In this course...

I. Brief introduction to the atmosphere
II. Overview of the Earth System
III. Survey of the atmosphere:
    1. Dynamics
    2. Thermodynamics
    3. Weather systems: Extratropical
    4. Chemistry
    5. Cloud processes
    6. Boundary layer
    7. Radiative transfer
    8. Remote sensing with radar
    9. Weather Systems: High latitude and tropical
    10. Numerical weather prediction
    11. Climate dynamics
IV. Useful research tools in atmospheric science

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Overview of the Earth System

Now that we have taken a brief overview of the atmosphere, we will briefly survey the rest of the Earth System before returning to the atmosphere for a more detailed examination

1. Components of the Earth System other than the atmosphere
   - ➔ Oceans
   - ➔ Cryosphere
   - ➔ Terrestrial biosphere
   - ➔ Earth's crust and mantle
2. History of climate and the Earth System

Oceans

The density of sea water depends on temperature, salinity, and pressure: $\sigma = \sigma(T, s, p)$.

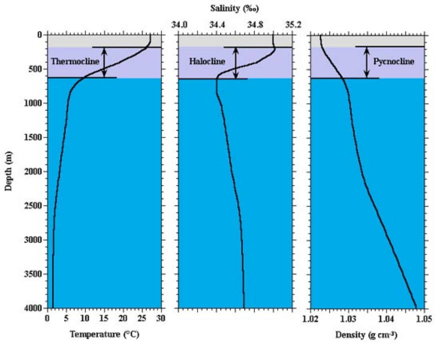
σ is expressed as a departure from 1000 g m^{-3} ($\sigma = \rho - 1000$)

s is expressed as the number of grams of dissolved salts per kg of fresh water (parts per thousand. Symbol is permille: ‰)

Sea water contains ∼34-36‰.

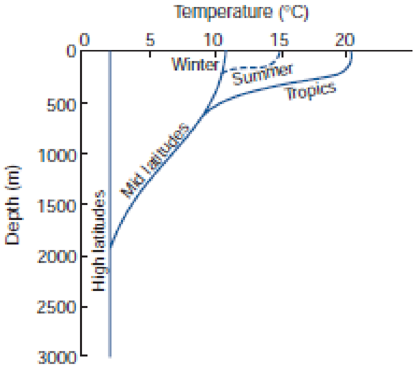
Potential density, σ_θ, is density that a water parcel would have if it were raised adiabatically to the surface without change in its salinity: $\sigma_\theta = \sigma(T, s, 0)$

Oceans



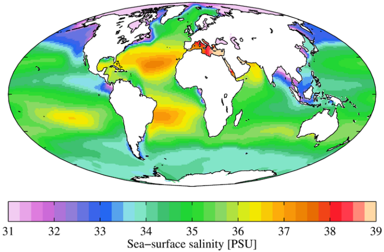
- The **pycnolcine** is the region where density transitions from lower values near the surface to higher values at depth. It is also called the **mixed layer** because vertical mixing tends to be inhibited below it.
- The **thermocline** is the layer in which temperature decreases with depth. It is often the same layer as the pycnocline in lower latitudes.
- The **halocline** is the layer in which salinity increases with depth.

Vertical oceanic structure



- Solar radiation can be absorbed in the oceans.
  - ➔ The strength and depth of the thermocline varies with latitude and season
- Most heating is confined to the mixed layer, with very little temperature variation below it.

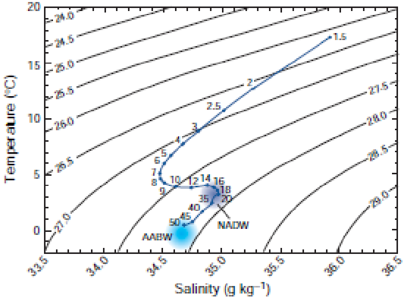
Salinity



- Precipitation lowers salinity by diluting the salts that are present in the oceanic mixed layer.
- Evaporation results in an increased concentration of salt, thus increasing salinity.
- Melting ice decreases salinity, and freezing sea water increases salinity.
  - ➔ Freezing sea ice induces vertical mixing because saline water is more dense than fresh water and sinks.

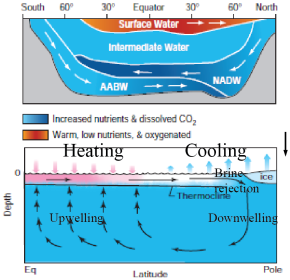
Relationship between temperature, salinity, and density

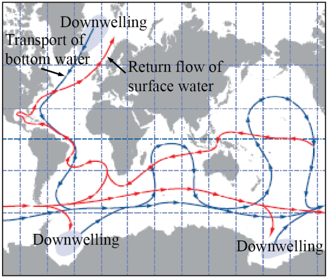
Temperature salinity diagram



- σ_θ generally decreases with T
- σ_θ increases with salinity
- Note that for temperatures near the freezing point of sea water (about -1.8°C), $\sigma \simeq \sigma($*salinity*$)$ only

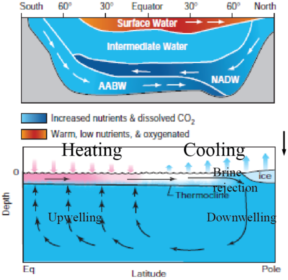
Thermohaline circulation

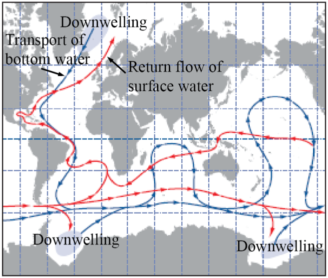




- Ocean circulation composed of a **wind-driven** component and *thermohaline* component:
  - ➔ Wind-driven is controls surface currents, limitied to top few hundred meters
  - ➔ Thermohaline = “Temperature-salty”

Thermohaline circulation



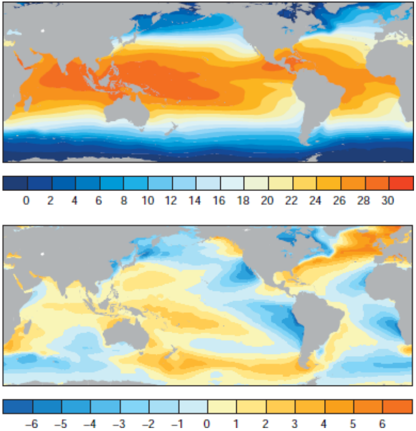


- **Brine rejection:** a process that occurs during sea ice formation where salt is pushed from forming ice into the surrounding seawater, creating saltier, denser brine.
- **North Atlantic deep water (NADW)**: Forms by the sinking water along the ice edge in the Greenland, Iceland, and Norwegian (GIN) Seas.
- **Antarctic bottom water (AABW)**: Forms by sinking along the ice edge in the Weddell Sea.

Sea surface temperature

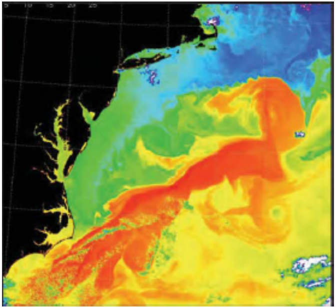
Annual mean SST

SST zonal-mean anomalies



- Colder waters generally correspond to subtropical west coasts, where the subtropical highs circulate water equatorward and promote upwelling.

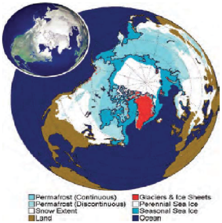
Sea surface temperature



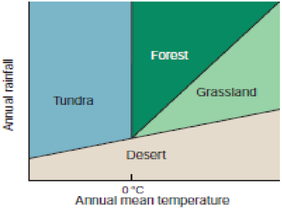
- On eastern coasts (such as North America), the anticyclonic flow around the “Bermuda high” drives a warm current poleward, called the **Gulf Stream.**
- Ocean currents are made up of smaller-scale “eddies” or ocean vortices; Boundaries are sharp, with local SST ranges of up to $\sim 15^{\circ}$C.

Cryosphere, Biosphere, and Crust

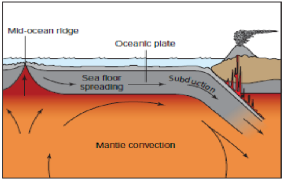
Cryosphere



Terrestrial biosphere



Crust and Mantle



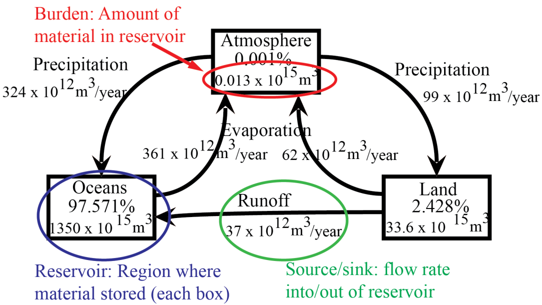
The **cryosphere** refers to components of the Earth system comprised of water in its solid state.

The **terrestrial biosphere** concerns the geographical distribution of forests, grasslands, tundra, and deserts.

The Earth's crust and mantle are important components that mediate the composition of the atmosphere (on timecales of tends to hundreds of millions of years)

The hydrologic cycle

Box model of the water cycle



What is the residence time of H_2O in the atmosphere?

$$\tau = \frac{M}{F}$$

where M is the amount of the constituent, and F is the rate of removal.

$$\tau = \frac{0.013 \times 10^{15} m^3}{423 \times 10^{12} m^3 yr^{-1}} = 11\ days$$

The hydrologic cycle

Let A be atmospheric water vapor, P precipitation, and E evaporation. Then:

$$\begin{aligned} \frac{dA}{dt} &= E - P \\ \frac{\partial A}{\partial t} + Tr &= E - P \end{aligned}$$

where Tr is horizontal transport (or flux). Assuming steady state conditions (atmospheric water vapor is not drifting), then

$$Tr = E - P.$$

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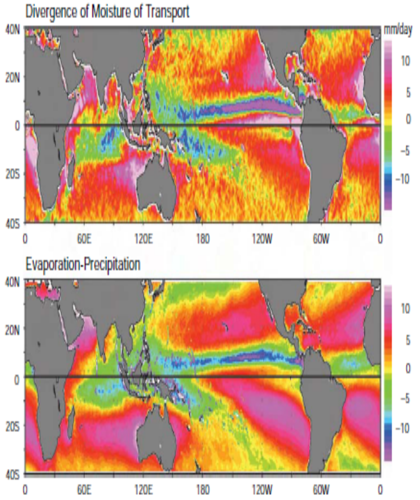
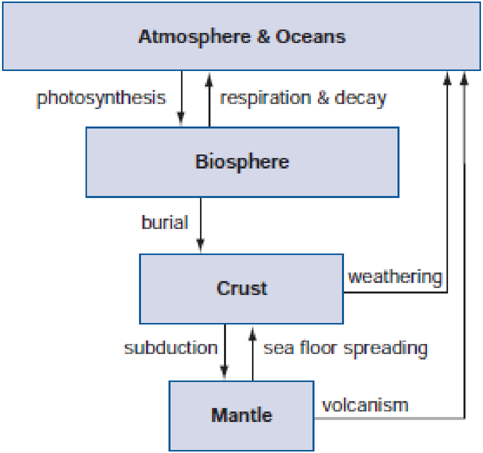
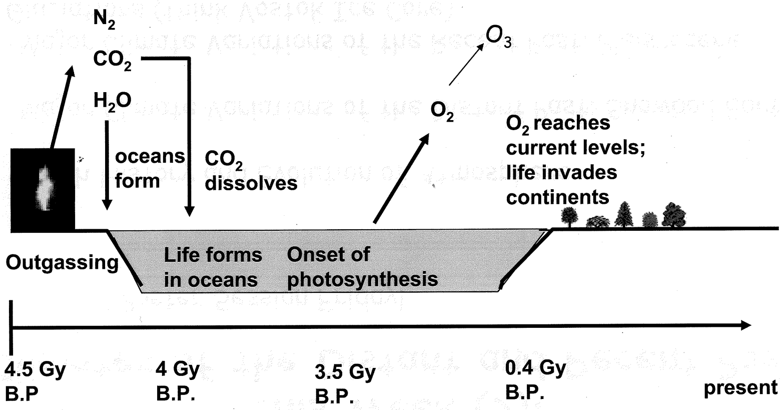


The Carbon Cycle

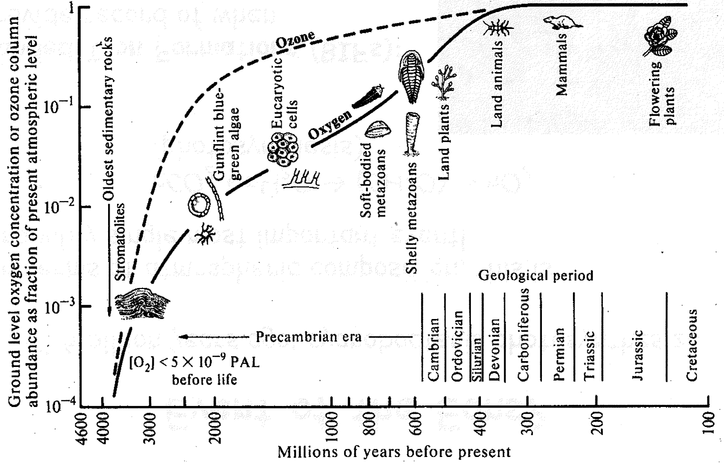


The carbon cycle regulates the concentrations of two of the atmosphere's most important greenhouse gases: CO_2 and CH_4.

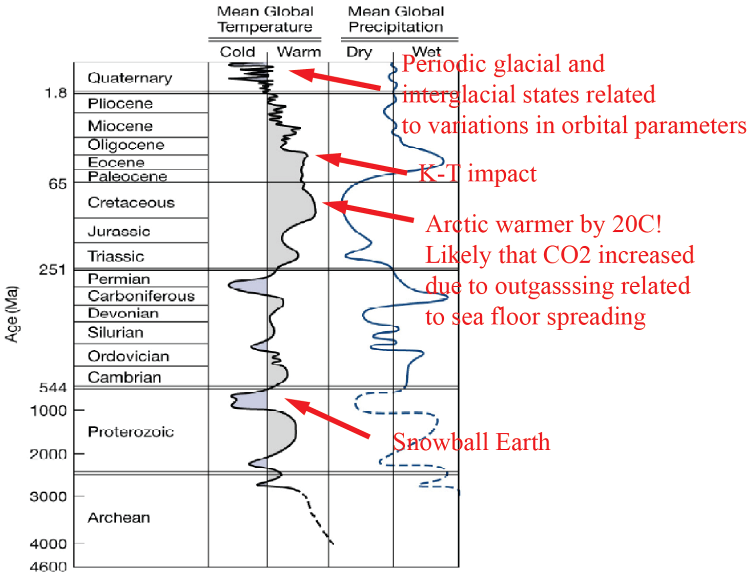
Summary of Atmospheric Evolution



Evolution of O_2 and O_3



Geological temperature and precipitation timeline



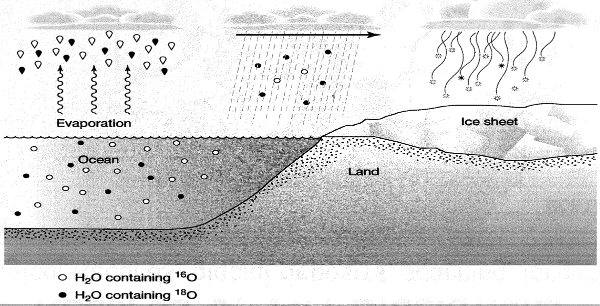
Records of Glaciations

Isotopic Records: oxygen isotopes

^{16}O vs ^{18}O

"light" (normal) — **"heavy"**

- evaporation selects for "light" oxygen, ^{16}O
- growth of ice-sheets selectively removes ^{16}O
- remaining ocean water is "heavier" (higher concentration of ^{18}O)



^{18}O in ocean sediments: records glacial ice volume:

More "light" water in ice-sheets means remaining ocean water is "heavier".

Earth: The lonely planet?

Well... at least in *our* solar system.

Table 2.5 Astronomical and atmospheric data for Earth and neighboring planets[a]

Parameter	Venus	Earth	Mars	Jupiter
Radius (km × 10^3)	6,051	6,371	3390	66,911
Gravity (m s^{-2})	8.87	9.80	3.71	24.79
Distance from sun (AU)	0.72	1.000	1.524	5.20
Length of year (Earth years)	0.615	1.000	1.88	11.86
Length of day (Earth days)	117	1.000	1.027	0.41
Orbital eccentricity	0.0067	0.0167	0.093	0.049
Orbital obliquity	2.36	23.45	25.19	3.13
Dominant constituent (% by volume)	CO_2 (96.5)	N_2 (78.1)	CO_2 (95.3)	H_2 (90)
Secondary constituent (% by volume)	N_2 (3.5)	O_2 (21)	N_2 (2.7)	He (10)
Surface pressure (hPa)	92,000	997	8[b]	$>>10^6$
Surface temperature (K)	737	288	210	
Diurnal temperature range (K)	~0	10	40	

[a] Based on *Planetary Fact Sheets* on NASA Web site; Mars surface data based on records at the Viking 1 Lander site.
[b] Varies seasonally from 7.0 hPa during the austral winter, when Mars is farthest from the sun, to 9.0 hPa during the austral summer.