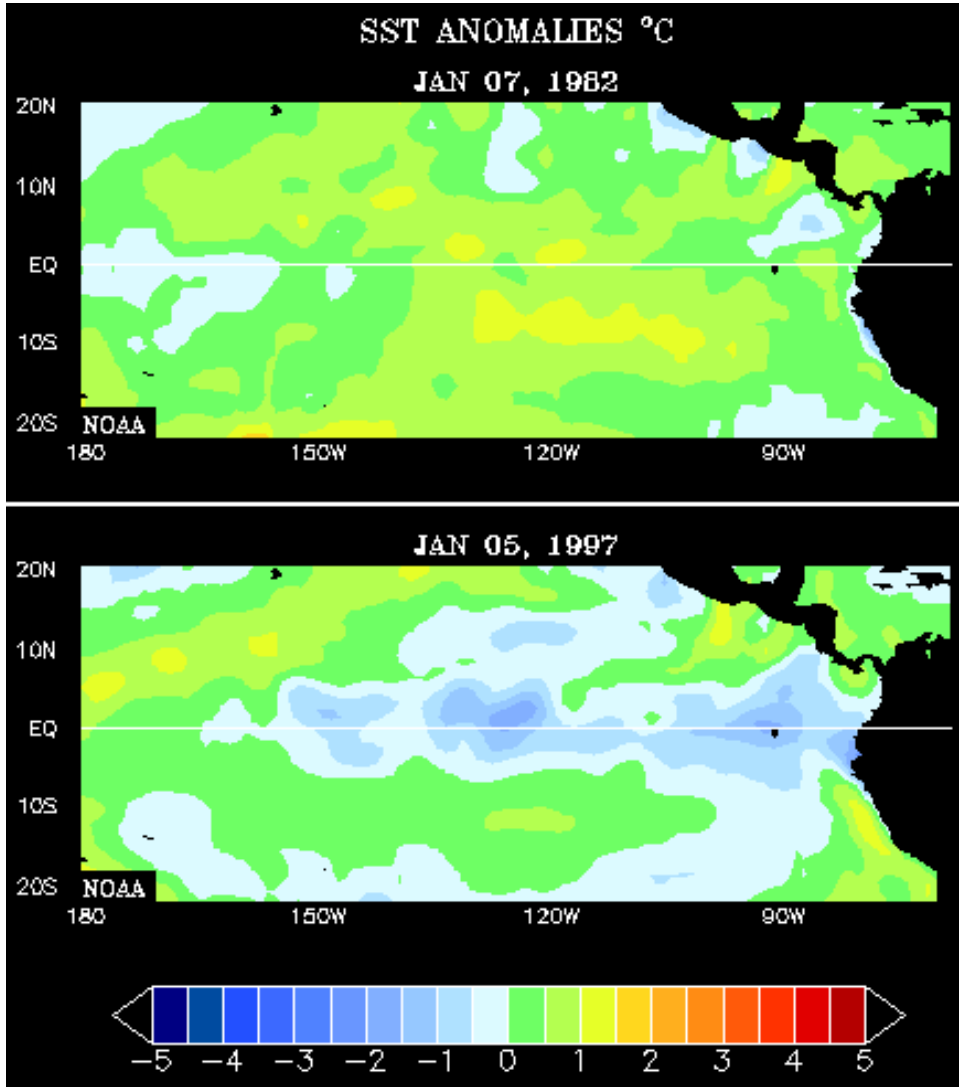
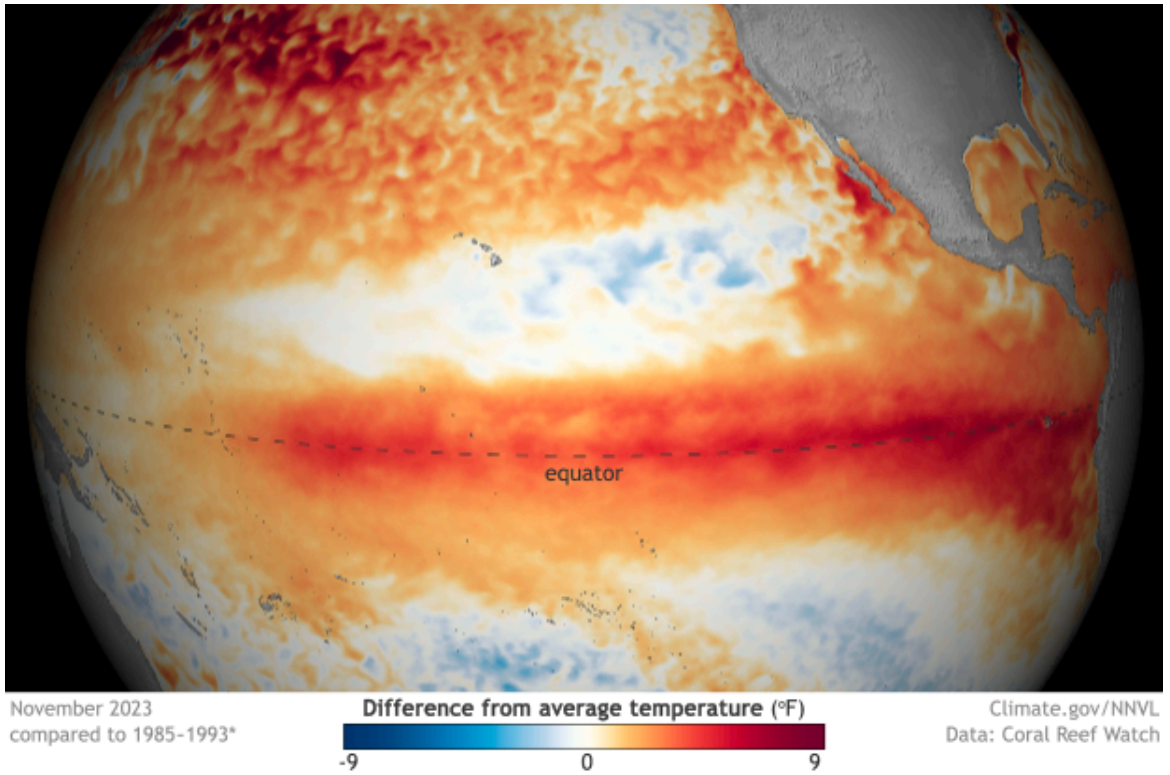


Observed sea surface temperature during 1982 & 1997 events

Observations, is El Niño changing?



Current conditions (Dec 2025): A La Niña advisory!

https://www.climate.gov/enso

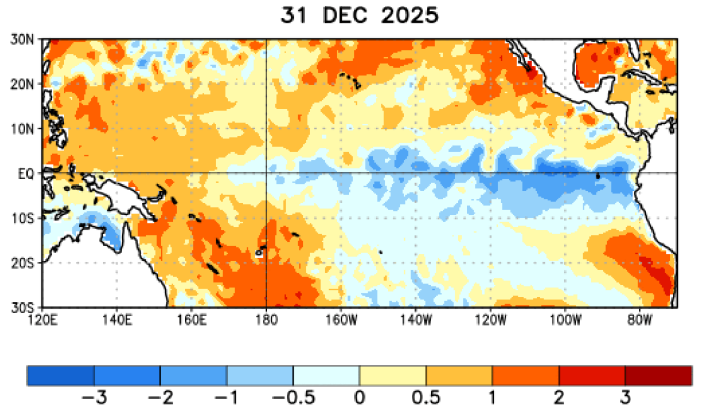


Figure 1. Average sea surface temperature (SST) anomalies (°C) for the week centered on 31 December 2025. Anomalies are computed with respect to the 1991-2020 base period weekly means.

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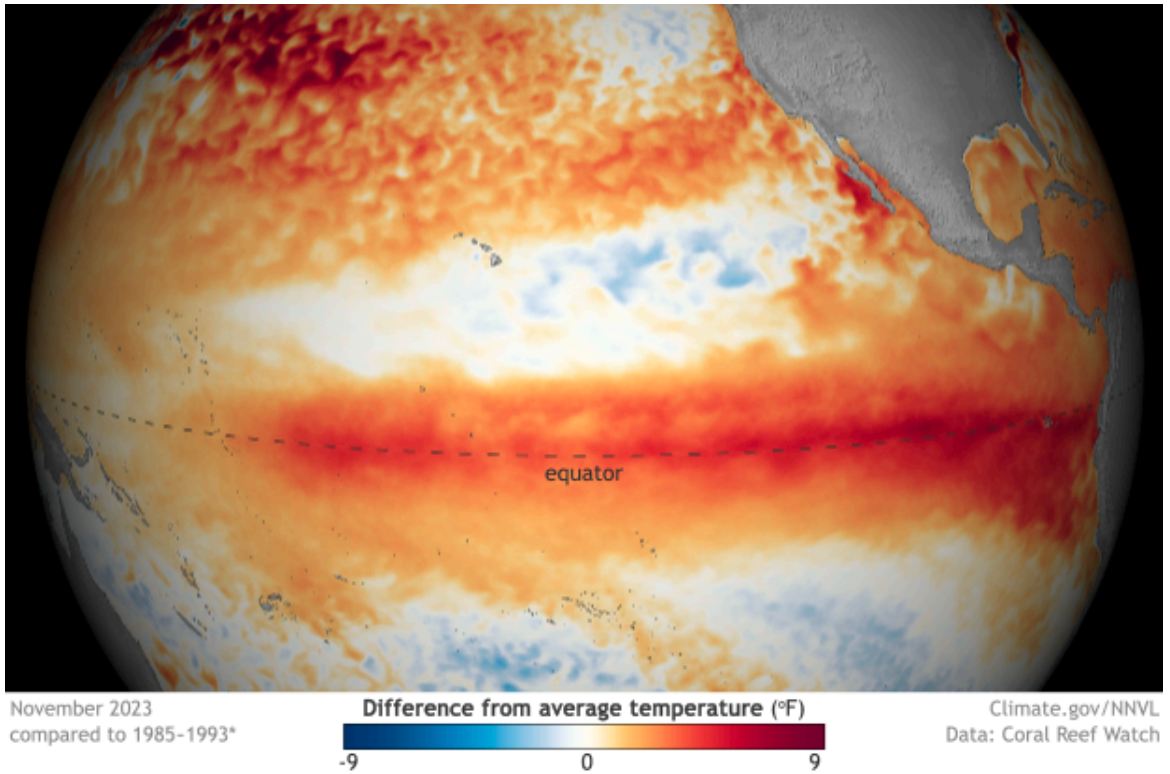

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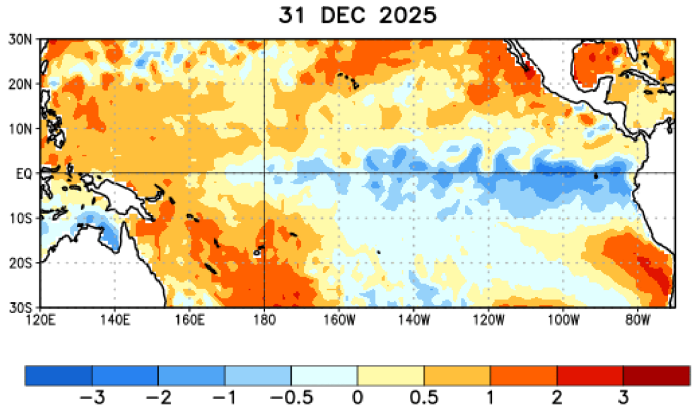

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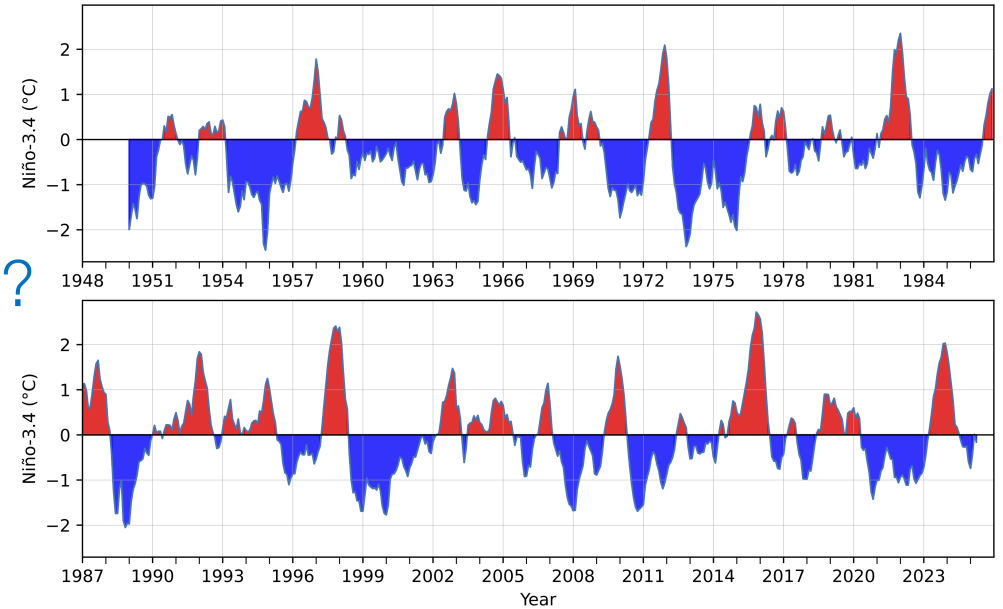

Back to the future

Ocean's role in global warming

- Sea level rise
- Abrupt climate change:
  - Sea ice;
  - AMOC
- Absorbing ¼ of emitted CO_2, ~95% of heat
- Ocean acidification

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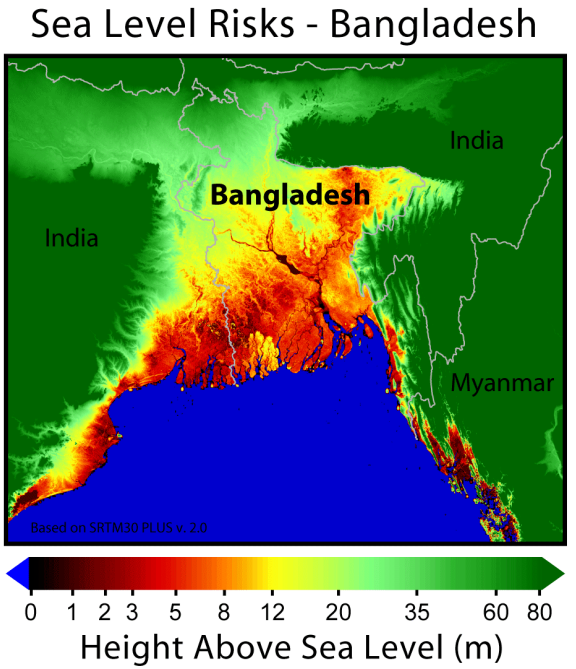

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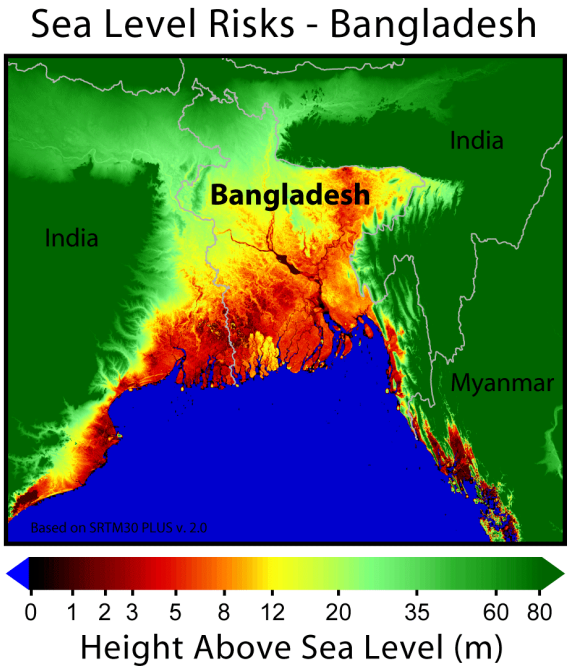

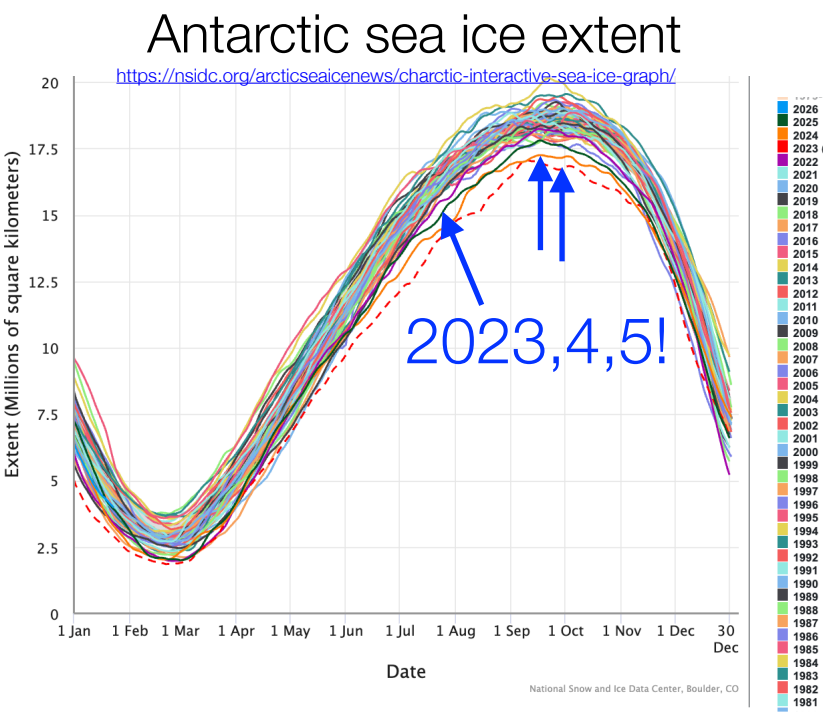

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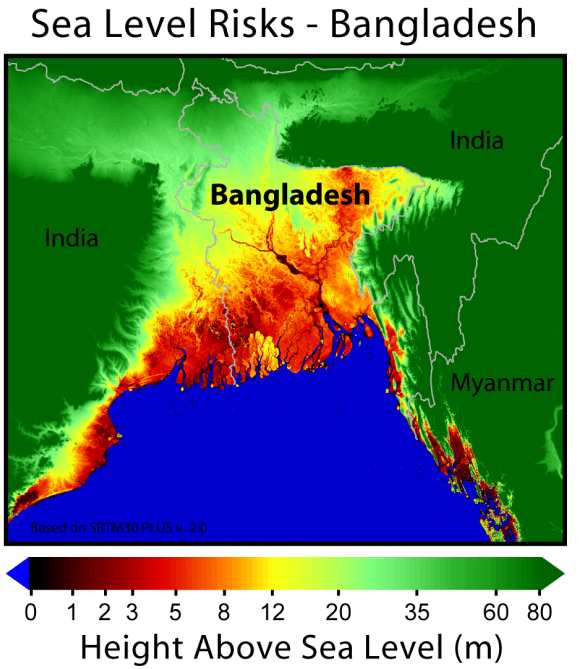

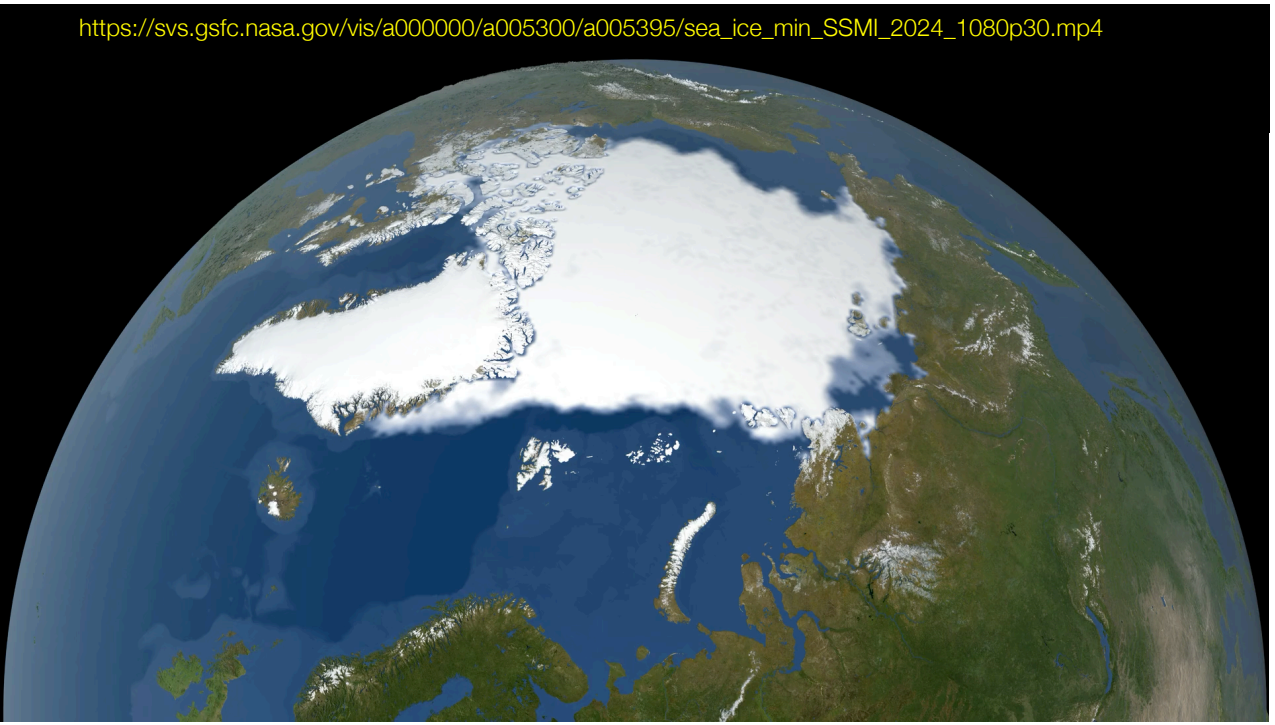

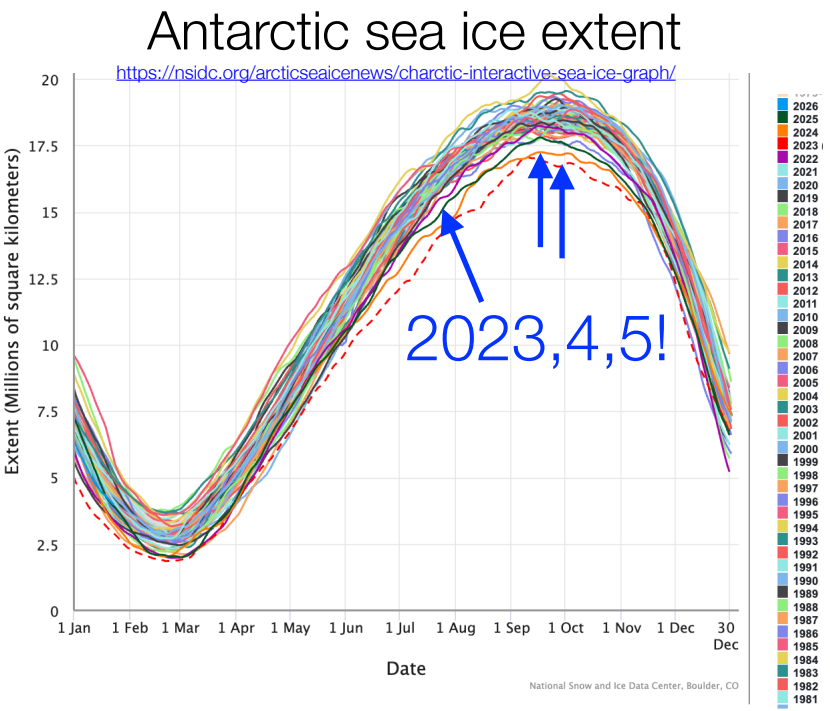

Navier-Stokes equations for fluid motion

The good old $F = ma$ is, for fluids,

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\nabla\mathbf{u} + 2\Omega \times \mathbf{u} = -\frac{1}{\rho}\nabla P + \rho\mathbf{g} + \nu\nabla^2\mathbf{u}$$

where $\mathbf{u} = (u, v, w)$ is the velocity vector, P pressure, ρ density, $\mathbf{g}$ gravity, Ω Earth rotation rate, $f = 2\Omega \sin\theta$ the Coriolis parameter... can also write this as

$$\begin{aligned}
\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv &= -\frac{1}{\rho}\frac{\partial P}{\partial x} + \nu\nabla^2 u \\
\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu &= -\frac{1}{\rho}\frac{\partial P}{\partial y} + \nu\nabla^2 v \\
\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} &= -\frac{1}{\rho}\frac{\partial P}{\partial z} + g\rho + \nu\nabla^2 u
\end{aligned}$$

Fluid mass and energy (heat) are conserved

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\mathbf{u}\rho) = 0; \qquad \frac{\partial T}{\partial t} + \mathbf{u}\nabla\mathbf{T} = \kappa\nabla^2 T$$

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$$\nu\nabla^2 v$$

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A simpler subset of these equations will be gradually introduced & used to understand major ocean phenomena

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Let the fun begin…