P3: Heat and Moisture Transport
The general circulation

12.307- project 3 (intro)

Project intro: Heat and Moisture Transport & the general Circulation of the Atmosphere

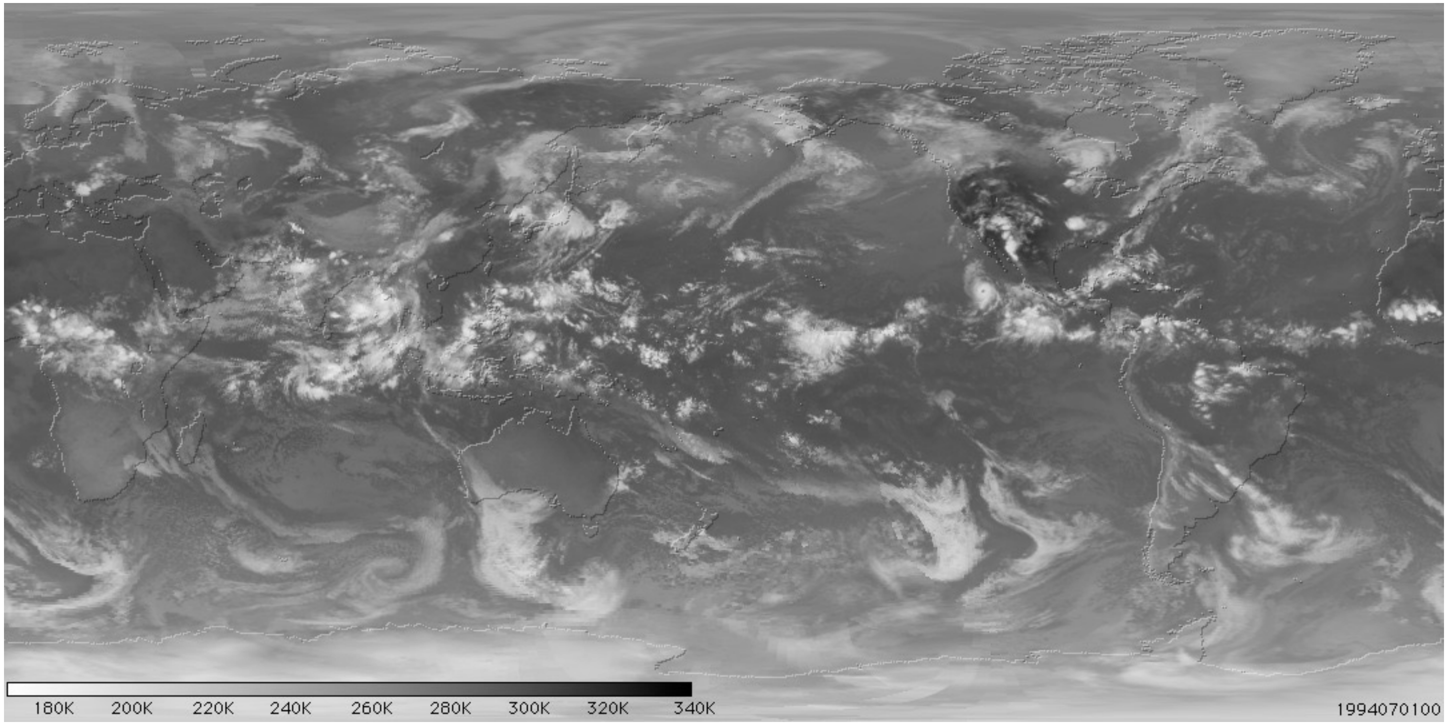
Fluid labs intro: description of experiments

Introduction to the lab experiments

- ***What are the drivers of the general atmospheric circulation?***
- ***What are the main features of the general atmospheric circulation?***

General atmospheric circulation

IR radiation (July 1994)



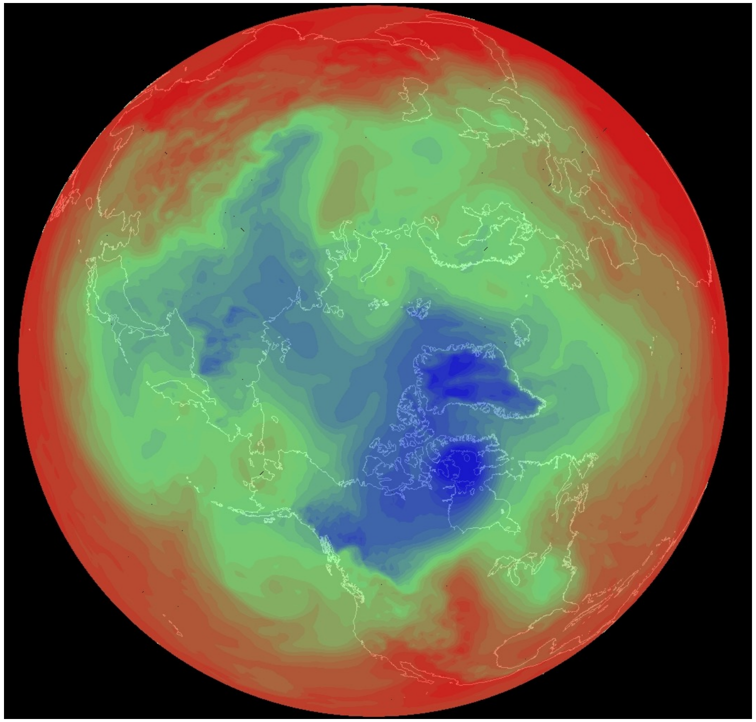
Tropics: convection, smaller scale tropical storms moving westward

Subtropics: no clouds! Drier conditions

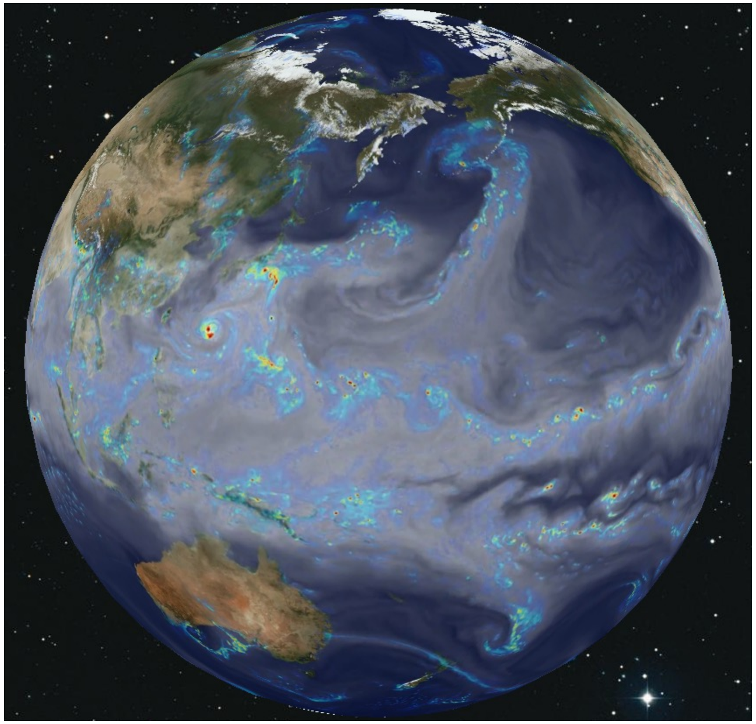
Extra-tropics: large scale waves (cyclones and anticyclones), eastward motion (on the jet streams)

Poleward transport of heat and moisture

Temperature

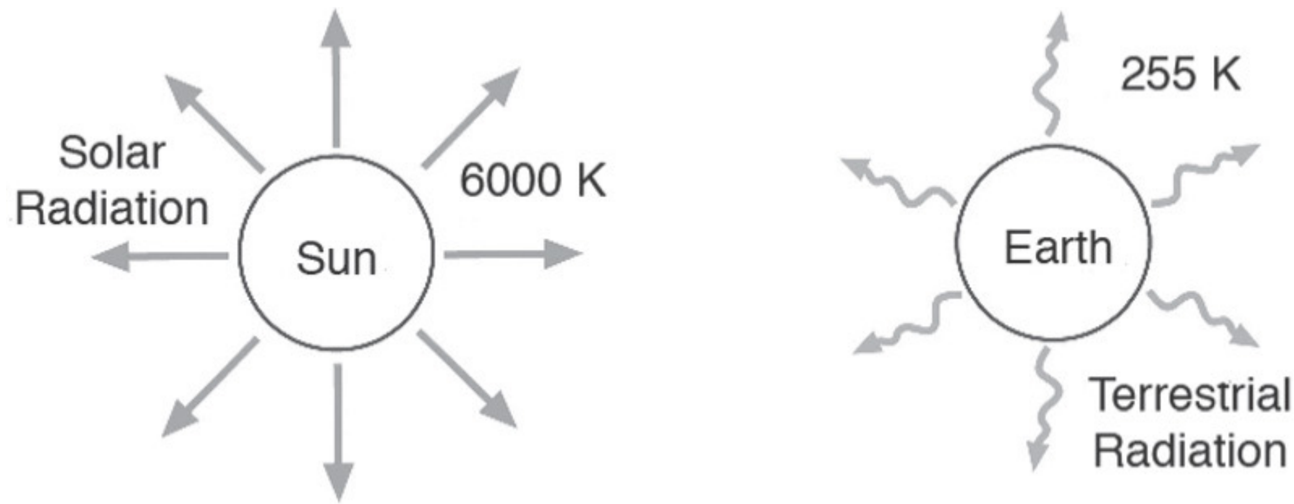


Moisture



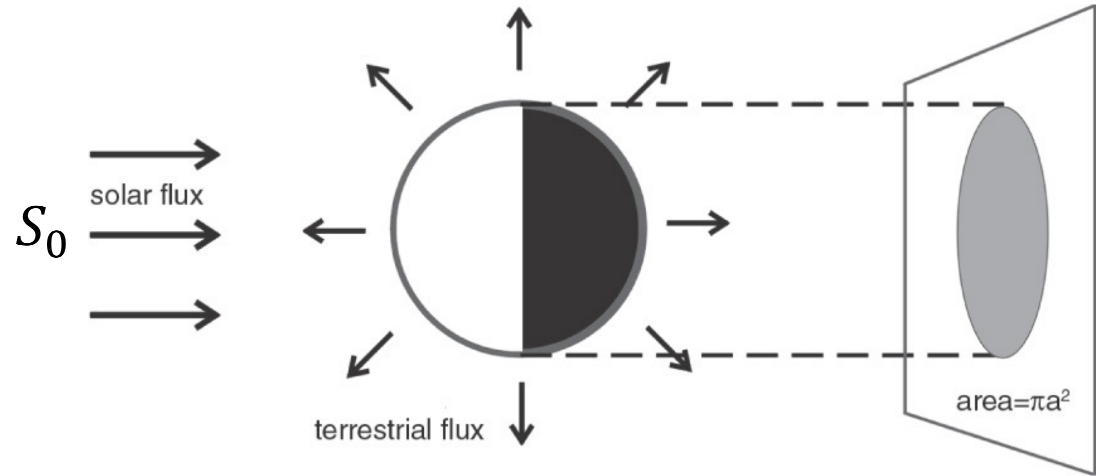
Both temperature (heat) and moisture are being carried around by the atmospheric circulations

The atmosphere is energized by the sun



- The sun is like a black body that radiates at ~6000K (with a peak in the visible wavelength)
- Earth warms up to a temperature ~255K, and radiates back to space like a balck body in the IR (longer wavelength)

The global energy balance



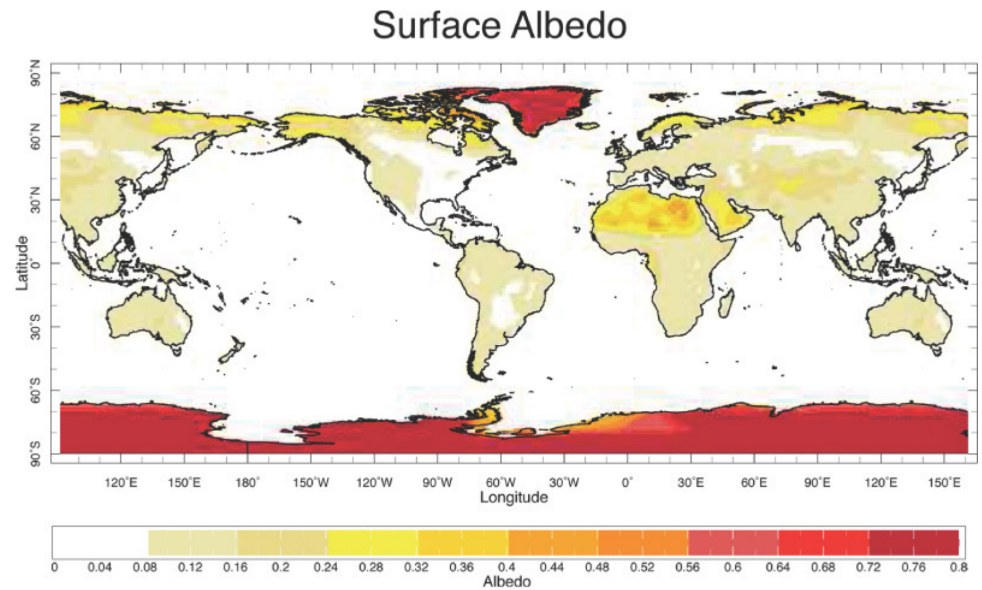
(Modified from Hartmann, 1994.)

- Some of the incoming radiation S_0 is reflected back to space (e.g., by clouds and ice which are white and thus reflective)
- The fraction of reflected radiation is called the “planetary albedo” (α_p)
- The absorbed solar radiation is balanced by the outgoing LW radiation emmited back by the Earth (balck body→ σT^4 where σ is the S-B constant, times surface area)

$$S_0(1-\alpha_p)\times\pi a^2 = \sigma T^4 \times 4\pi a^2 \quad \Rightarrow \quad T_e = \left[\frac{S_o(1-\alpha_p)}{4\sigma}\right]^{1/4}$$

Emission temperature

Most of the albedo is from clouds, but the surfaces contributes too



- Clouds, snow, and ice have largest albedos (very reflective)
- Ocean have very low albedo, absorbs most of the energy
- Determining alpha is very complicated, but we can measure it
- Earth's albedo is around 1/3

TABLE 2.2. Albedos for different surfaces. Note that the albedo of clouds is highly variable and depends on the type and form. See also the horizontal map of albedo shown in Fig. 2.5.

Type of surface	Albedo (%)
Ocean	2–10
Forest	6–18
Cities	14–18
Grass	7–25
Soil	10–20
Grassland	16–20
Desert (sand)	35–45
Ice	20–70
Cloud (thin, thick stratus)	30, 60–70
Snow (old)	40–60
Snow (fresh)	75–95

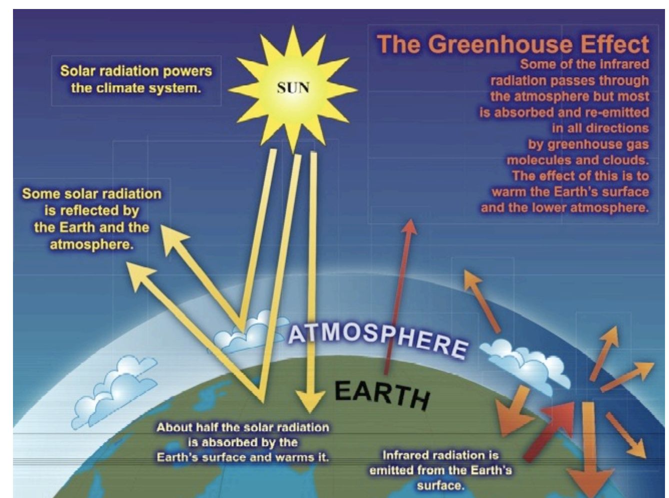
Green house gas effect

TABLE 2.1. Properties of some of the planets. S_0 is the solar constant at a distance r from the Sun, α_p is the planetary albedo, T_e is the emission temperature computed from Eq. 2 4, T_m is the measured emission temperature, and T_s is the global mean surface temperature. The rotation period, τ, is given in Earth days.

	r 10^9 m	S_0 W m^{-2}	α_p	T_e K	T_m K	T_s K	τ Earth days
Venus	108	2632	0.77	227	230	760	243
Earth	150	1367	0.30	255	250	288	1.00
Mars	228	589	0.24	211	220	230	1.03
Jupiter	780	51	0.51	103	130	134	0.41

Surface temperature is much higher then the emitted temperature!

The atmosphere (clouds and other greenhouse gases) absorbs part of the radiation and emits it upwards & downwards → the surface gets more radiation → warmer

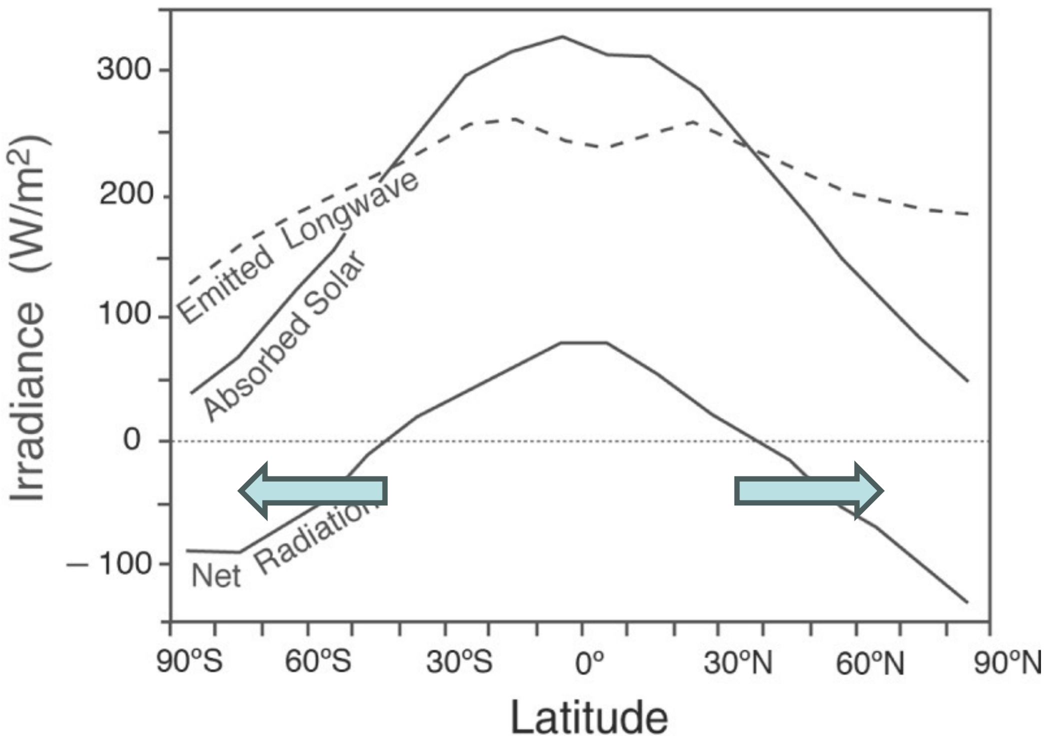


Credit: Intergovernmental Panel on Climate Change Working Group I

The absorption of the solar radiation varies with latitude

- More energy is absorbed near the equator due to the sphericity
- Parallel beams of light strike a larger area near the poles, so the flux per unit area (W/m^2) is smaller there compared to the equator

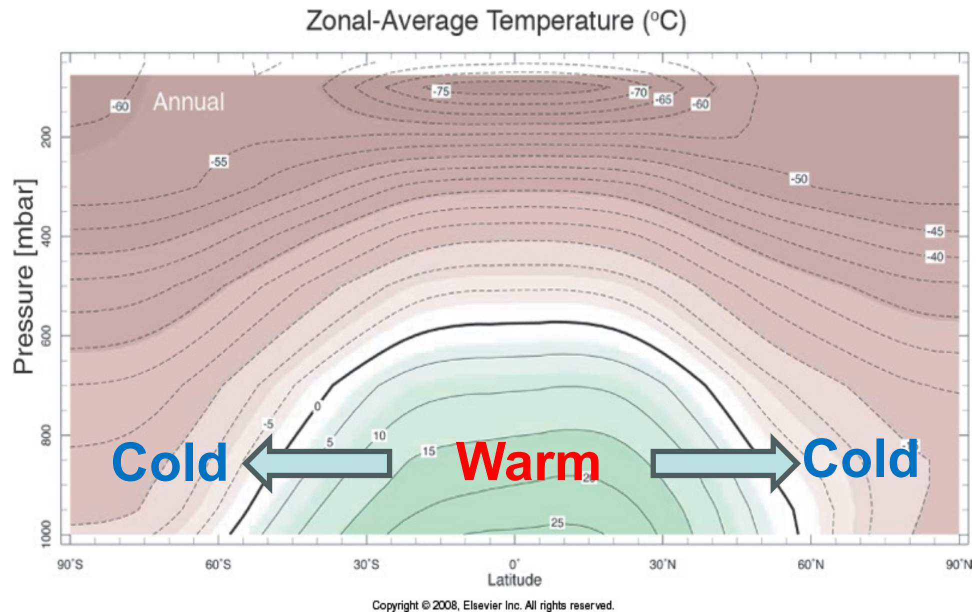
Meridional distribution of absorbed and emitted radiation



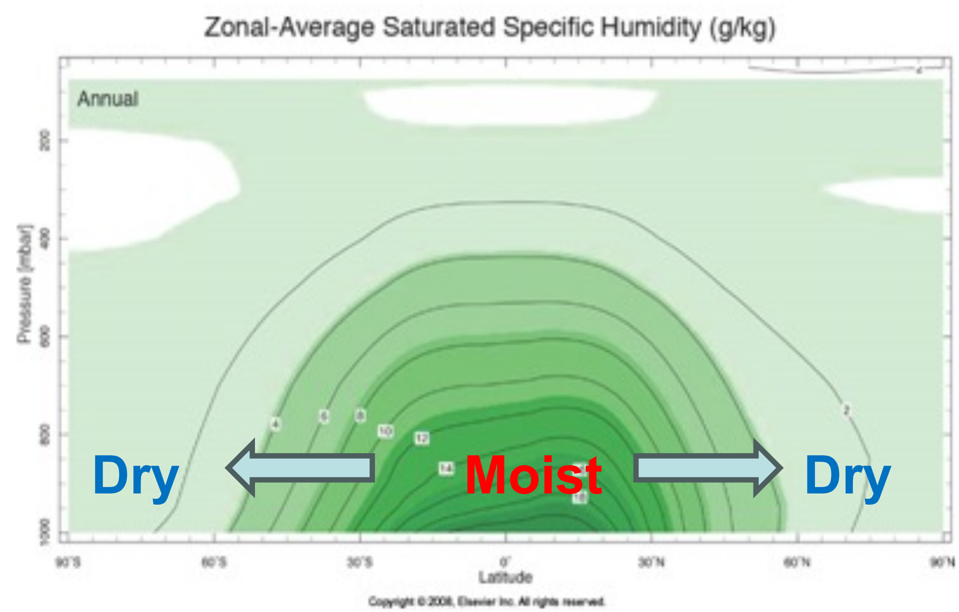
- Absorbed energy peaks around the equator, low near the poles
- Emitted longwave radiation is more uniform latitudinally
- Net radiation: excess of energy (warming) in the tropics, deficit of energy at the poles (cooling)
- The atmosphere is carrying energy out from the tropics to the poles!

Poleward transfer of heat and moisture

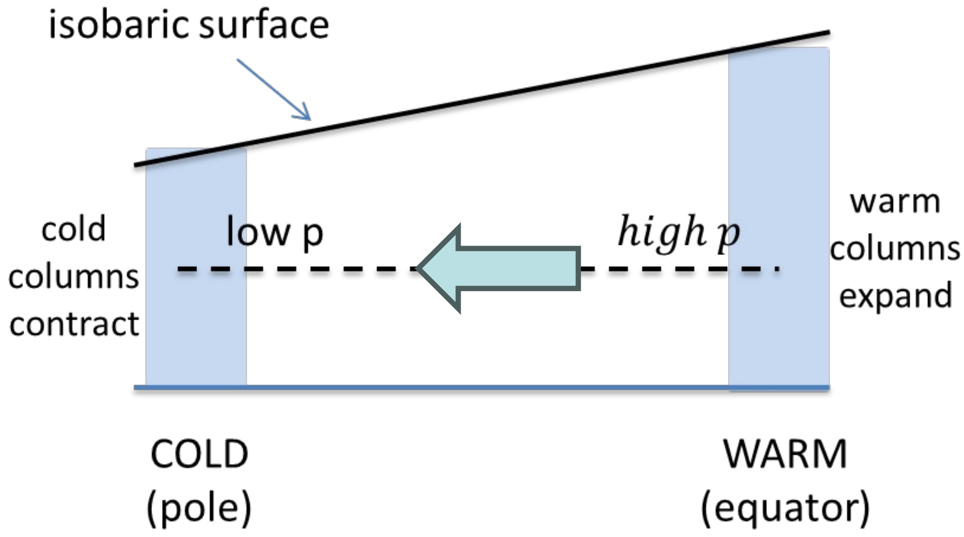
- Warm air holds more water vaoour
- Hence, it is both warm & moist in the tropics, while it is both cold & dry near the poles

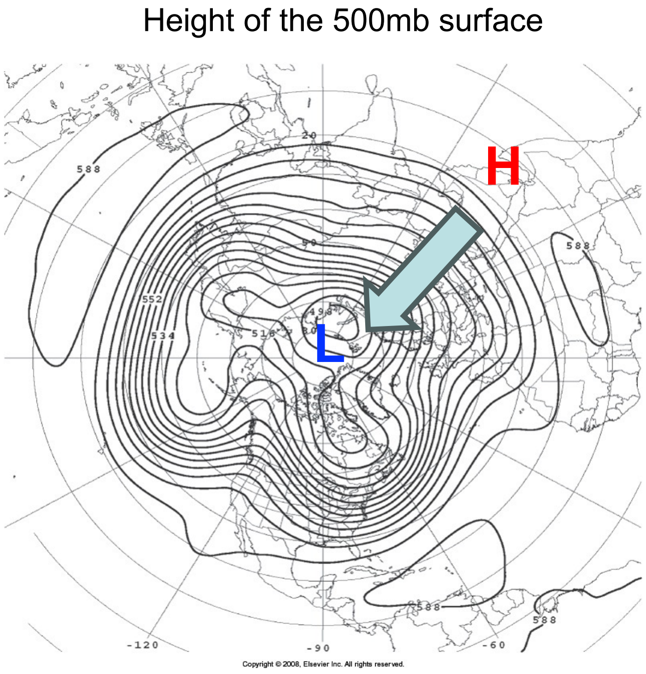


→ The atmosphere carries not just heat but also moisture from low to high latitudes



Differential equator-to-pole heating



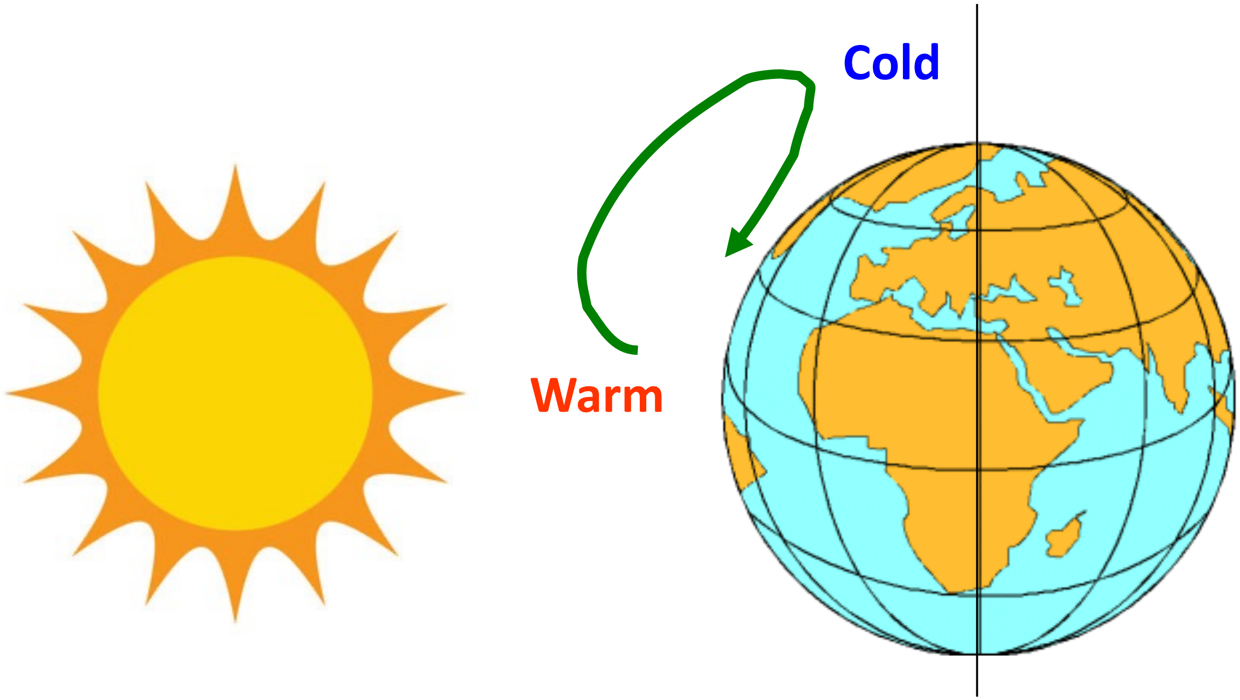


- The cold air in the poles leads to a low pressure, while the warm air near the equator leads to a high pressure
- Hence, the pressure gradient force is from the equator to the pole

Why is the air not flowing directly to the poles then?

Global atmospheric circulation basic recipe:

differential heating on a sphere



Differential heating → warm air rising in the tropics, flowing poleward and returning near the ground

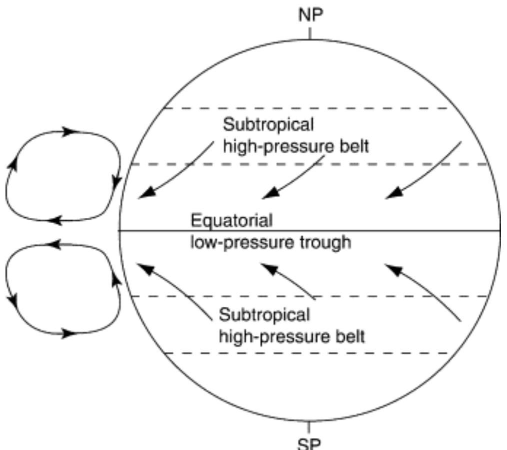
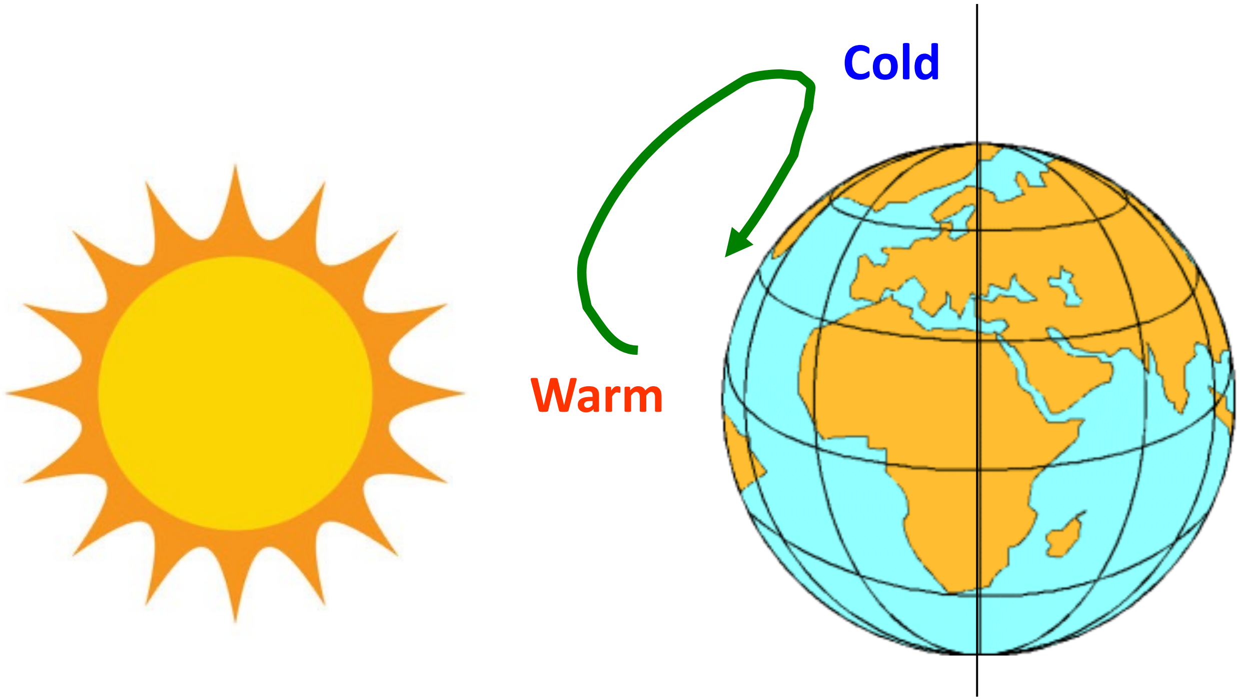
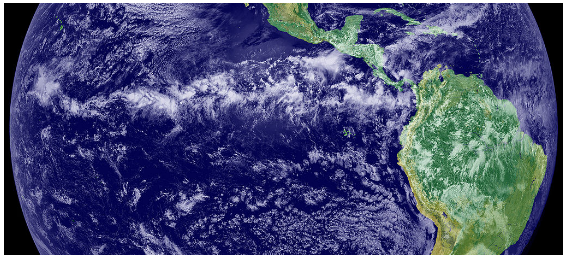


Figure from Encyclopedia of Atmospheric Sciences, 2003

Global atmospheric circulation basic recipe:

differential heating on a sphere





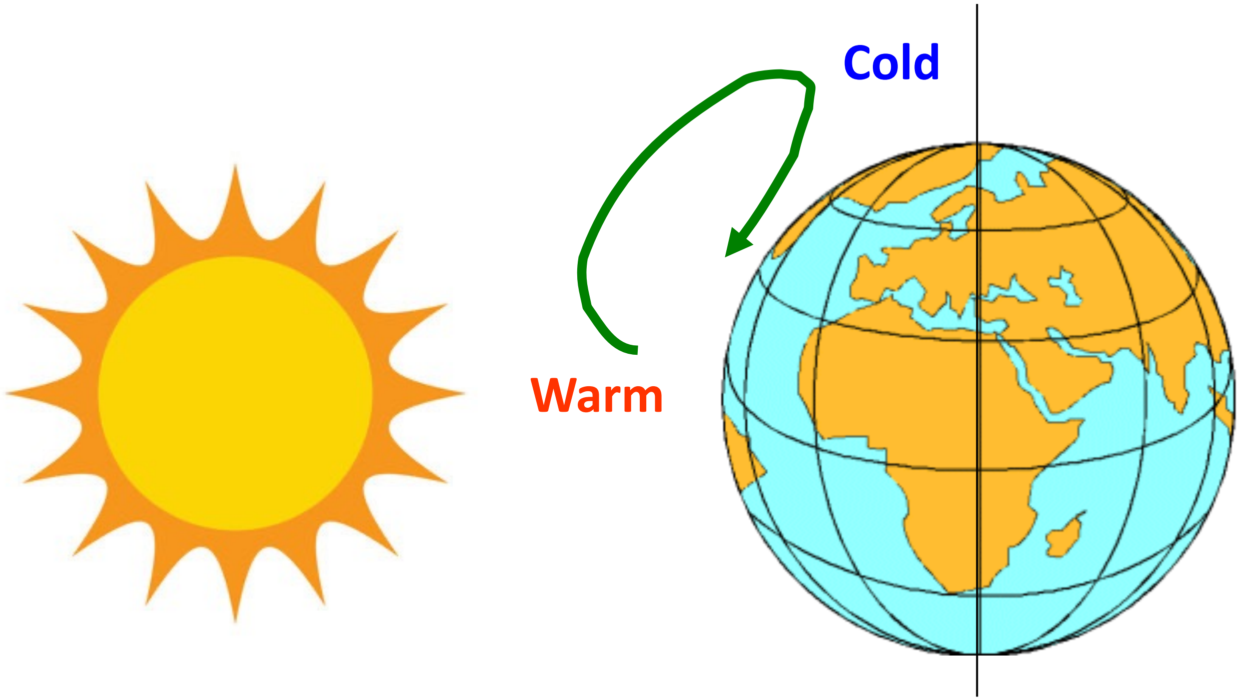
The Intertropical Convergence Zone is visible as a band of clouds encircling Earth near the Equator.
Source: Wikicommons/NOAA

Differential heating → warm air rising in the tropics, flowing poleward and returning near the ground

But the air does not reach all the way to the poles!

Global atmospheric circulation basic recipe:

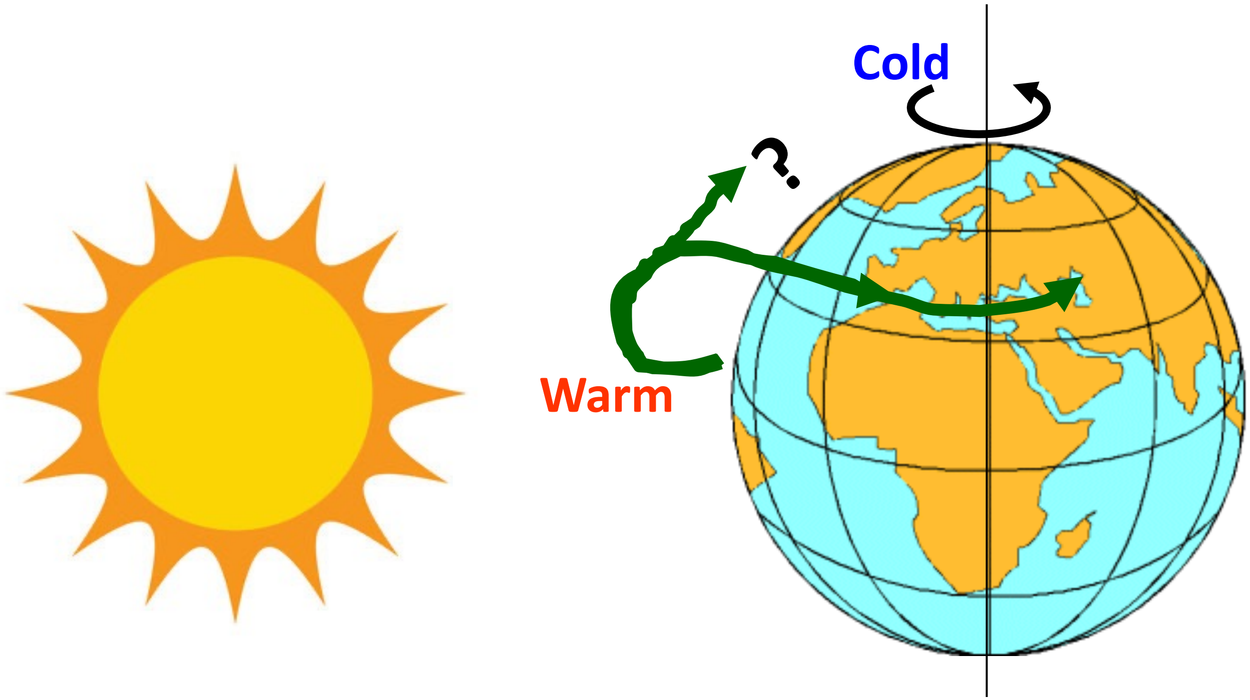
differential heating on a sphere



Add rotation:

Global atmospheric circulation basic recipe:

differential heating + rotation, on a sphere



Coriolis force causes poleward moving air to spin eastward

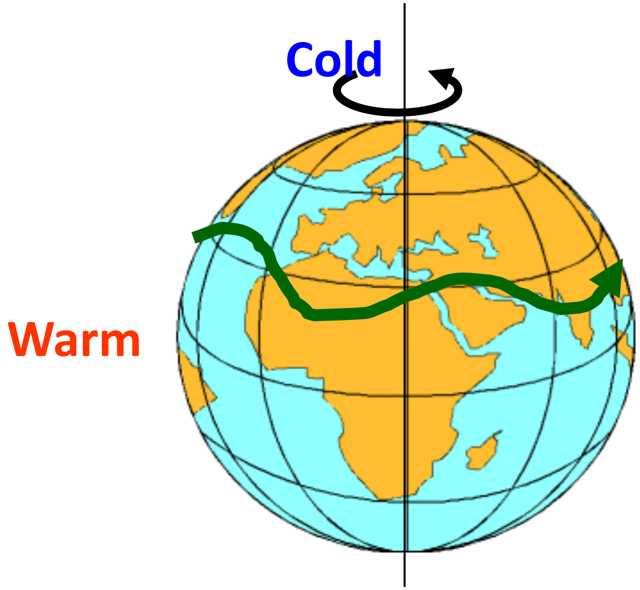
The air descends around ~30N/S and forms the **Hadley cell** and the **subtropical jet stream**

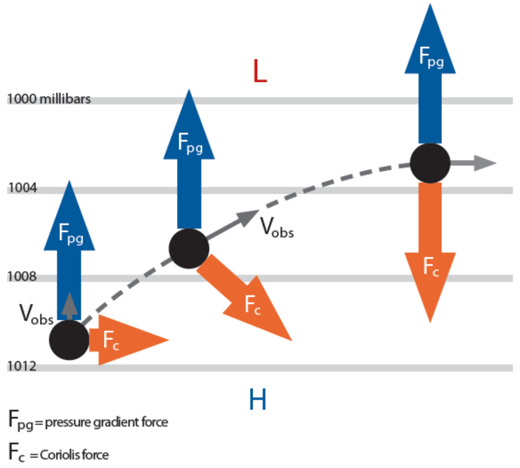
The subtropical jet stream

The Equator-to-pole temperature difference induces a meridional (north-south) pressure gradient, with a **Low** pressure over the **Cold** Pole

Coriolis force causes poleward moving air to spin eastward

The jet stream is in therefore in *geostrophic balance:* the pressure gradient force is balanced by the Coriolis force

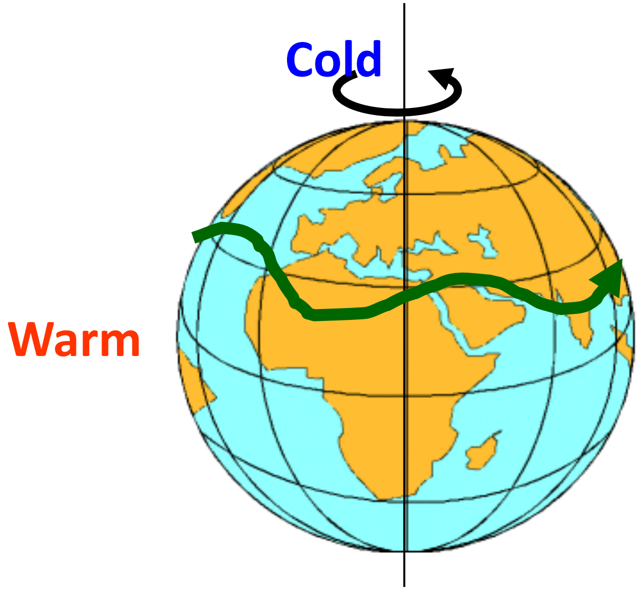




At altitude, friction with the Earth lessens and the pressure gradient and the Coriolis forces balance out.

The jet stream is strongest at upper levels

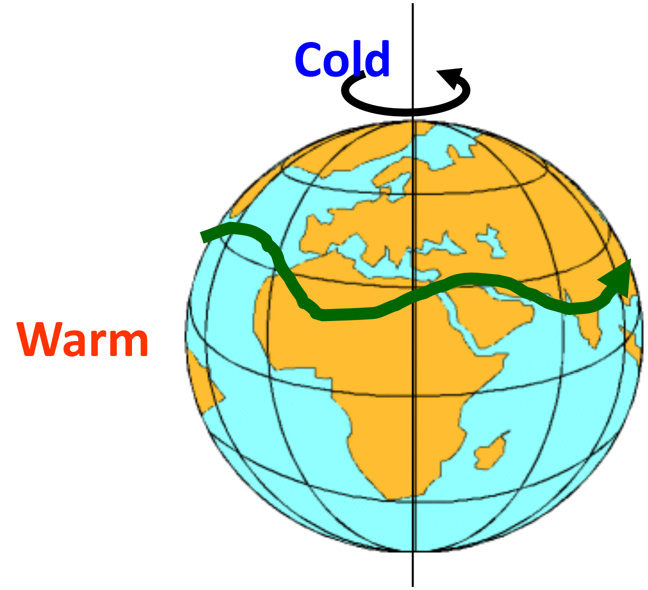
- Because of the N-S temperature difference, pressure gradient force is increasing with height.

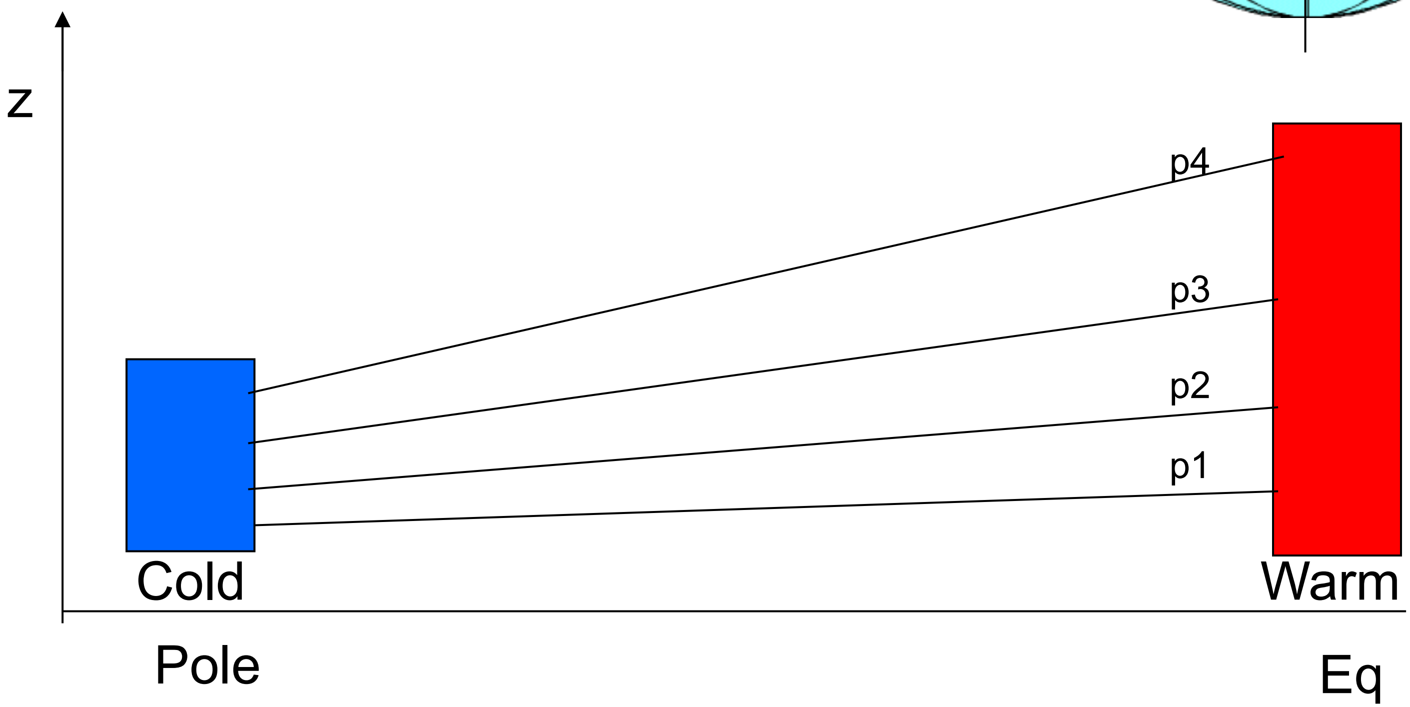


The jet stream is strongest at upper levels

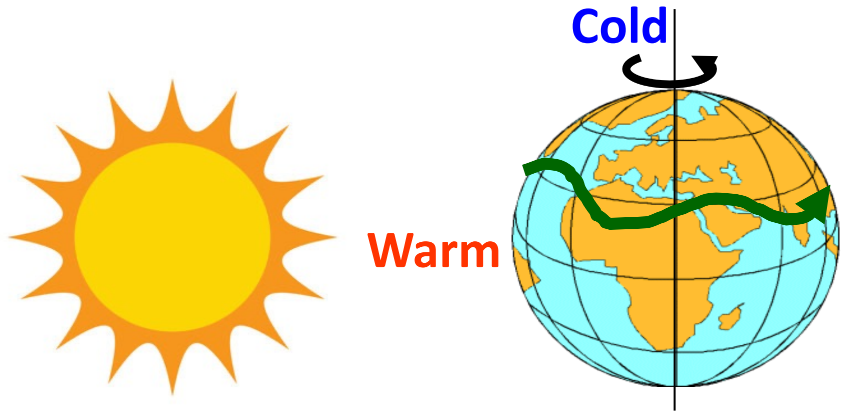
- Because of the N-S temperature difference, pressure gradient force is increasing with height.
- The geostrophic wind is therefore also increasing with height (reaching a maximum at the tropopause)

→ Thermal wind balance!

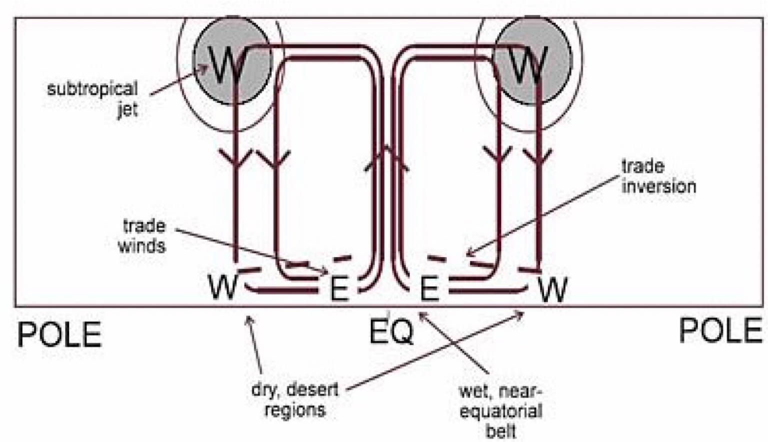




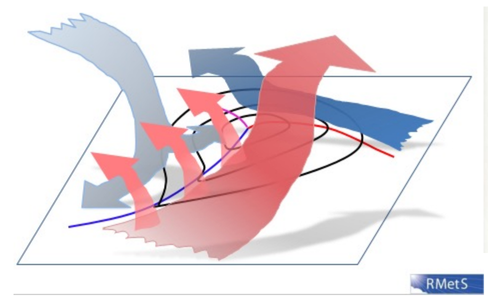
So how does heat get mixed between the equator and pole?

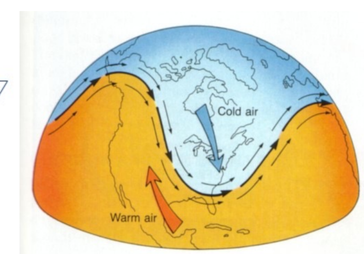


- Tropics: heat is transported by the mean meridional circulation (Hadley cell)



- Midlatitudes: heat is transported by weather systems that arise due to sharp temperature gradients (*baroclinic instability)*

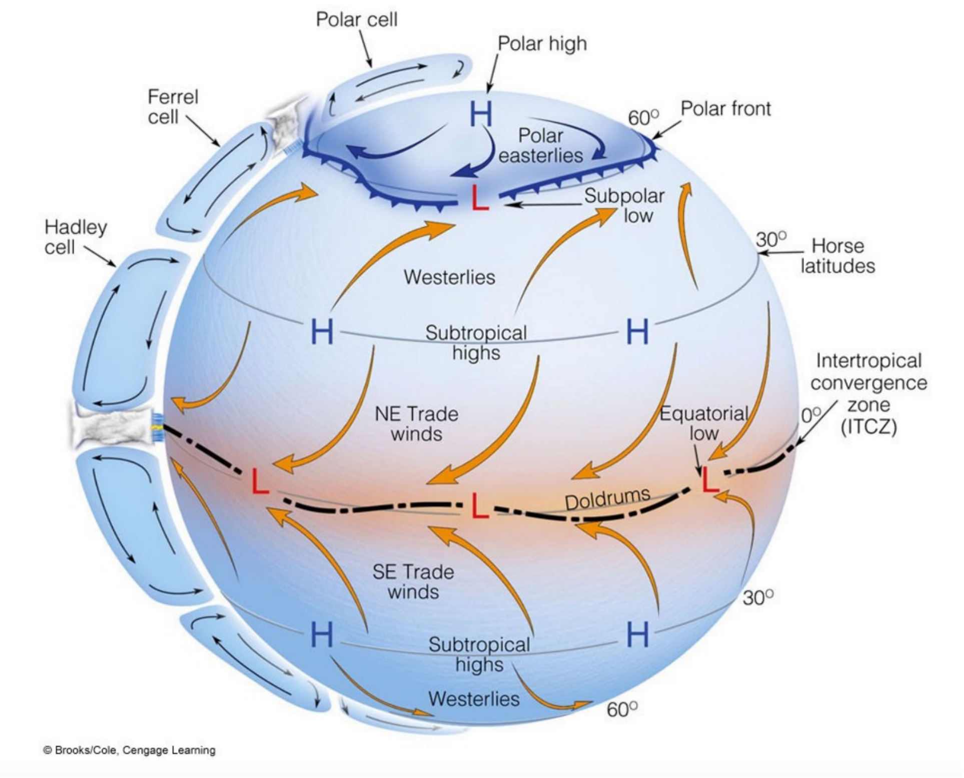




The global atmospheric circulation

Hadley cell: Eq-30°

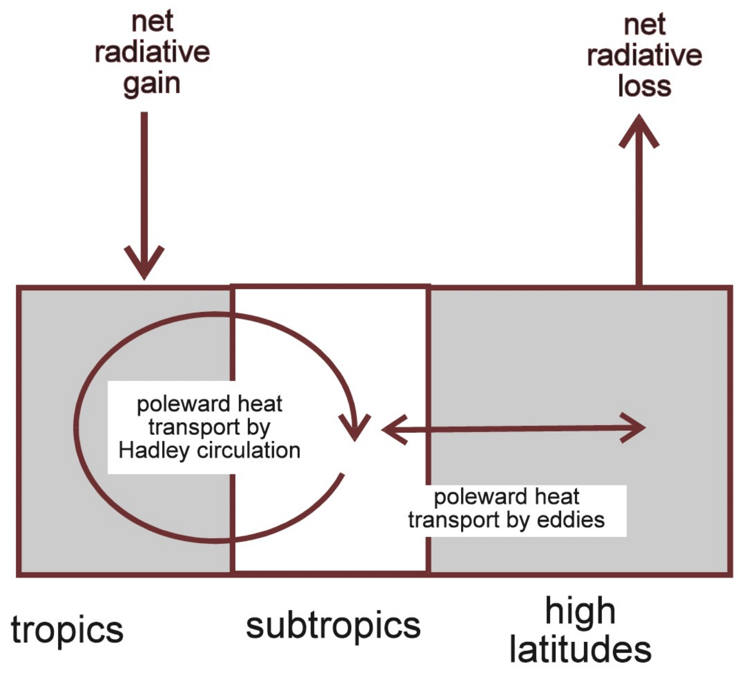
"Eddy driven" (Ferrel) cell: 30-60°



→*Hadley cell is the main mechaisms for heat and moisture transport between the equator and the subtropics*

→*In the midlatitudes, it is the weather sytems that carry the heat and moisture further poleward*

The global atmospheric circulation



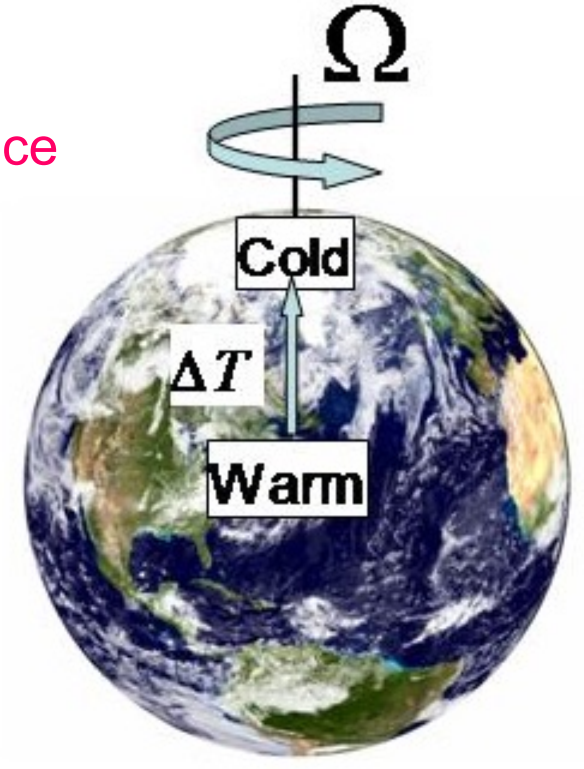
Two distinct regimes-

- Tropics: Rotation is less important. Poleward heat transport by the mean Hadley circulation (George Hadley, 1735)
- Mid-to-high latitudes: The effect of rotation is strong, poleward heat transport is by "eddies"

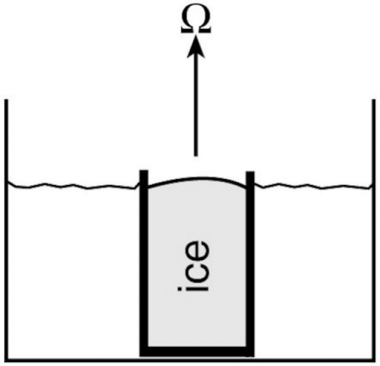
What are we going to do in the lab?

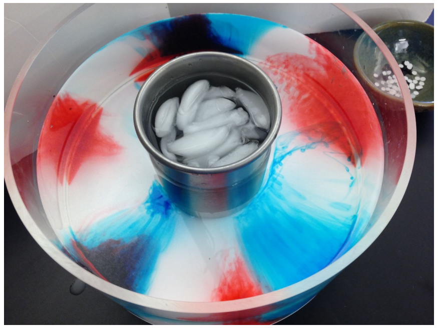
Basic ingredients of the general circulation:

1. Temperature difference
2. Rotation

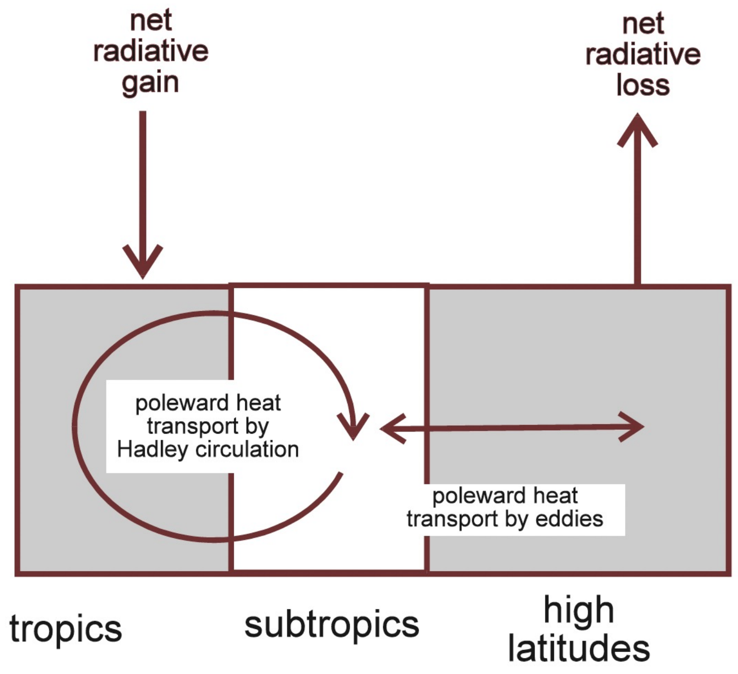


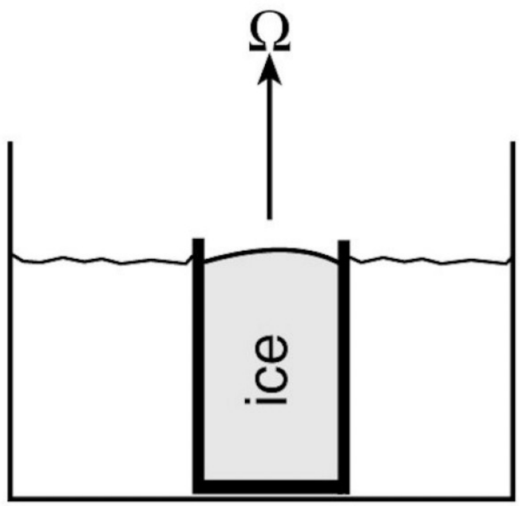
Laboratory abstraction of Earth's weather:





Idealized global atmospheric circulation setup



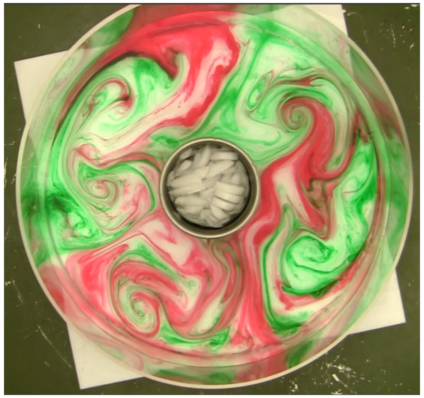


Two distinct regimes:

- Tropics- rotation is less important → Ω small
- Mid-to-high latitudes- the effect of rotation is strong→ Ω large

Three experimental setups

1. $\Omega = 0 \quad \Delta T = \text{large}$
2. $\Omega = \text{small} \quad \Delta T = \text{large}$
3. $\Omega = \text{large} \quad \Delta T = \text{large}$



$\Omega = 0$ ΔT =large	Ω = small ΔT =large	Ω = large ΔT =large
?	?	?