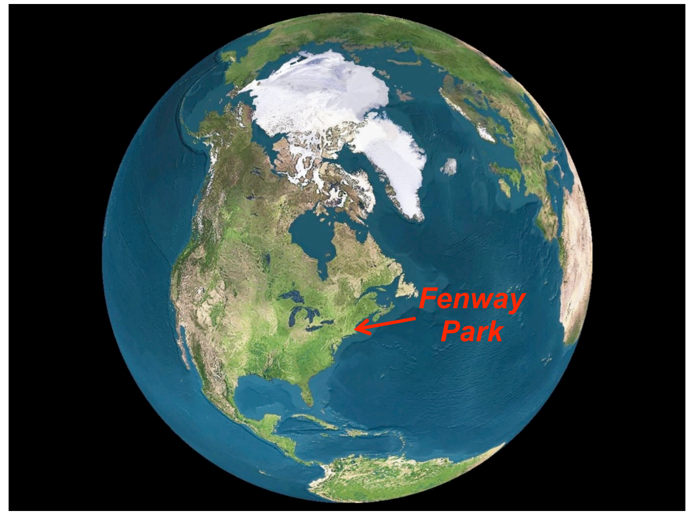
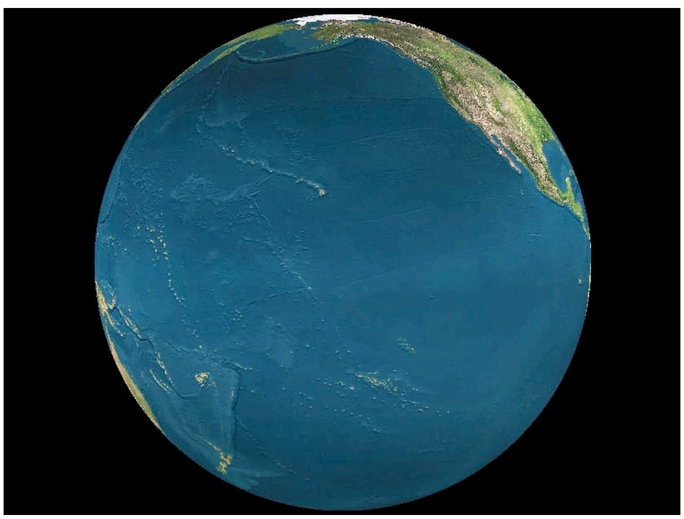
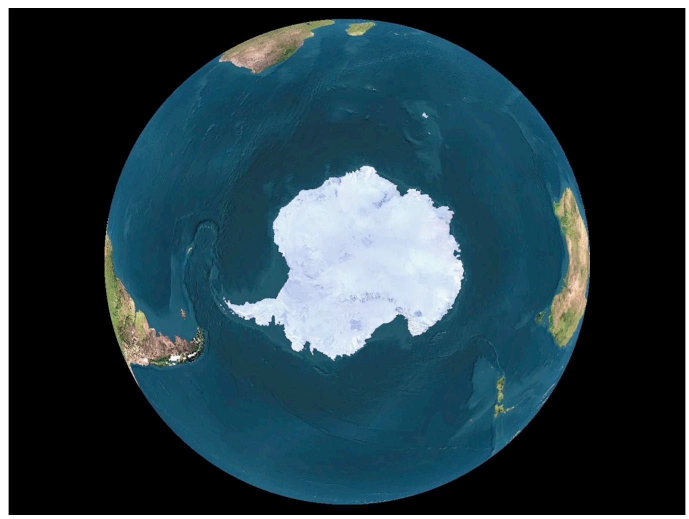


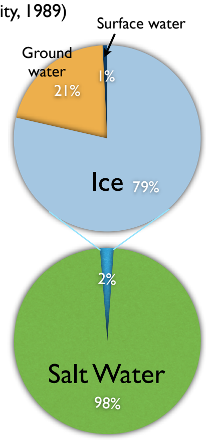




Distribution of Water on Earth

(Units of 10^{15} kg, data from Open University, 1989)

Land: Rivers and Streams	1
Freshwater Lakes	125
Salt Lakes / Inland Seas	104
Glaciers and Ice Caps	29,300
Soil Moisture / Seepage	70
Ground Water	8,400
Total On Land	38,000
Oceans:	1,322,000

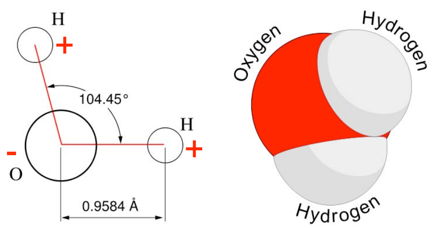


Overview

- Special properties of water.
- What makes the oceans move?
  Wind stress - coriolis effect - thermohaline circulation.
- Interactions between land - ocean - atmosphere:
  the carbon cycle.
- Historical perspective: connection between ocean circulation and climate.

Important Properties of Water

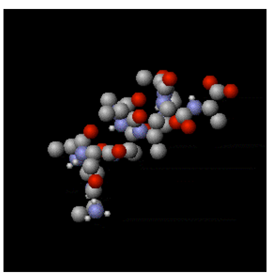
1. Polar molecule – high dissolving power



Important dissolved components: NaCl (salt), CO_2

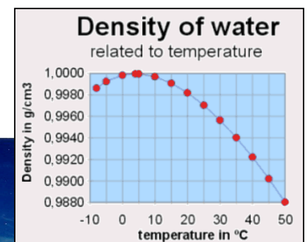
2. Surface tension – resists stress.

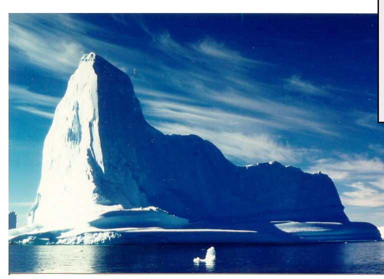
3. High Heat capacity – acts as thermal buffer.



Water has five times the heat capacity of soil: it takes five times the amount of energy to heat up 1 kg of water than it does to heat up 1 kg of soil.

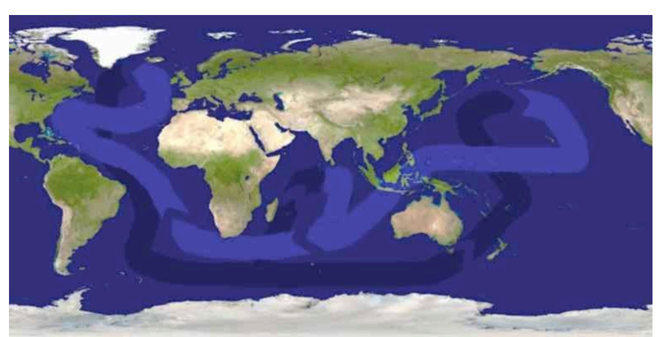
4. Maximum density at 4°C - solid water less dense than liquid water - ice floats!





5. Transparent – light can penetrate

Ocean Circulation: A global phenomenon

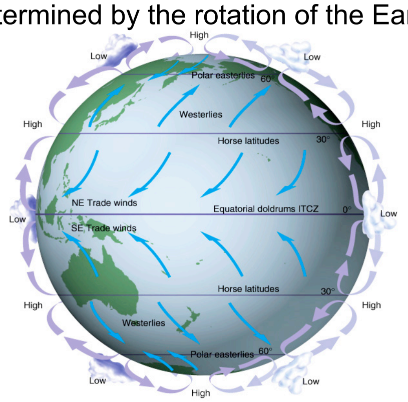


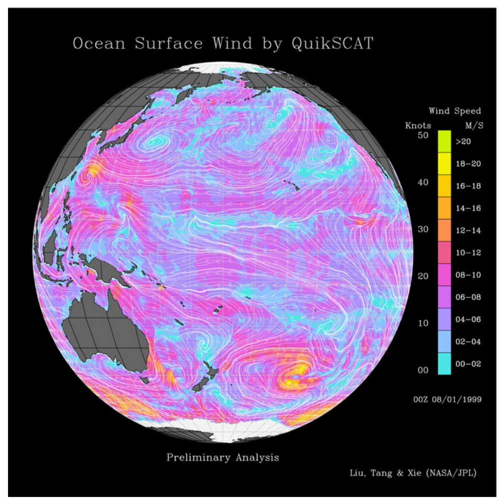
What forces cause ocean water to move?

1. Friction: Results from relative motion between wind and water (wind stress).
2. Coriolis: Results from motion in a rotating coordinate system.
3. Gravity: Gives rise to pressure gradients, buoyancy, and tides.

Wind friction → Waves, currents

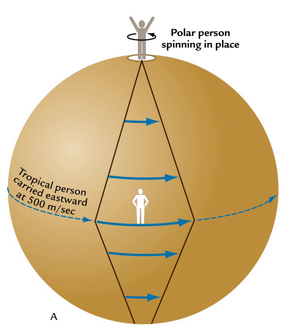
Prevalent global wind direction is not random!
- determined by the rotation of the Earth.





Satellite-based wind speed measurements

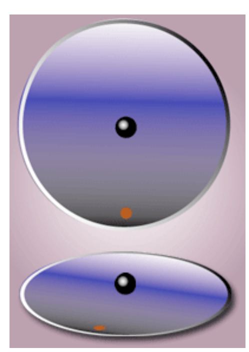
How does the rotation of the Earth affect moving water and air masses ?
→ Different velocity for different latitude: Fastest at the equator, slowest at poles.



Faster

Faster

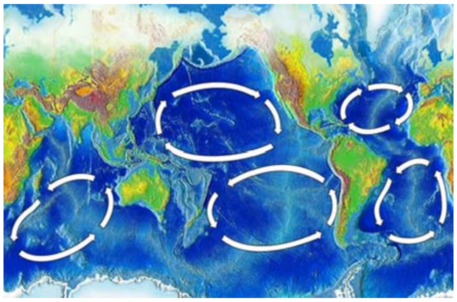
How does the rotation of the Earth affect moving water and air masses ?
→ Coriolis effect.



Looking from above : ball moves in a straight line.

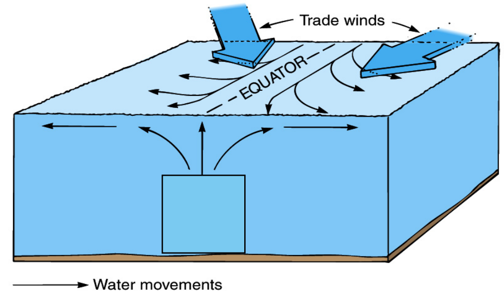
Standing on the rotating plate (fixed - red dot), the ball moves in a curve!

Ocean gyres: circular motion of water masses

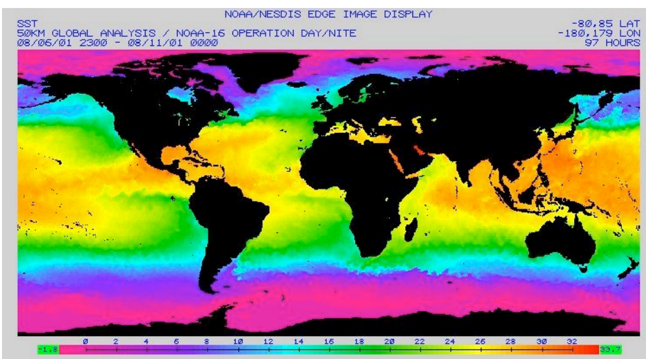


Earth's rotation direction

Surface currents also also involve deep water:
Equatorial divergence and upwelling.

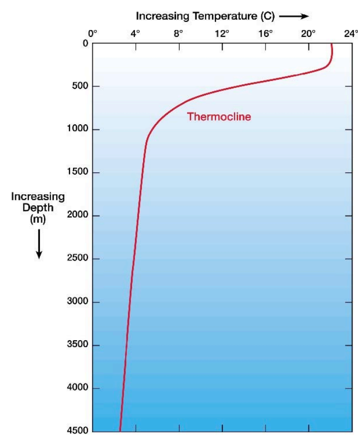


3. Gravity - Density of water



Global Sea-surface Temperatures (°C)
Warm at the equator, cold at the poles.

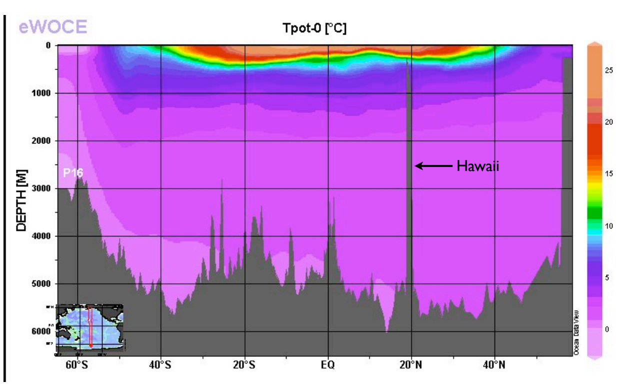
Temperature vs Depth in the Oceans



Sun heats the ocean surface only, with a penetration depth of a few 100's of meters.

Thermocline: Narrow depth range over which a large temperature decrease from warm surface water occurs.

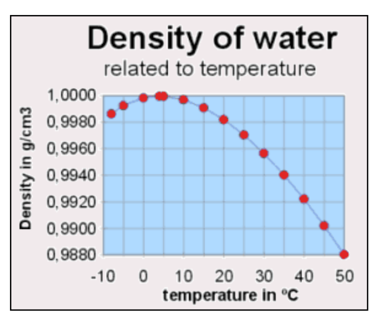
Temperature in a cross-section of the Pacific



Most of the ocean water is below 5°C!

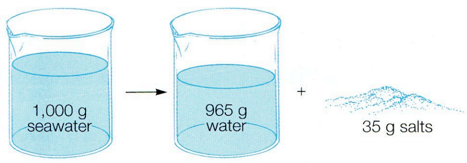
Aside: How to change the density of water:

(1) Change temperature



How to change the density of water: (2) Add salt

Density of water increases with increasing amounts of dissolved solids



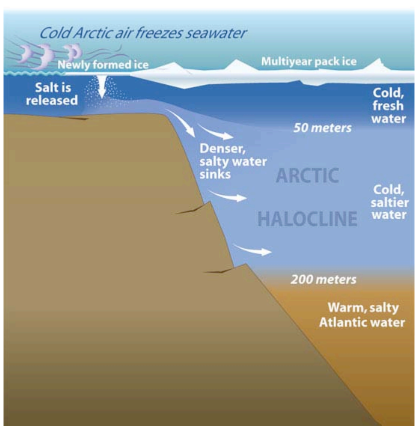
Can also change the relative amount of dissolved material by adding or subtracting water (H_2O): Evaporation, formation of sea ice, river input.

Density driven circulation: Thermohaline circulation

Thermo = temperature

Haline = salt

How does the global ocean circulation work?

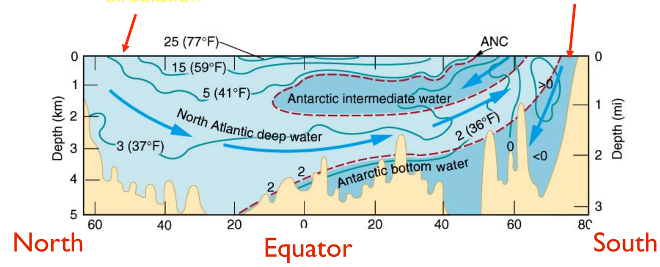


Newly formed ice excludes salt, makes left-over water saltier - more dense, sinks.

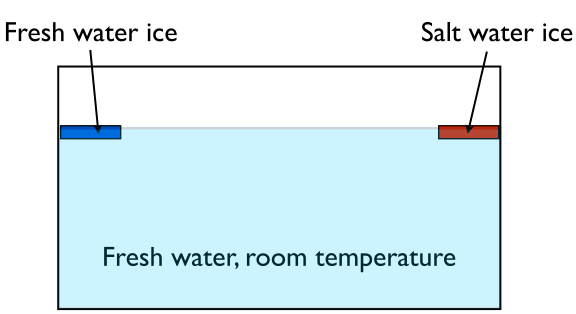
Vertical temperature distribution in a cross section of the Atlantic

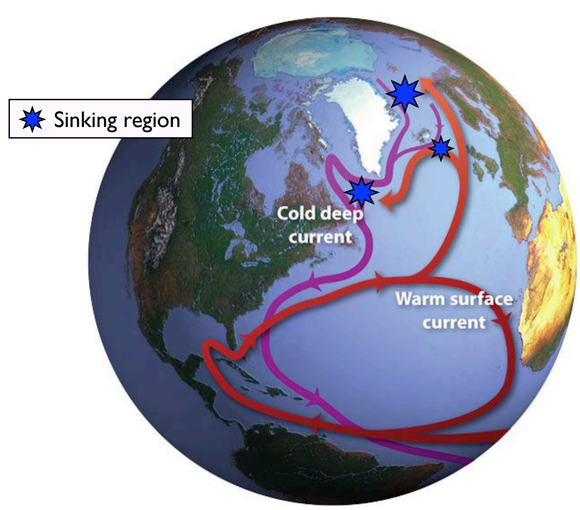
North Atlantic deep water = "Start" of thermohaline circulation

Joined by Antarctic bottom water

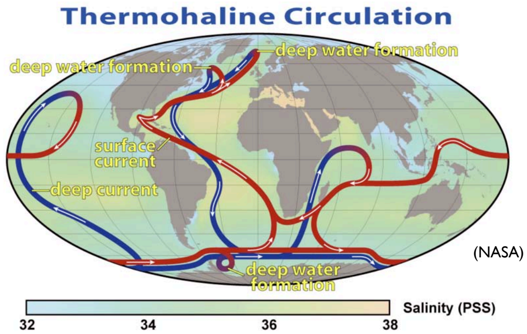


Tank experiment, thermohaline circulation



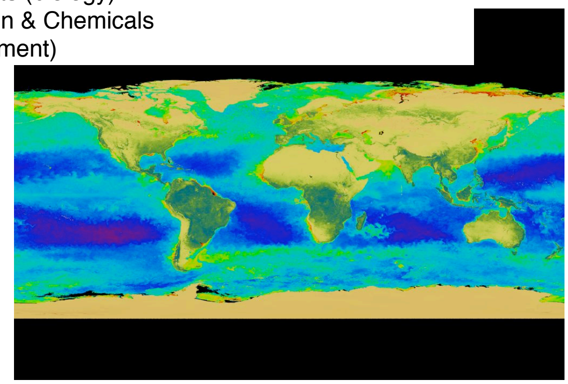


Global Conveyor Belt of Thermohaline Circulation



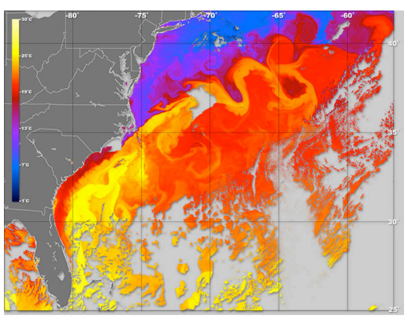
What are the effects of global ocean circulation?

Ocean currents are water masses in motion.
Currents transport:
- Heat (climate)
- Nutrients (biology)
- Pollution & Chemicals (Environment)



Gulf stream:
Energy transport: ~ 1.4 petawatts of heat, equivalent to 100 times the world energy demand.
Water transport: up to 80 million m^3/s
For comparison: All rivers draining into the Atlantic: ~ 0.6 m^3/s

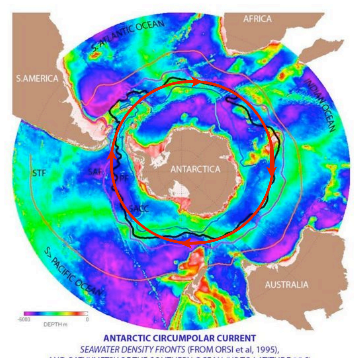
Surface speed:
40 -120 km/day,
width 80–150 km,
depth: 800–1200 m.



NASA Aqua satellite MODIS image

Antarctic Circumpolar Current

Water transport: 135 m^3/s.
Driven by west winds, unimpeded by land.

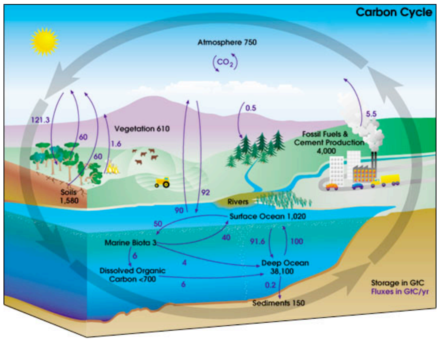


Summary so far:

Distribution of water on the Earth
Key properties of water
Three factors driving ocean circulation (Wind, Earth's rotation, gravity)
Global thermohaline circulation - global transport of heat (energy) and nutrients

Interaction of ocean, land surface and atmosphere:

The carbon cycle
Carbon chemistry
Weathering reactions
Effect of increasing CO_2 in the atmosphere



Carbon storage in black in Gigatons (10^9 t)

Carbon fluxes (transfer) in purple in Gt/year

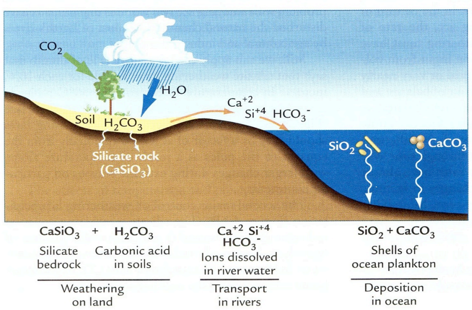
Storage:
in Atmosphere 750 Gt
in Vegetation 610 Gt
in Ocean 38,100 Gt

Key point: Atmosphere, oceans and solid Earth are part of a linked system!

Carbon chemistry

- Solution:
  CO_2(atmospheric) $\rightleftharpoons$ CO_2(dissolved)
- Conversion to carbonic acid:
  CO_2(dissolved) + H_2O $\rightleftharpoons$ H_2CO_3
- First ionization:
  $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ (bicarbonate ion)
- Second ionization:
  $HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$ (carbonate ion)

Chemical weathering

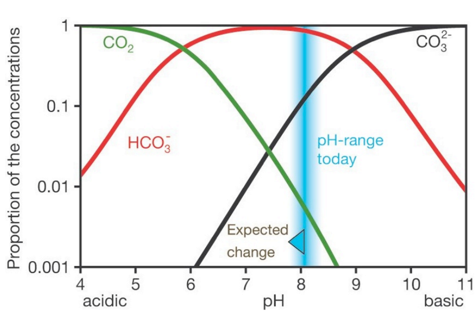


1. Weathering reactions involving carbonic acid dissolve silicate minerals.
2. Transport of dissolved ions into the ocean.
3. Reaction of dissolved Ca^{2+}, Mg^{2+} to form $CaCO_3$ and $MgCO_3$ sequesters carbon in limestone.

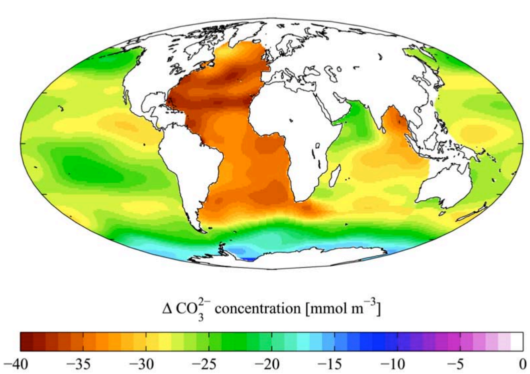
$CaCO_3$ is used by calcifying organisms, for example coccolithophores, foraminiferans or pteropods

Link between weathering of rocks, CO_2 in the atmosphere and in the ocean: marine life sequesters CO_2 !

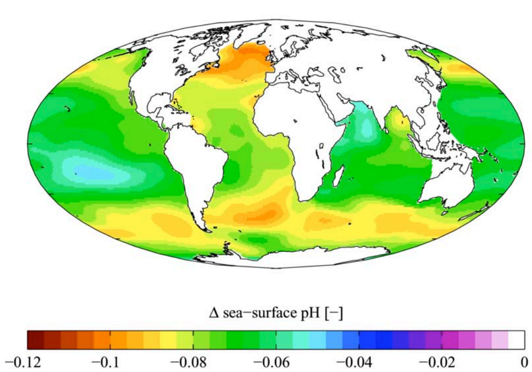
But: Increased CO_2 content makes oceans more acidic

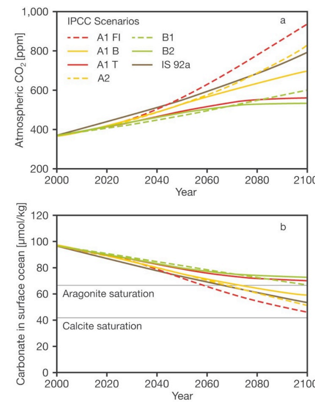


Key point: In more acid ocean calcium carbonate shells and skeletons are more difficult to form.
Since these creatures are at the bottom of the food chain, the whole food chain up to baleen whales will be affected.



Change in sea surface carbonate ion (CO_3^{2-}) concentration from the pre-industrial period (1700s) to the present day (1990s).





Projection of atmospheric CO_2 concentration

Calcite, aragonite are $CaCO_3$ in shells of marine organisms

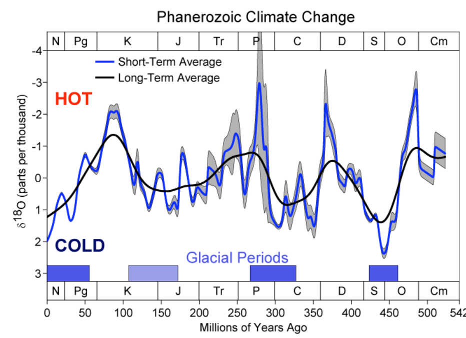
Key point: If ocean is too acidic, $CaCO_3$ shells will no longer be formed, CO_2 sequestration into sediments will stop.

Historical perspective: What was the climate like in the past?

Is there a connection between climate and ocean circulation?

Past climate inferred from "proxies", e.g. oxygen isotope ratio.

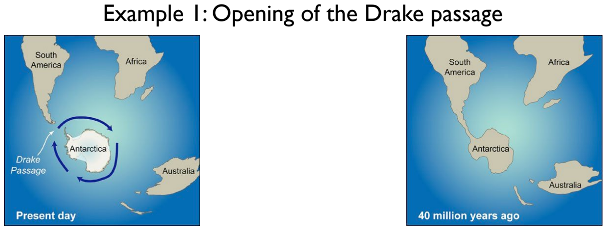
Climate during the last ~ 500 Million years

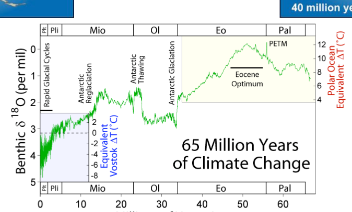


Glacial periods: Ice sheets exist.

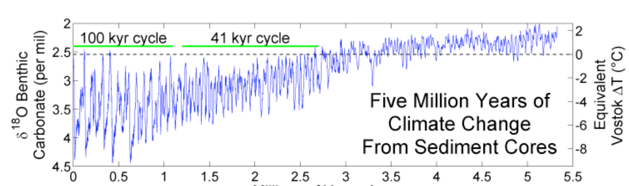
Message from this diagram:
Substantial climate changes have occurred over this time period!

At time scale of millions of years interaction of plate configuration and ocean currents influence climate.
Example 1: Opening of the Drake passage





Example 2: Gulf stream



Earth's climate system