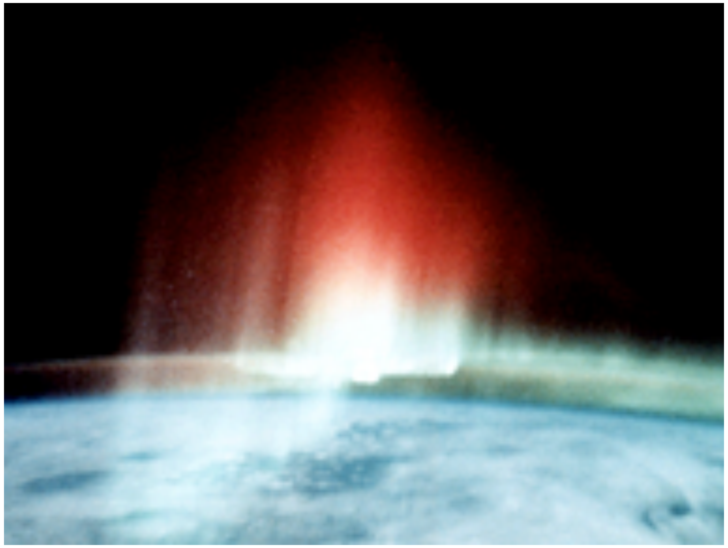
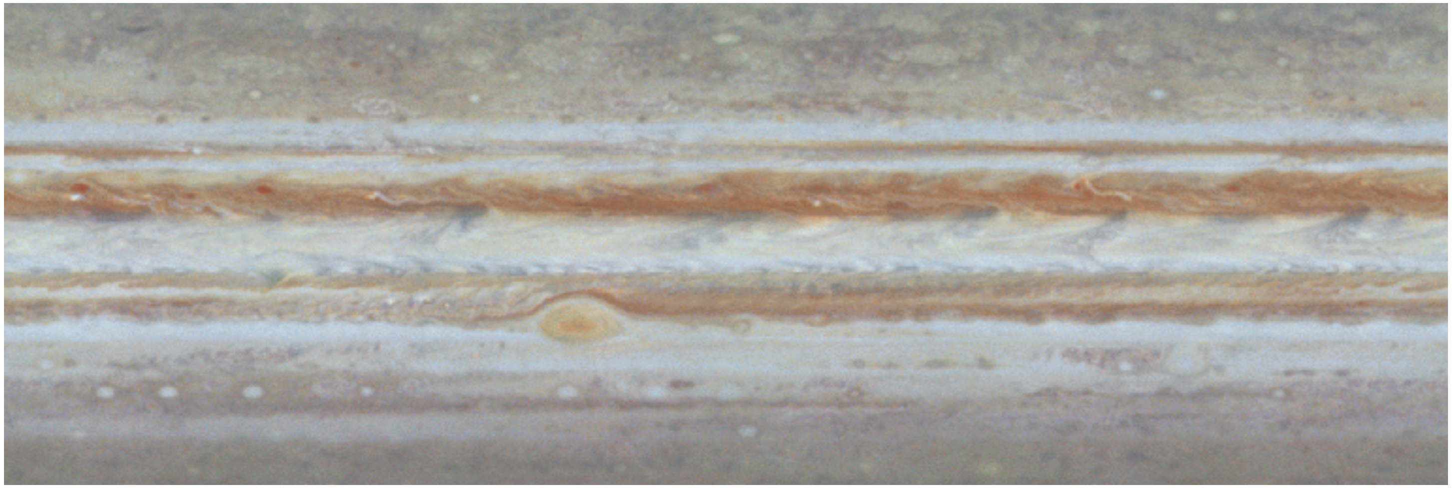
Planetary Atmospheres

Structure
Composition
Clouds
Photochemistry
Meteorology
Atmospheric Escape





Photochemistry

We can characterize chemical reactions in the atmosphere in the following way:

1. Photolysis: Molecular breakup directly driven by solar radiation (also referred to as *photodissociation*)
2. Photoionization: Reactions that result in the ionization of atoms and molecules
3. Recombination: Direct/indirect reversing of the photolysis and photoionization reactions
4. Dissociative Recombination: Reversing the process of photoionization via breaking a chemical bond
5. Charge Exchange: Direct electron exchange between a close passing ion and neutral
6. Atom-Ion Interchange: Interaction between an ion and atom that results in compositional alteration of the ion.

Photolysis

Oxygen in the Earth atmosphere processed by photons:

(1) $$O_2 + h\nu \rightarrow O + O$$ for λ < 175nm

$$\frac{d[O]}{dt} = 2[O_2]J_1(z)$$ Production rate of O

Where $J_i(z)$ is the reaction rate for a reaction 'i' as a function of altitude, and [atom or molecule] indicates the number per unit volume

$$J_i(z) = \int \sigma_{x_\nu} \mathcal{F}_\nu e^{-\tau_\nu(z)/\mu_\theta} d\nu$$

Since the number of photons decreases exponentially with depth penetrated into the atmosphere, production of O increases with altitude even though $[O_2]$ increases as you approach the surface.

Recombination

Direct two body recombination reverses photolysis:

$$O + O \rightarrow O_2 + h\nu \tag{2}$$

However, this reaction is slow, so three body processes dominate instead:

$$O + O + M \rightarrow O_2 + M \tag{3}$$

$$O_2 + O + M \rightarrow O_3 + M \tag{4}$$

Where the reaction rates can be written:

$$\frac{d[O_2]}{dt} = ?$$

$$\frac{d[O_2]}{dt} = [O]^2[M]k_{r3}$$

k_{ri} is the reaction rate dependent on the collision rate (thus T) of the molecules

Photoionization

Oxygen and Nitrogen in the Earth atmosphere ionized by photons:

$$O_2 + h\nu \rightarrow O_2^{+} + e^{-}$$

$$N_2 + h\nu \rightarrow N_2^{+} + e^{-}$$

$$O + h\nu \rightarrow O^{+} + e^{-}$$

However, these products are efficiently processed via charge exchange and atom-ion interchange to yield mostly NO^+ and O_2^+

$$N_2^{+} + O_2 \rightarrow N_2 + O_2^{+}$$

$$O^{+} + O_2 \rightarrow O_2^{+} + O$$

$$N_2^{+} + O \rightarrow NO^{+} + N$$

Ion Loss: Recombination

Dissociative Recombination:

$$O_2^+ + e^- \rightarrow O + O$$

$$NO^+ + e^- \rightarrow N + O$$

Radiative Recombination is much less efficient:

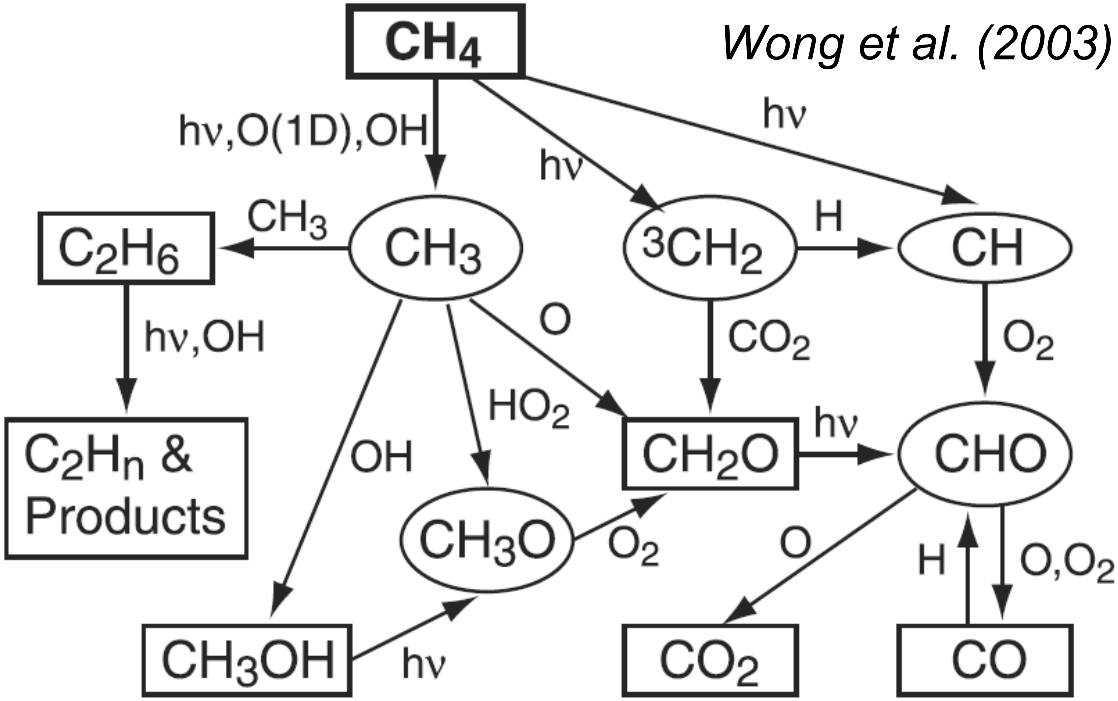
$$O^+ + e^- \rightarrow O + h\nu$$

Hence rapid processes like charge exchange and atom-ion interchange quickly replace the produced ions with dominant ions that can undergo dissociative recombination

Methane on Mars

- Destroyed by photochemistry
  - ➔ *300–600 yr lifetime*
    …not fast enough??

Wong et al. (2003)



- Bar-Nun & Dimitrov (2006) argued that methane could also be produced photochemically
  - → ***controversial***

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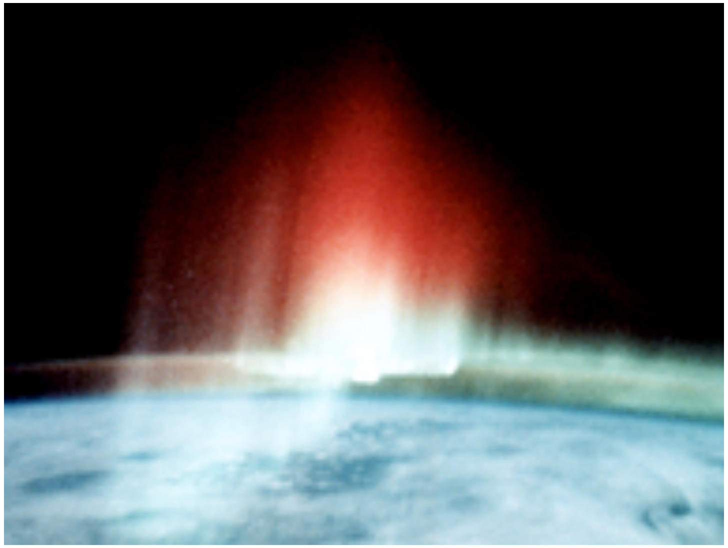
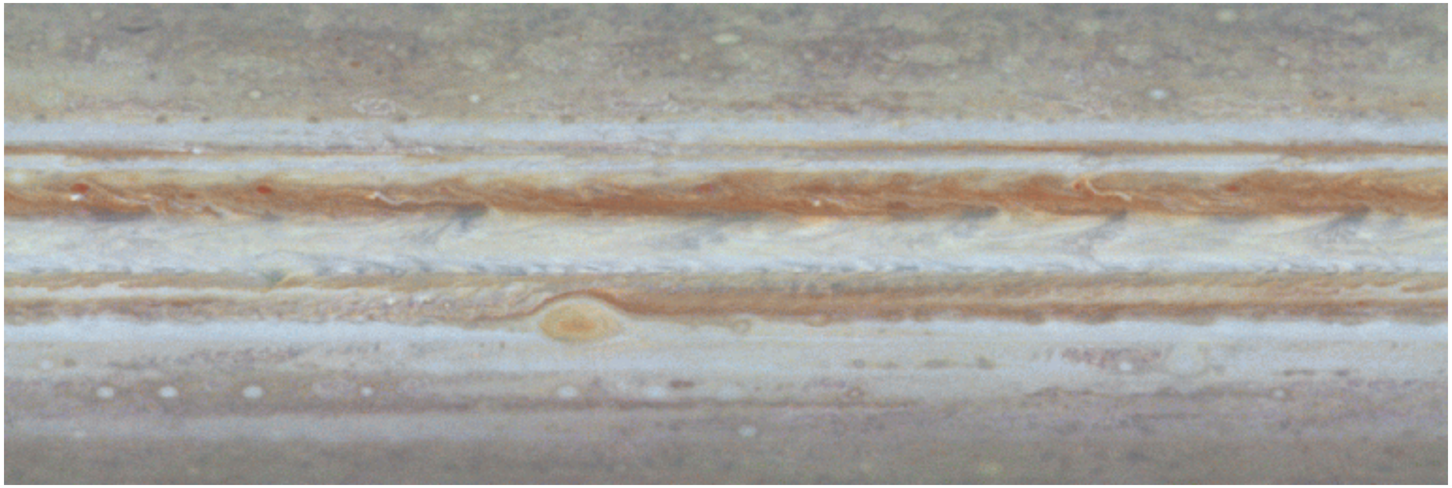
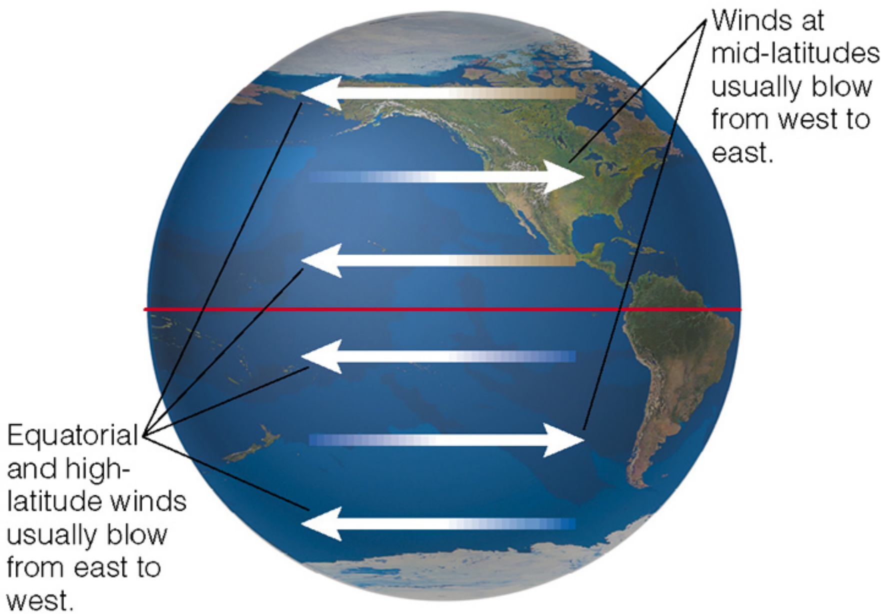




What are Weather and Climate?

weather – short-term changes in wind, clouds, temperature, and pressure in an atmosphere at a given location

climate – long-term average of the weather at a given location



- These are Earth's **global wind patterns** or circulation
  - local weather systems move along with them
  - weather moves from W to E at mid-latitudes in N hemisphere
- Two factors cause these patterns
  - atmospheric heating
  - planetary rotation

Atmospheric Dynamics

Everything Starts with the Navier-Stokes Equation:

$$\frac{D\vec{v}}{Dt} \equiv \frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} = -\frac{1}{\rho}\nabla P + \vec{g}_p + \frac{\mu}{\rho}\nabla^2\vec{v} + f_c\vec{v}\times\hat{z}$$

Material Derivative

Inertial Term

Gravity

Coriolis

Local Derivative

Pressure Gradient

Viscous

$$\frac{\mu}{\rho} = \nu_v$$

μ is the dynamic viscosity

ν_v is the kinematic viscosity

Atmospheric dynamics: Rotation

- Coriolis effect – objects moving on a rotating planet get deflected (e.g. cyclones)
- Angular momentum – as an object moves farther away from the pole, *r* increases, so to conserve angular momentum ω decreases (it moves backwards relative to the rotation rate)
- Coriolis acceleration = $2\,\omega\, v \sin(\theta)$ — θ is latitude
- How important is the Coriolis effect?

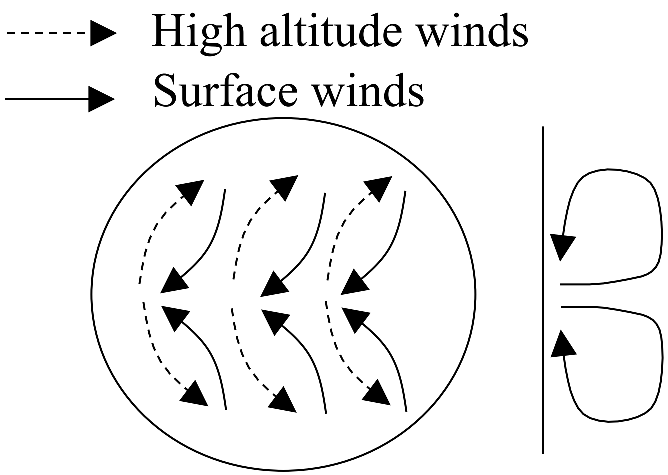
$$\frac{v}{2L\omega\sin\theta}$$

Rossby number = The ratio of inertial forces to Coriolis forces, a measure of relative importance.

e.g. Jupiter v~100 m/s, L~10,000 km we get ~1/30 so important

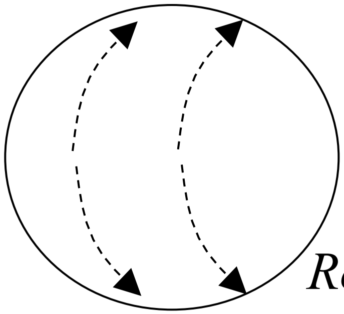
Coriolis Effect + Hadley Cells

Coriolis effect is complicated by fact that parcels of atmosphere rise and fall due to buoyancy creating Hadley cells (equator is hotter than the poles)



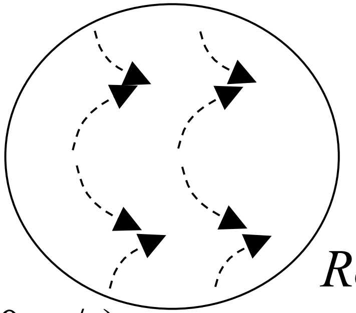
- The result is that the atmosphere is broken up into several Hadley cells (see diagram)
- How many cells depends on the Rossby number (size, rotation rate)

Slow rotator e.g. Venus



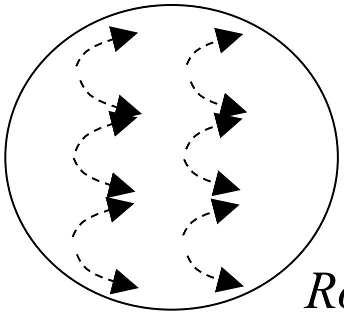
Ro>>1
(assumes v=100 m/s)

Medium rotator e.g. Earth



Ro~1/4

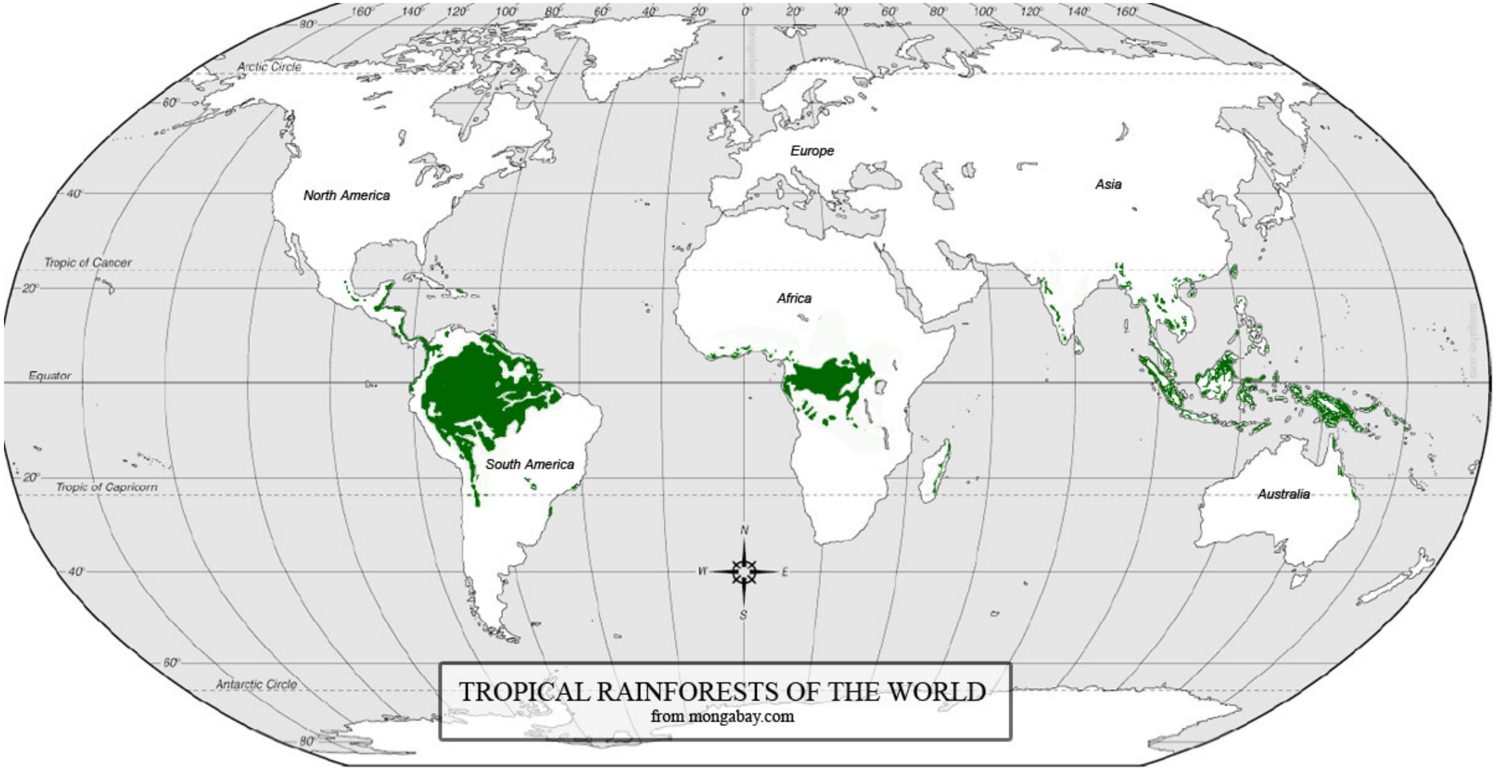
Fast rotator e.g. Jupiter



Ro~1/30

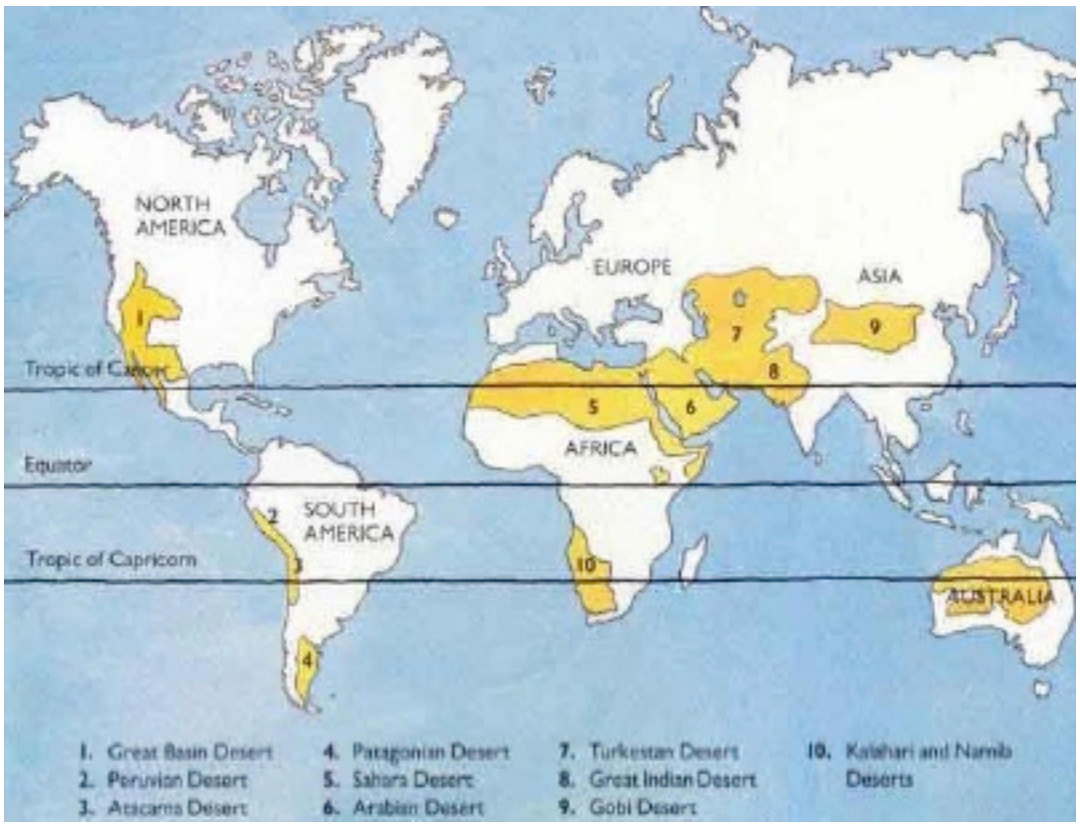
Global Wind Patterns: Hadley Cells

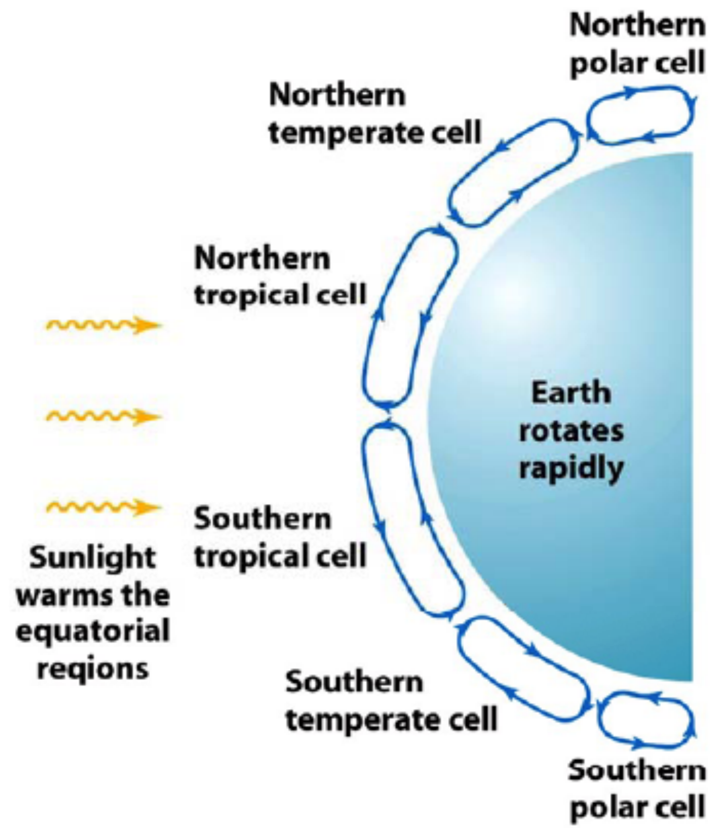
- Air is heated at the equator and rises
- As it rises it cools, clouds condense and generates rain



Global Wind Patterns: Hadley Cells

- Air (now dry) is pushed away from equatorial upwelling and moved toward the tropics
- As it descends, it heats up - dry hotter air helps create deserts





Global Wind Patterns: Hadley Cells

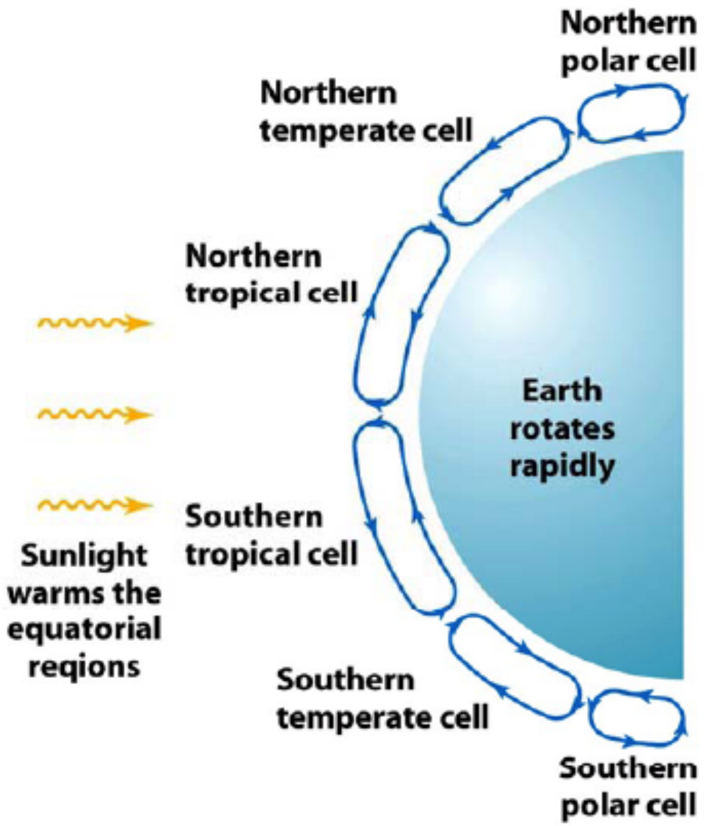
Polar cells work the same way

- Cold air descends over the poles
- Flows along the ground and eventually warms from being in contact with the surface
- Rises at ~60° N/S latitude

Ferrell Cells (Temperate Cells)

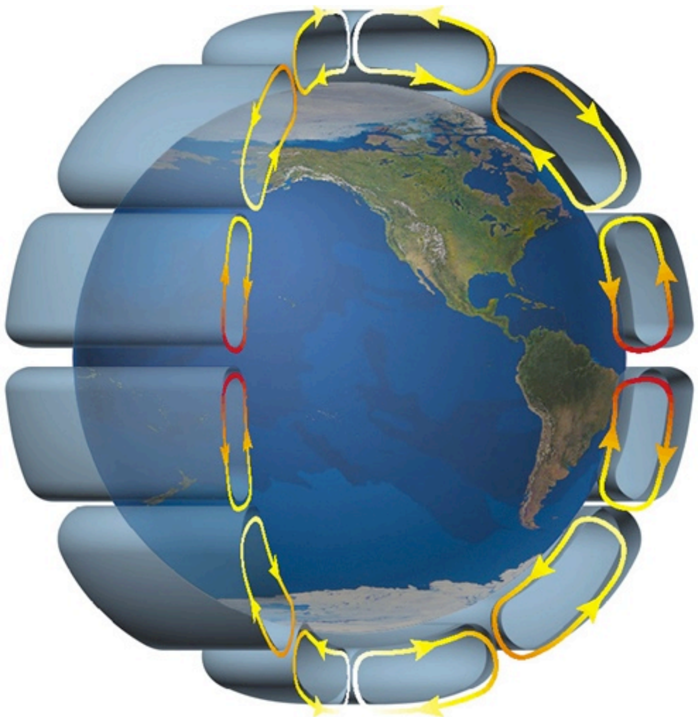
- Sandwiched between the polar and tropical Hadley cells
- Driven by their motion

The simple equator-to-poles convective motion is complicated by the Coriolis force due to the rotation of the Earth



Global Wind Patterns

- On Earth, the Coriolis effect breaks each circulation cell into three separate cells
  - winds move either W to E or E to W

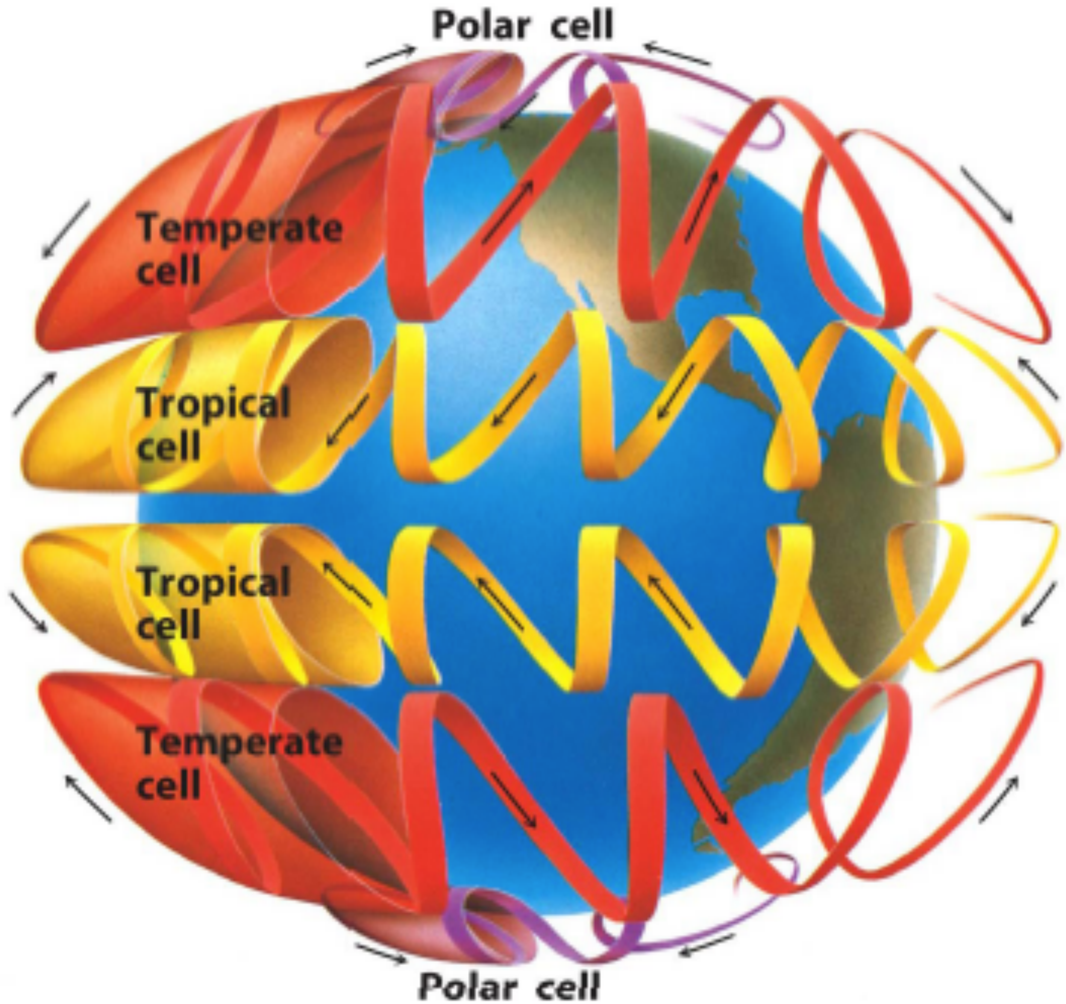


Coriolis effect not strong on Mars & Venus

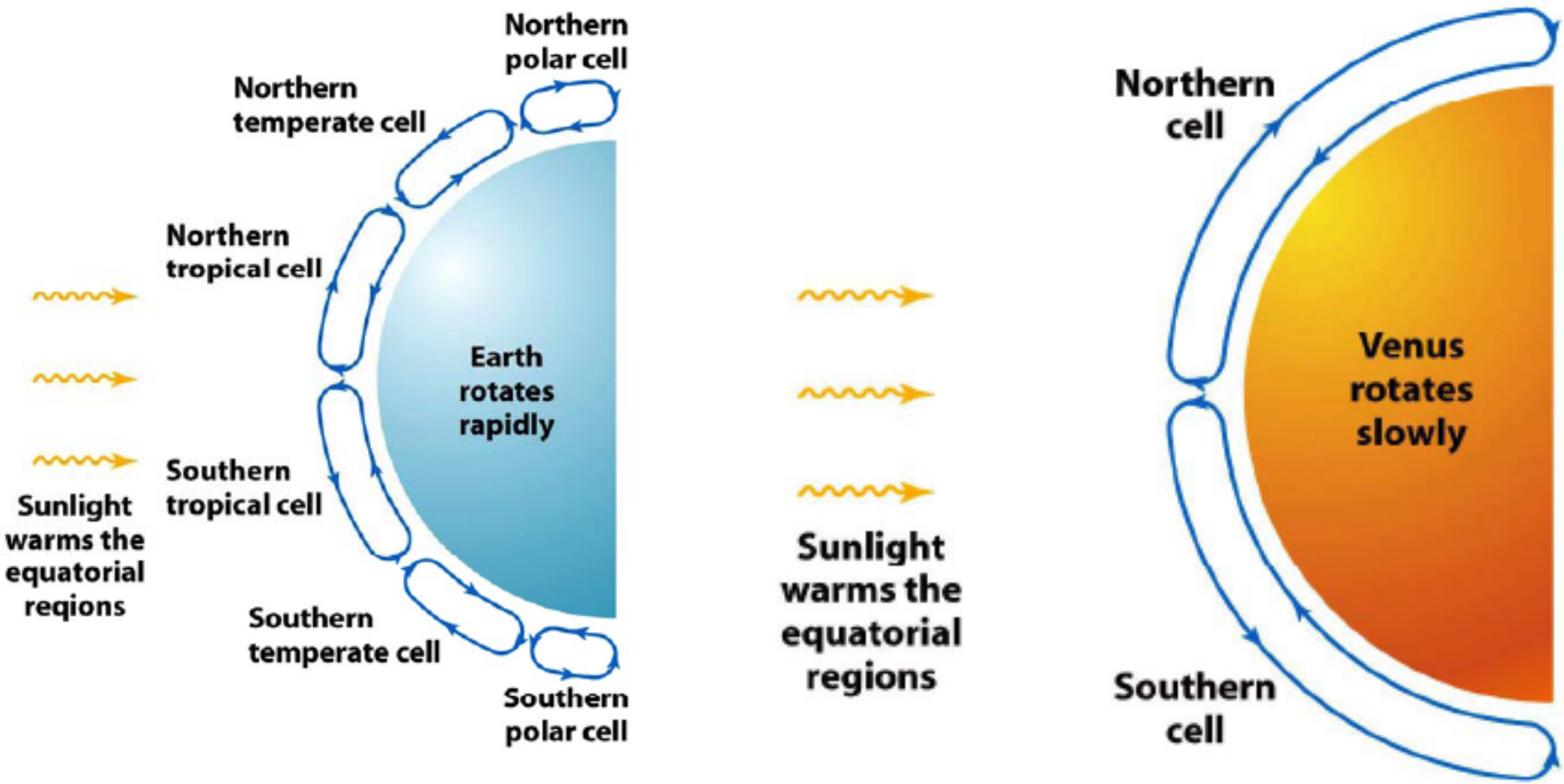
- Mars is too small
- Venus rotates too slowly

Rapid rotators such as the giant planets are significantly affected by the Coriolis force.

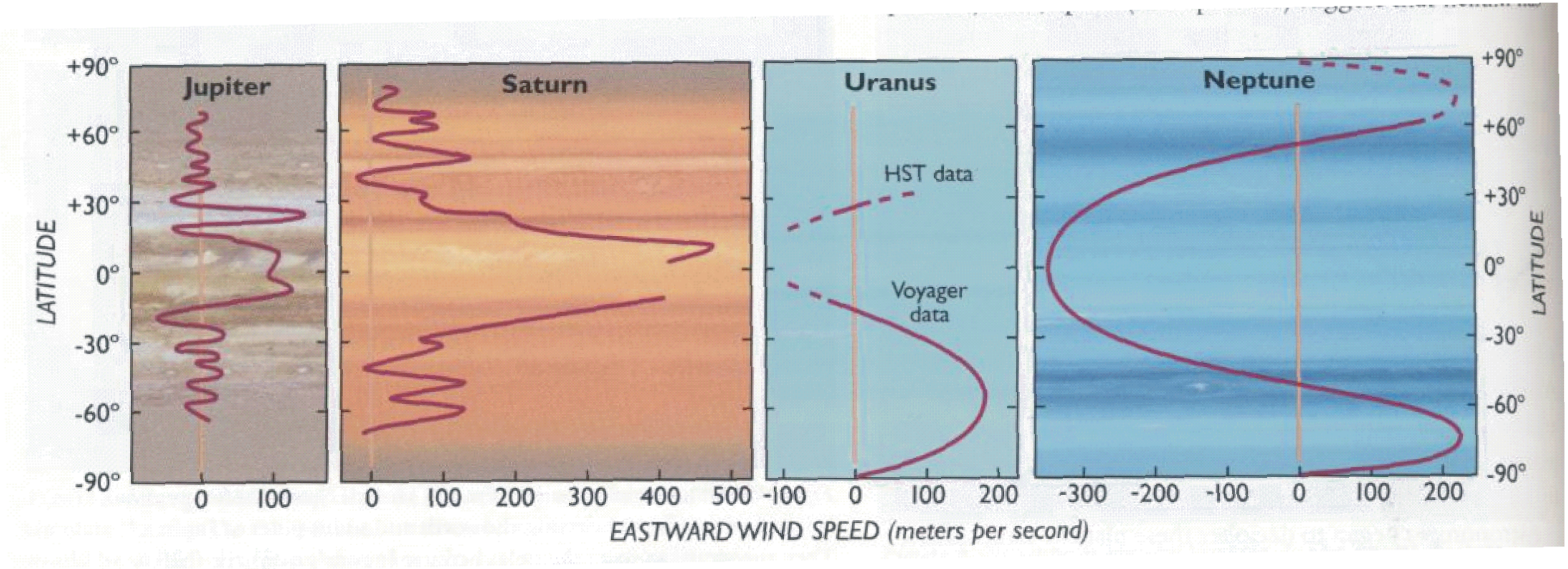
Global Wind Patterns



Comparisons



Zonal Winds



- The reason Jupiter, Saturn, Uranus and Neptune have bands is because of rapid rotations (periods ~ 10 hrs)
- The winds in each band can be measured by following individual objects (e.g. clouds)
- Winds alternate between prograde (eastwards) and retrograde (westwards)