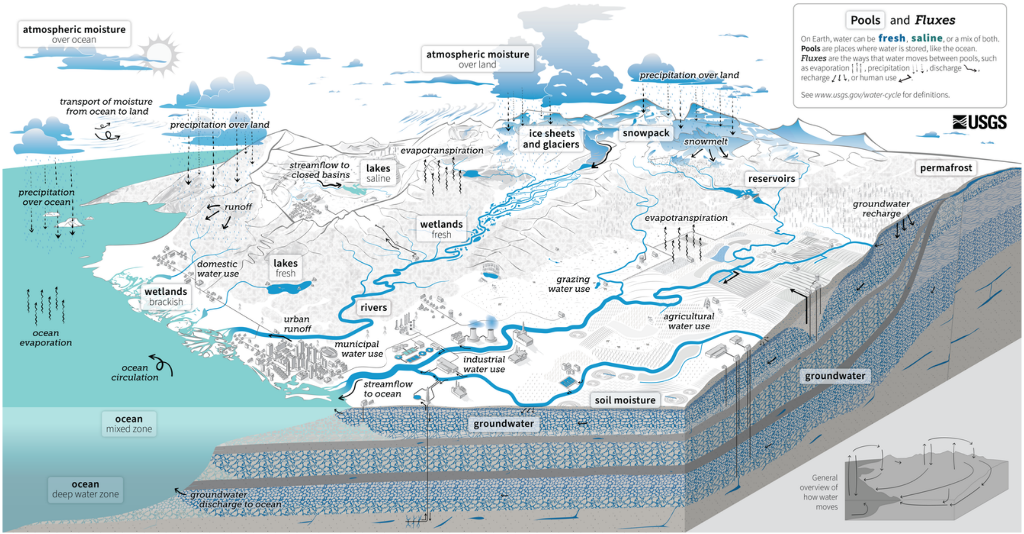
The Climate System

Katie Markovich, EPS 522/ ENVS 423L (Fall 2025)

Water Cycle



atmospheric moisture
over ocean
transport of moisture
from ocean to land
precipitation over land
atmospheric moisture
over land
precipitation over land
Pools and Fluxes
On Earth, water can be fresh, saline, or a mix of both.
Pools are places where water is stored, like the ocean.
Fluxes are the ways that water moves between pools, such as evaporation, precipitation, discharge, recharge, or human use.
See www.usgs.gov/water-cycle for definitions.
USGS
ice sheets
and glaciers
snowpack
snowmelt
evapotranspiration
streamflow to
closed basins
lakes
saline
permafrost
reservoirs
precipitation
over ocean
runoff
wetlands
fresh
groundwater
recharge
evapotranspiration
domestic
water use
lakes
fresh
wetlands
brackish
grazing
water use
rivers
urban
runoff
agricultural
water use
ocean
evaporation
municipal
water use
industrial
water use
ocean
circulation
streamflow
to ocean
soil moisture
groundwater
ocean
mixed zone
groundwater
ocean
deep water zone
groundwater
discharge to ocean
General
overview of
how water
moves

What is the difference between climate and weather?

What is the difference between climate and weather?

Weather (meteorology): state (e.g., temperature, humidity, wind speed, etc.) of the atmosphere at a given time/place.

Climate (climatology): average of weather in terms of mean state and its variability over defined time period/region.

Physics of Radiant Energy

All matter above absolute zero (0 K) radiates energy in the form of electromagnetic waves that travel at the speed of light. The rate at which this energy is emitted is given by Stefan Boltzmann Law:

$$Q_r = \varepsilon \cdot \sigma * T^4$$

where Q_r is rate of energy emission per unit surface area per unit time, T is absolute temperature of surface, σ is the Stefan Boltzmann constant (4.9x10^{-9} Wm^{-2}K^{-4}), and ε is emissivity of the surface (dimensionless). The value of ε ranges from 0 to 1, with 1 being referred to as a **blackbody**.

From this, what state variable controls energy emission?

Emissivity

Ranges from 0 to 1, with 0 acting as a perfect reflector and 1 as a perfect emitter.

TABLE 3.1. TYPICAL BROADBAND EMISSIVITIES FOR VARYING LAND SURFACE TYPES (FROM ARYA, 2001)

SURFACE TYPE	EMISSIVITY
Water	0.92-0.97
Snow	0.82-0.99
Ice	0.92-0.97
Bare soil	0.84-0.97
Grass (long, 1m)	0.90
Grass (short, 0.02m)	0.95
Agricultural crops	0.90-0.99
Forests	0.97-0.99

Albedo

Ranges from 0 to 1, with 0 absorbing all incoming radiation and 1 reflecting all.

TABLE 3.2. TYPICAL BROADBAND ALBEDO FOR VARYING LAND SURFACE TYPES (FROM ARYA, 2001)

SURFACE TYPE	ALBEDO
Water (small zenith angle)	0.03-0.10
Water (large zenith angle)	0.10-1.0
Snow (old)	0.40-0.70
Snow (fresh)	0.45-0.95
Ice	0.20-0.45
Bare soil	0.05-0.40
Grass (long, 1m)	0.16
Grass (short, 0.02m)	0.26
Agricultural crops	0.10-0.25
Forests	0.05-0.20

Relationship of Radiative Properties

For non-transparent objects:

$$\varepsilon = 1 - A$$

where ε is emissivity and A is albedo.

Physics of Radiant Energy

Wavelength and frequency of electromagnetic radiation are inversely related:

$$\lambda \cdot f = c$$

where λ is wavelength and f is frequency, and c is speed of light (2.998×10^8 m/s).
λ (measured in μm) varies over 21 orders of magnitude, but mostly the infrared, visible, and ultraviolet wavelengths matter for Earth energy budget.

The Sun

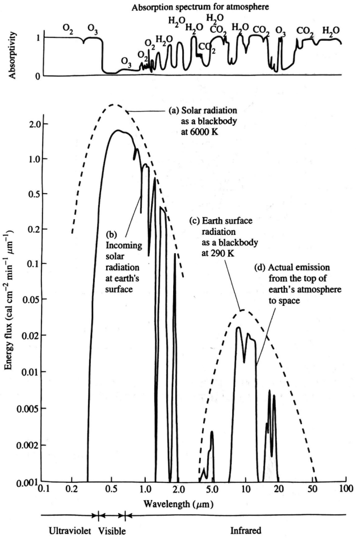
The Sun radiates energy as a blackbody with a temperature of 5773 K.
What is the total energy emitted at the sun's surface, and what is the rate of energy delivered to the top of earth's atmosphere (TOA)?

The Sun

Gases in the atmosphere absorb much of the lower wavelength (ultraviolet) radiation.

What arrives at the Earth's surface is called **solar** or **shortwave radiation**

On average, the sun's energy arrives at the top of atmosphere (TOA) at an average rate of 1367 Wm^{-2} (this is called the **solar constant**).



Composition of Atmosphere

TABLE 2.1. PRIMARY CONSTITUENTS OF THE STANDARD ATMOSPHERE IN THE TROPOSPHERE

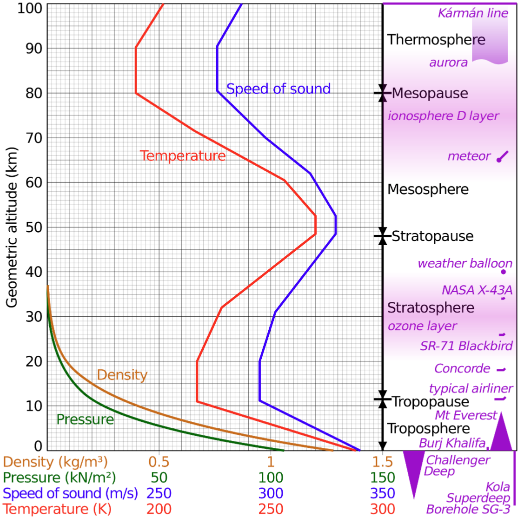
GAS	% BY VOLUME
Nitrogen (N_2)	78.084
Oxygen (O_2)*	20.946
Argon (A)	0.934
Carbon Dioxide (CO_2)*	0.040
Neon (Ne)	0.00182
Helium (He)	0.000524
Methane (CH_4)*	0.00016
Krypton (Kr)	0.0014
Hydrogen (H_2)	0.00005
Nitrous Oxide (N_2O)	0.000035
Ozone (O_3)*	0 - 0.000007
Water (H_2O)*	0 - 4

*radiatively active gases

Structure of Atmosphere

Pressure, density, and temperature decrease with increasing altitude, with one exception: temperature in stratosphere. Here, temperature increases from tropopause to stratopause due to the presence of ozone (O_3)

Troposphere and stratosphere are only spheres that directly impact climate, weather, and hydrologic activity.



Pressure Temperature Relations

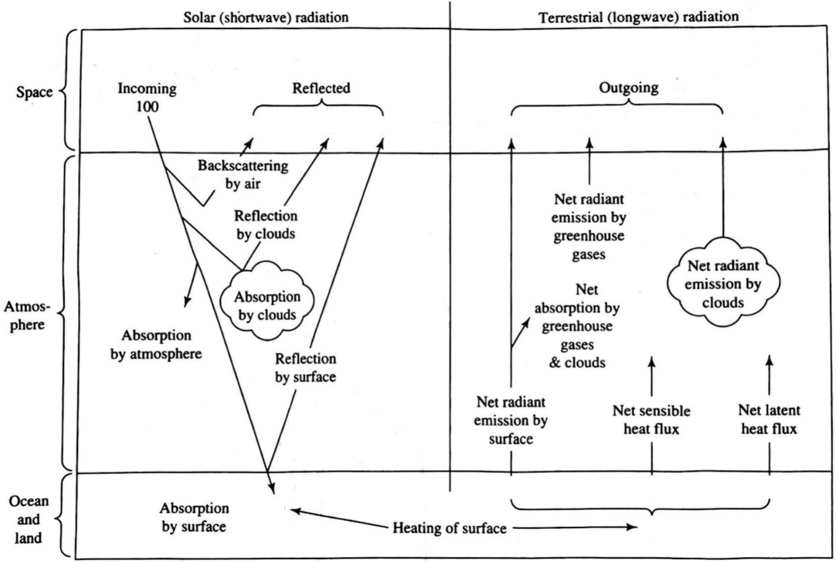
The variations with pressure, temperature, and density with altitude in the atmosphere can be explain by the Ideal Gas Law:

$$\frac{P}{T_a \cdot \rho_a} = R_a$$

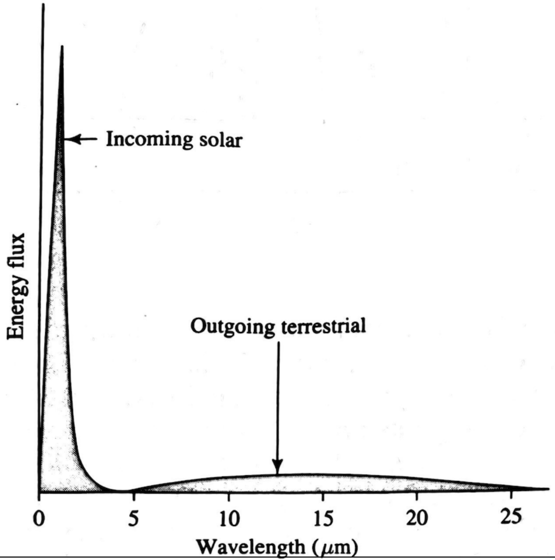
where P is atmospheric pressure in kPA, T_a is air temperature in K, ρ_a is density of air in kgm^{-3}, and R_a is the gas constant for dry air (0.288).

These are the major state variables of the atmosphere (not including water vapor, which we will discuss in the next lecture).

Earth Energy Budget



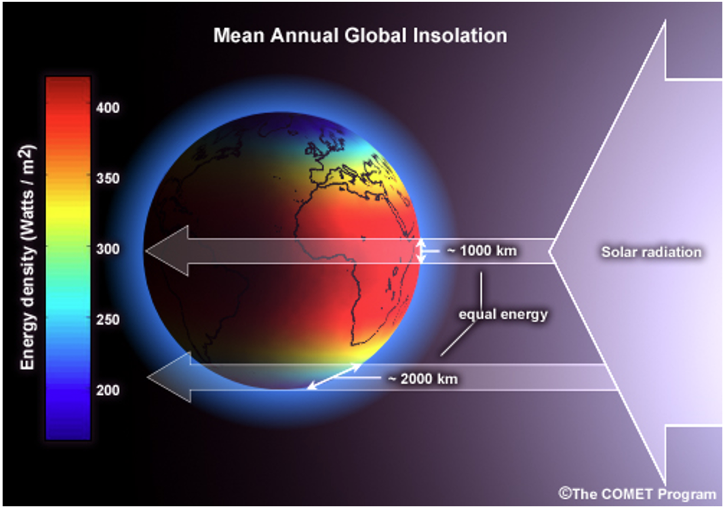
Earth Energy Budget



Latent and Sensible Heat Transfer

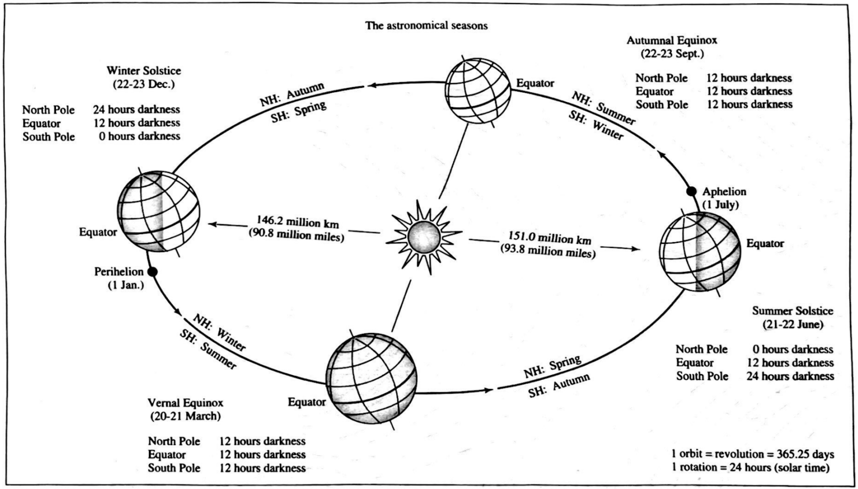
1. **Latent** heat transfer is energy stored or released due to a phase change, in this case, mainly evaporation of water from oceans.
2. **Sensible** heat transfer is from conduction/convection from earth's surface to warm air.

Latitudinal Variation of TOA SR



Lower intensity at higher latitudes (same energy spread over larger area).

Seasonal Variation of TOA SR



Tilt of 23.5° relative to orbital plane combined with revolution around sun creates seasons.

Estimating SW Radiation at TOA

The solar radiative flux (R_{s0}) at the TOA is as follows (assuming daytime, at nighttime R_{s0} is 0)

$$R_{s0} = I_0 \frac{cos(\theta)}{r^2}$$

$$cos(\theta) = sin(\delta) \cdot sin(\lambda) + cost(\delta) \cdot cos(\lambda) \cdot cost(\tau)$$

$$\delta = \frac{23.45\pi}{180} \cdot cos[\frac{2\pi}{365} \cdot (172 - DOY))]$$

$$\tau = 2\pi \cdot \frac{T_h - 12}{124}$$

$$r = 1 + 0.017 \cdot cos[\frac{2\pi}{365} \cdot (186 - DOY)]$$

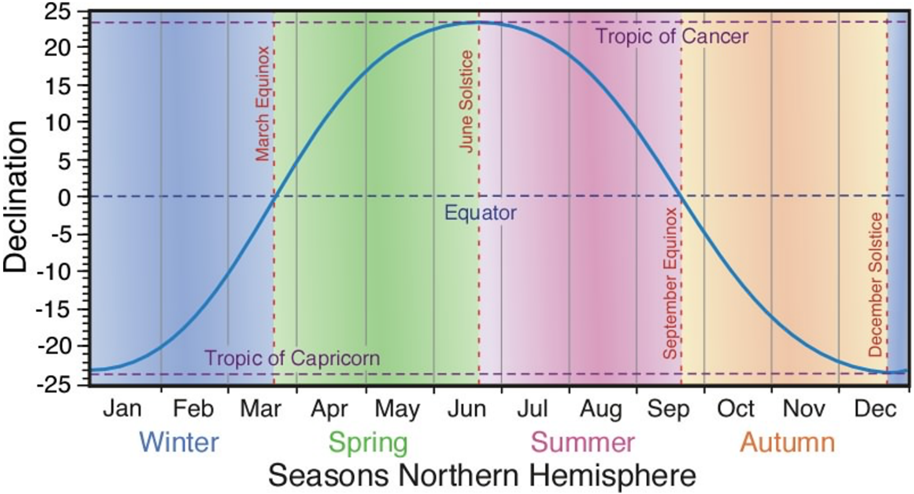
I_0 = solar constant (1367 W/m^2)
δ = declination angle (radians)
DOY = day of year
λ = latitude (radians)
τ = hour angle (radians)
T_h = hour of day (0..23)
r = ratio of actual to mean Earth-Sun distance (-)

TOA solar radiation in ABQ right now!

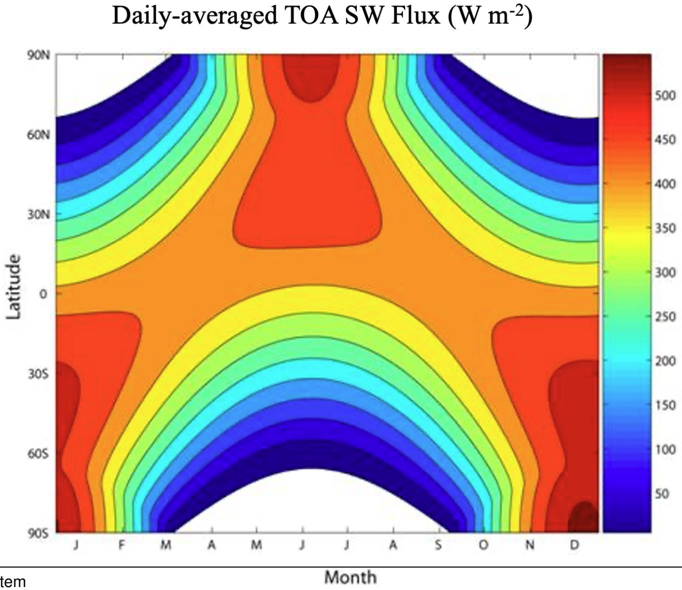
DOY = august xx is
T_h = 9
I_0 = 1367 W/m^2
latitude of ABQ = 35.0844
radians = degrees x π/180

Declination

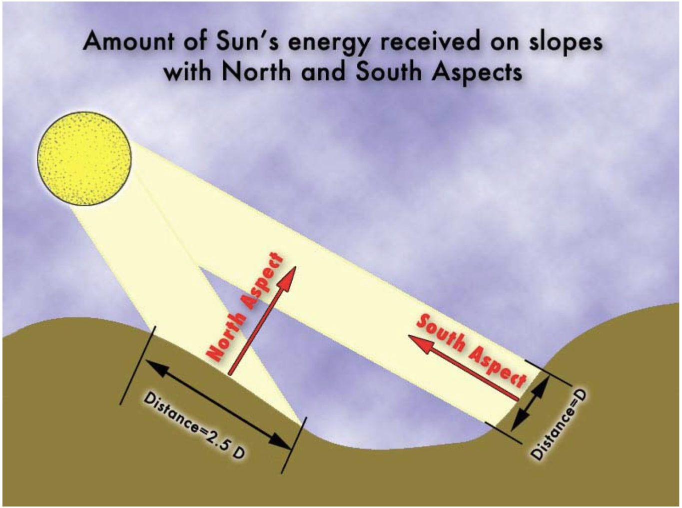
Declination: latitude at which the sun is directly overhead at noon.



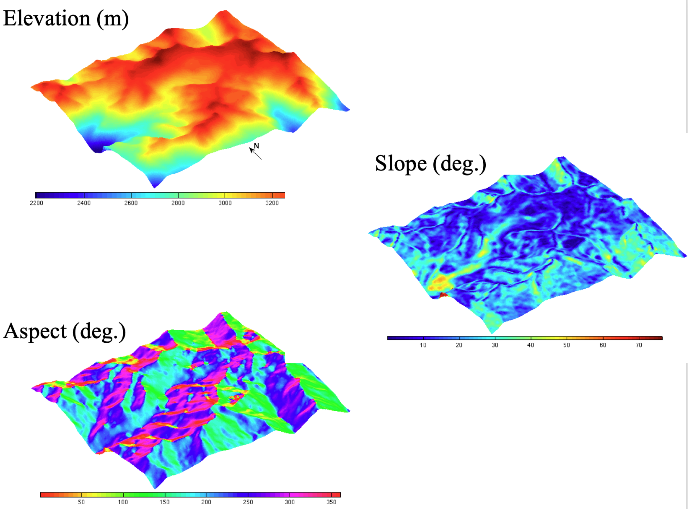
TOA SR Variation



Topographic Controls

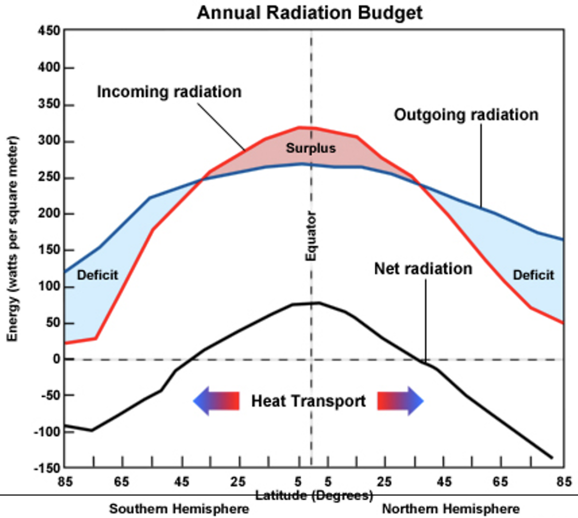


Topographic Controls



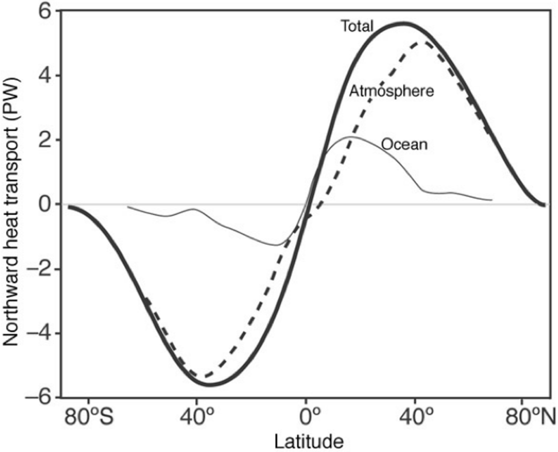
Latitudinal Energy Transfer

Differential energy intensity leads to poleward energy transfer (entropy!)



Latitudinal Energy Transfer

The poleward transport of energy occurs mostly in the atmosphere, but also via ocean circulation



Recap

Putting this all together...

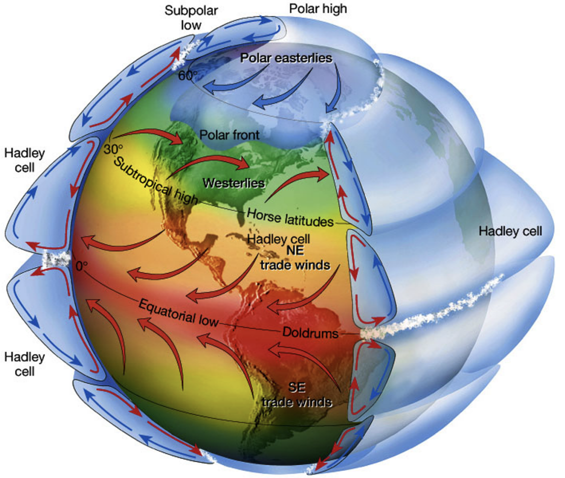
1. We have learned about solar (shortwave) radiation and
2. how it is filtered through the atmosphere to be absorbed by the Earth's surface (and re-emitted back as longwave radiation)
3. how this energy input is unevenly distributed due to the Earth being a sphere and rotates around the Sun at a tilt
4. that this uneven distribution of energy drives heat transport from the equator to the poles

These processes drive **general circulation**

General Circulation

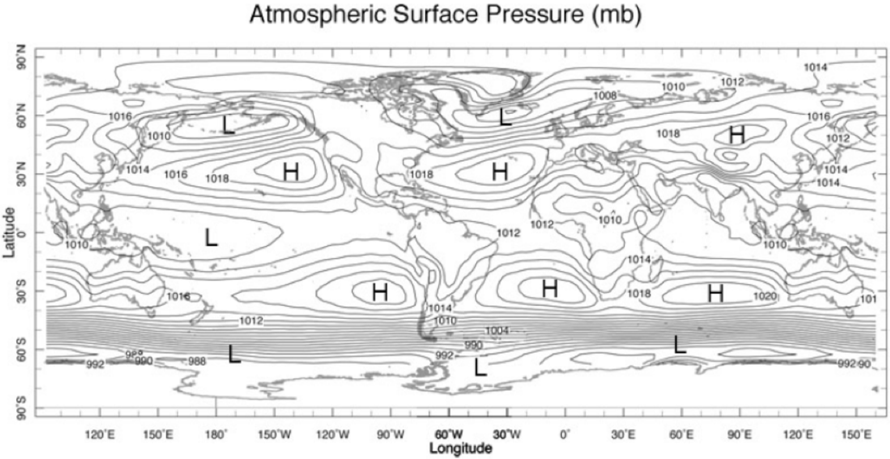
The unequal distribution of radiation and rotation of the Earth give rise to a system of 3 circulation cells in each hemisphere.

- 0-30°, Hadley Cells, most energy transfer, via convection.
- 30-60°, subtropical or Ferrel cells, medium energy transfer, via winds (westerlies)
- 60-90°, polar cells, least energy transfer via winds (easterlies)



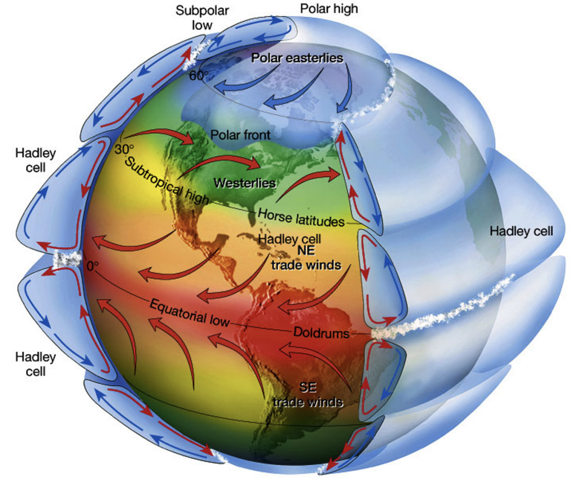
Global Distribution of Pressure

Zones of rising air correspond with low atmospheric pressure and zones of falling air with high pressure.



Winds

Pressure differential combined with centrifugal forces, the Coriolos effect, and friction of the Earth's surface lead to surface wind.
These have a tendency to spiral inward towards low pressure centers and outward to high pressure centers.
In the northern hemisphere, this is clockwise around high pressure zones (**anti-cyclonic**) and counter-clockwise around low pressure zones (**cyclonic**).



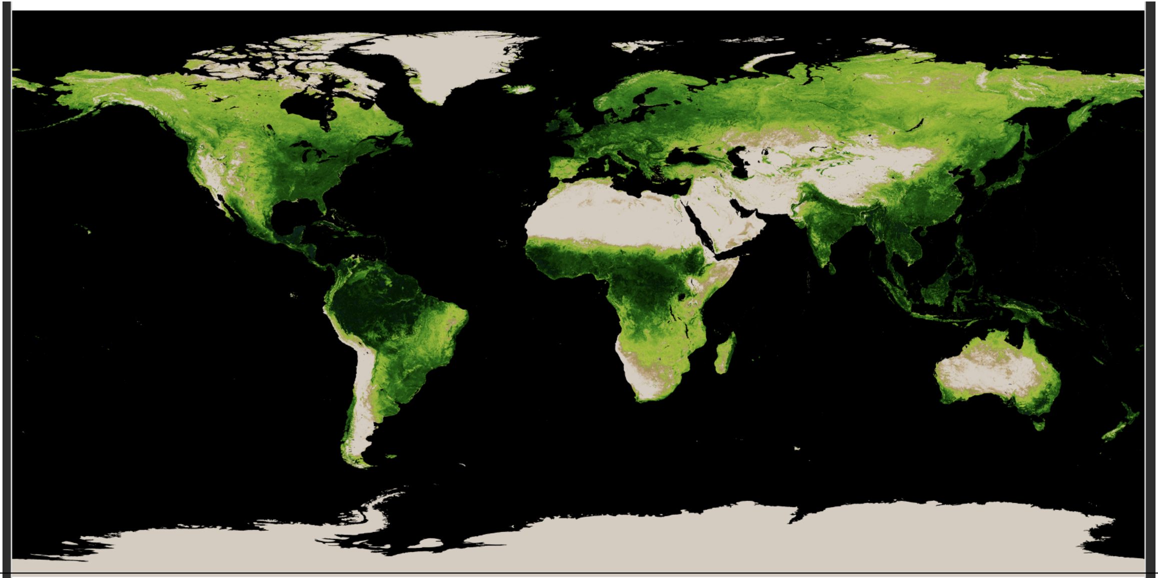
Jet Streams

two main ones: subtropical and polar occurring between Hadley and Ferrel and Ferrel and Polar cells, respectively. These are super important for weather forecasting!

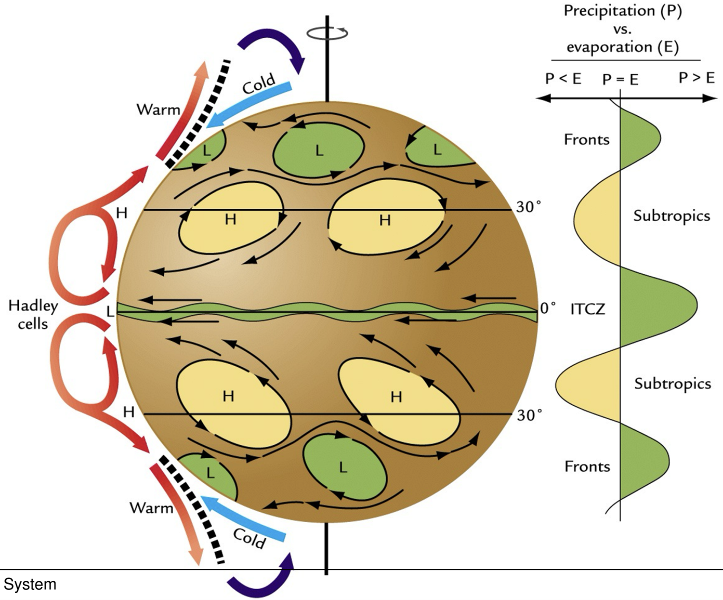
Global Distribution of Temperature

Global Distribution of Precipitation

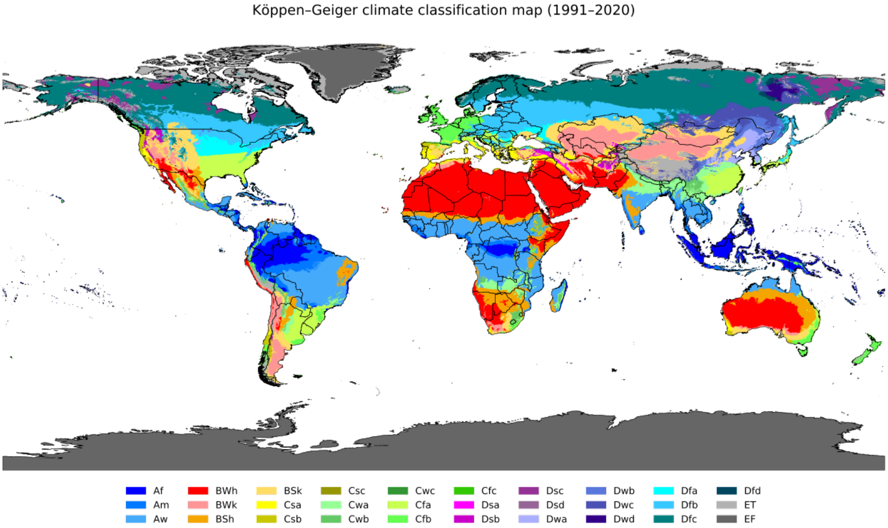
Global Distribution of Evapotranspiration



Global Distribution of Aridity



Global Climate Zones



Source: Beck et al. (2023): High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections, Scientific Data 10:724, doi:10.1038/s41597-023-02549-6.

Biome Types

Putting it together

How does general circulation relate to El Niño Southern Oscillation (ENSO) and New Mexico climate?