

Introduction to physical oceanography & climate

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

Eli Tziperman

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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: Elle Weeks, elleweeks@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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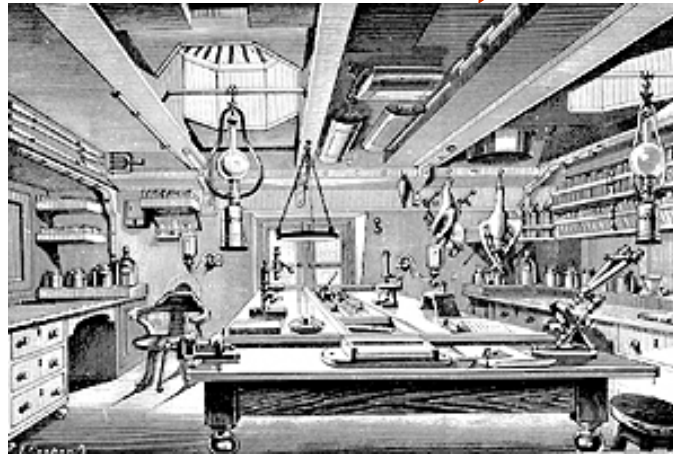
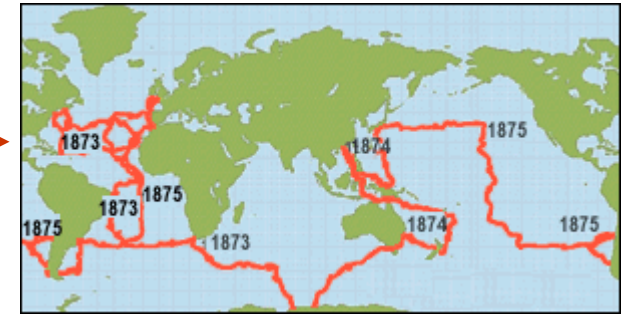
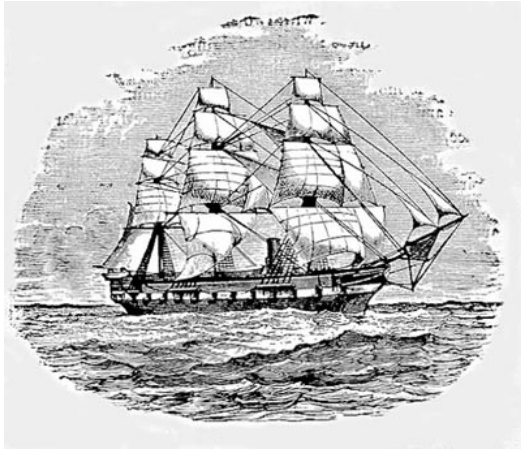
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Origins... and today

The first oceanographic expedition:
H.M.S. Challenger 1872–6

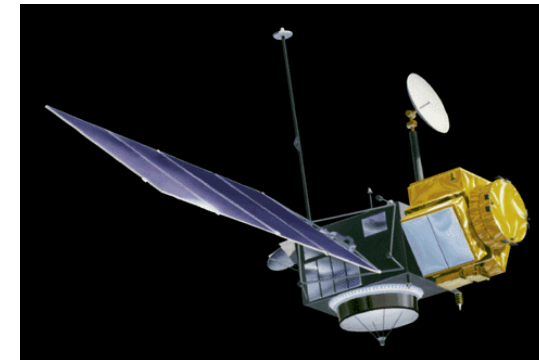
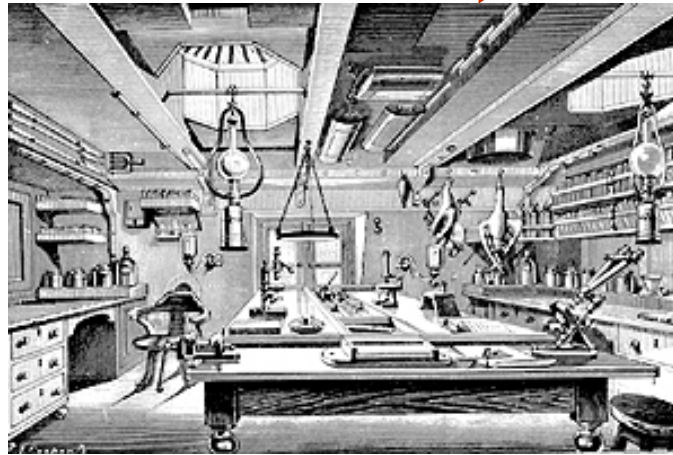
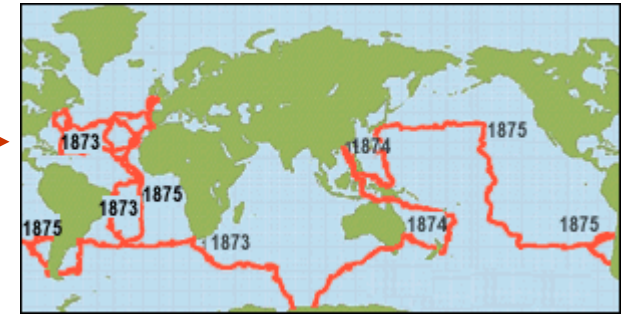
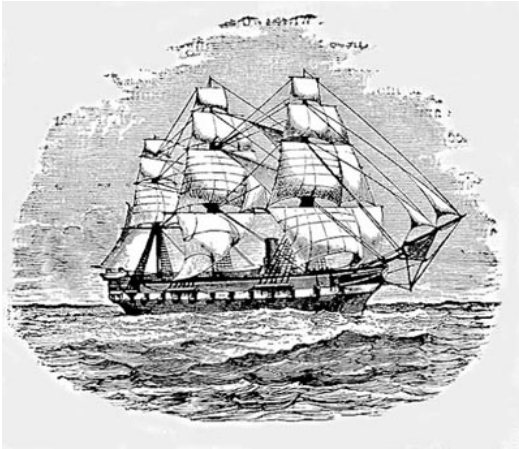
250 crew (incl. fifty 15-yr old);
30 miles of sounding line (ropes)



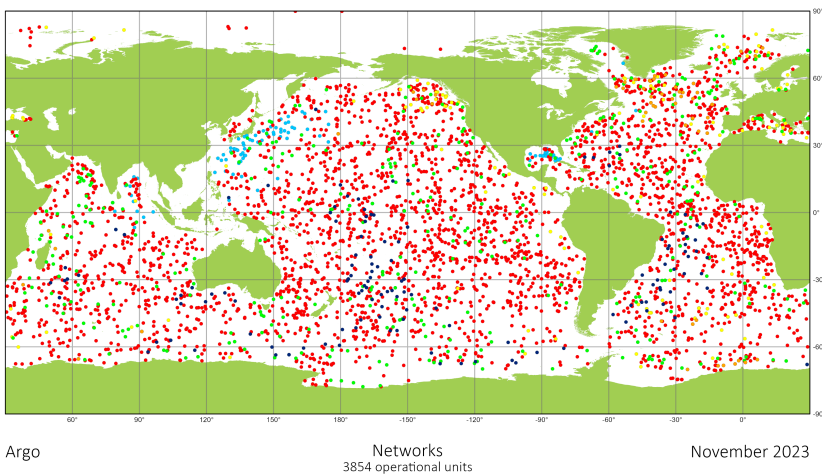
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Today: Autonomous floats continuously sampling the upper ocean; multiple satellites; super computers



temperature, salinity | currents, Coriolis | waves | observations | climate

Outline

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- Ocean phenomena we would like to understand:
 - What drives major ocean currents, such as the Gulf Stream?
 - Waves: from beach waves to tides and tsunamis.
 - Large-scale ocean temperature and salinity; their relation to climate.

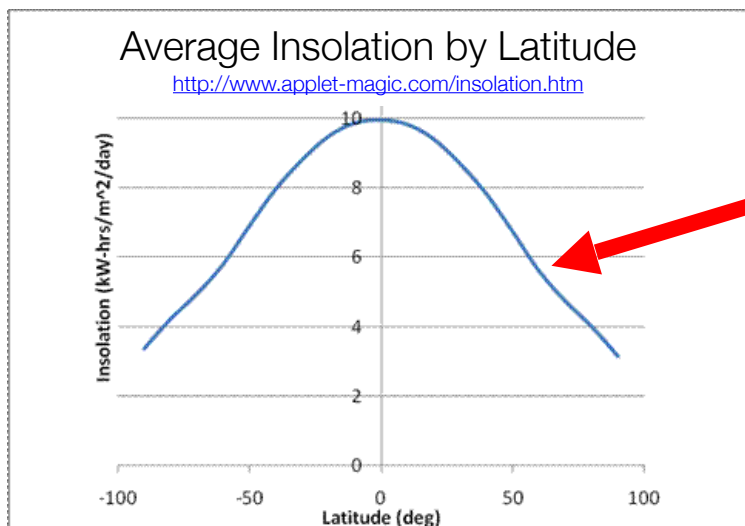
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 - El Niño.
 - The Meridional Overturning Circulation, abrupt climate change, climate tipping points.
 - The ocean's role in future global warming.
- How we observe:

Outline

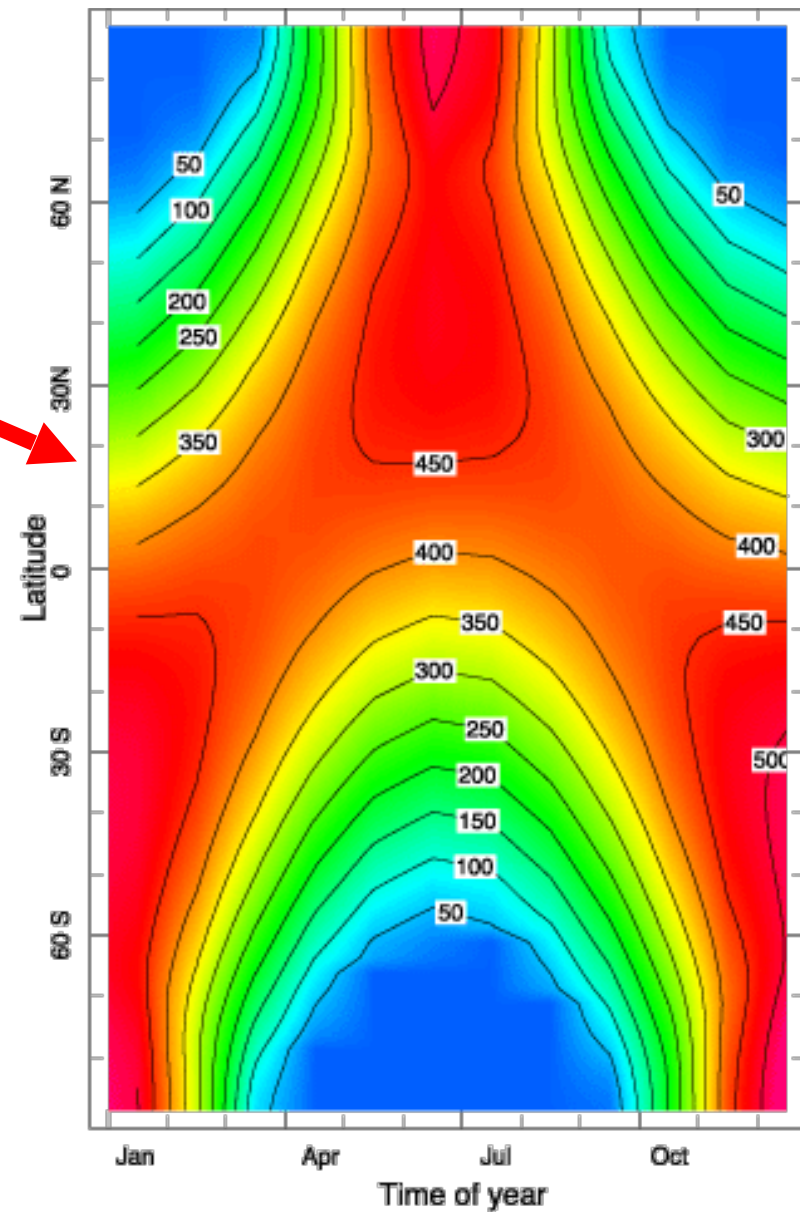
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 - The ocean's role in future global warming.
- How we observe:
 - Ships, satellites, airplanes, moorings, current meters, buoys, floats.

Temperature



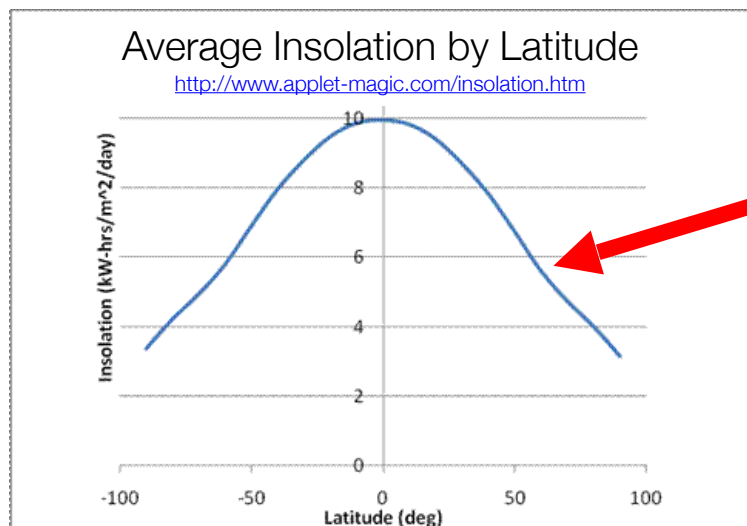
Solar radiation as a function of latitude and month...

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



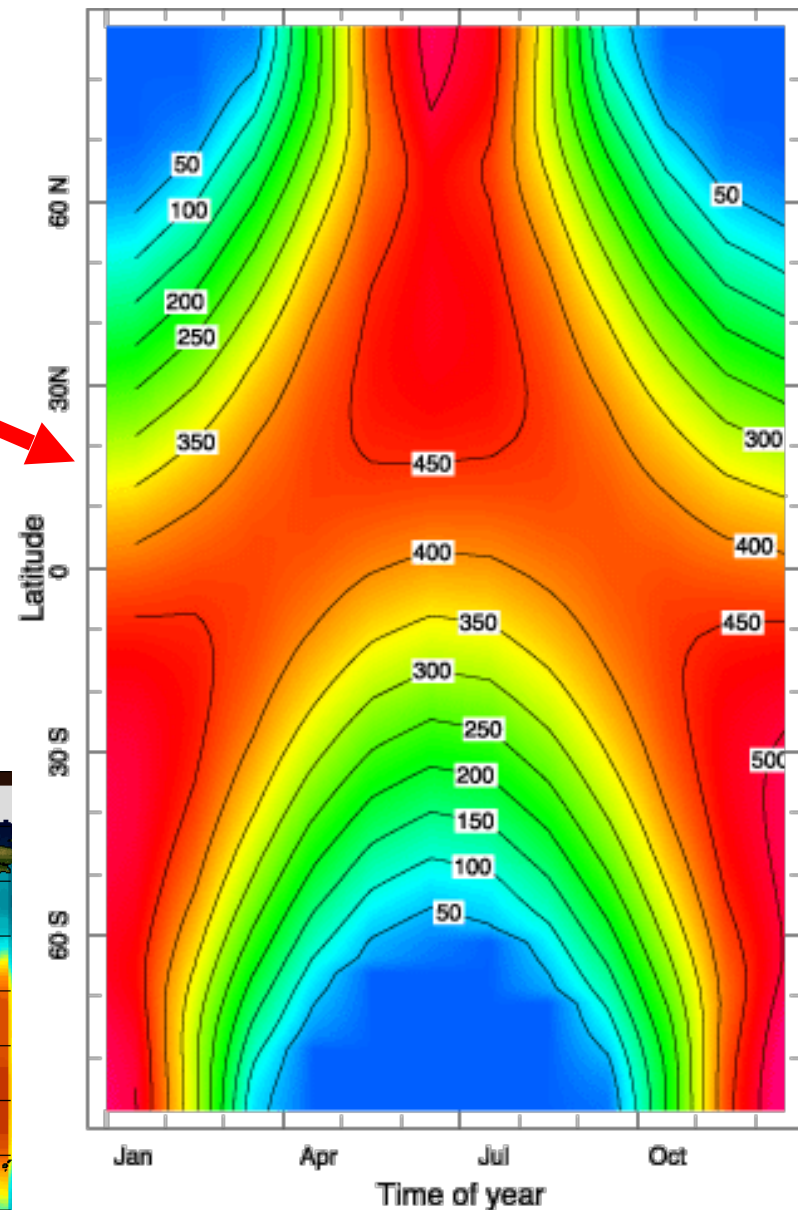
Based on ERBE data. Units are W/m²

Temperature



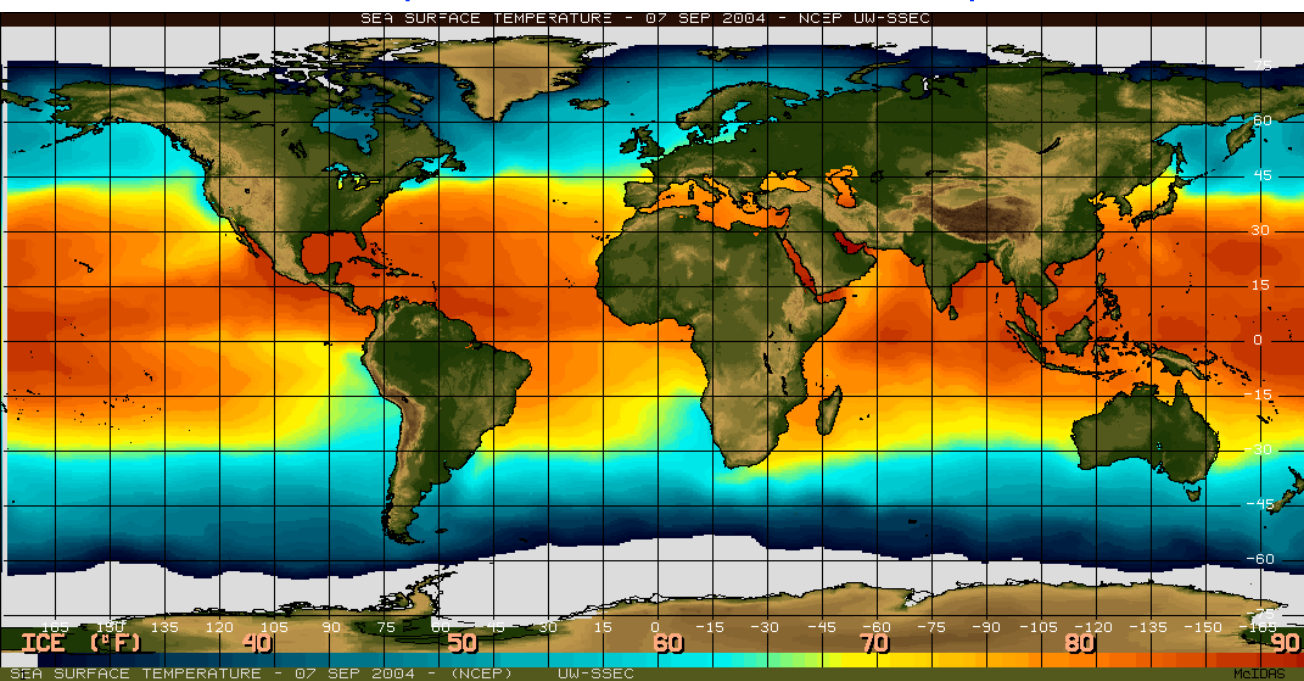
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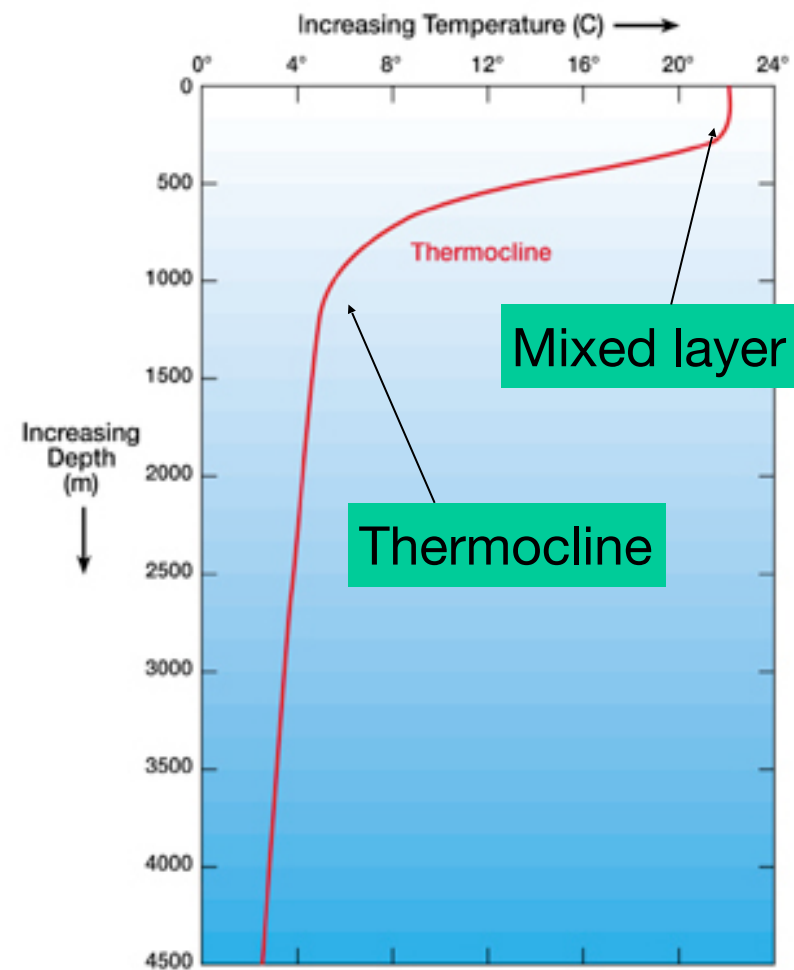


Based on ERBE data. Units are W/m²

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



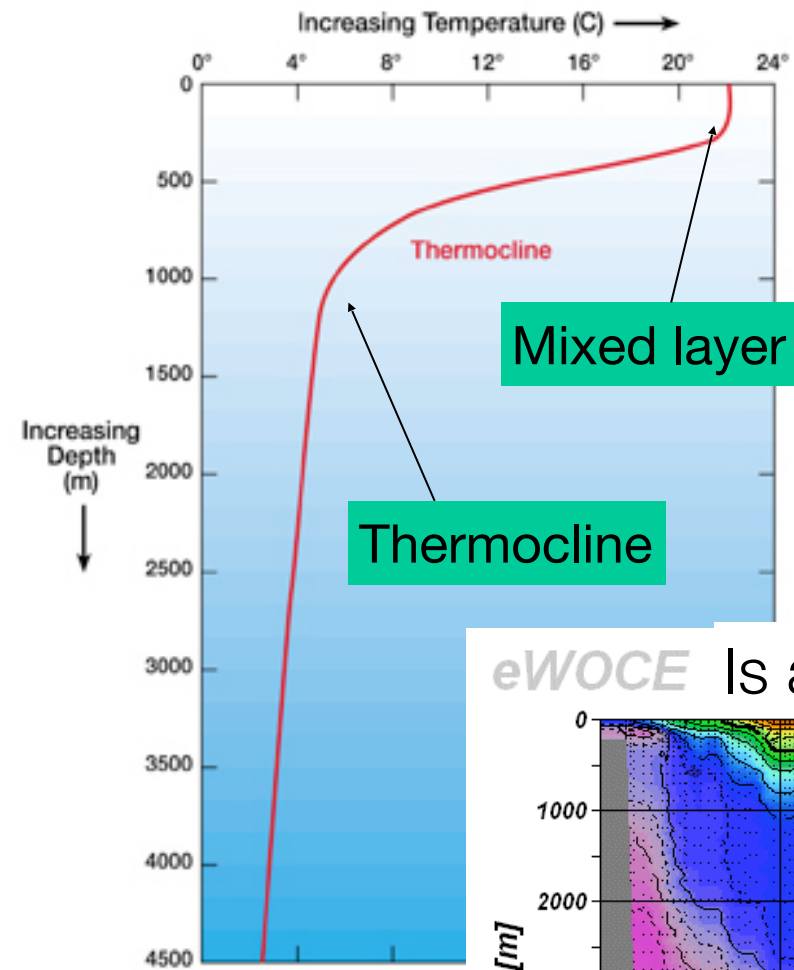
Temperature



Vertical temperature profile

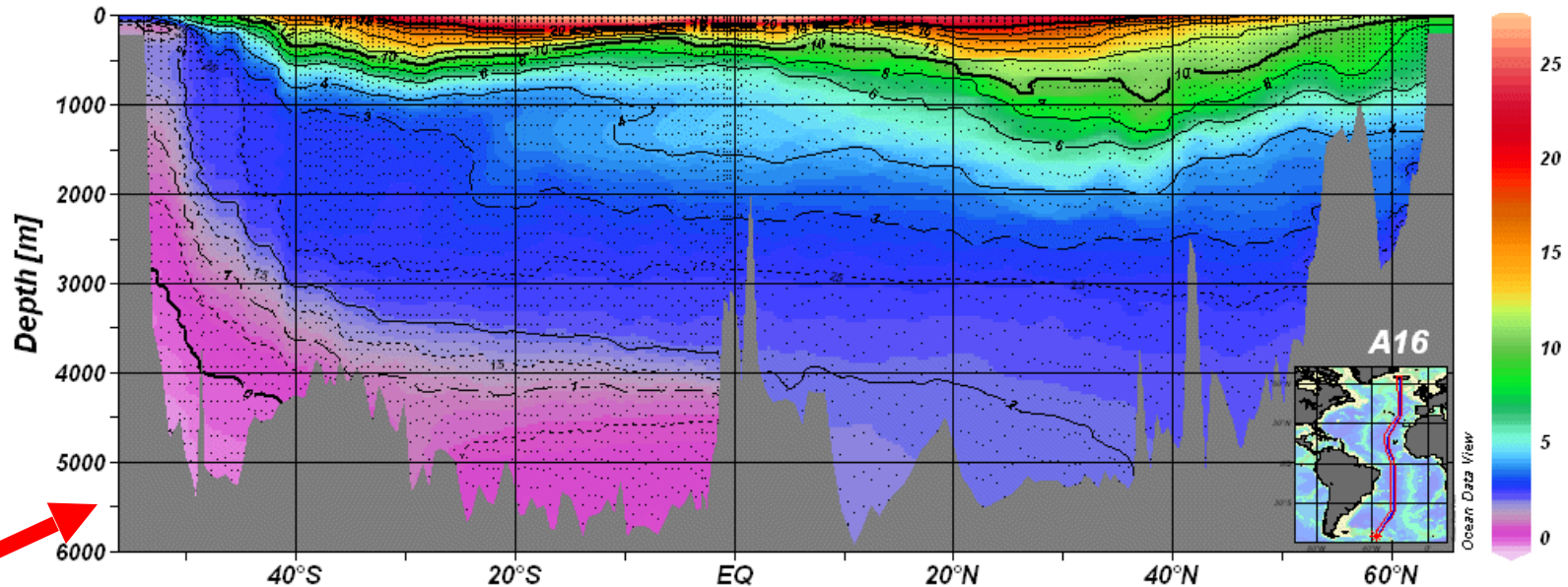


Temperature



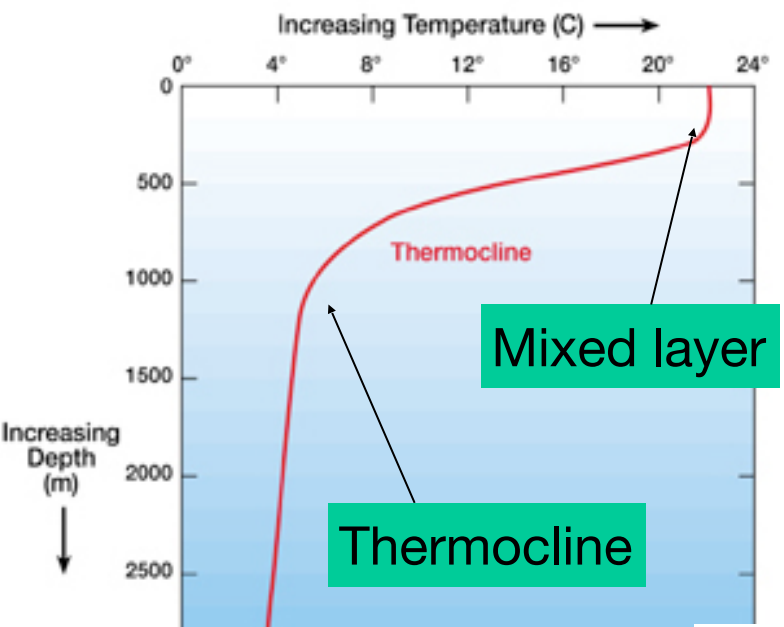
Vertical temperature profile

eWOCE Is an evidence for a meridional circulation



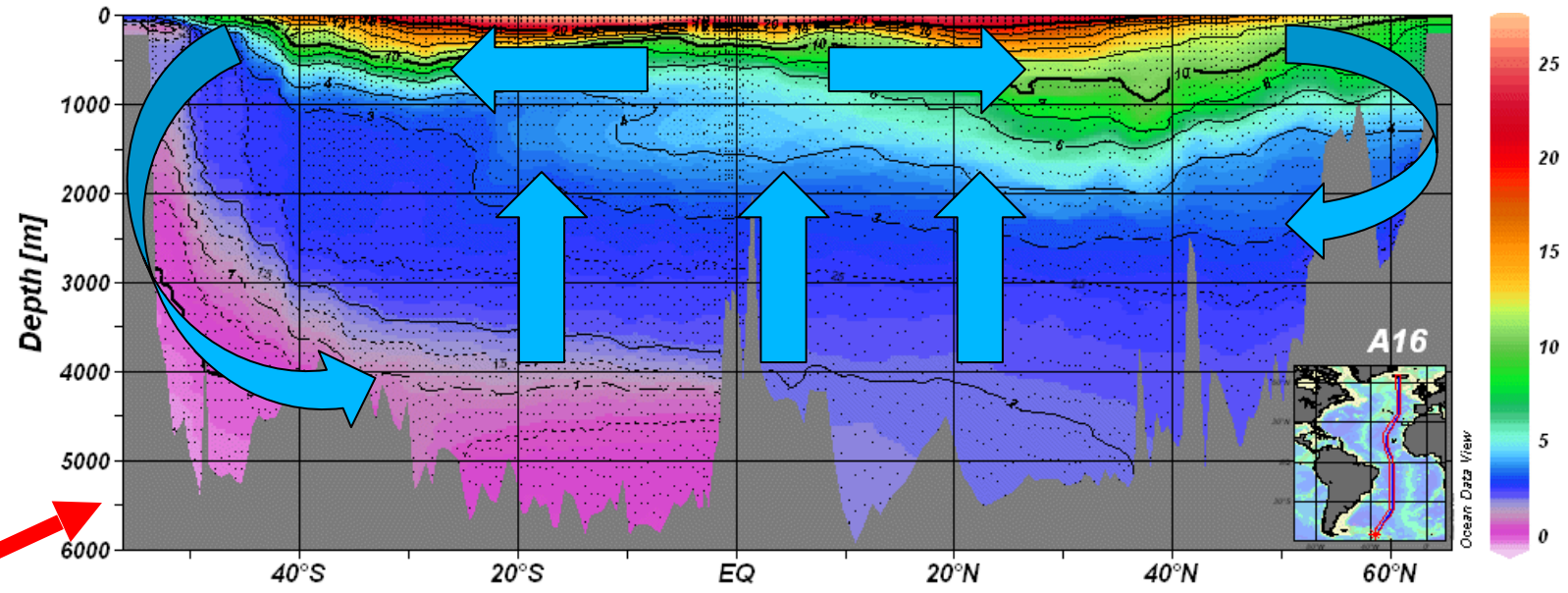
North-South Section. Bottom temperature is near 0 deg even at Equator

Temperature



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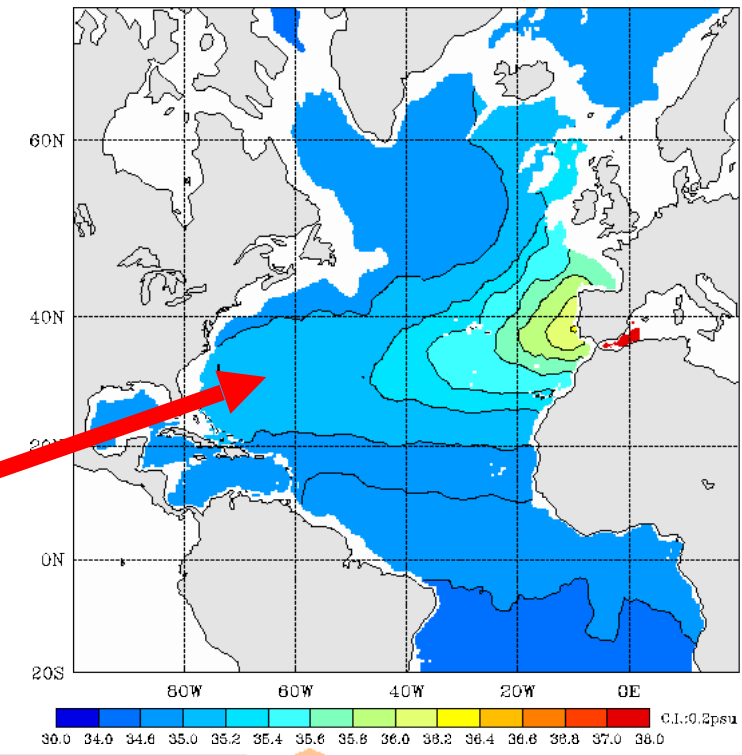
Salinity

?? kg salt/meter cubed

Evaporation, precipitation, ice melt...

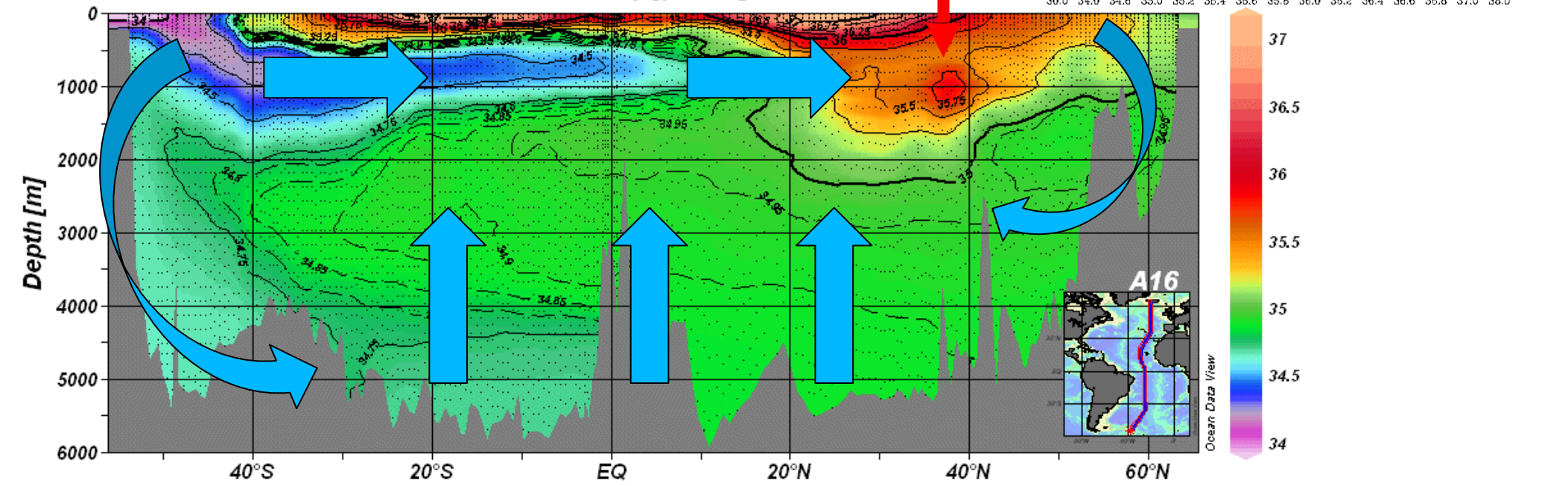
lead to salinity variations in space and time:

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



eWOCE

Salinity [pss-78]

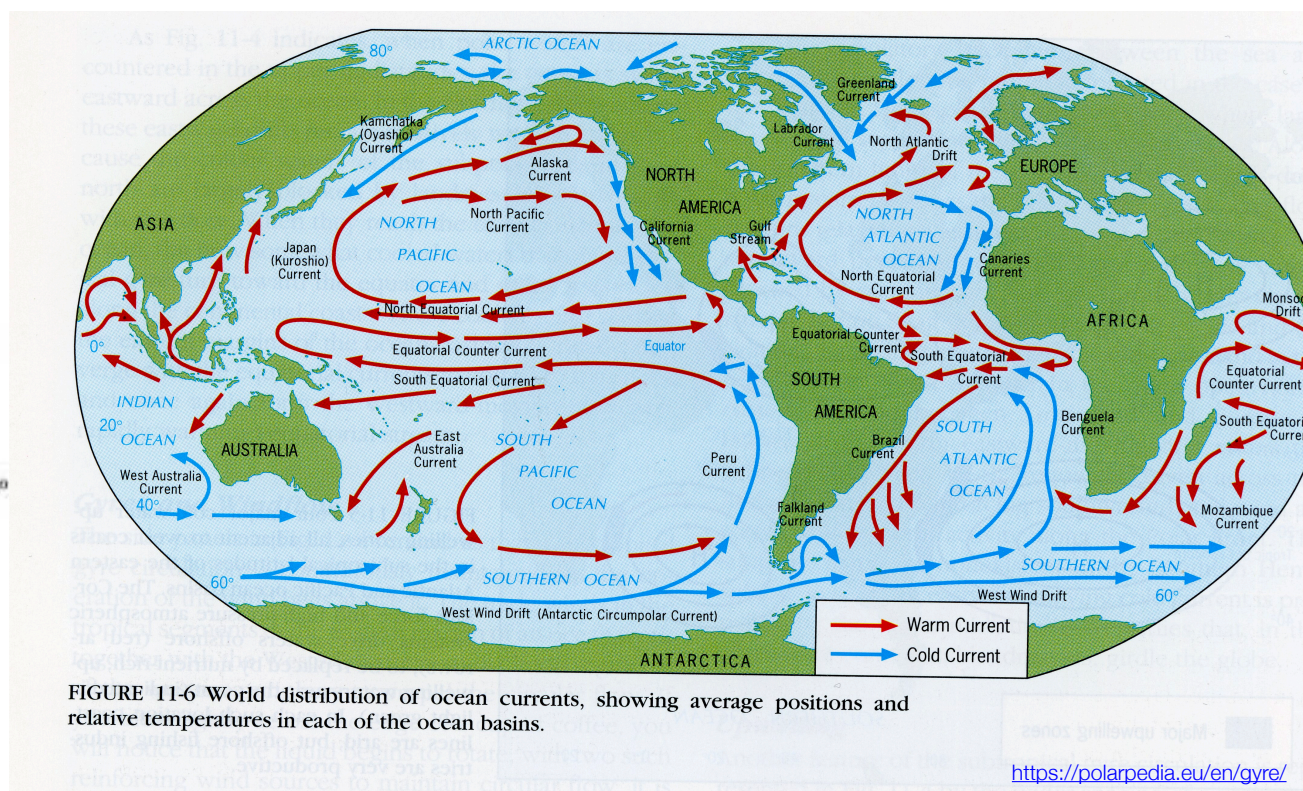
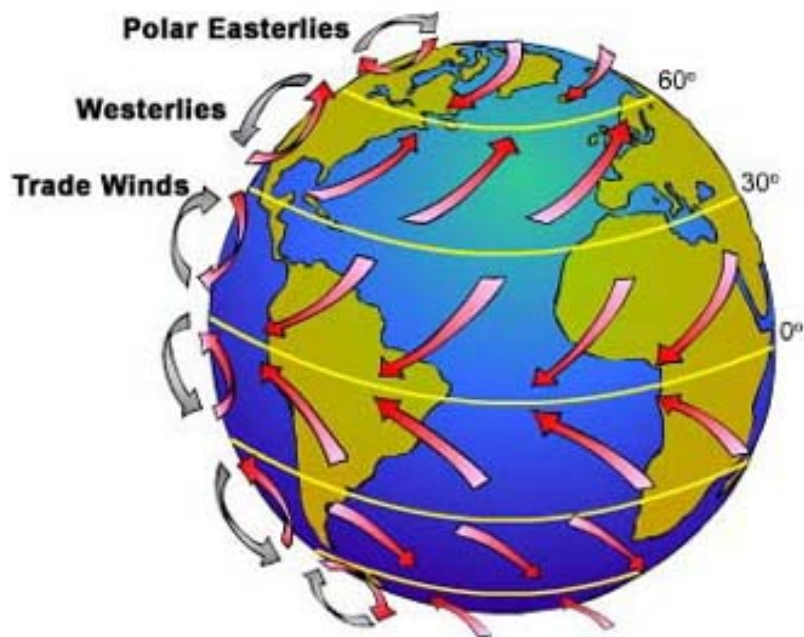


Salinity along Atlantic ocean, vertical axis exaggerated by x1000s

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

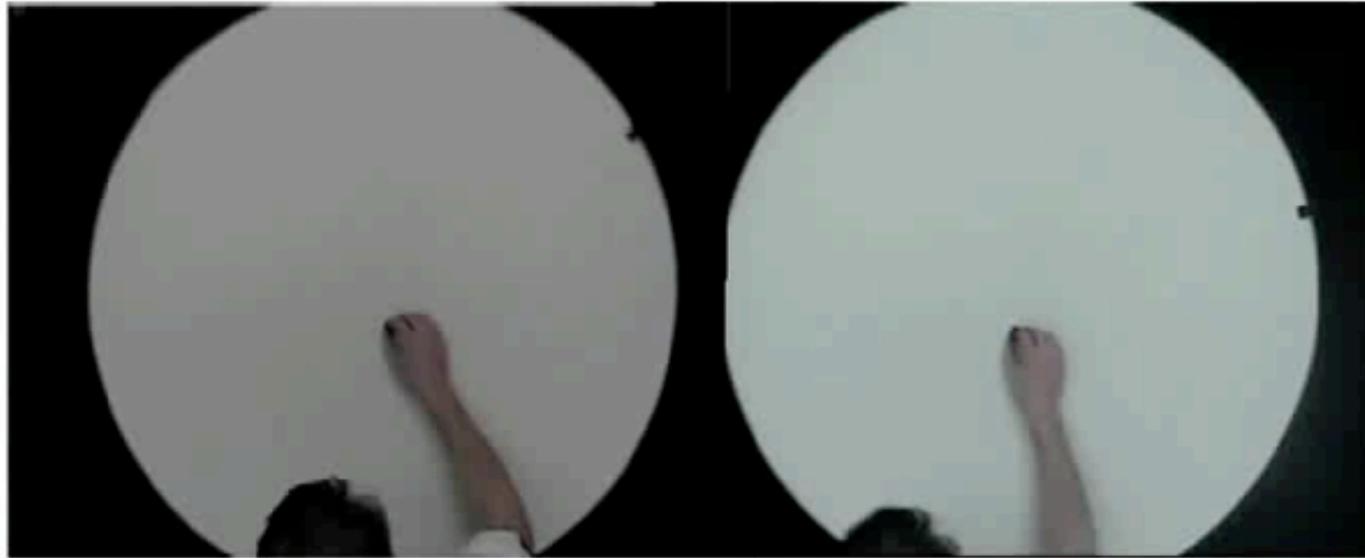
...drive global circulation

Global winds...



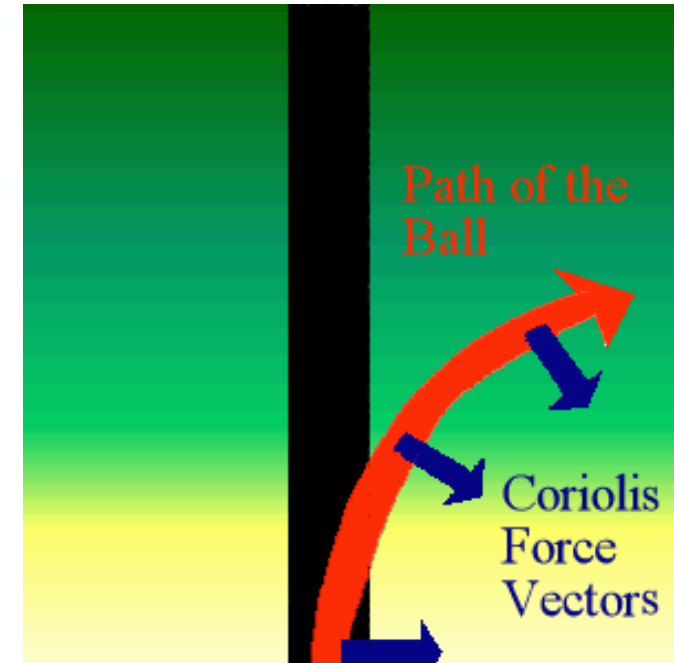
schematic of wind-driven ocean gyres

The Coriolis force



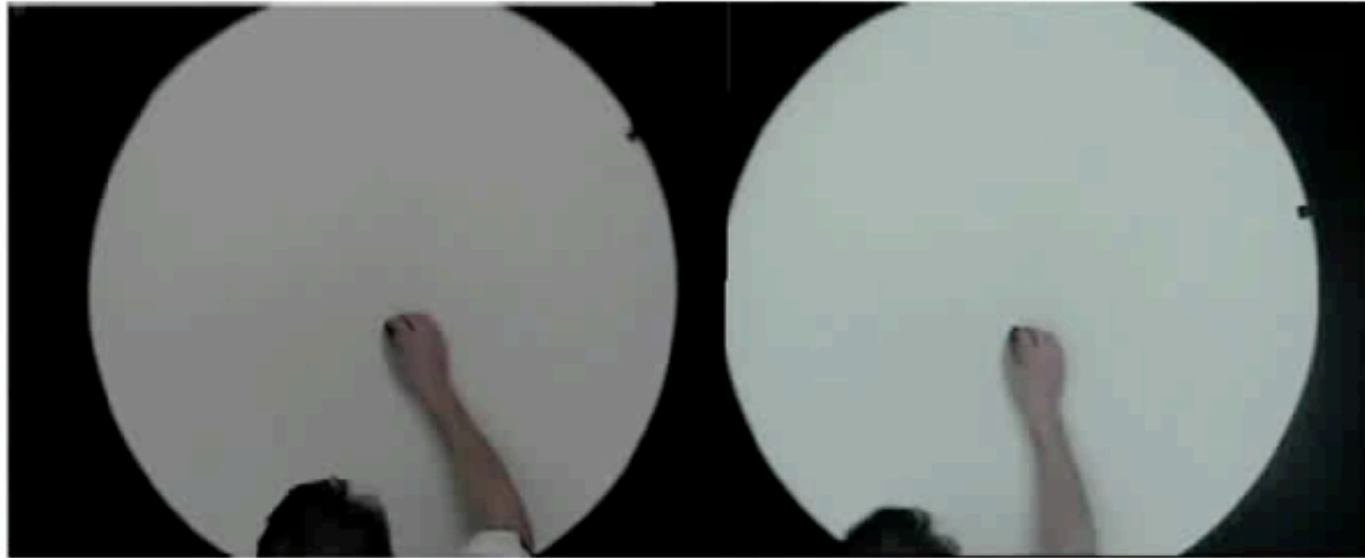
(<https://www.youtube.com/watch?v=RrWKS0vqV-0> J. Marshall, MIT)

Ocean currents
are driven by
Earth rotation &
resulting Coriolis
force



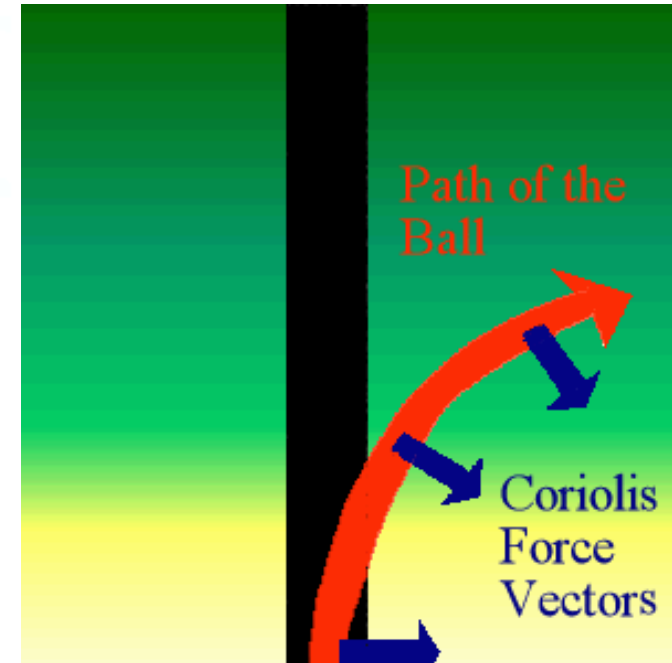
Coriolis force is to right
of motion in north
hemisphere; left in south

The Coriolis force



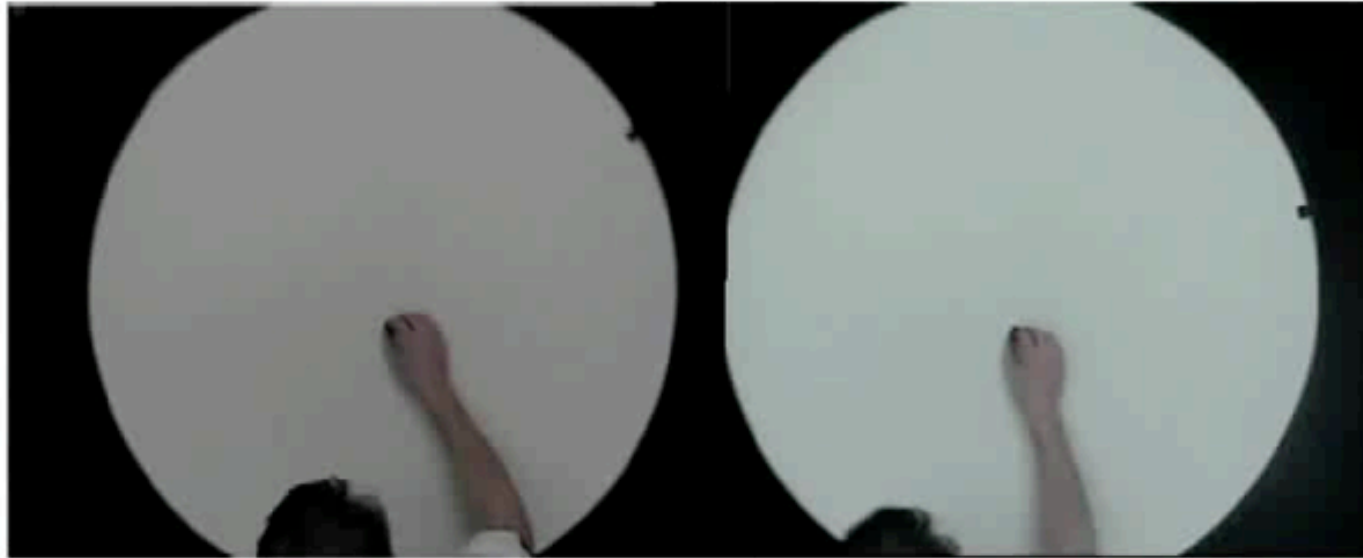
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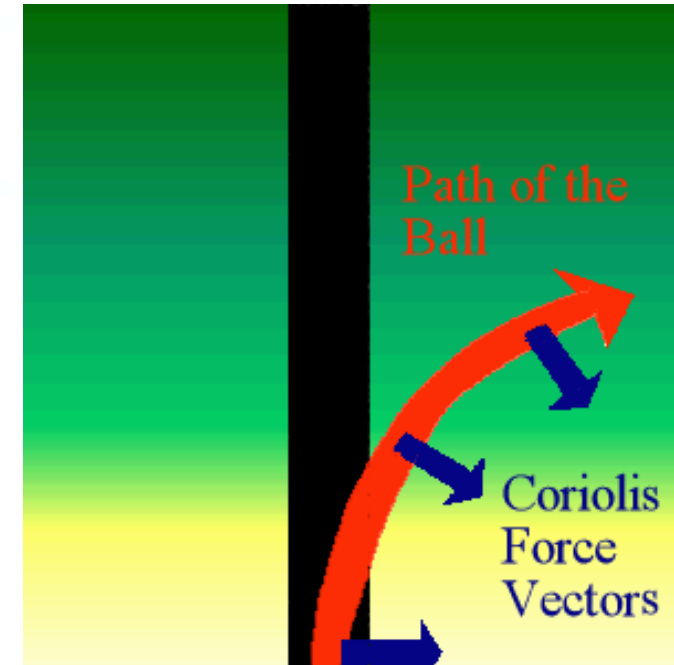
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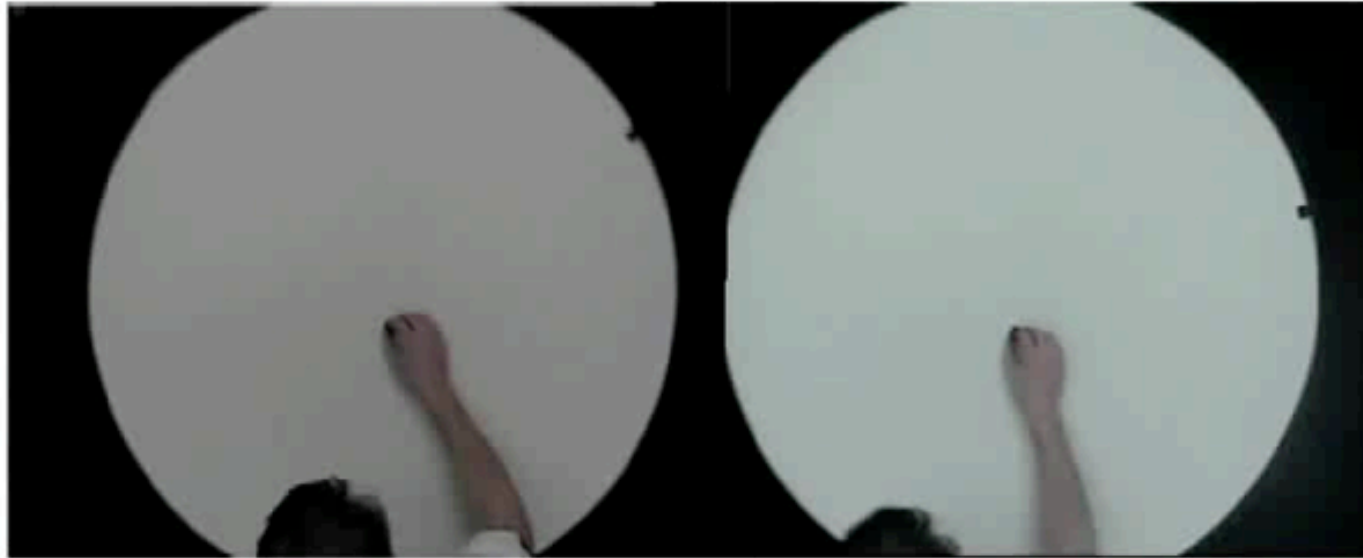


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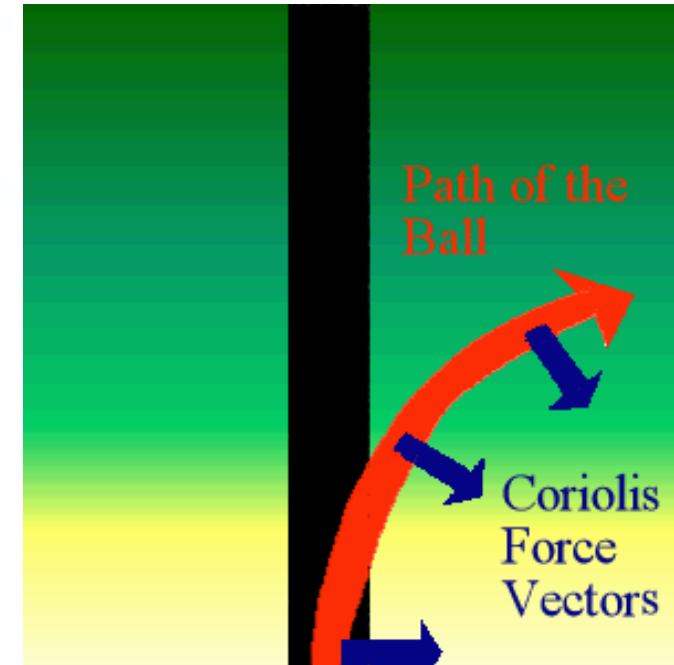
Sink/toilet bowl water swirls clockwise?
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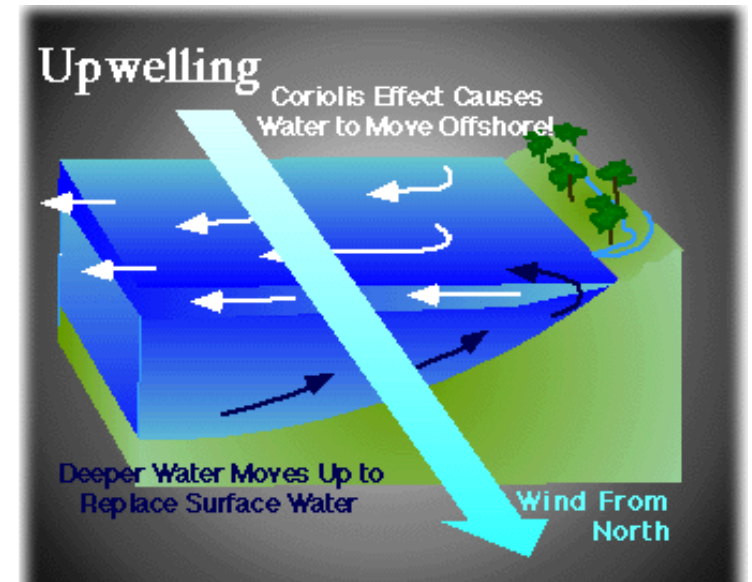
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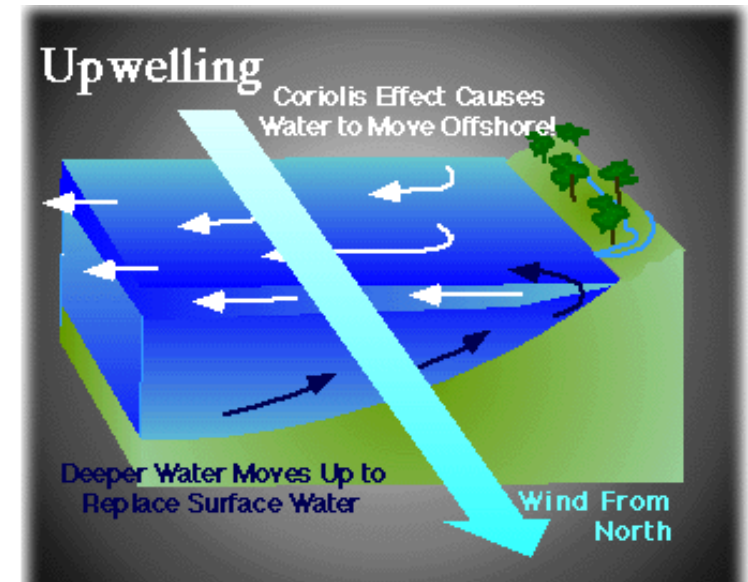
Coriolis force, Coastal Upwelling and fisheries

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



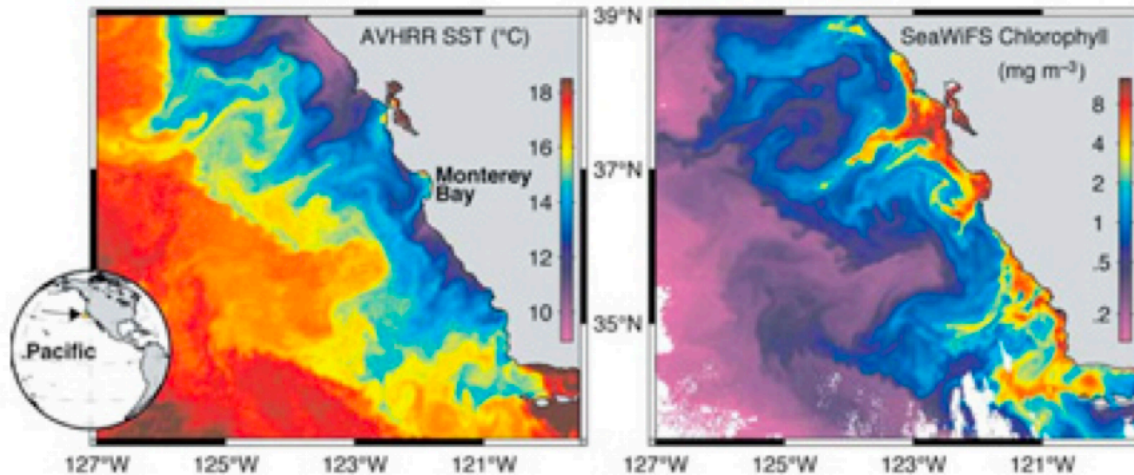
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The rising cold water is rich in nutrients, attracts plankton & creates rich fisheries:

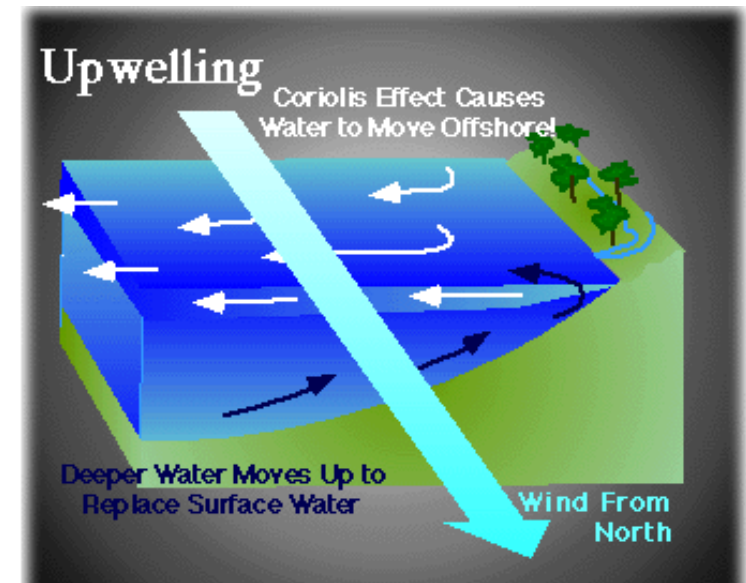
(Ryan et al. 2005).



Temperature and chlorophyll concentrations along the California coast

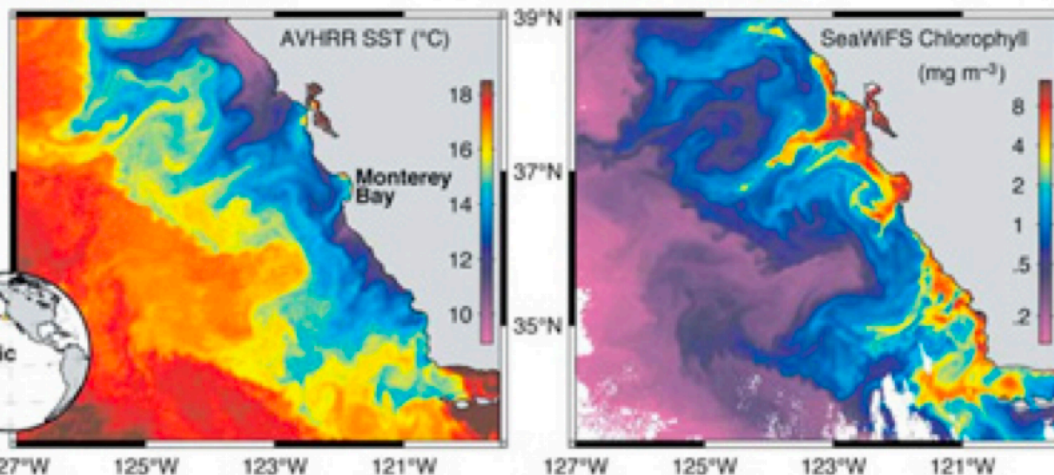
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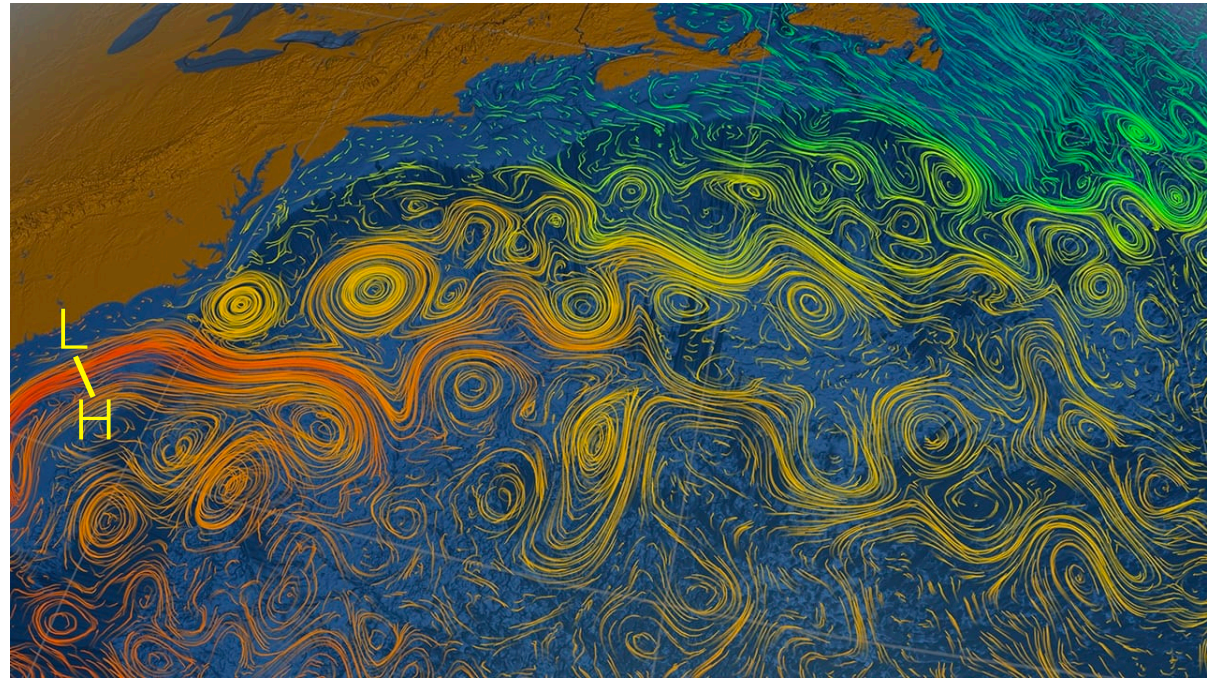
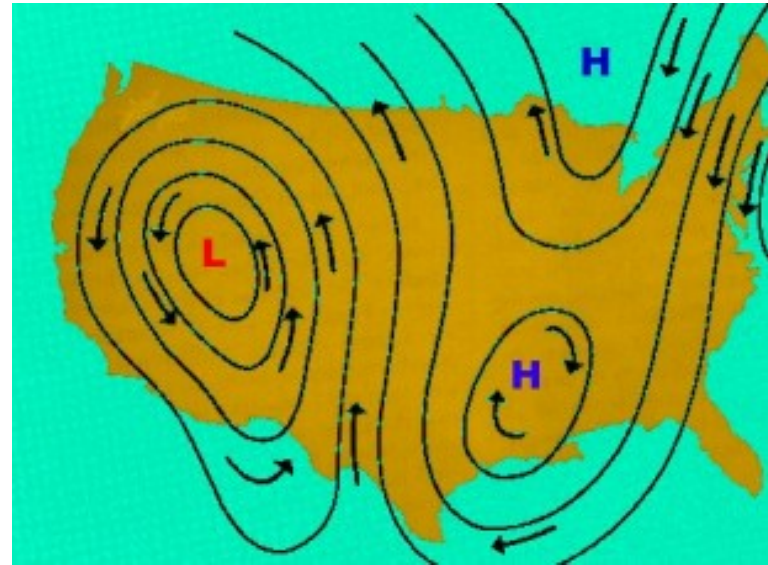


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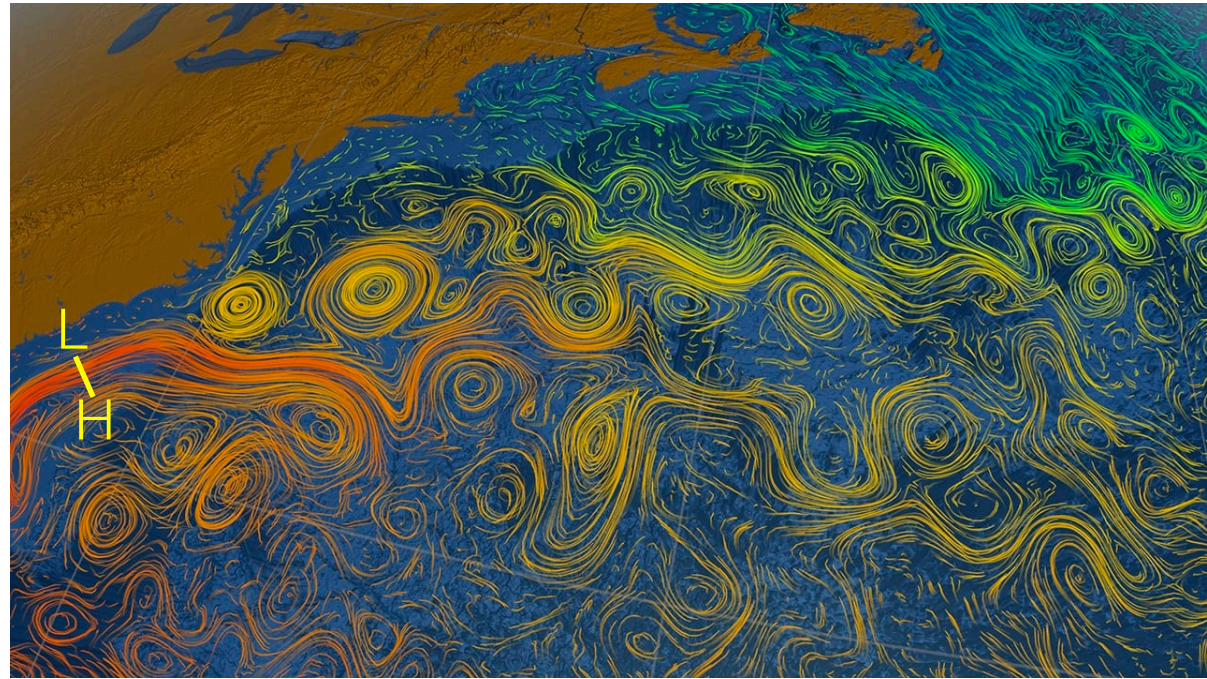
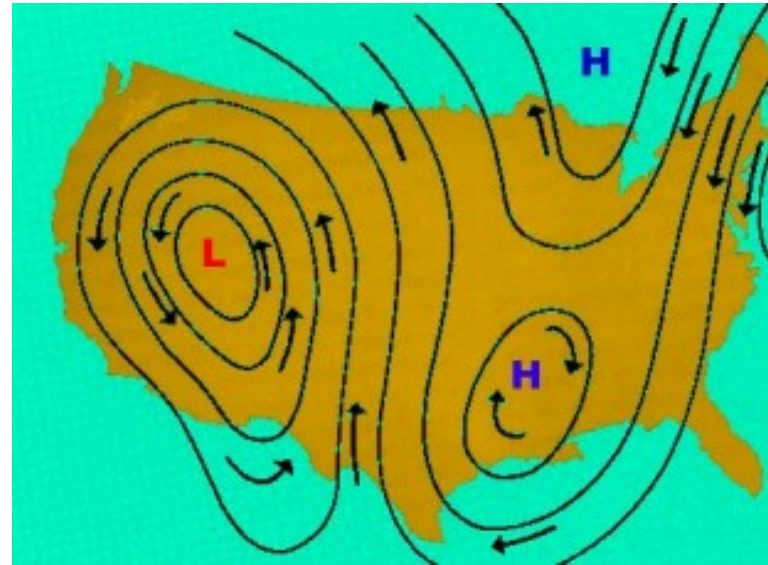
Fishing boats, Ecuador due to El Niño's effect on upwelling

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



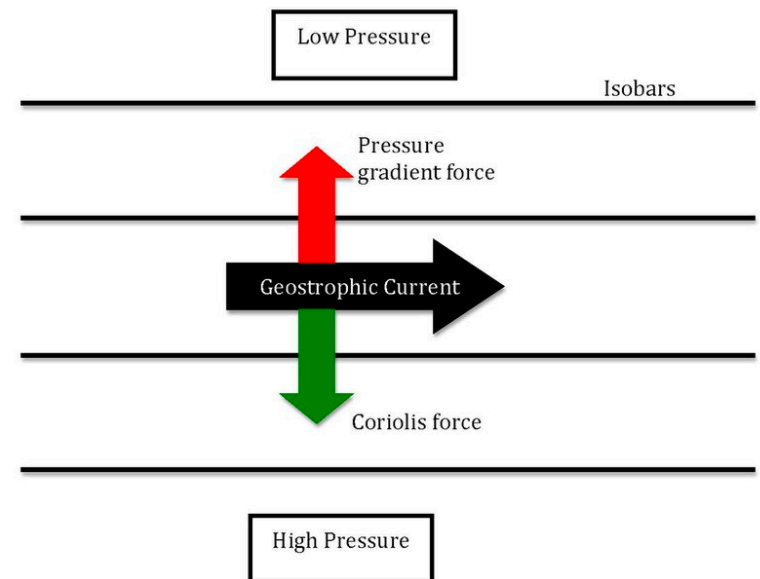
<https://www.whoi.edu/know-your-ocean/ocean-topics/how-the-ocean-works/ocean-circulation/currents-gyres-eddies/>

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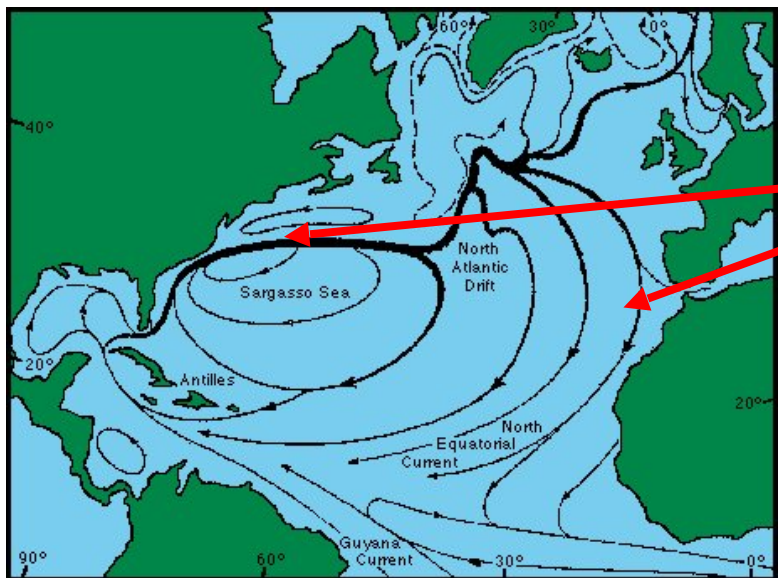
- Air/water do not flow from high to low pressure...
- Instead, the Coriolis force causes flow along equal pressure lines
- The surface height difference across the Gulf Stream (50 km) is about one meter(!)



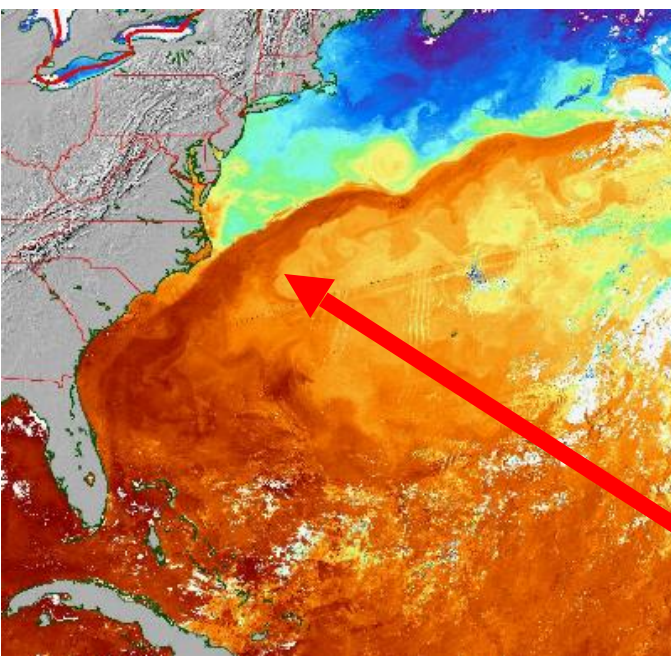
https://en.wikipedia.org/wiki/Geostrophic_current

Gulf Stream/ Kuroshio: western boundary currents

(Strong western vs. weaker eastern boundary currents)



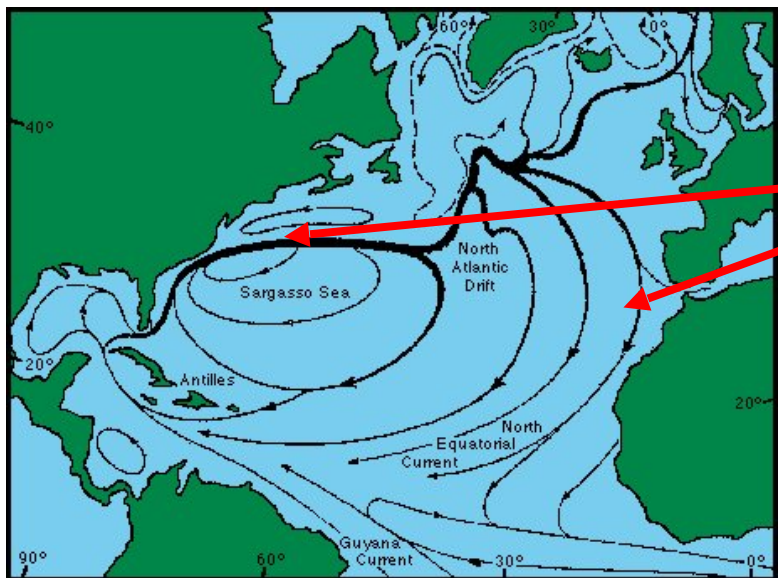
Note east-west
Asymmetry!



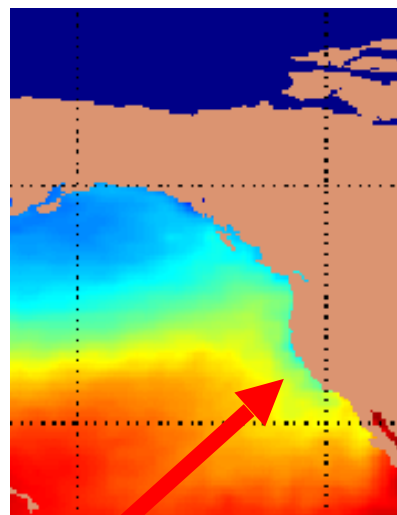
Warm Gulf Stream:
150M m³/sec,
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Gulf Stream/ Kuroshio: western boundary currents

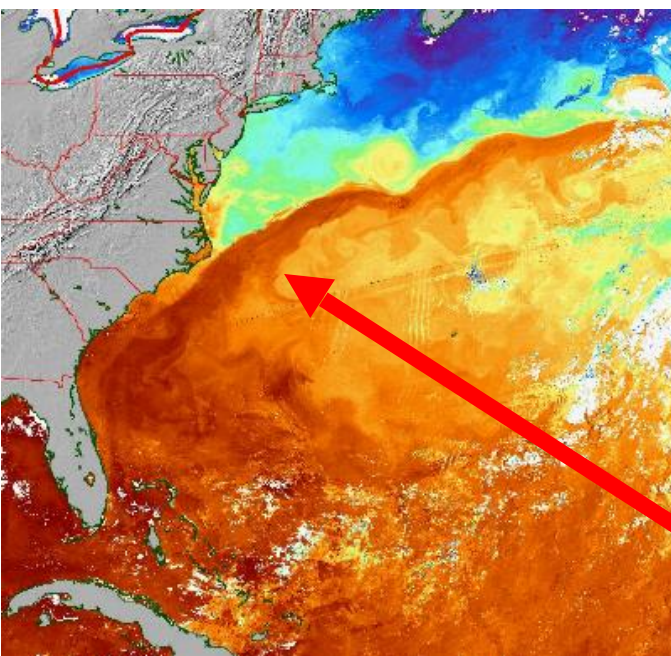
(Strong western vs. weaker eastern boundary currents)



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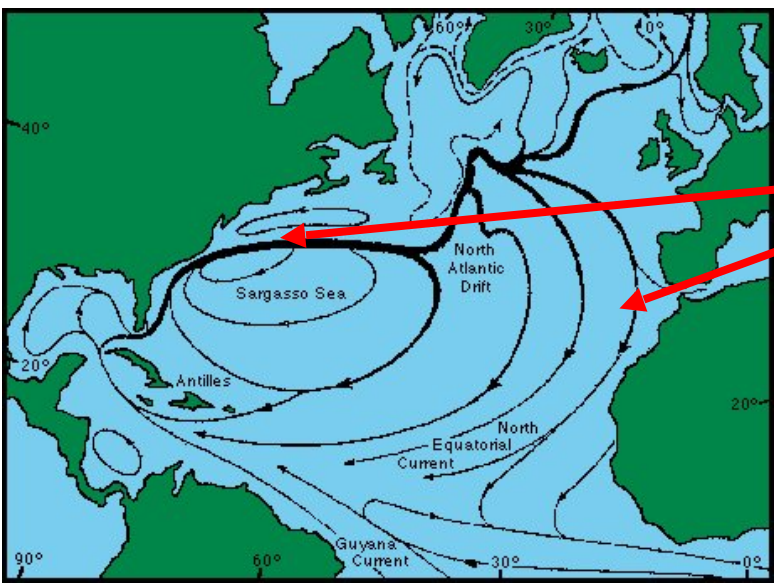
Cold California
Current: 2M m³/sec;
0.1m/s



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Gulf Stream/ Kuroshio: western boundary currents

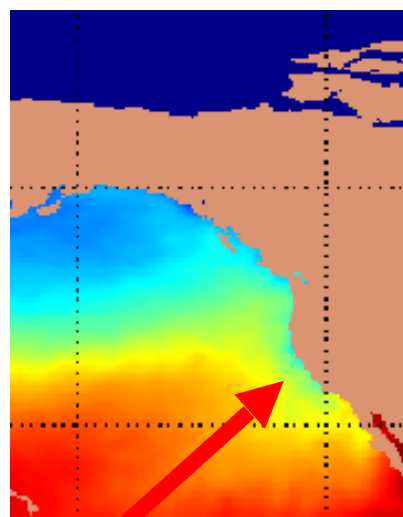
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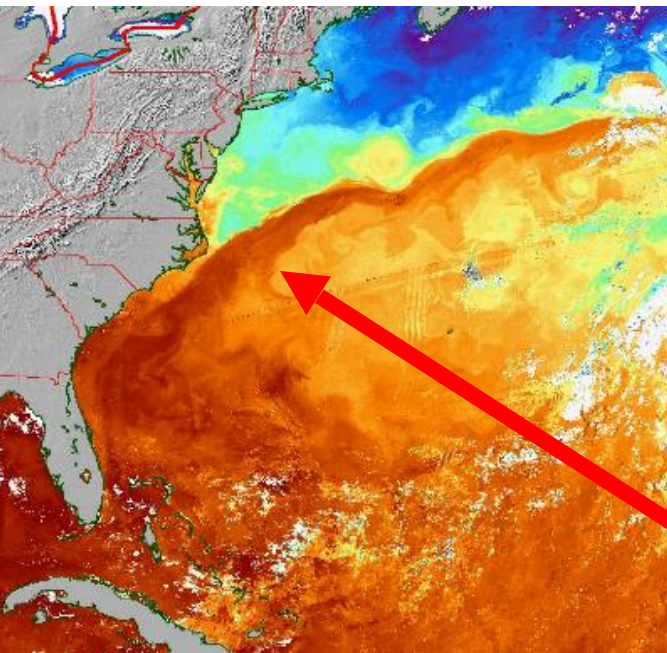
Note east-west Asymmetry!



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



Cold California Current: 2M m³/sec; 0.1m/s



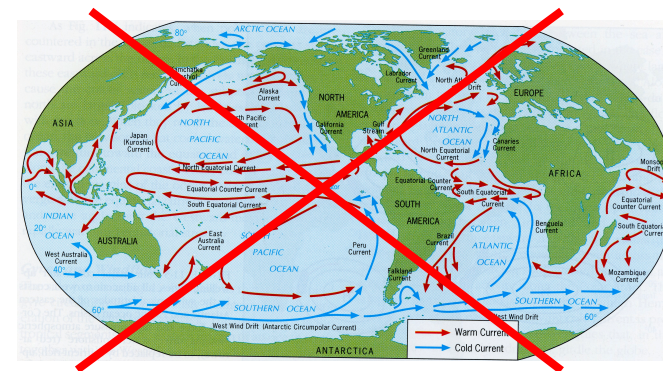
Warm Gulf Stream: 150M m³/sec, 1-2 m/sec



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



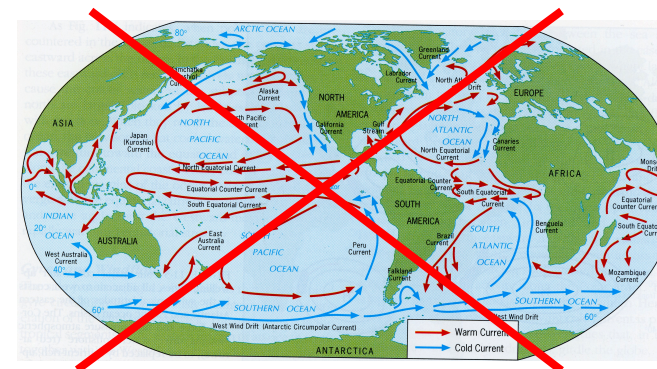
Eddies in the Southern ocean, NCI Australia
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NATIONAL
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INFRASTRUCTURE

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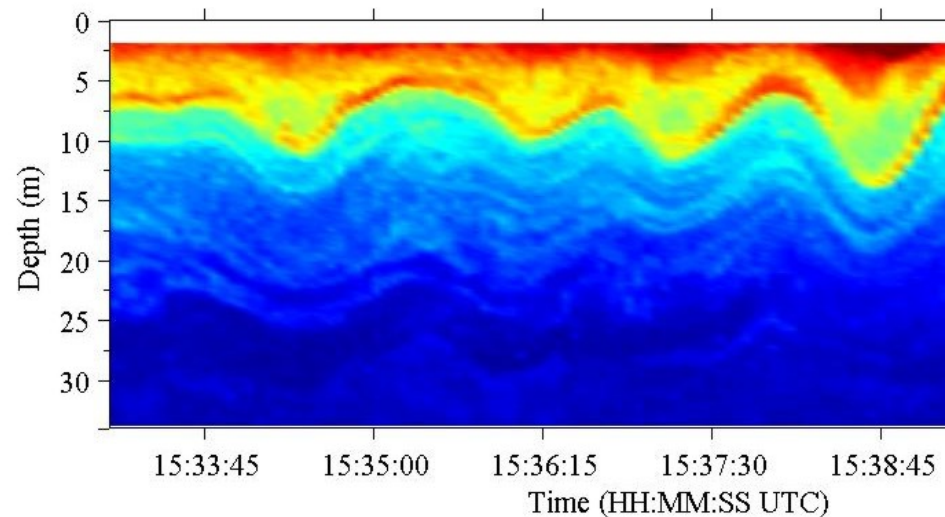
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Waves, Tides, Tsunami

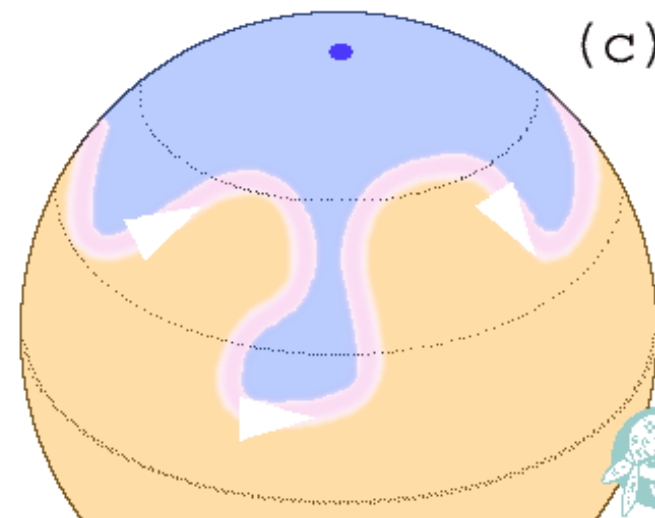
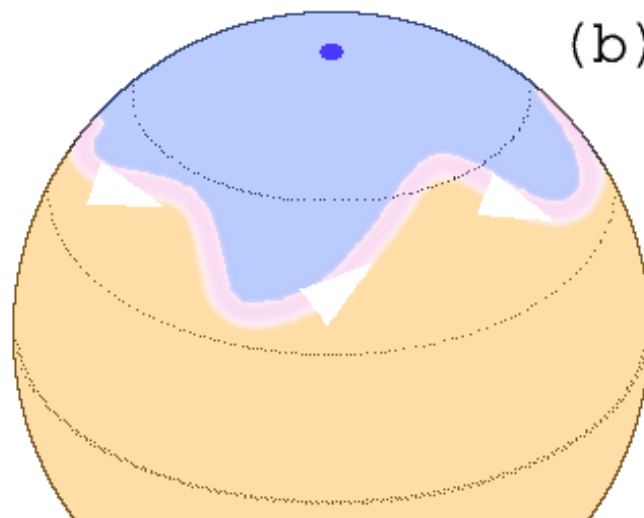
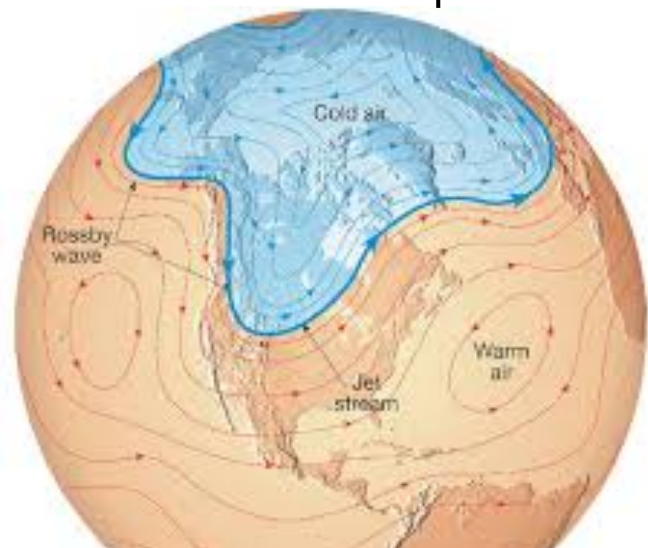
surface waves



internal waves



“planetary” waves (of atmospheric jet stream)



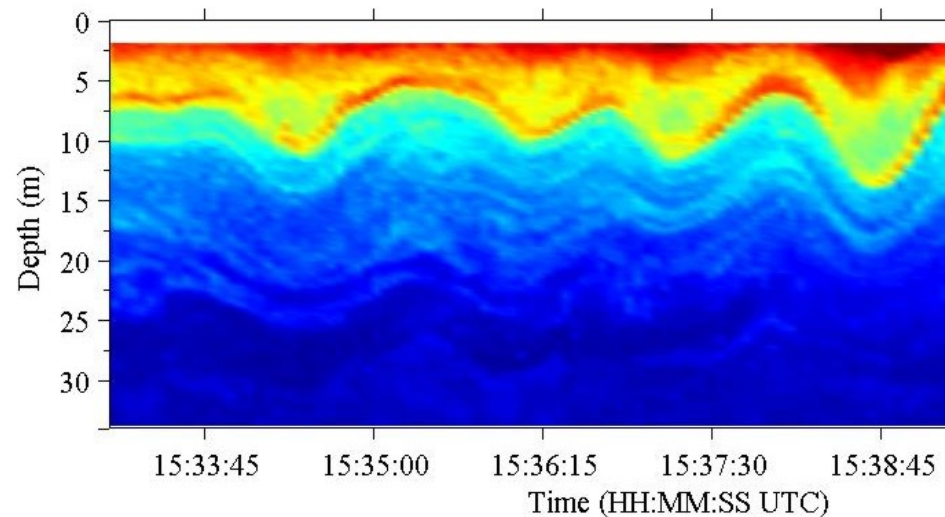
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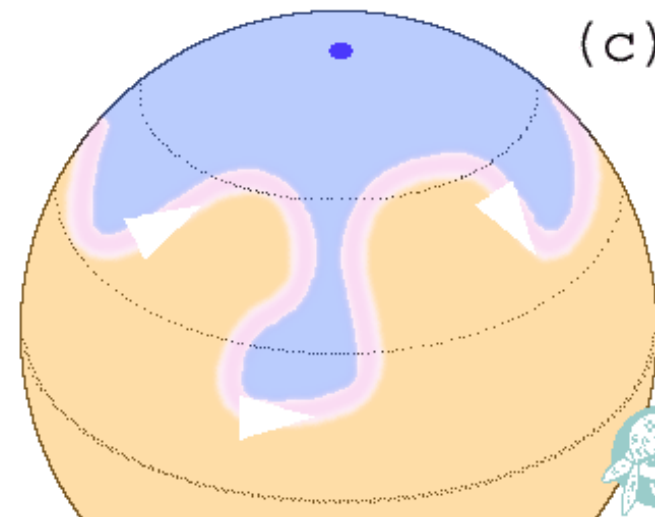
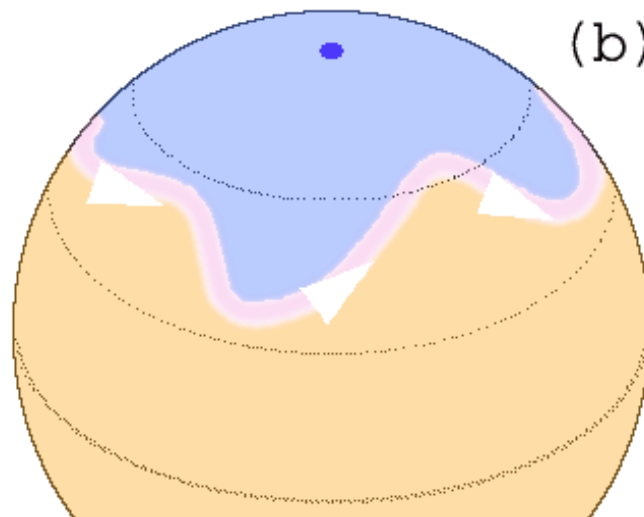
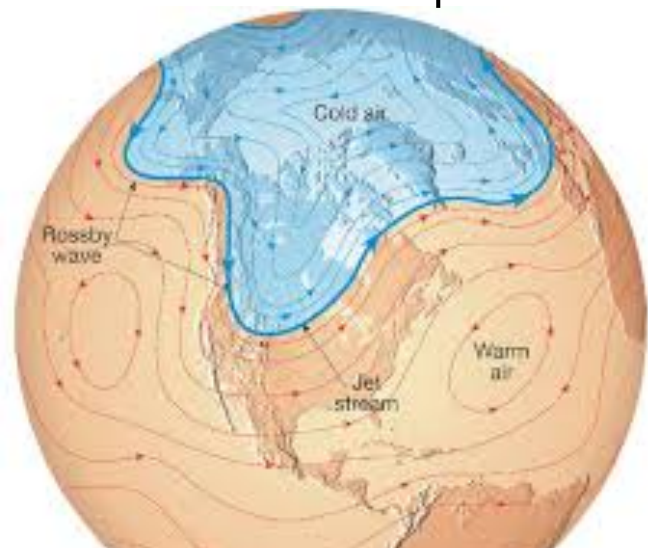


<https://www.youtube.com/watch?v=-nbnnFzk0bA>

internal waves

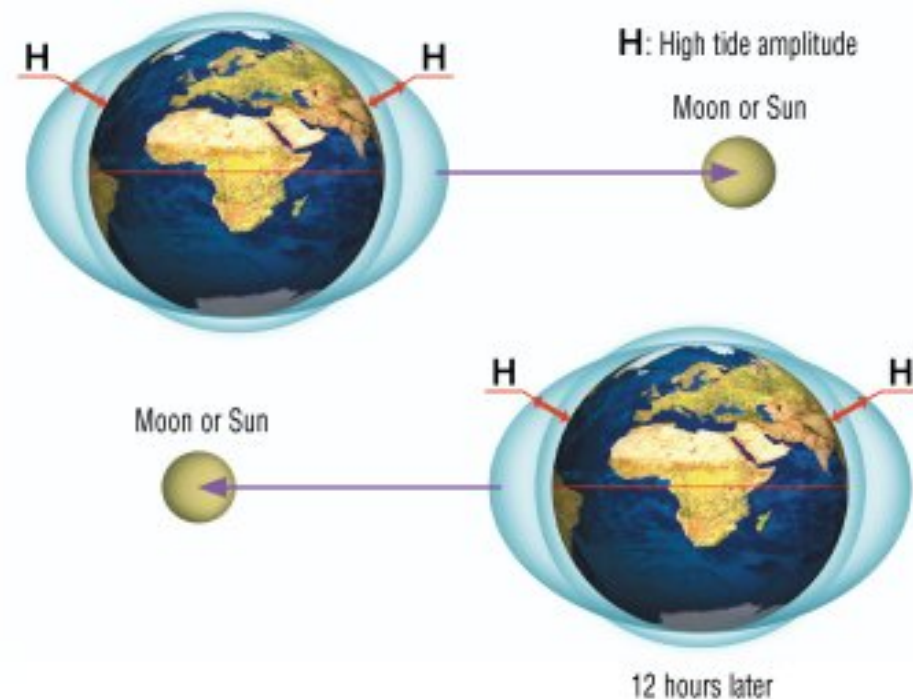


“planetary” waves (of atmospheric jet stream)



Waves, Tides, Tsunami

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

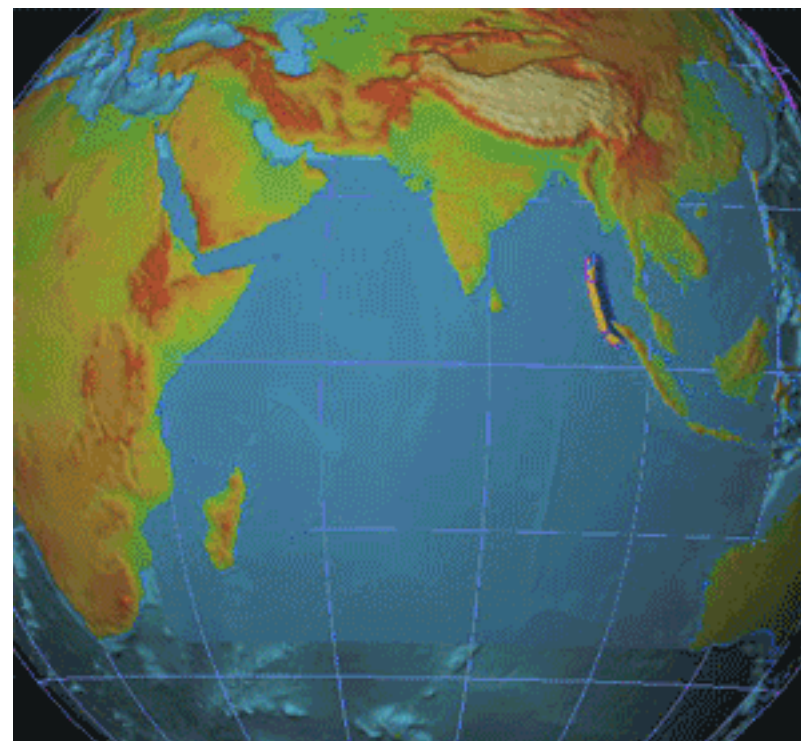


Mont-Saint-Michel (town of Normandy — France)



Waves, Tides, **Tsunami**

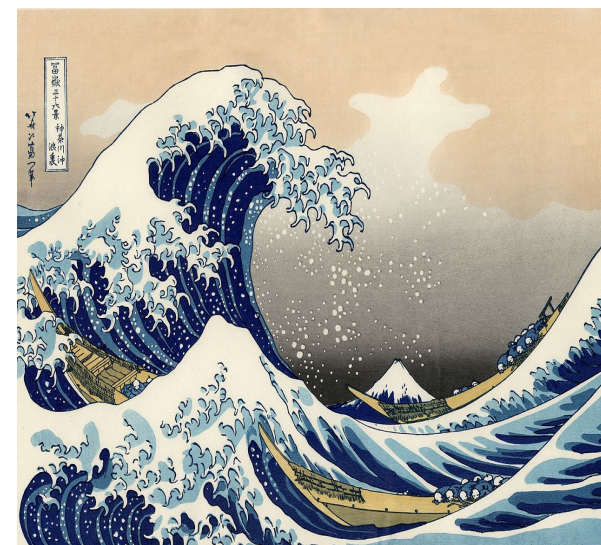
- caused by undersea earthquakes, landfalls
- propagate as **undetectable** low-amplitude surface waves
- speed = $\sqrt{gH} \approx 200m/sec \approx 400mph$
- slow down and height increases to 10s m when approaching shallow coast.



Sumatra, 2004, www.thelivingmoon.com/

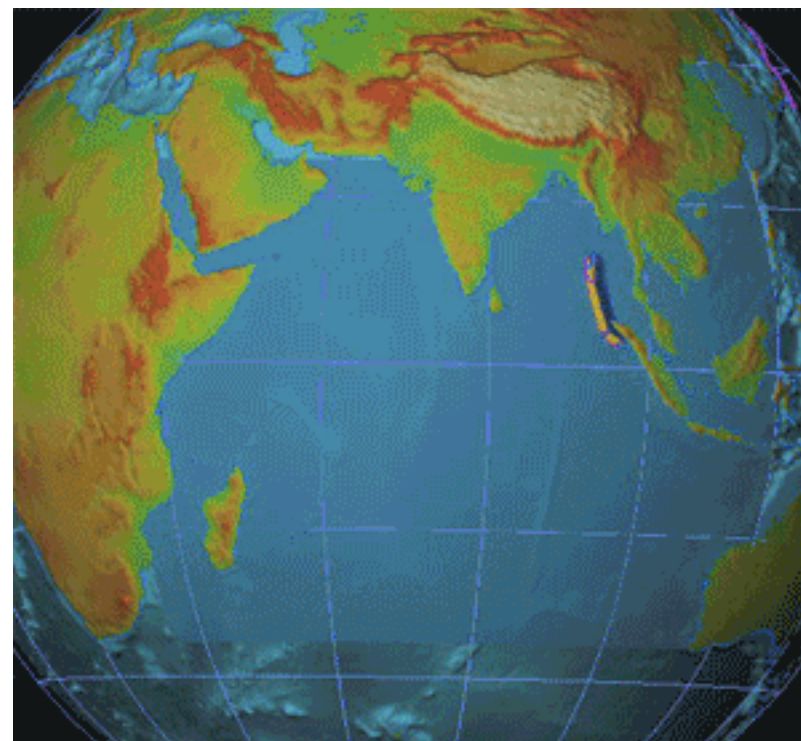


1992, Indonesia, 3-4m waves



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1992, Indonesia, 3-4m waves



Observing the oceans

Ships, satellites, **moorings, floats**

Challenger, 1870s



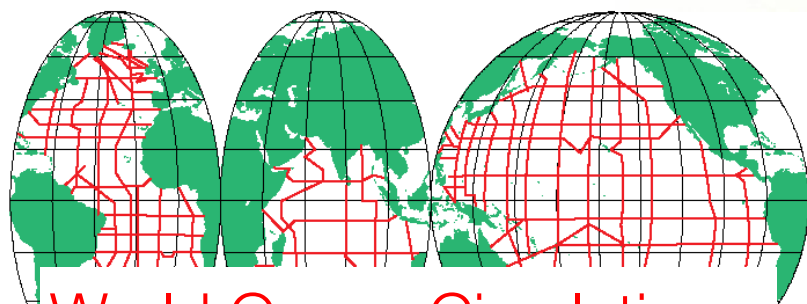
(EPS/ESE 131 field trip to WHOI @ Cape
Cod will take place during the term...)

Ships, satellites, **moorings, floats**

Challenger, 1870s



H.M.S. CHALLENGER UNDER SAIL, 1874.

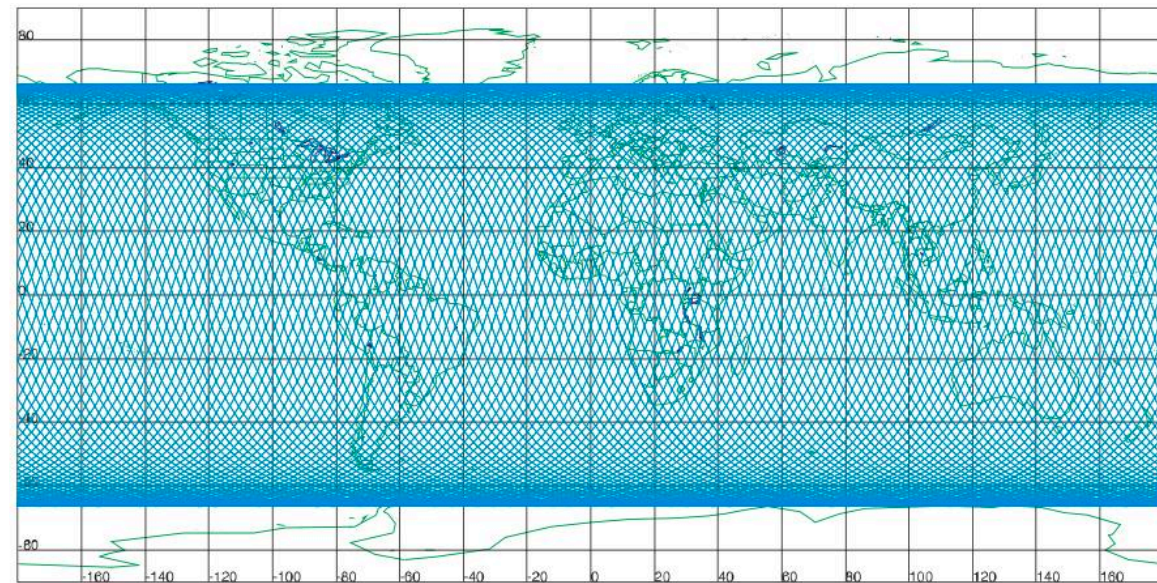


World Ocean Circulation
Experiment, 1990s



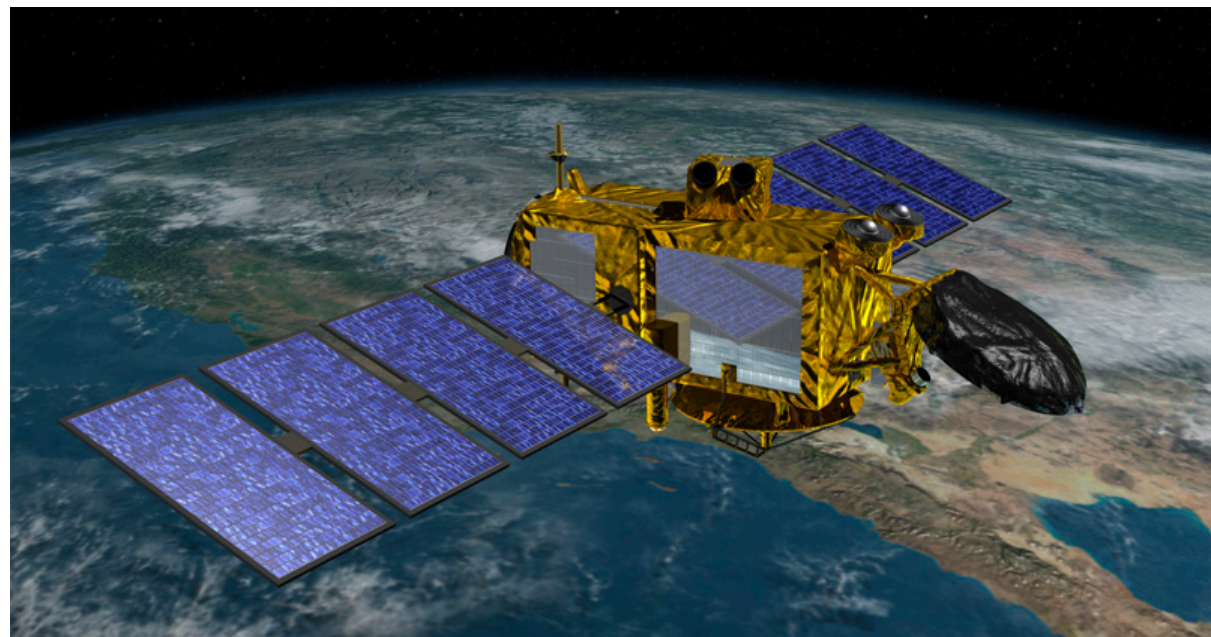
(EPS/ESE 131 field trip to WHOI @ Cape Cod will take place during the term...)

Ships, satellites, **moorings, floats**

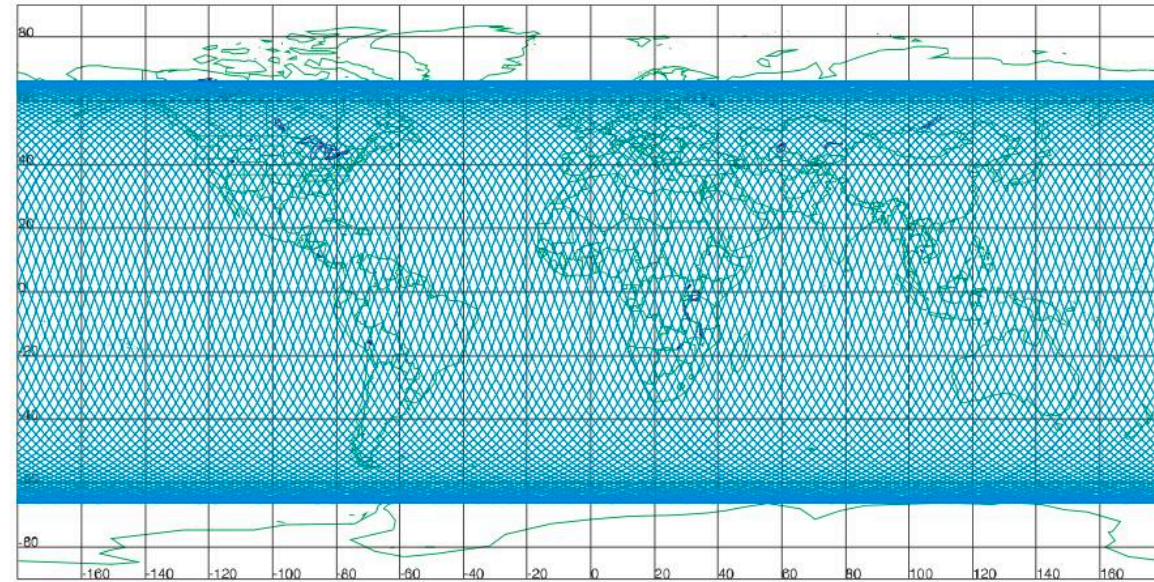


Altimeter: radar measuring
ocean surface height

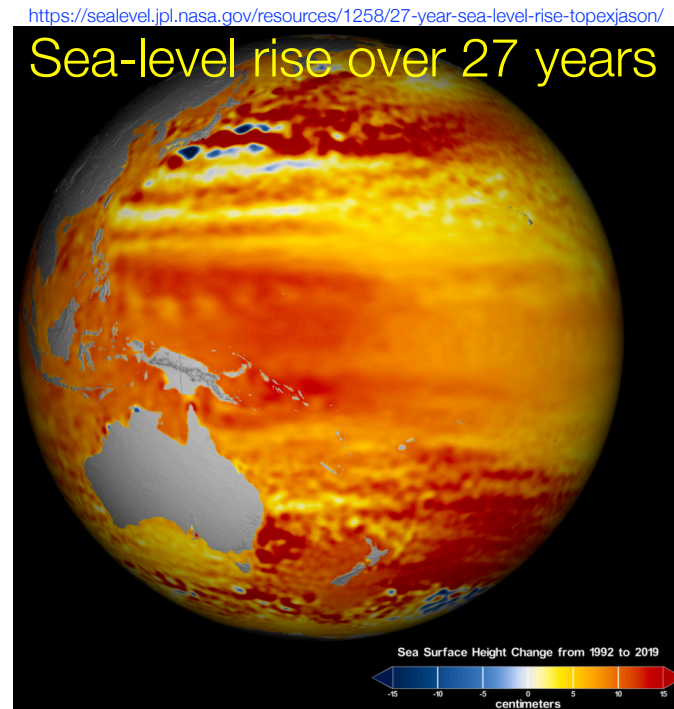
“The satellite's orbital period is 112 minutes. TOPEX/
POSEIDON will repeat the same ground track every
10 days (127 revolutions)” NASA/JPL



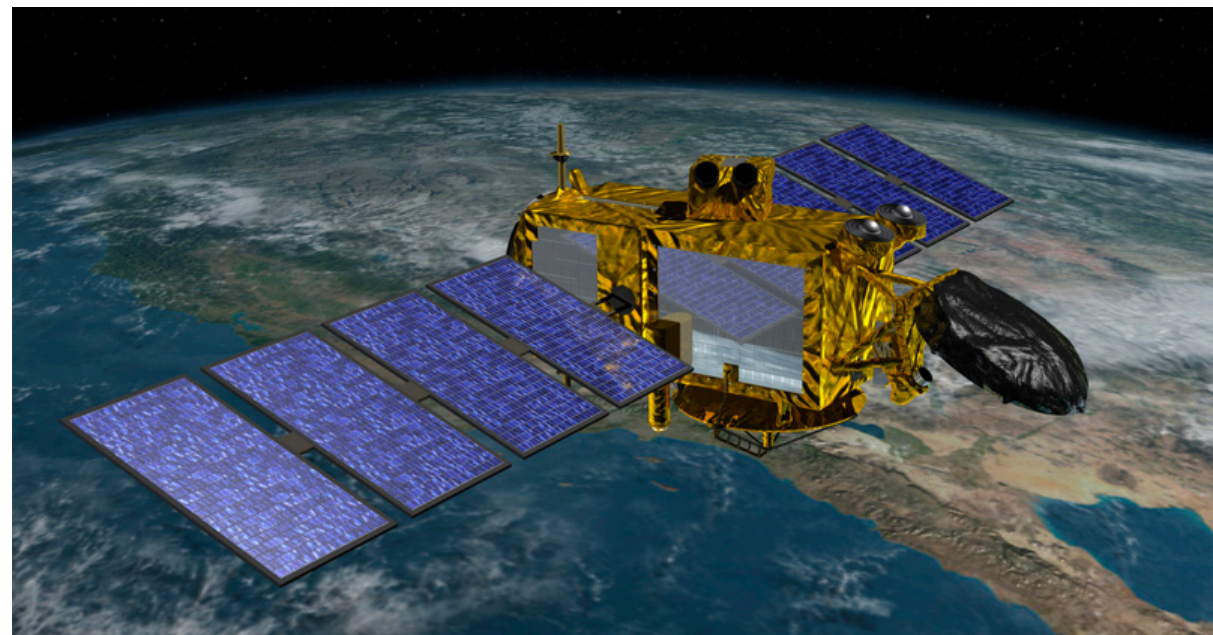
Ships, **satellites**, moorings, floats



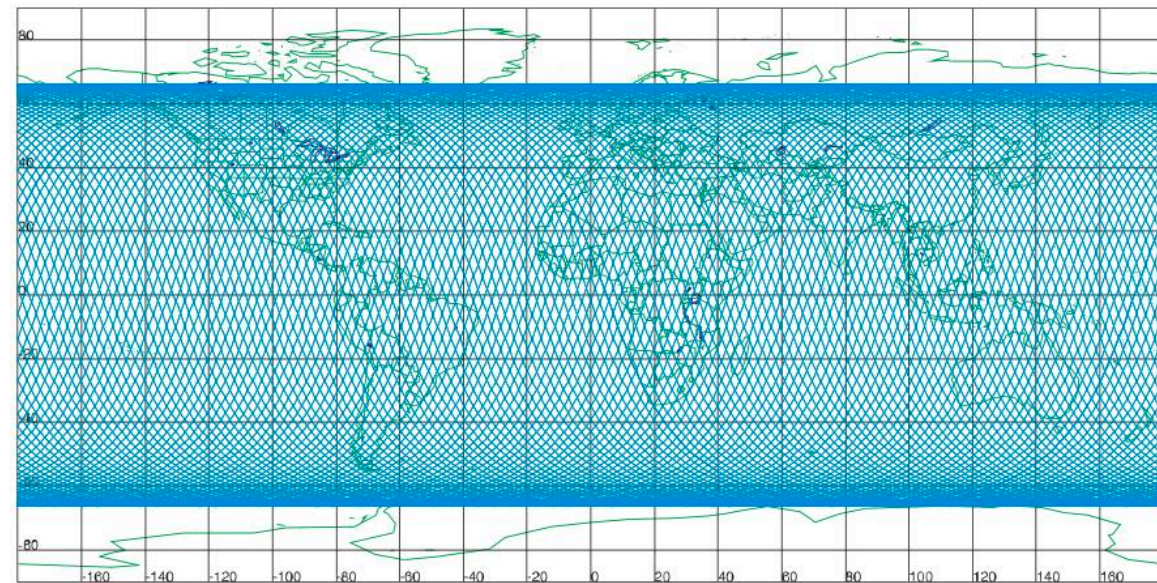
“The satellite's orbital period is 112 minutes. TOPEX/POSEIDON will repeat the same ground track every 10 days (127 revolutions)” NASA/JPL



Altimeter: radar measuring ocean surface height

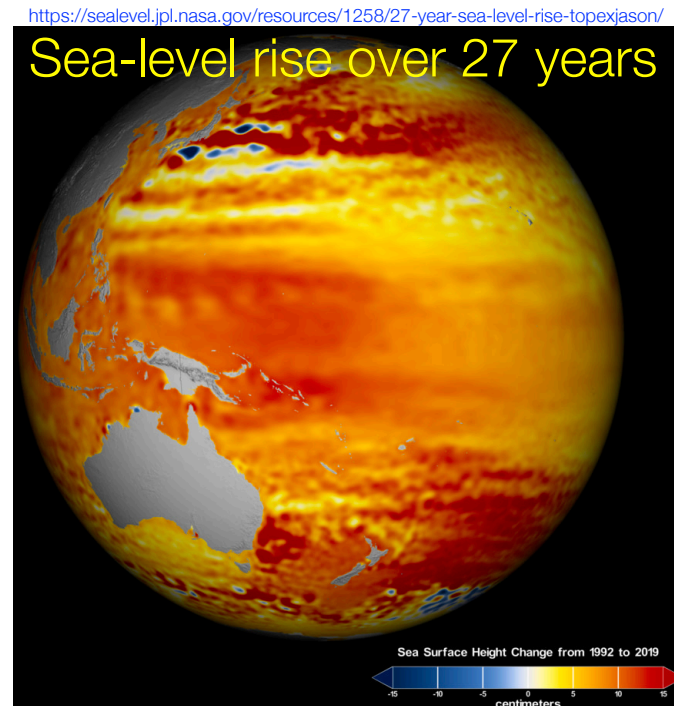


Ships, **satellites**, moorings, floats

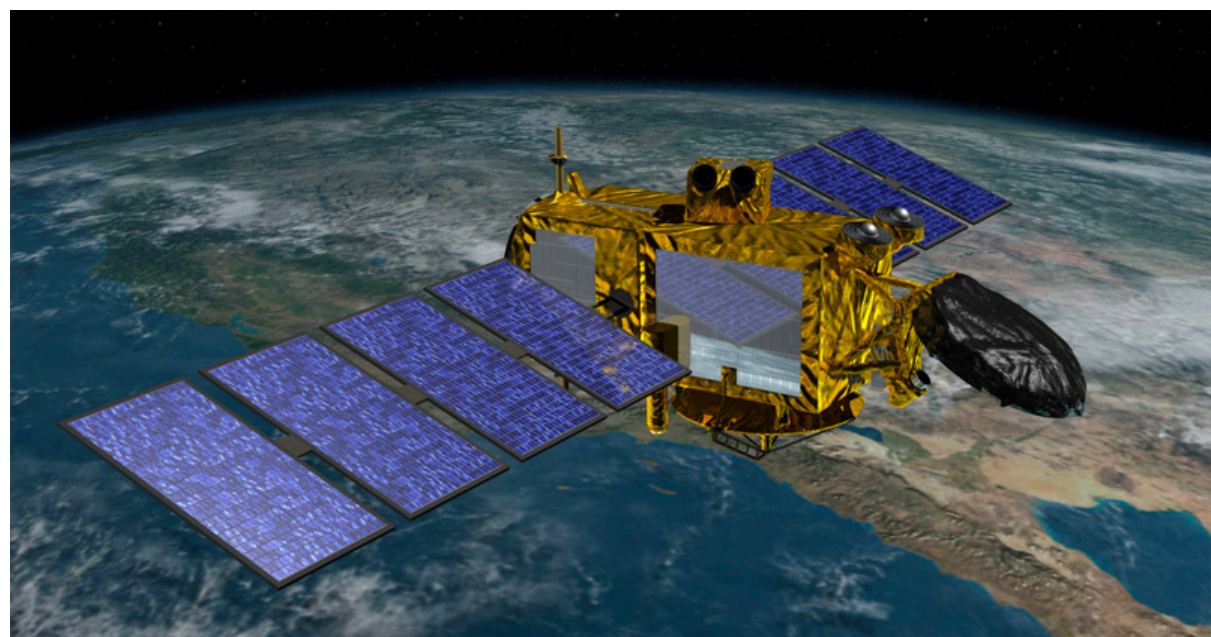


“The satellite's orbital period is 112 minutes. TOPEX/POSEIDON will repeat the same ground track every 10 days (127 revolutions)” NASA/JPL

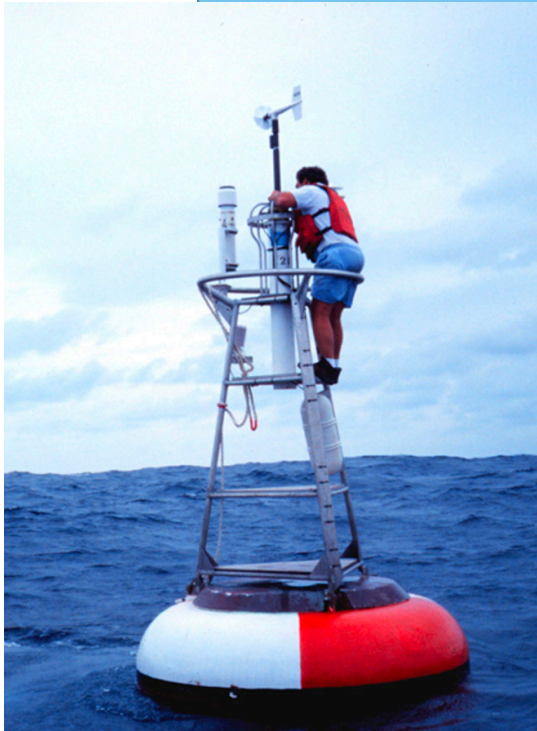
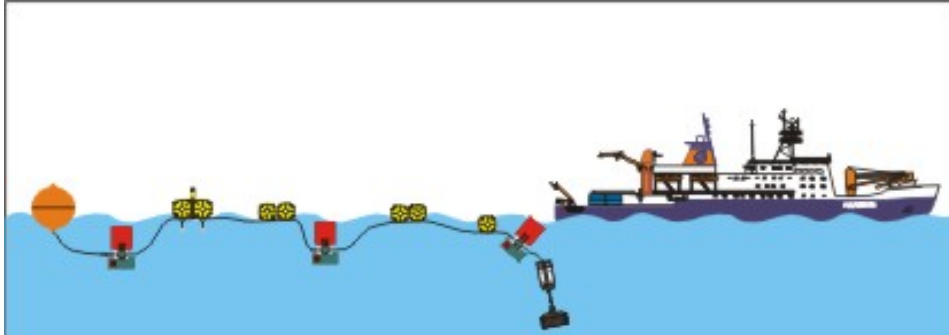
Satellites observe surface temperature, salinity, height, winds, waves, ice, chlorophyll... **but** not the ocean interior...



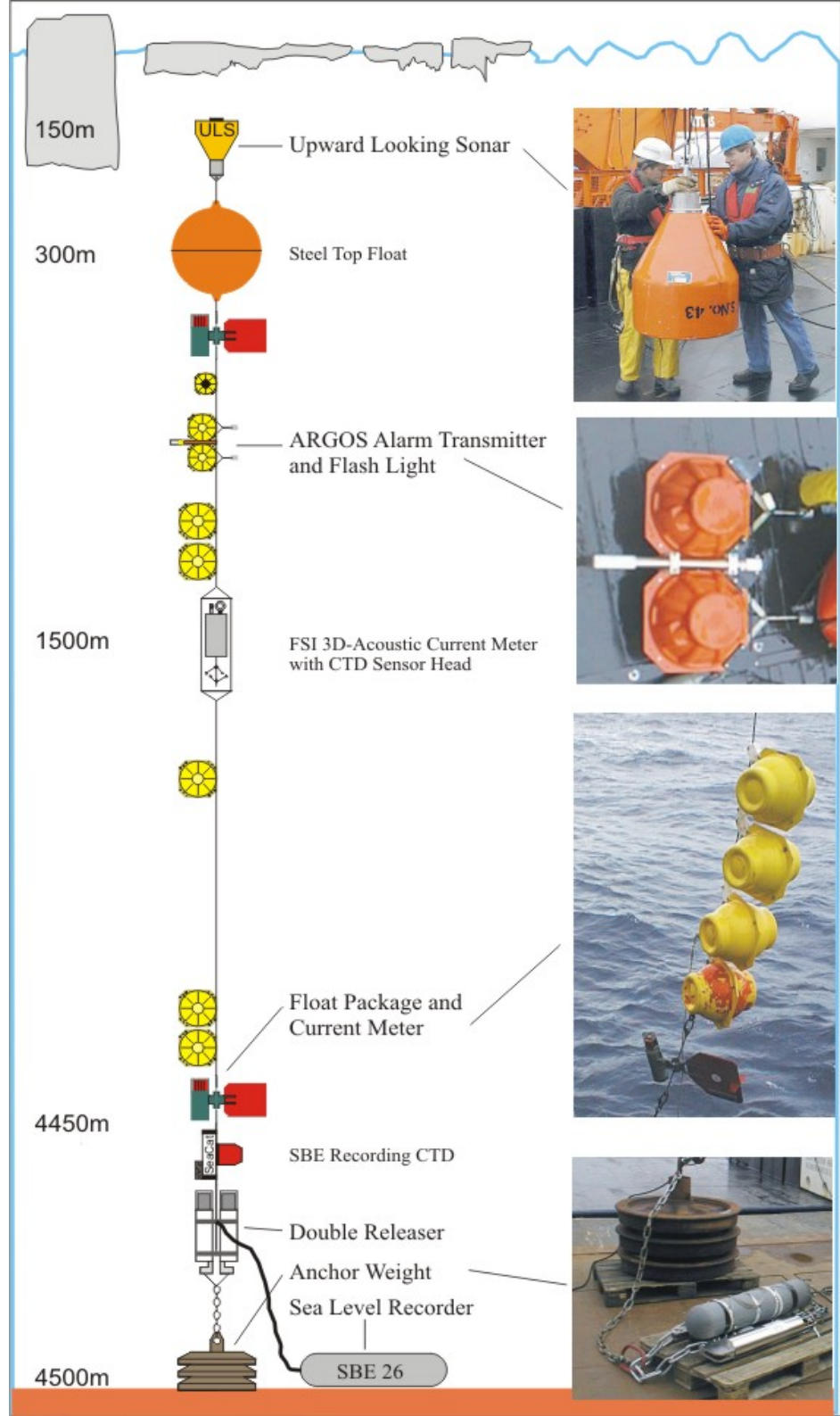
Altimeter: radar measuring ocean surface height



Ships, satellites, moorings, floats



<https://education.nationalgeographic.org/resource/el-nino/>



150m

ULS — Upward Looking Sonar

300m

Steel Top Float

1500m

ARGOS Alarm Transmitter and Flash Light

FSI 3D-Acoustic Current Meter with CTD Sensor Head

4450m

Float Package and Current Meter

SBE Recording CTD

Double Releaser

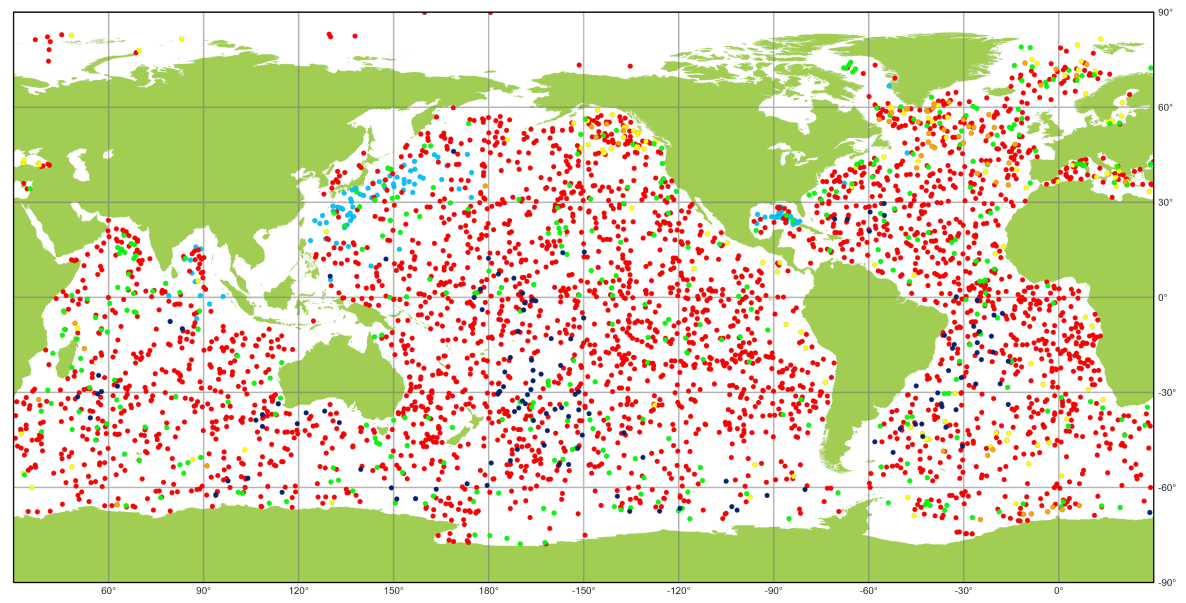
Anchor Weight

Sea Level Recorder

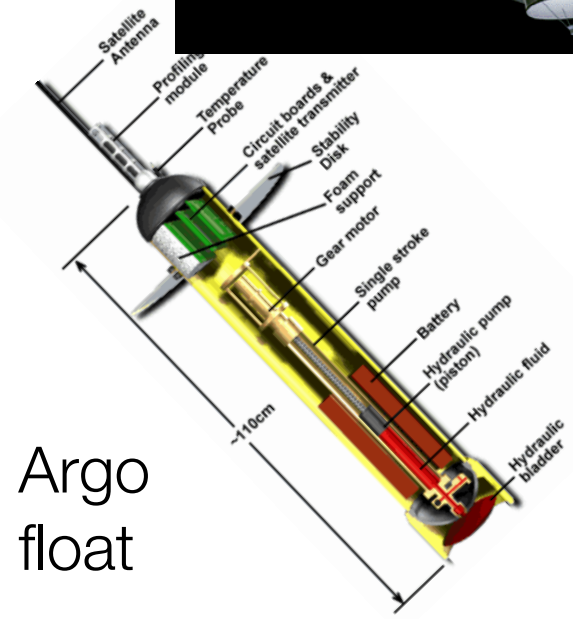
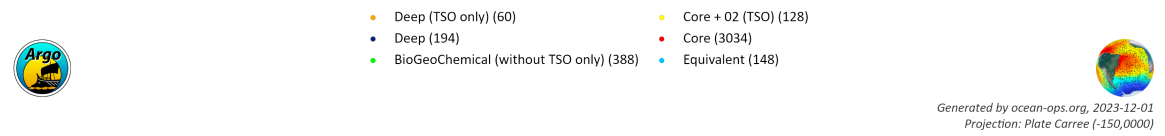
4500m

SBE 26

Ships, satellites, moorings, **floats**



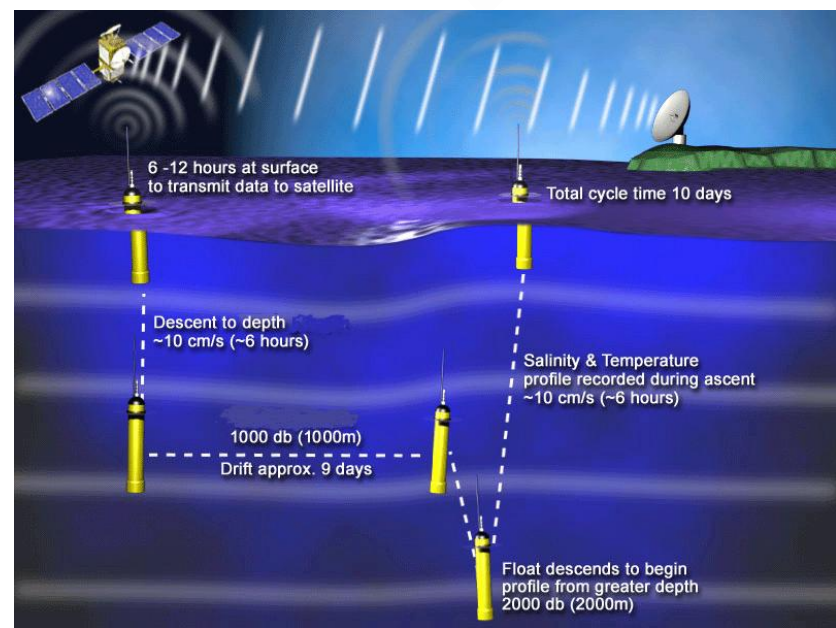
Argo Networks November 2023
3854 operational units



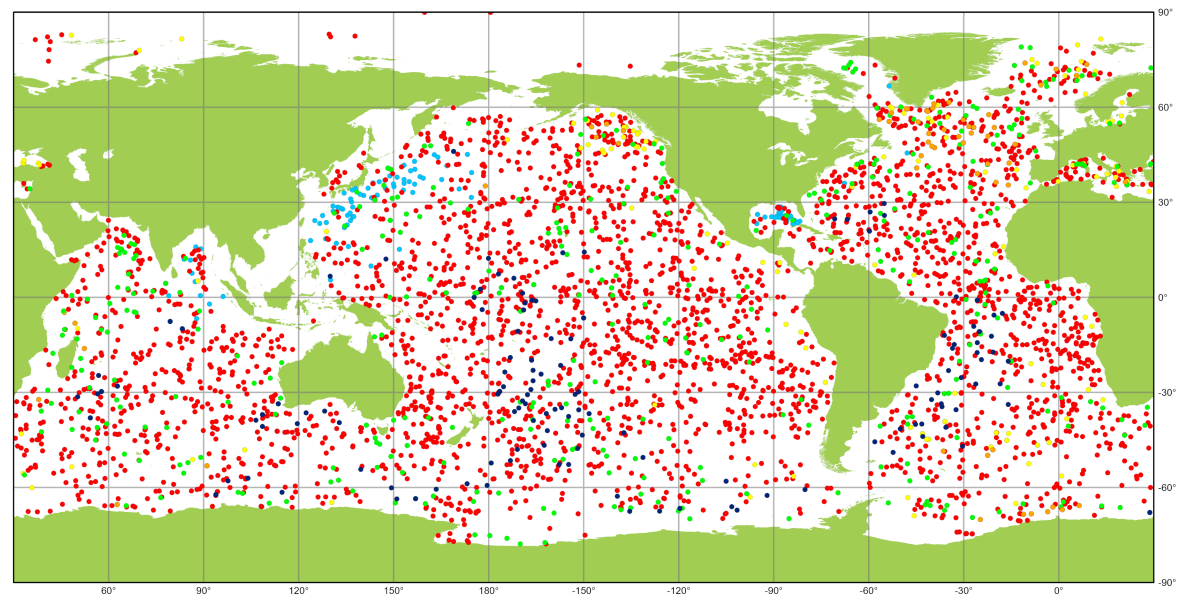
Argo float

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

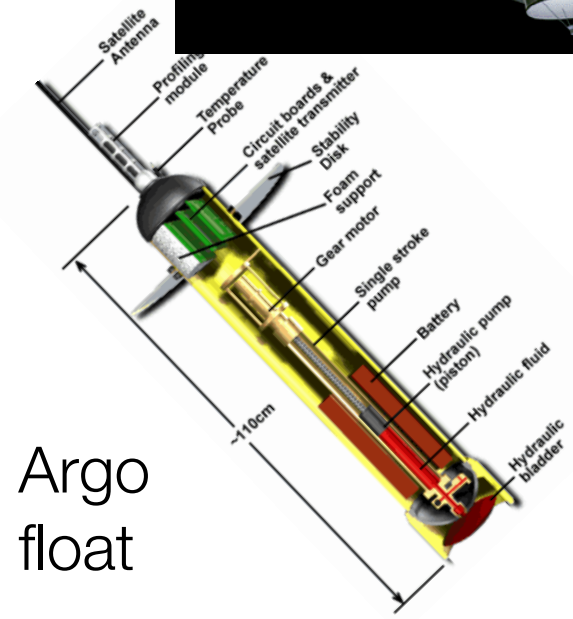
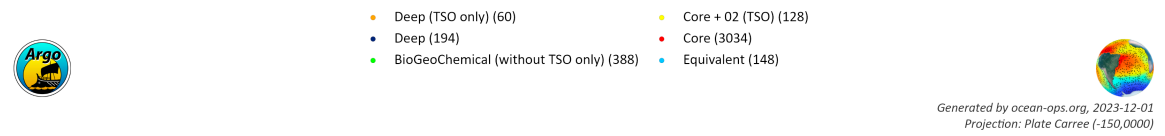
Argo floats cycle between 2000 m and the surface every 10 days & drift with currents



Ships, satellites, moorings, **floats**



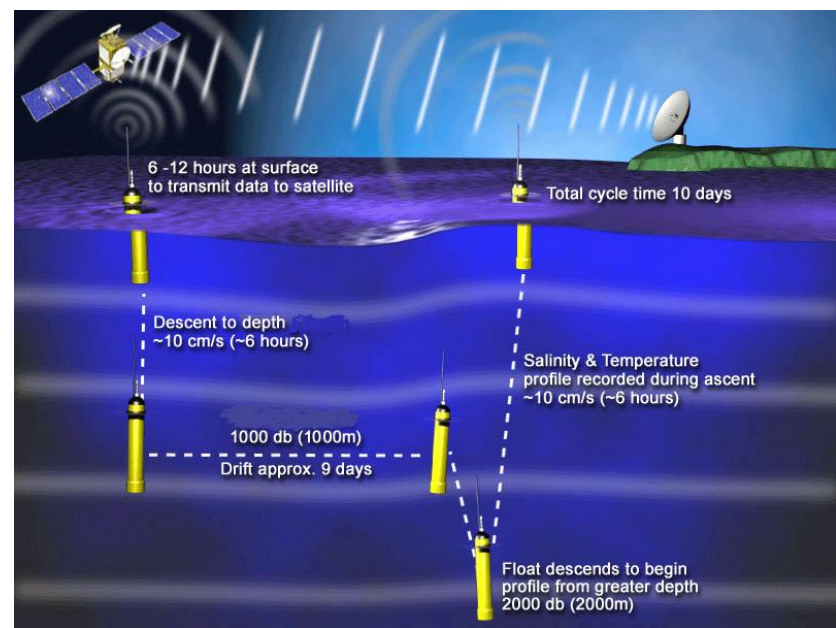
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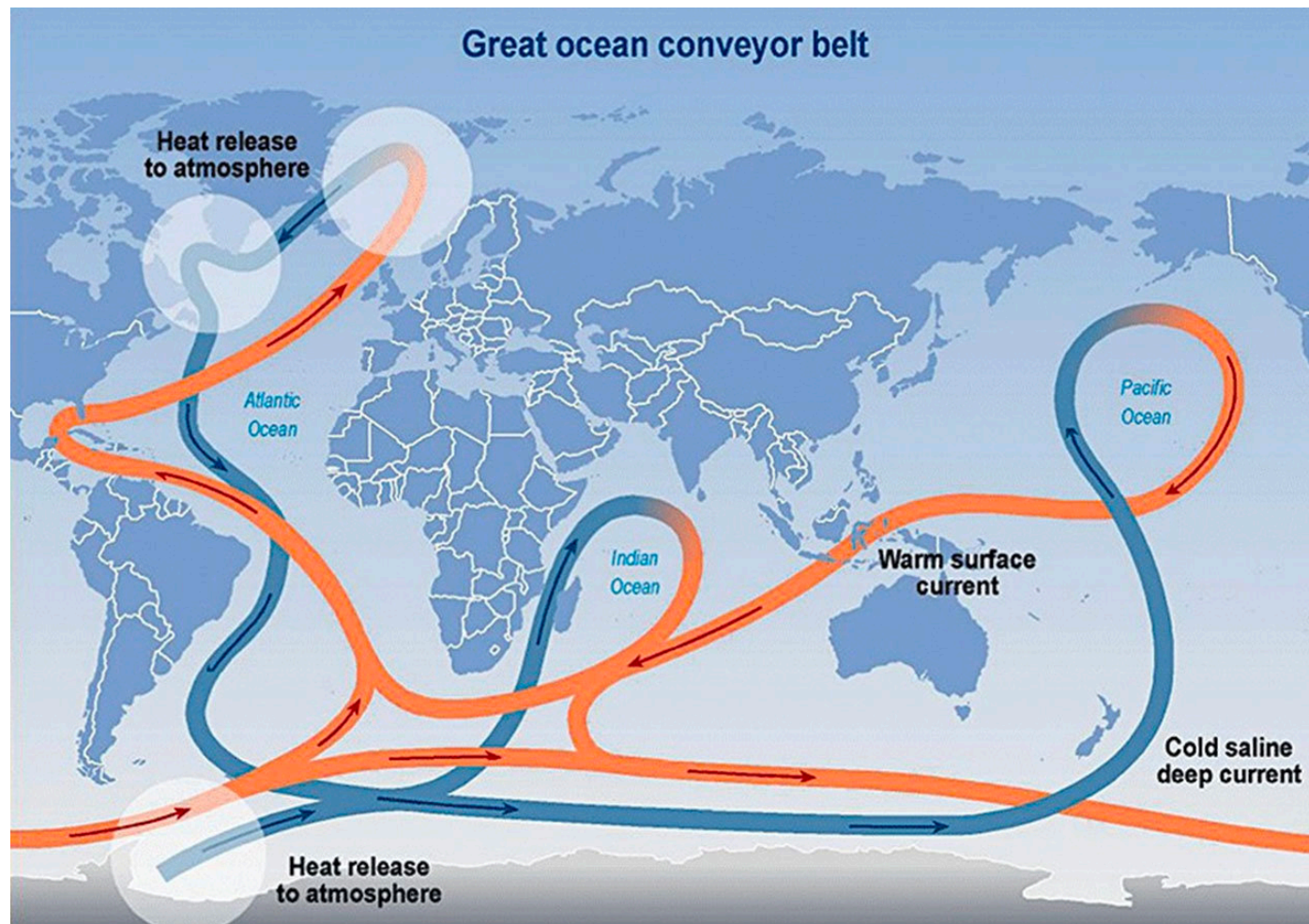


Climate!

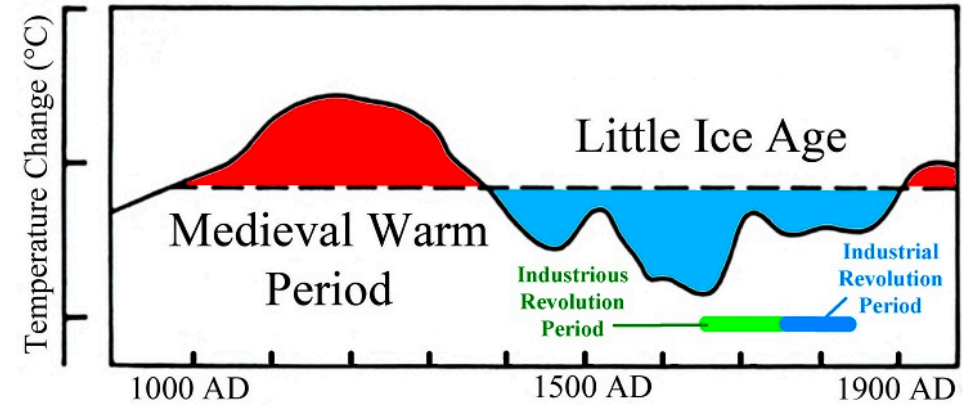
- Atlantic Meridional Overturning Circulation
- Abrupt climate change due to AMOC/sea ice changes
- Climate tipping points
- El Niño

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.



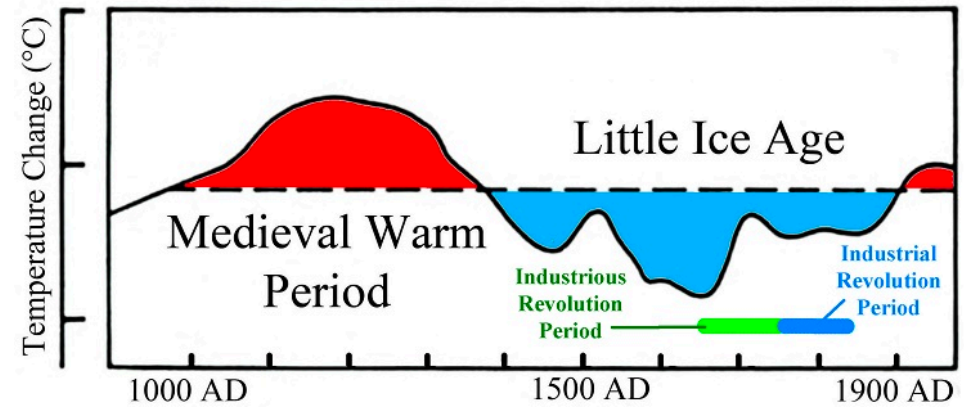
The AMOC and past climate



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

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

The AMOC and past climate



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



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



Norse ruins from Brattahlíð, 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.

Brattahlíð

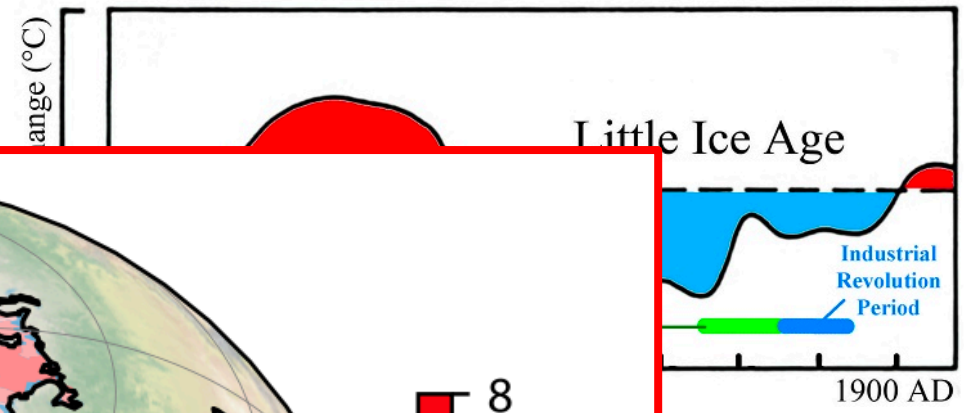
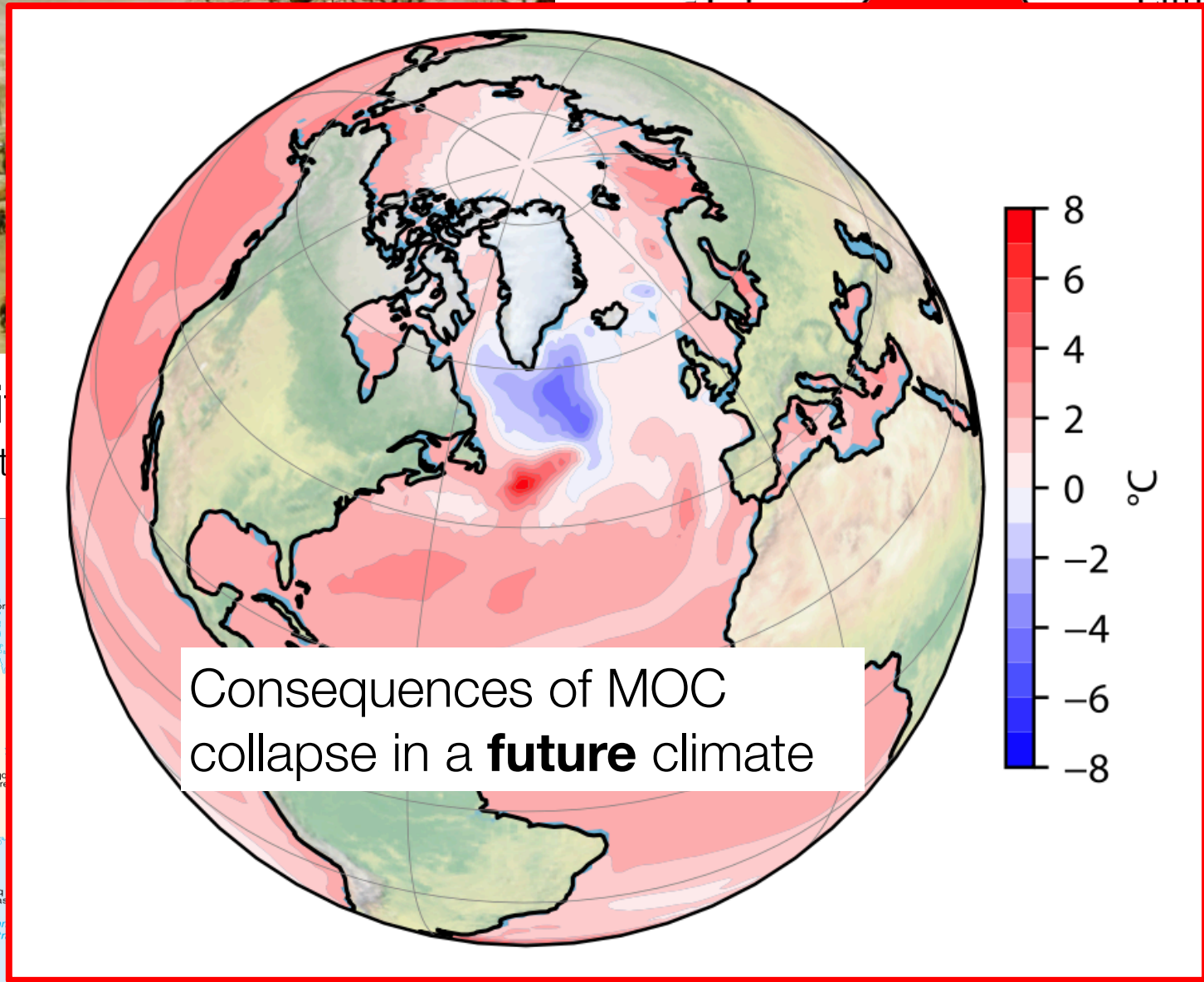
The AMOC and past climate



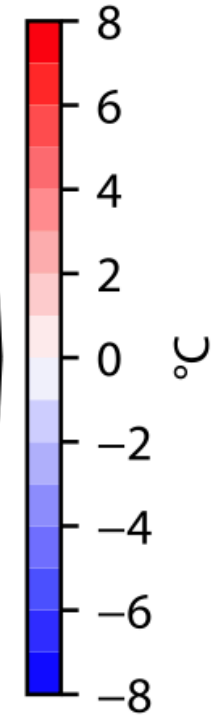
Europe's Little Ice Age
Pieter Breugel the Elder



Brattahlíð



<http://title-ice-age/utp0151/>



Brattahlíð, "the Red," for his red sail and red hair. ~1,000 people lived there until 1480 due to

The day after tomorrow

https://www.youtube.com/watch?v=Ku_lseK3xTc

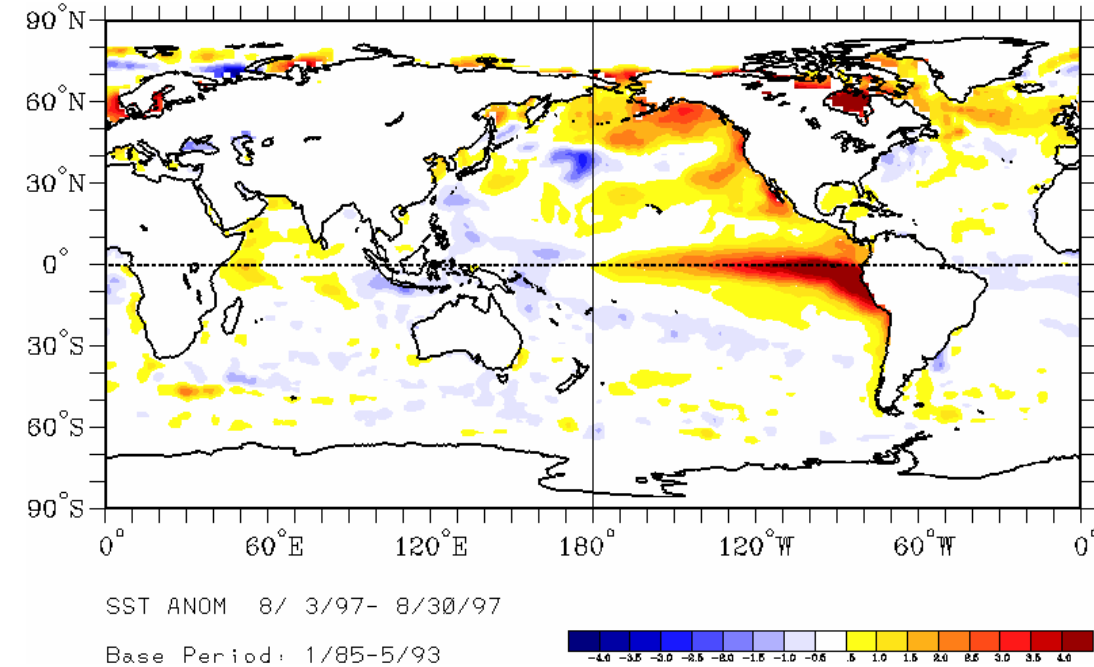
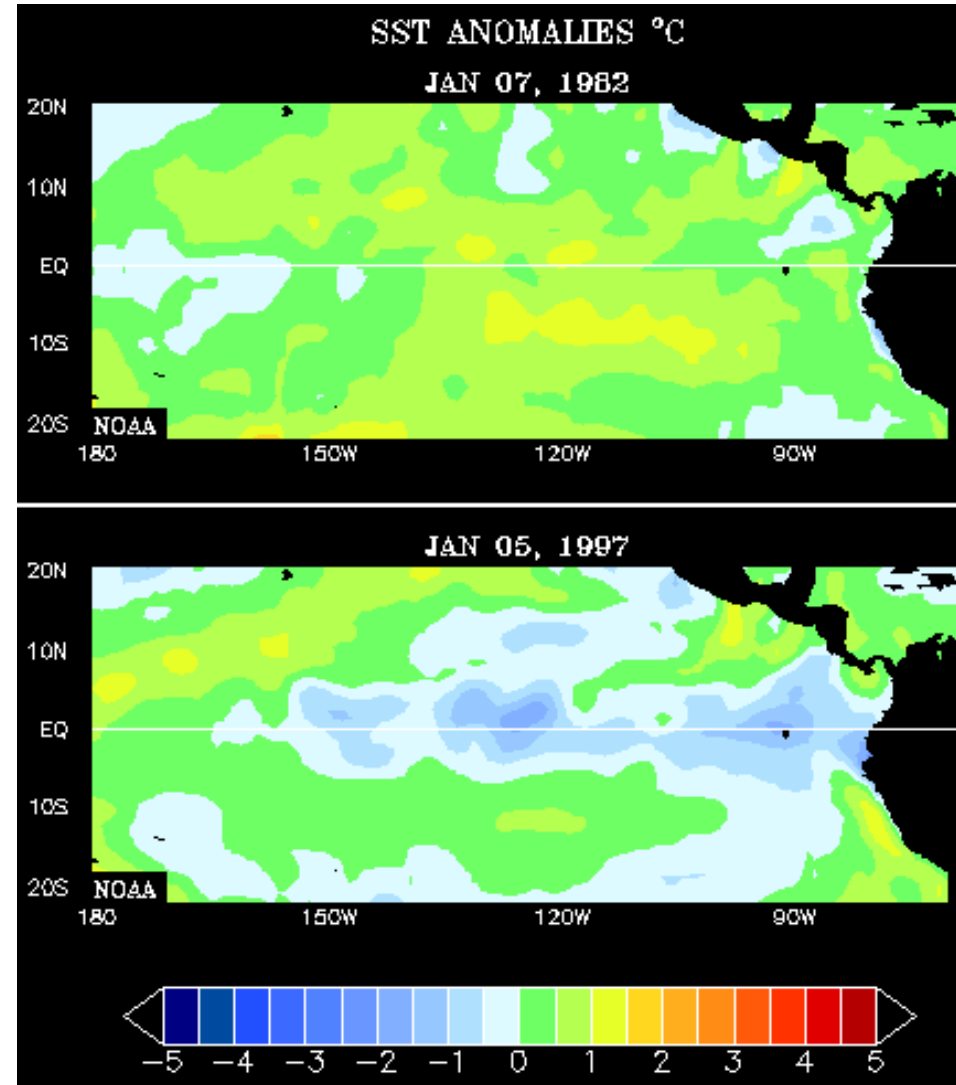
The day after tomorrow

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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.



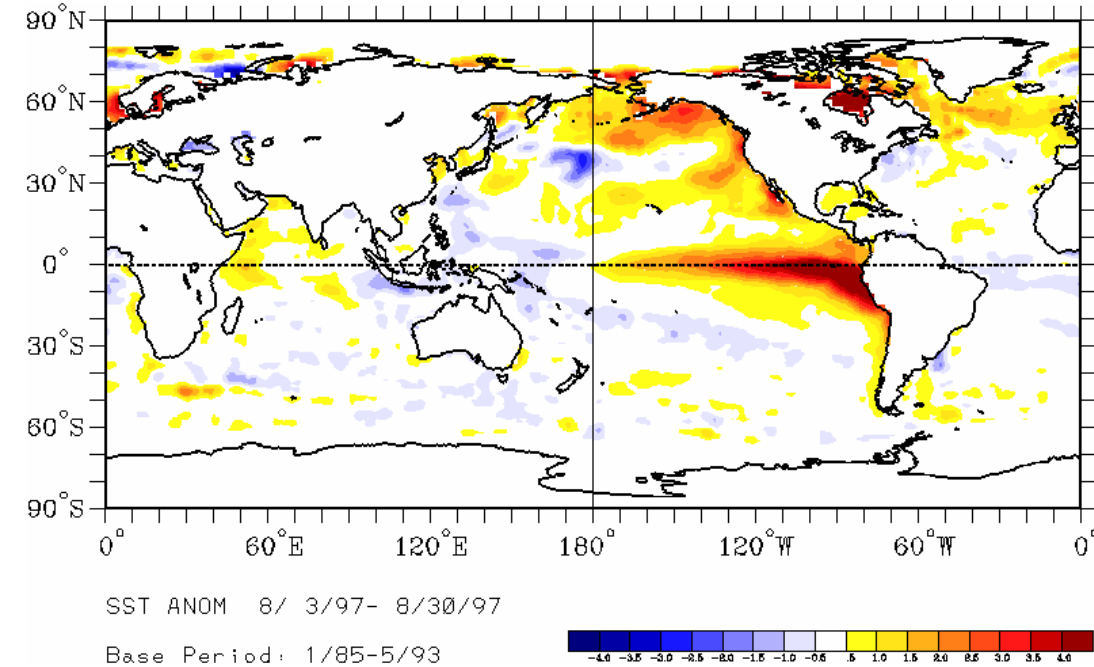
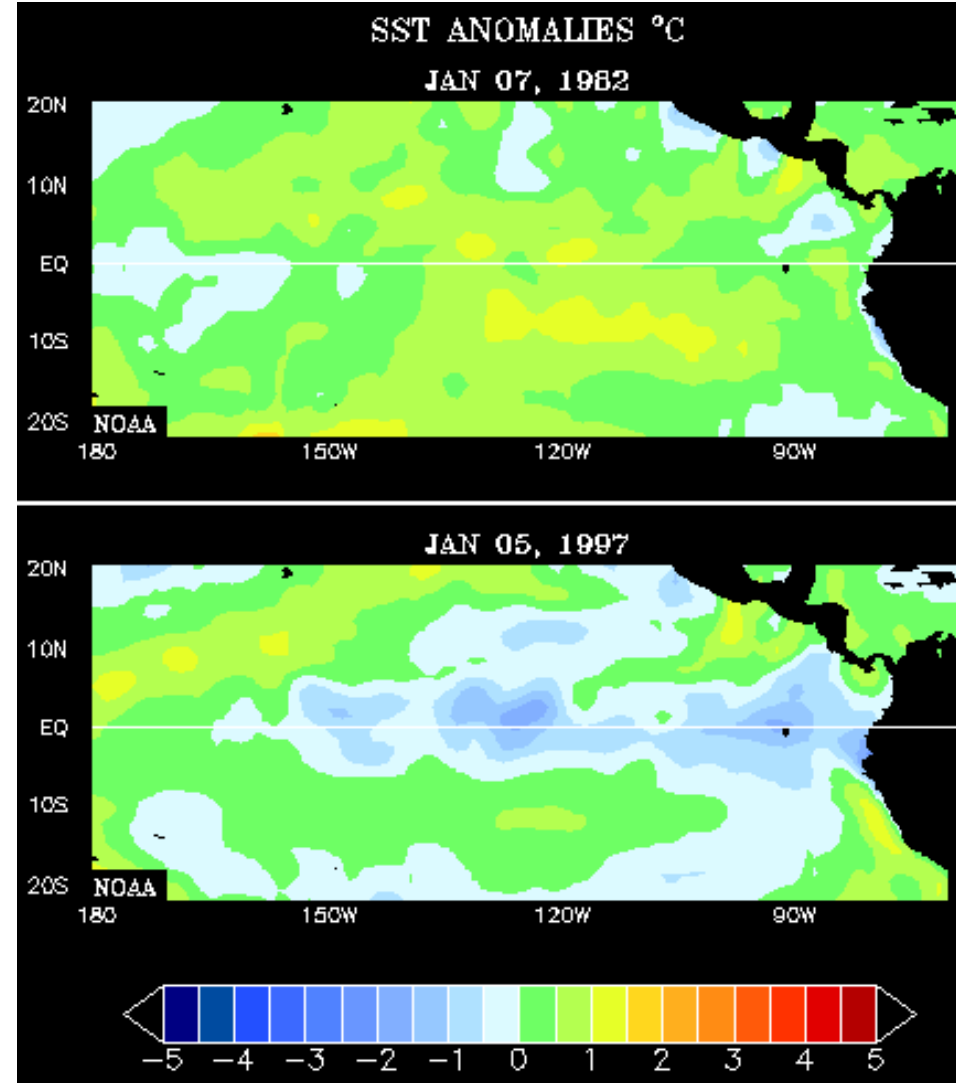
Observed sea surface temperature anomaly during 1997 event

Observed sea surface temperature during 1982 & 1997 events

El Niño

El Niño events:

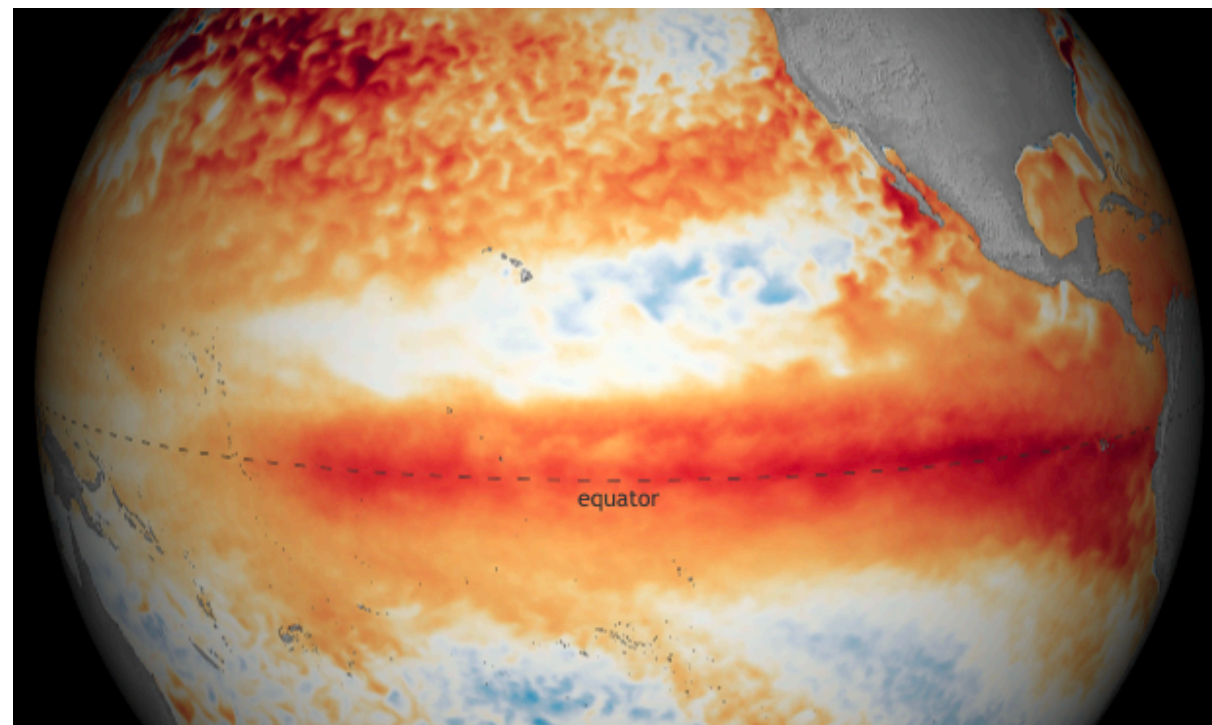
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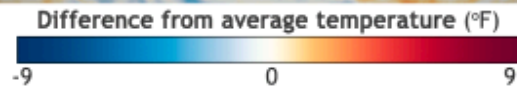
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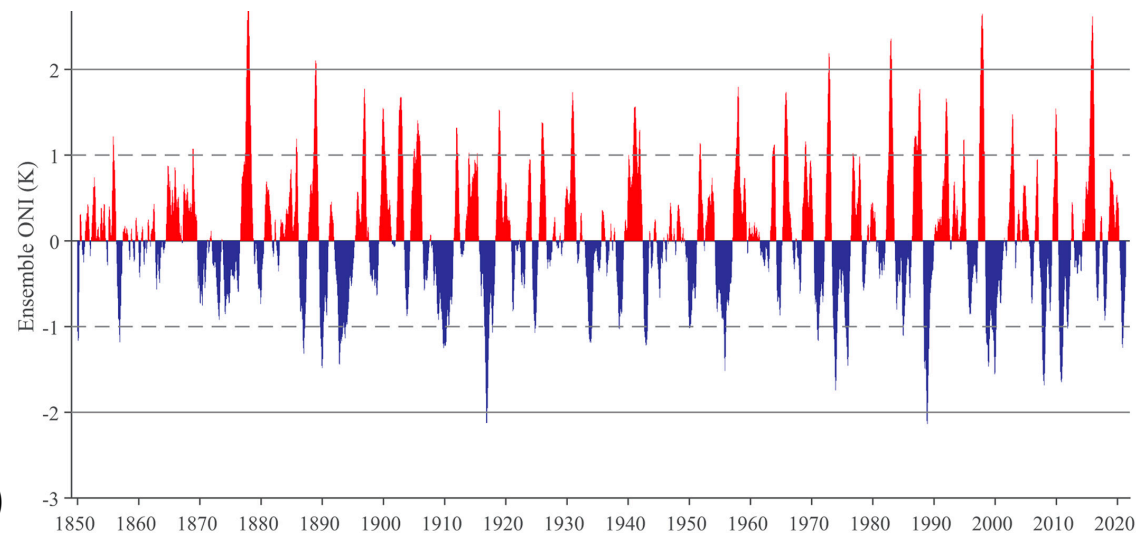
Observations, is El Niño changing?



November 2023
compared to 1985-1993*



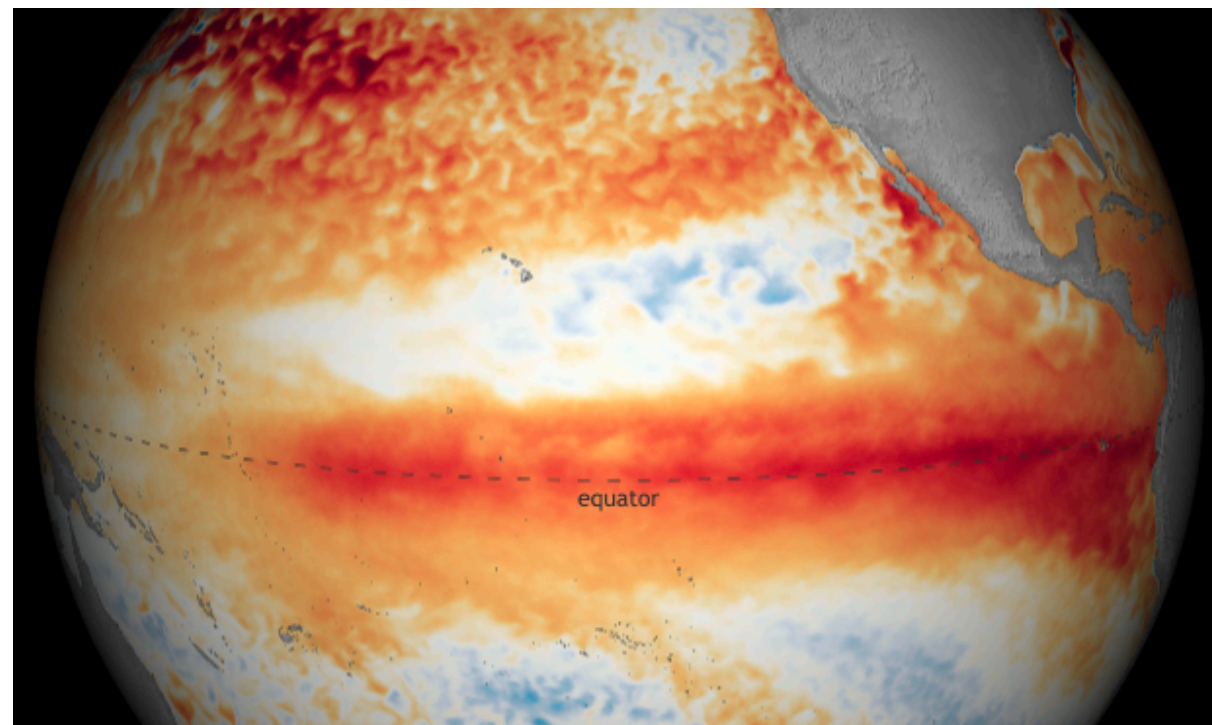
Climate.gov/NNVL
Data: Coral Reef Watch



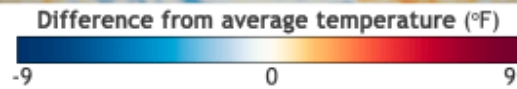
(Webb and Magi 2022)

Current conditions (Dec 2023):
An El Niño advisory!
<https://www.climate.gov/enso>

Observations, is El Niño changing?



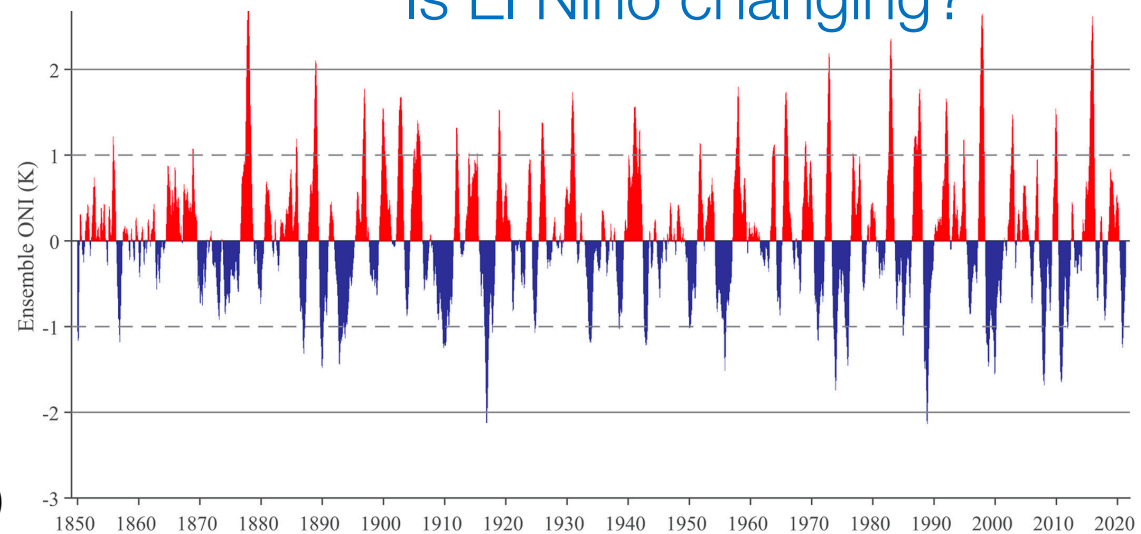
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Climate.gov/NNVL
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(Webb and Magi 2022)

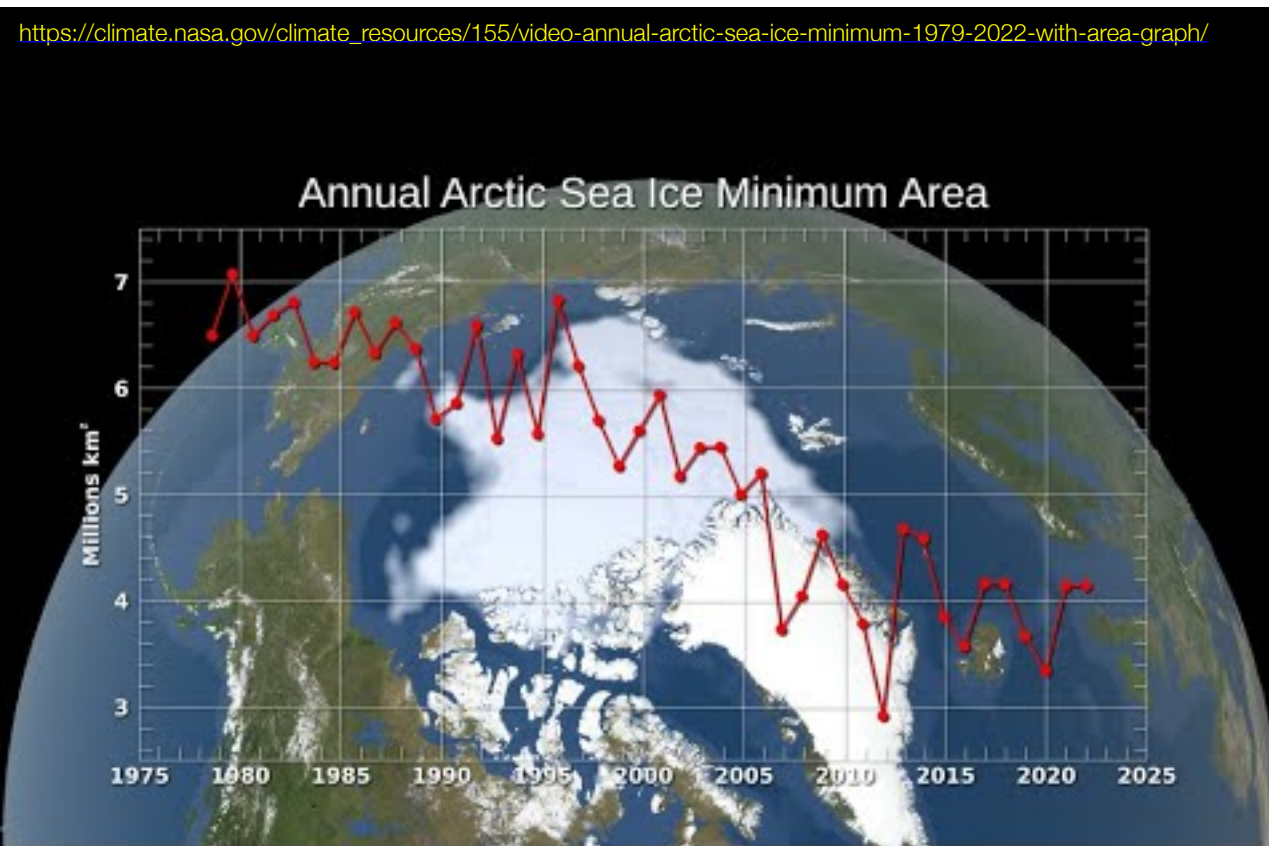
Back to the future



Ocean's role in global warming

- Sea level rise
- Abrupt climate change:
 - Sea ice;
 - AMOC
- Absorbing $\frac{1}{4}$ of emitted CO_2 , $\sim 95\%$ of heat
- Ocean acidification

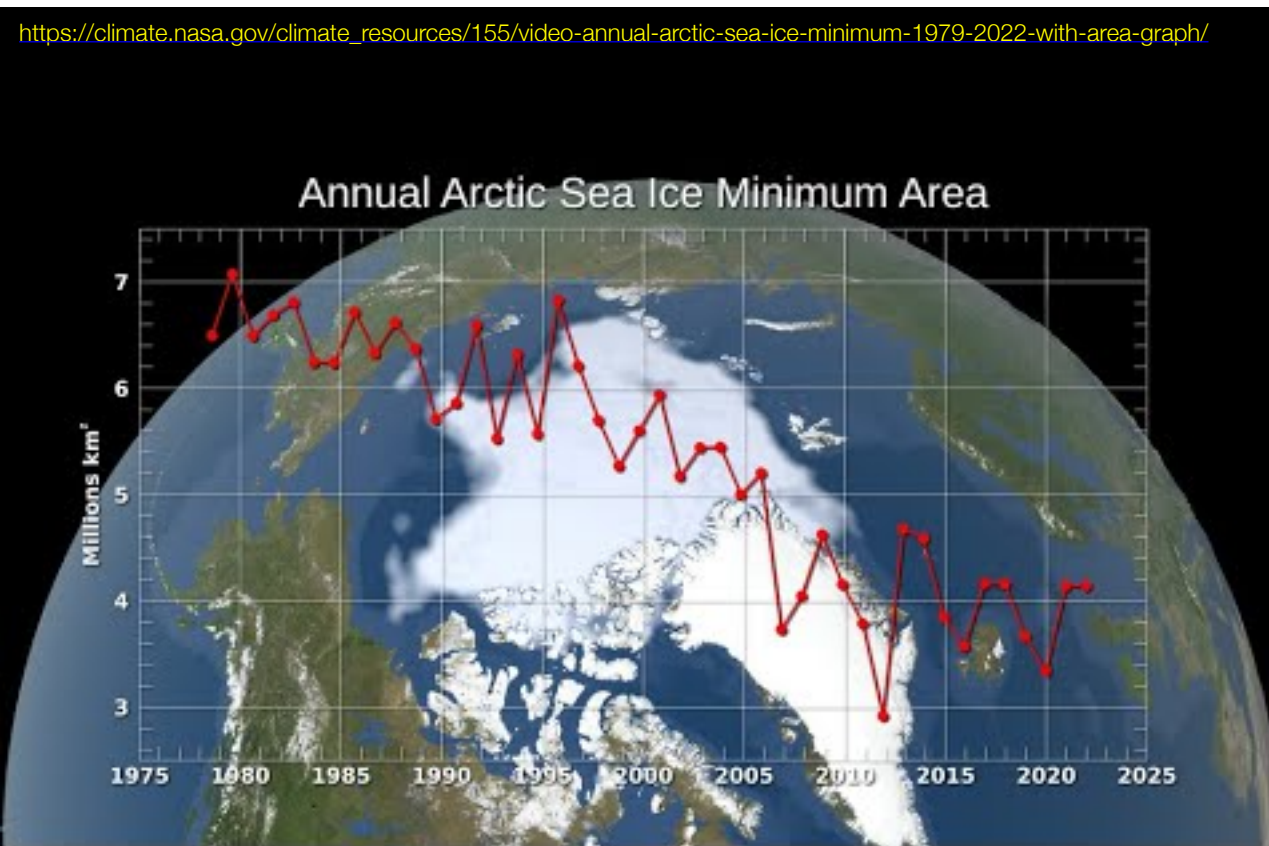
https://climate.nasa.gov/climate_resources/155/video-annual-arctic-sea-ice-minimum-1979-2022-with-area-graph/



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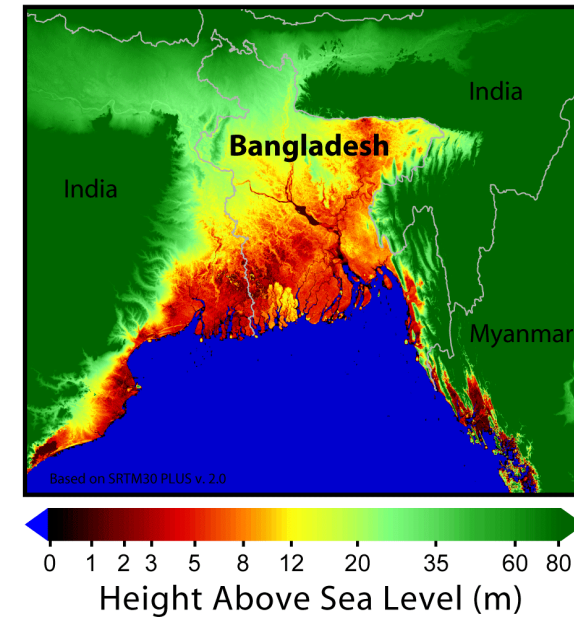
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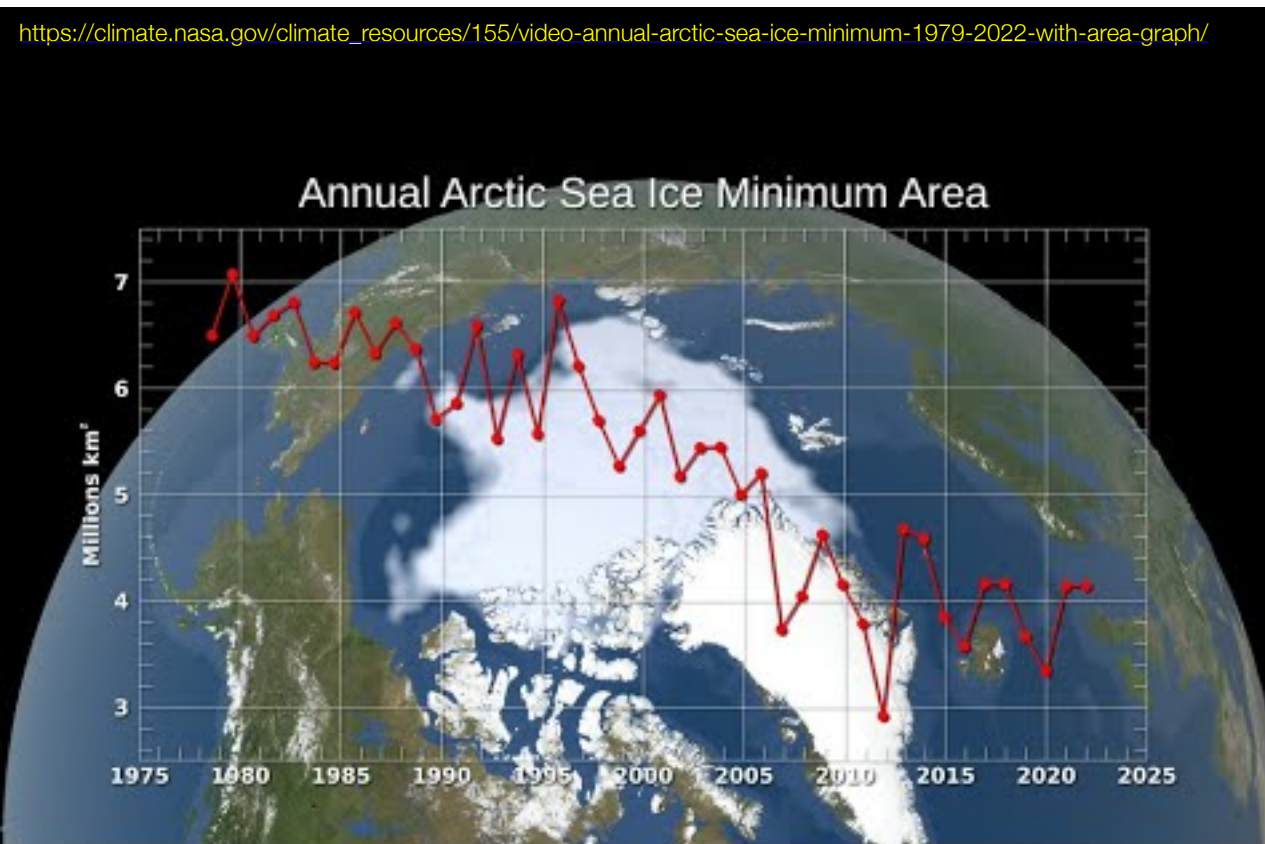
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Sea Level Risks - Bangladesh



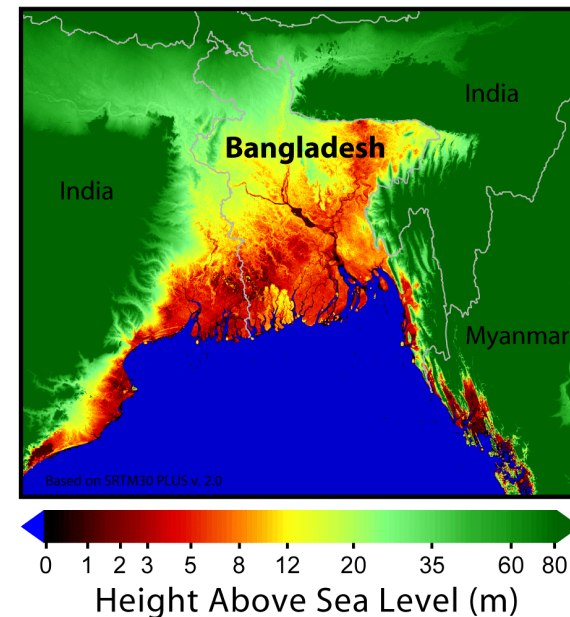
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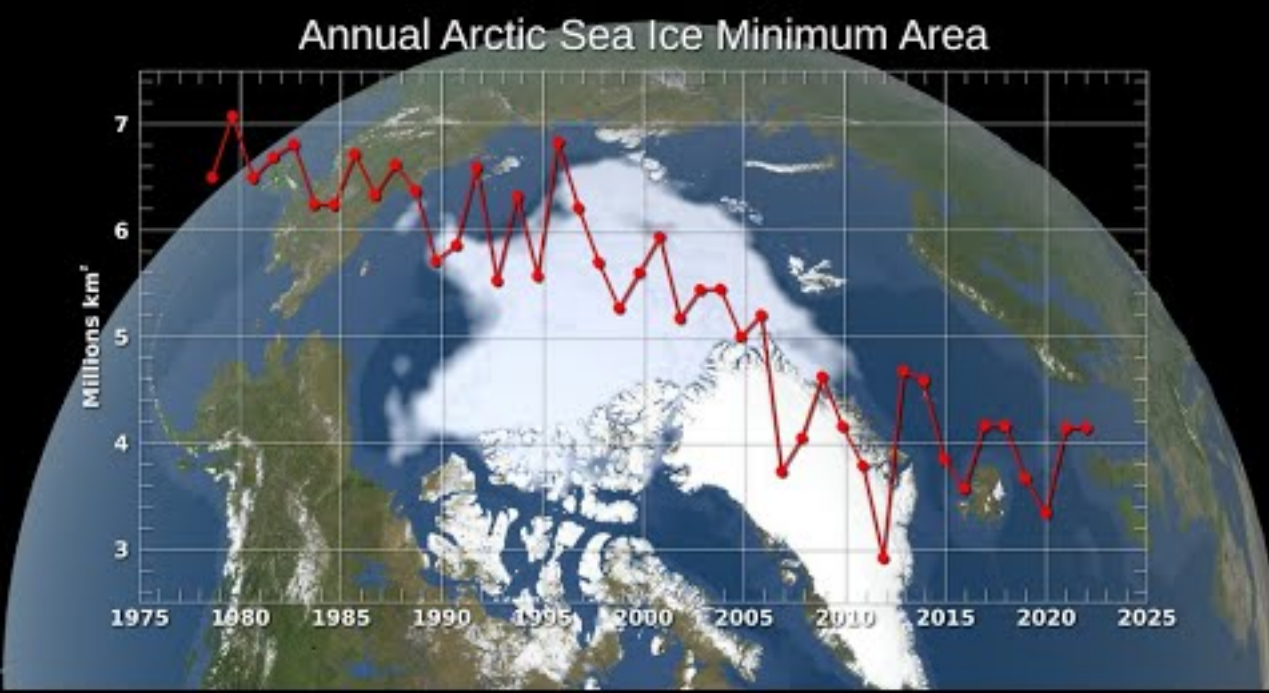
Ocean's role in global warming

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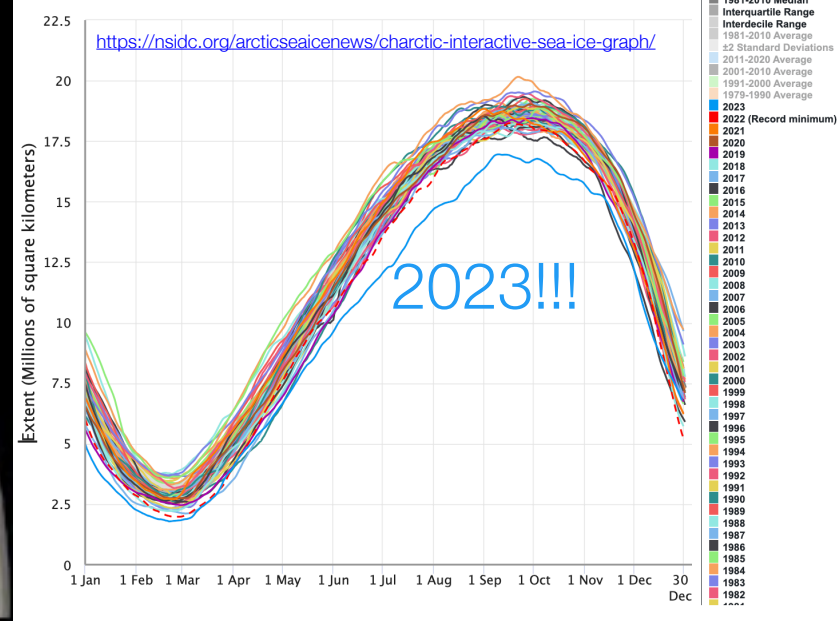
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Antarctic sea ice extent



temperature, salinity | currents, Coriolis | waves | observations | climate

Thanks Elle!!

And thank you, everyone,
for being so engaged and
for a fun semester!

The End