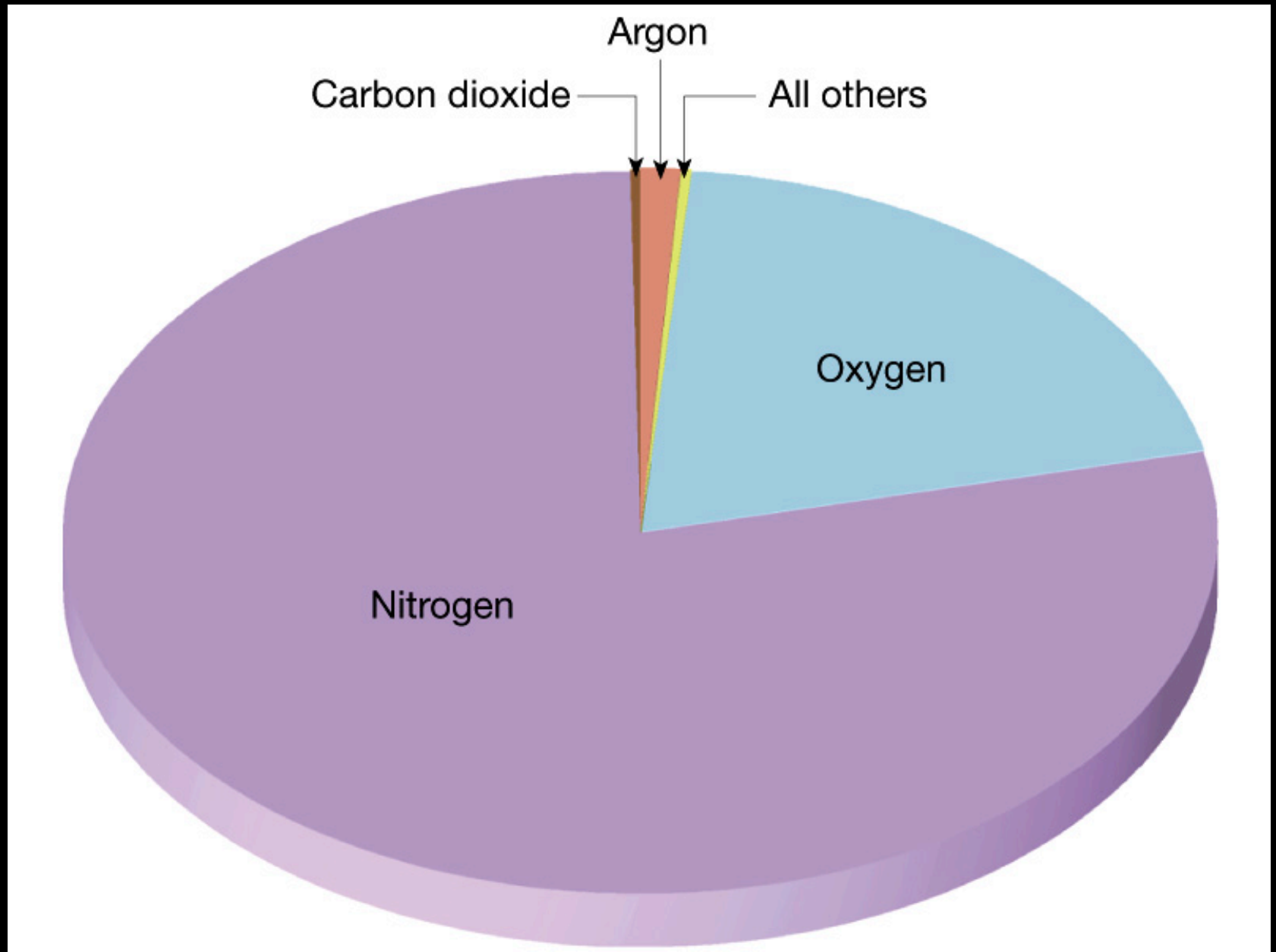


# **K32: The Structure of the Earth's Atmosphere**

- Chemical composition
- Vertical Layers
- Temperature structure
- Coriolis Force and horizontal structure
- Hadley Cells and Heat sources

# Current Molecular Composition

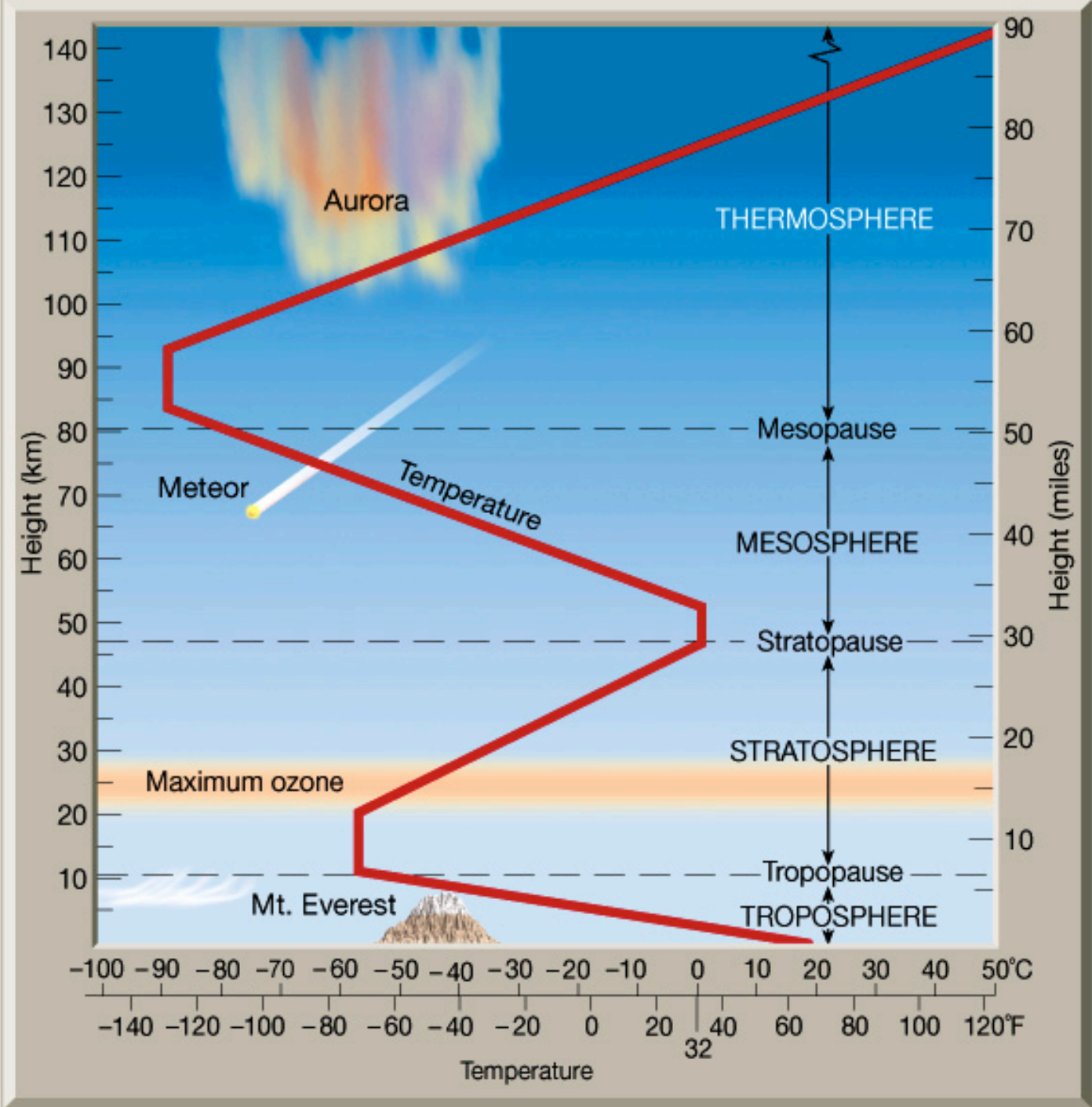


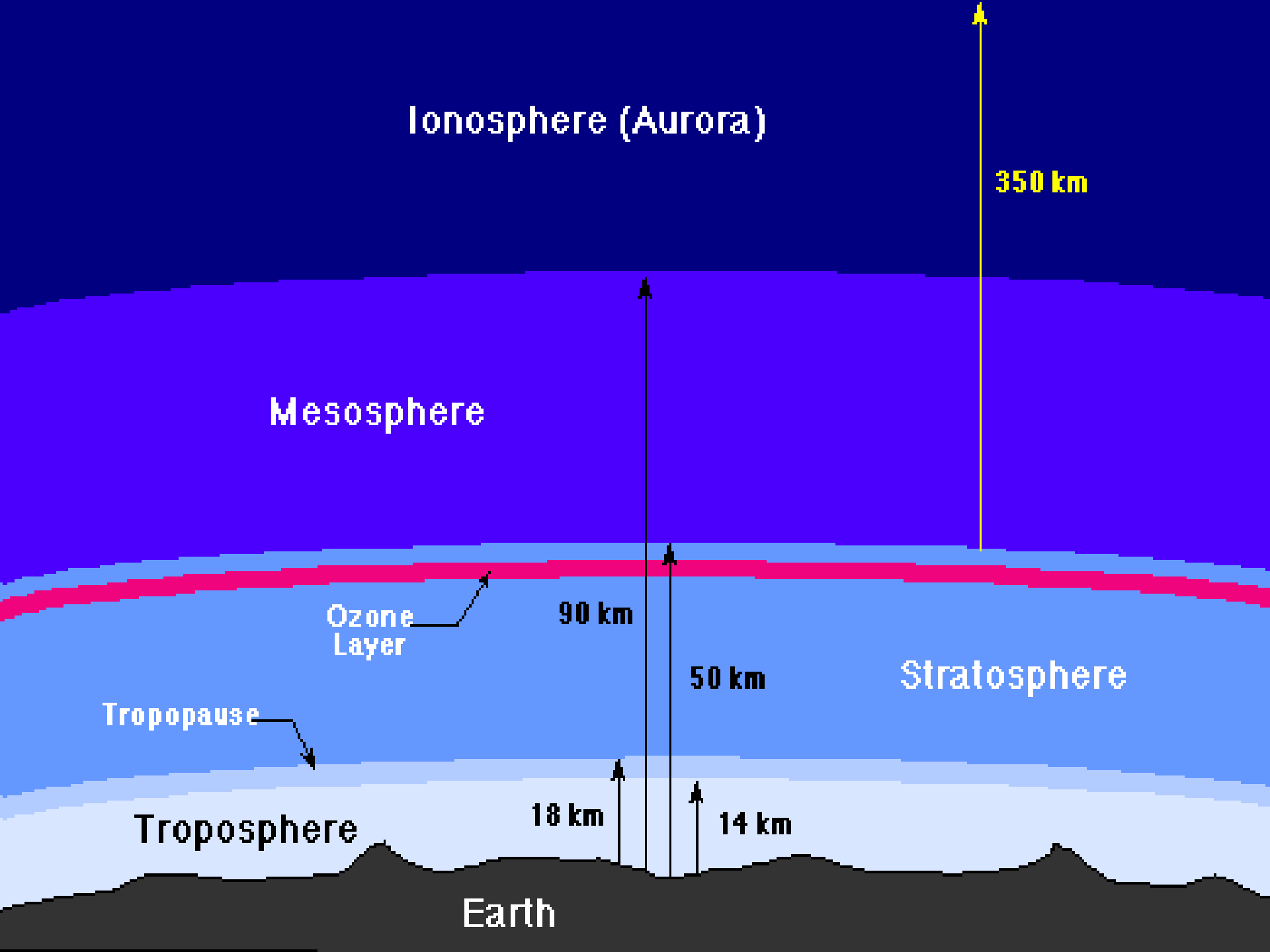
# More detail: Atmospheric Composition today

**Table 1–2** Principal gases of dry air

<b>Constituent</b>	<b>Percent by Volume</b>	<b>Concentration in Parts Per Million (PPM)</b>
Nitrogen (N <sub>2</sub> )	78.084	780,840.0
Oxygen (O <sub>2</sub> )	20.946	209,460.0
Argon (Ar)	0.934	9,340.0
Carbon dioxide (CO <sub>2</sub> )	0.036	360.0
Neon (Ne)	0.00182	18.2
Helium (He)	0.000524	5.24
Methane (CH <sub>4</sub> )	0.00015	1.5
Krypton (Kr)	0.000114	1.14
Hydrogen (H <sub>2</sub> )	0.00005	0.5

# **First let's do the Vertical Structure of our Atmosphere**





# The Troposphere

- The surface layer up to about 30,000 ft
- Heated from below, by ground having absorbed solar energy
- Temperature highest near the ground, and cools all the way up to about 30,000 ft
- This means the possibility of convection, and therefore weather, as clouds form from rising air which cools by pressure drop, and clouds dissipate as air falls and heats.

# The Stratosphere

- Heated mostly by absorbing UV light from the sun by O<sub>3</sub> (ozone), breaking it apart into O<sub>2</sub> + atomic oxygen with speedier particles. Then when they recombine to re-make ozone, you get additional energy release and heating as well.
- Ozone in the stratosphere absorbs ultraviolet radiation, warming it up in the mid-upper parts of the layer. The reason for the increase in temperatures in the stratosphere with height relates to the wavelength of the incoming solar energy. At higher altitudes in the stratosphere, ozone very efficiently absorbs UV, especially the highest energy UV.
- The longer wavelength UV is absorbed less well in the atmosphere, depositing what heat it can at a mix of altitudes.
- This results in a rate of warming in the lower stratosphere that is less than the rate higher in the stratosphere, causing the temperature to increase with height – a “temperature inversion”, stable against convection.

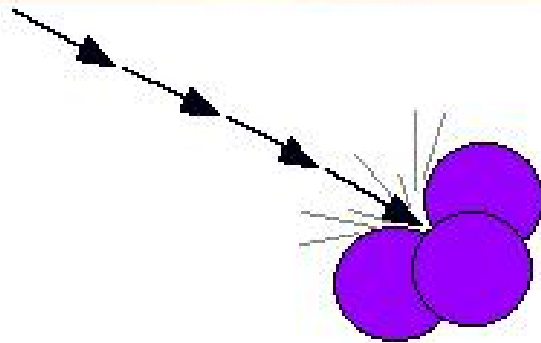


# Ozone Formation is Slow

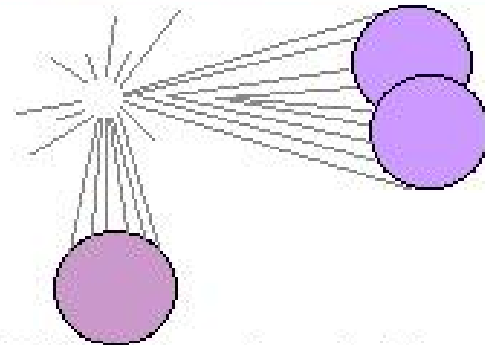
- The reaction of oxygen atoms with an oxygen molecule requires a collision involving a third body to remove excess energy and momentum
- Otherwise the newly formed ozone molecule would almost immediately decompose. The third body can be a nitrogen or another oxygen molecule.
- In the rarified conditions of the stratosphere two body collisions are infrequent and three body ones even more so.
- Ozone formation is therefore slow.
- So the absorption rate of solar UV and therefore the heating rate of the stratosphere is a bit of a complex interplay of ozone density, the amount of UV already absorbed above, and the rate of formation.

# Ozone is created by solar UV and destroyed as well, converting solar UV into the kinetic energy (heat) of the O<sub>2</sub> and O particles

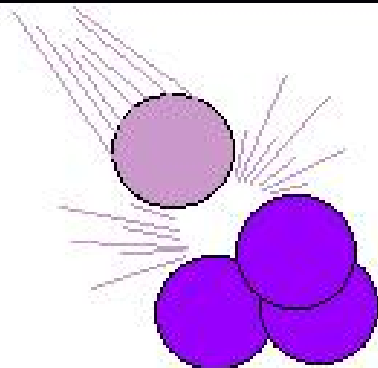
## THE CHAPMAN PROCESS OF OZONE DESTRUCTION



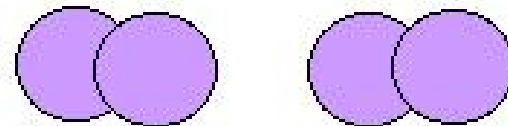
Ozone absorbs a range of ultraviolet radiation. . .



. . .splitting the molecule into one free oxygen atom and one molecule ordinary oxygen.

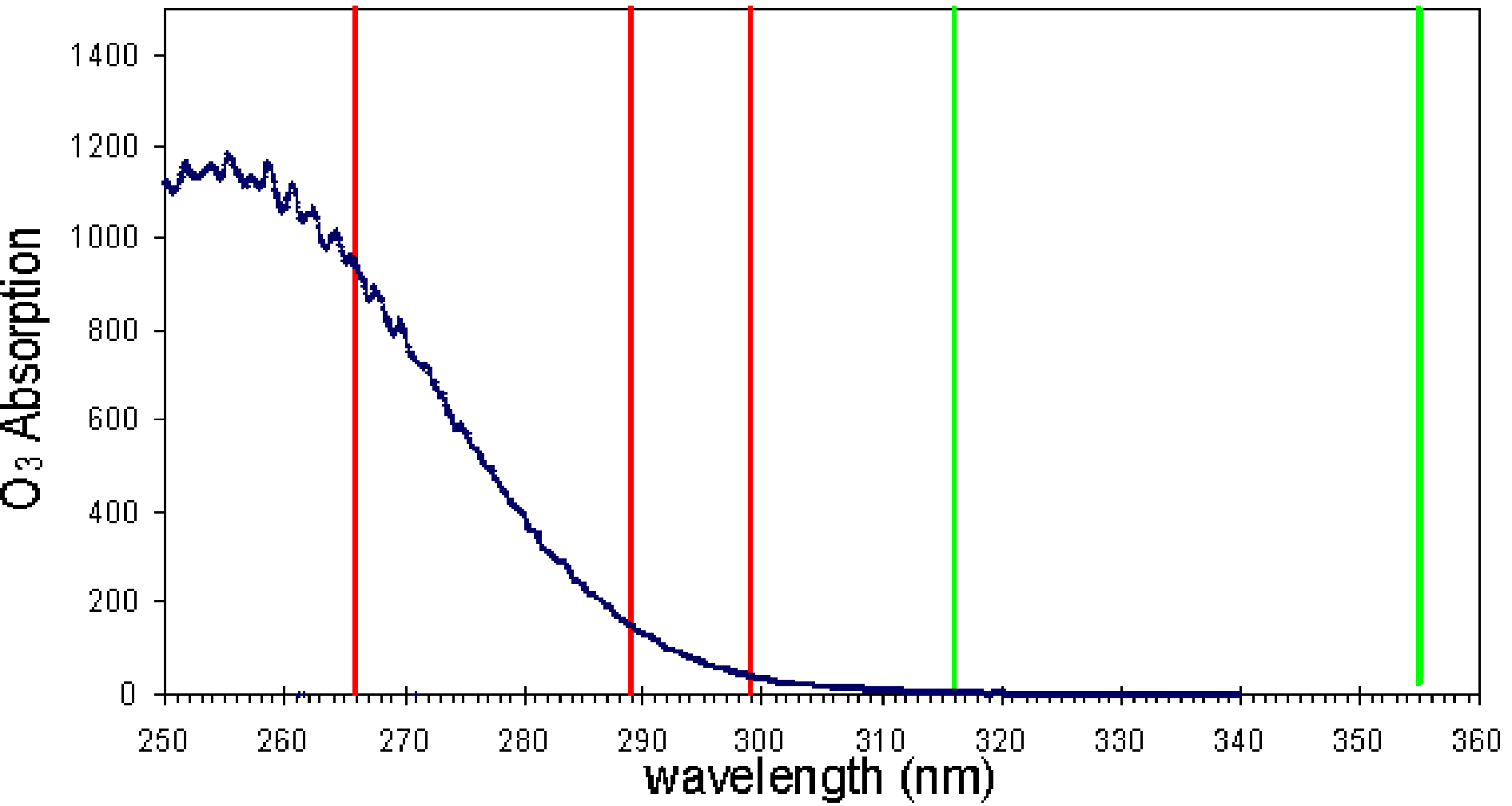


The free oxygen atom then can collide with an ozone molecule. . .

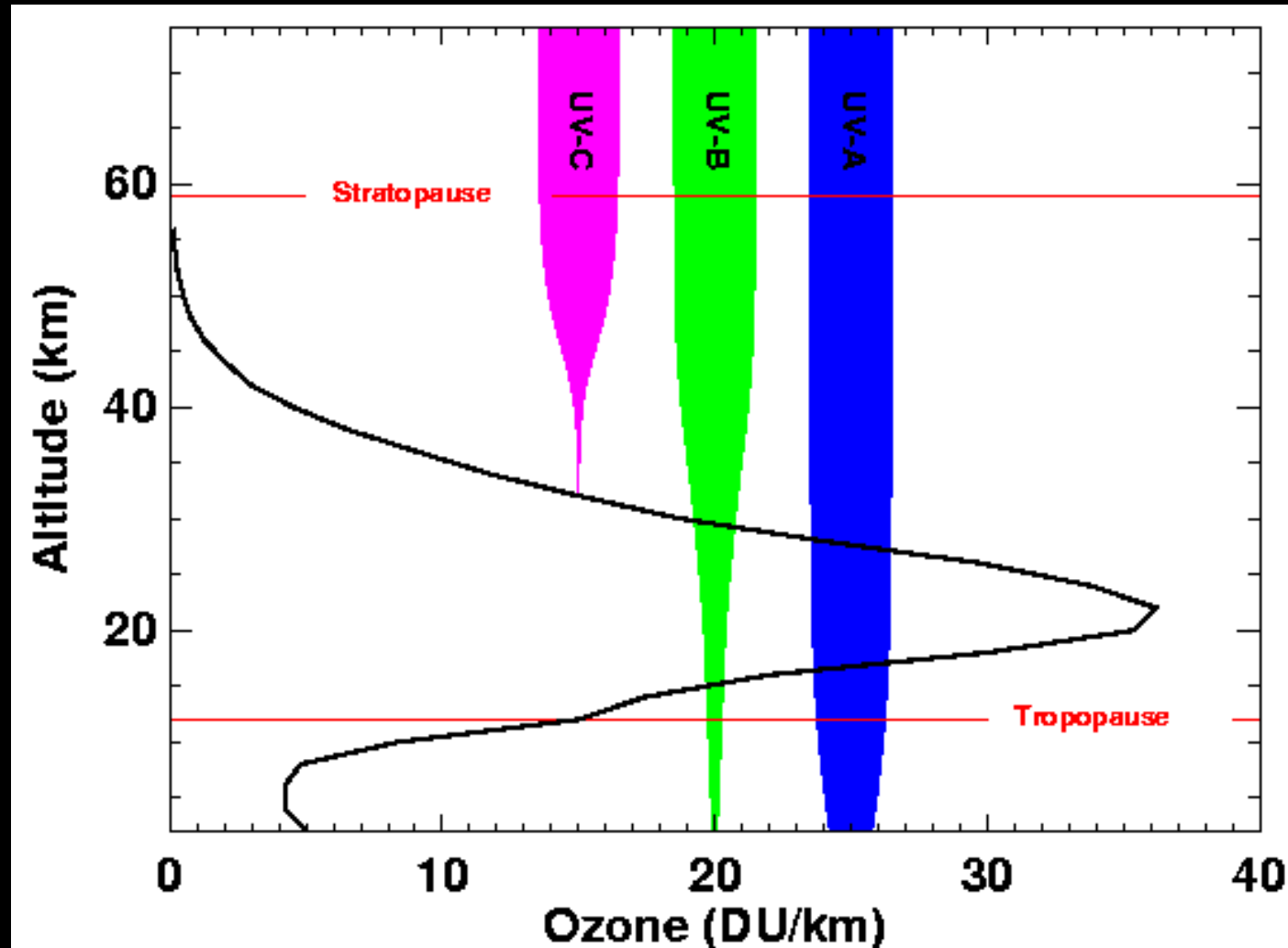


. . .to form two molecules of oxygen

Ozone absorption is almost entirely in the UV, which is below ~300 nm wavelength. Graph is a bit confusing if you expect absorption to be a down direction as it is in an absorption line spectrum. Here higher absorption is up, on y-axis



The most powerful UV (which is UV-C, pink) is entirely absorbed in the upper stratosphere. Wavelengths closer to visible (blue) can penetrate lower, but deposit much less heat to the atmosphere



# Therefore the Stratosphere is **HOTTER** the Higher You Go

- Hottest at the highest layers, and cooler down where it contacts the cold upper troposphere
- At the bottom of the stratosphere, most UV has already been absorbed, so further heating is very reduced,
- The heat source is from ABOVE, not BELOW as in the Troposphere. Hence the temperature vs. height is the opposite from the Troposphere
- **This temperature inversion means no convection, no weather.**

# You Might Wonder why the Diagram Shows the Temperature Inversion Persists Above the Max Ozone Layer?

- The reason is, because the altitude of maximum **heating** is above the altitude of maximum Ozone **amount**. Can you see the difference?
- This may make it clearer...Put another way, for down-going UV photons, by the time you've penetrated down to maximum ozone concentration altitude, much of your UV energy has already been absorbed higher up.

# The Mesosphere

- Above the stratosphere, the mass of atmosphere is **only 0.1%** of the total, and the density is too low for ozone chemistry to heat the atmosphere
- The hotter stratosphere is now below; heating from below again re-asserts itself... deserving of labelling as a new layer: the Mesosphere
- Hence, we get the normal trend we saw in the troposphere – lower temperature with lower pressure and lower altitude.
- This layer is 30-50 miles above the ground.
- **But this layer has so little air, it's not important for climate.**

# The Ionosphere (= Thermosphere)

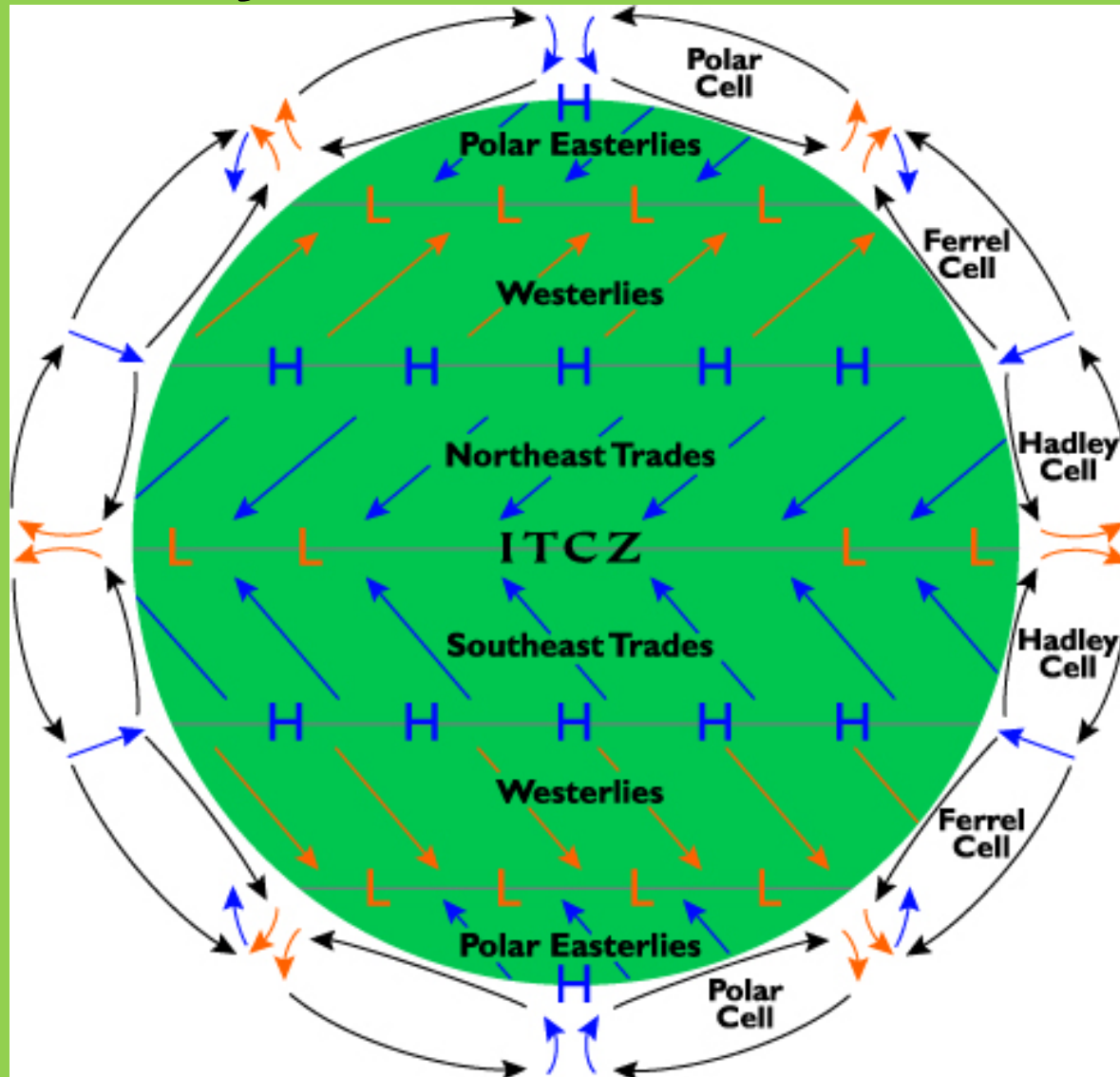
- Above the mesosphere; density so extremely low the Space Shuttle and ISS orbit here, with little drag
- Temperature can be very high; 4,000F. But no significant heat because density is so low. Remember, temperature is a measure of energy PER PARTICLE, and there just aren't many particles up here!
- Heated by ionization from solar UV, and collisions from the solar wind, and cosmic rays.



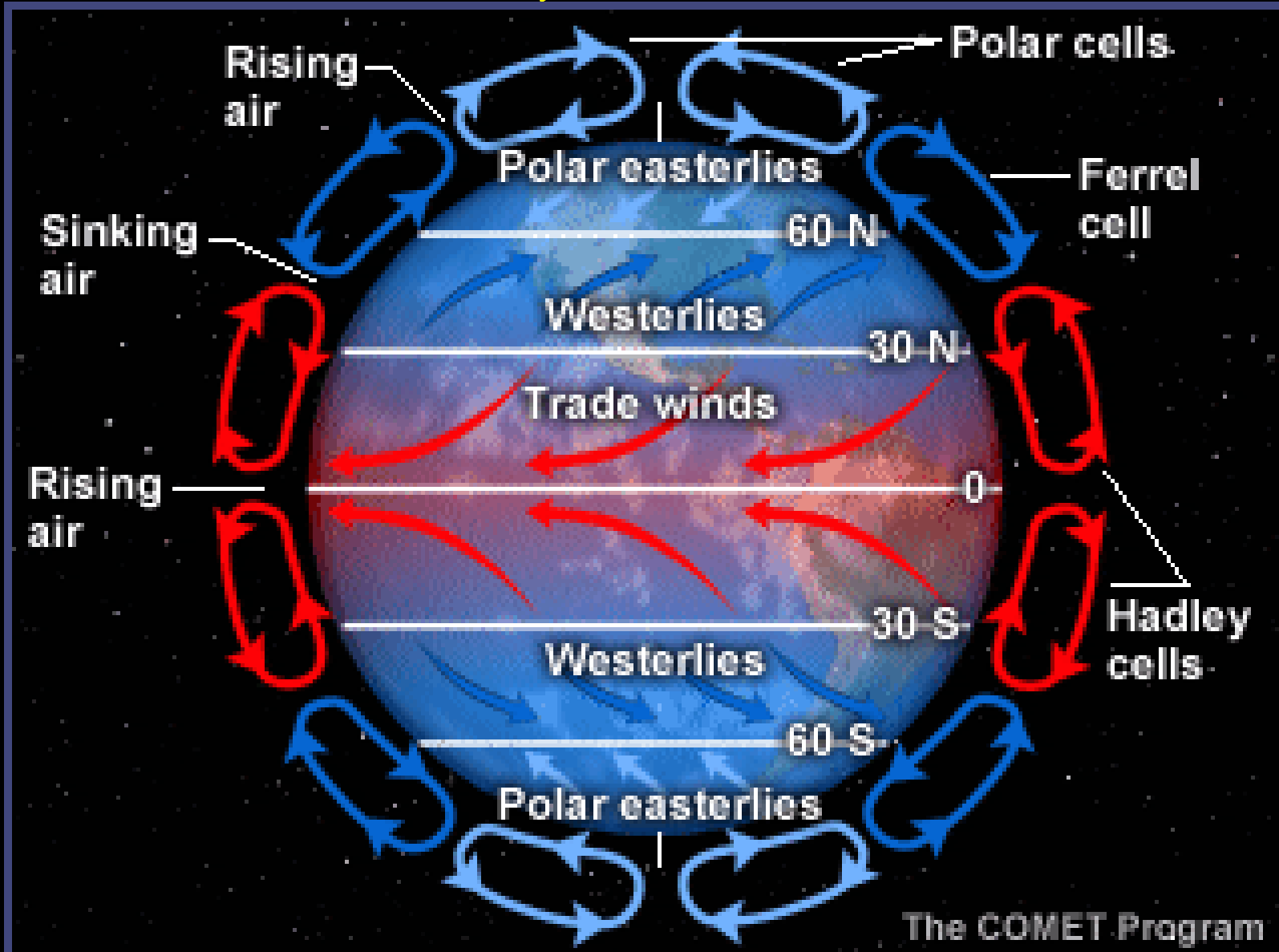
**Only the Troposphere and Stratosphere are substantial enough to affect climate and weather.**

**They will be our exclusive focus in later chapters. Don't worry about the mesosphere or ionosphere**

# The Horizontal Structure of our Atmosphere. Wind directions determined by the Coriolis Force



# The 3 Hadley Cells: Tropical, Ferrel, and Polar



# Hadley, Ferrel, Polar Cells

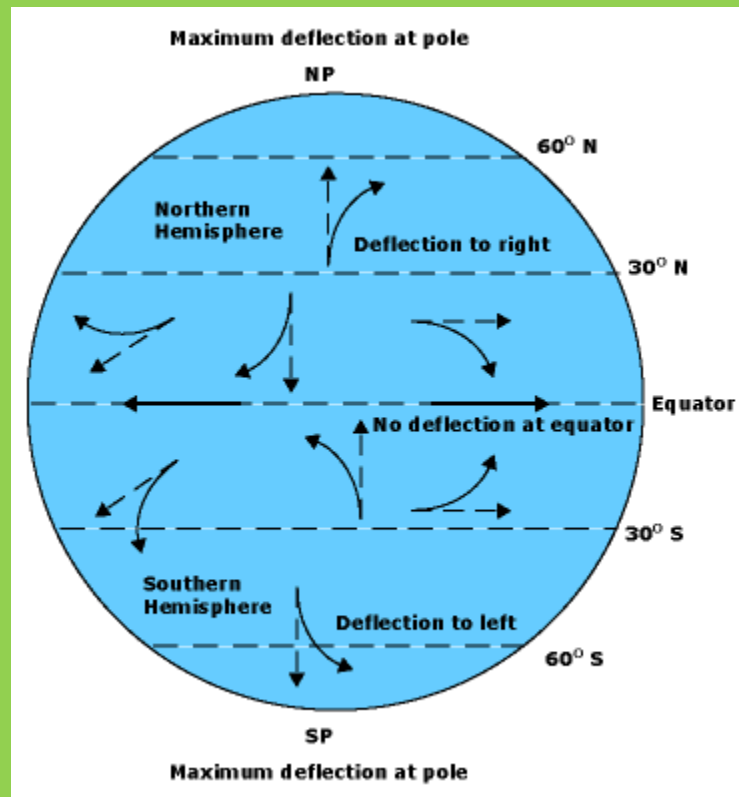
- Rotating planets with thermal gradients in latitude, will have their atmosphere divided into “cells”. In each cell, air is heated at one latitude and rises, and cools and descends at the other latitude.
- The Coriolis deflection sets the major constraint on how many cells the atmosphere of a planet divides into.
- The Coriolis force is stronger if more rapid rotation. It is the size of the planet and speed of rotation (and a lesser extent, the depth of the atmosphere) which determines how many of these are created. Earth’s atmosphere divides into 3 cells per hemisphere.
- For Jupiter, it is many more, as it is 12 times larger in diameter and yet has a day only 12 hrs long. “**The Coriolis Force is very strong in this one”**”

# How Many Cells Will a Planet Have?

- Faster rotation means more cells. Also, the faster the atmosphere's vertical "bounce" is, the more cells too.
- To get mathematical about it, in the latitude direction, the width of a cell goes as...
- **(Cell width)<sup>2</sup> ~ NΩ**
- Where N is the natural vertical frequency of the atmosphere, and Ω is the angular speed of rotation (high Ω means faster rotation period)

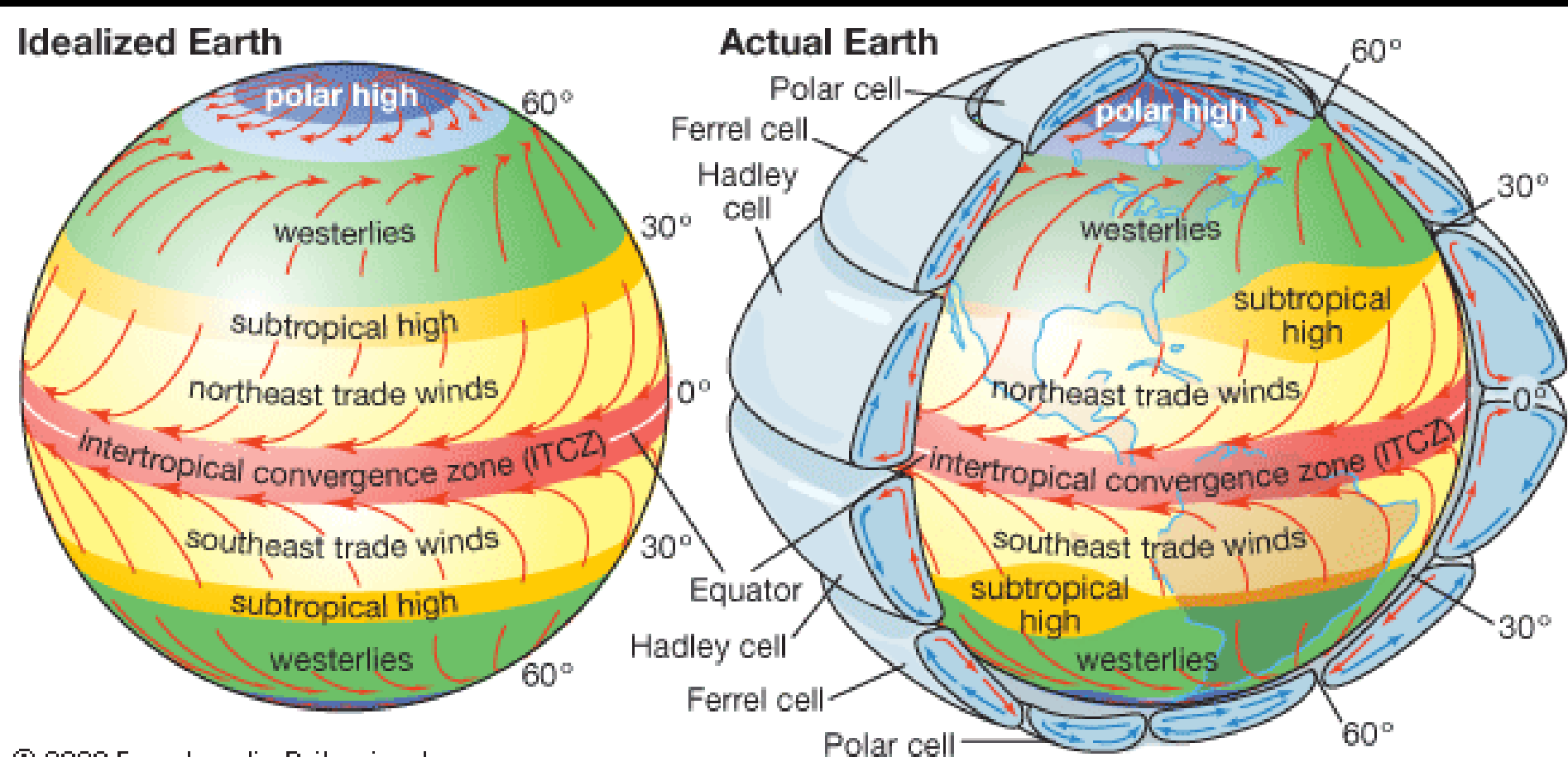
# The Coriolis Effect

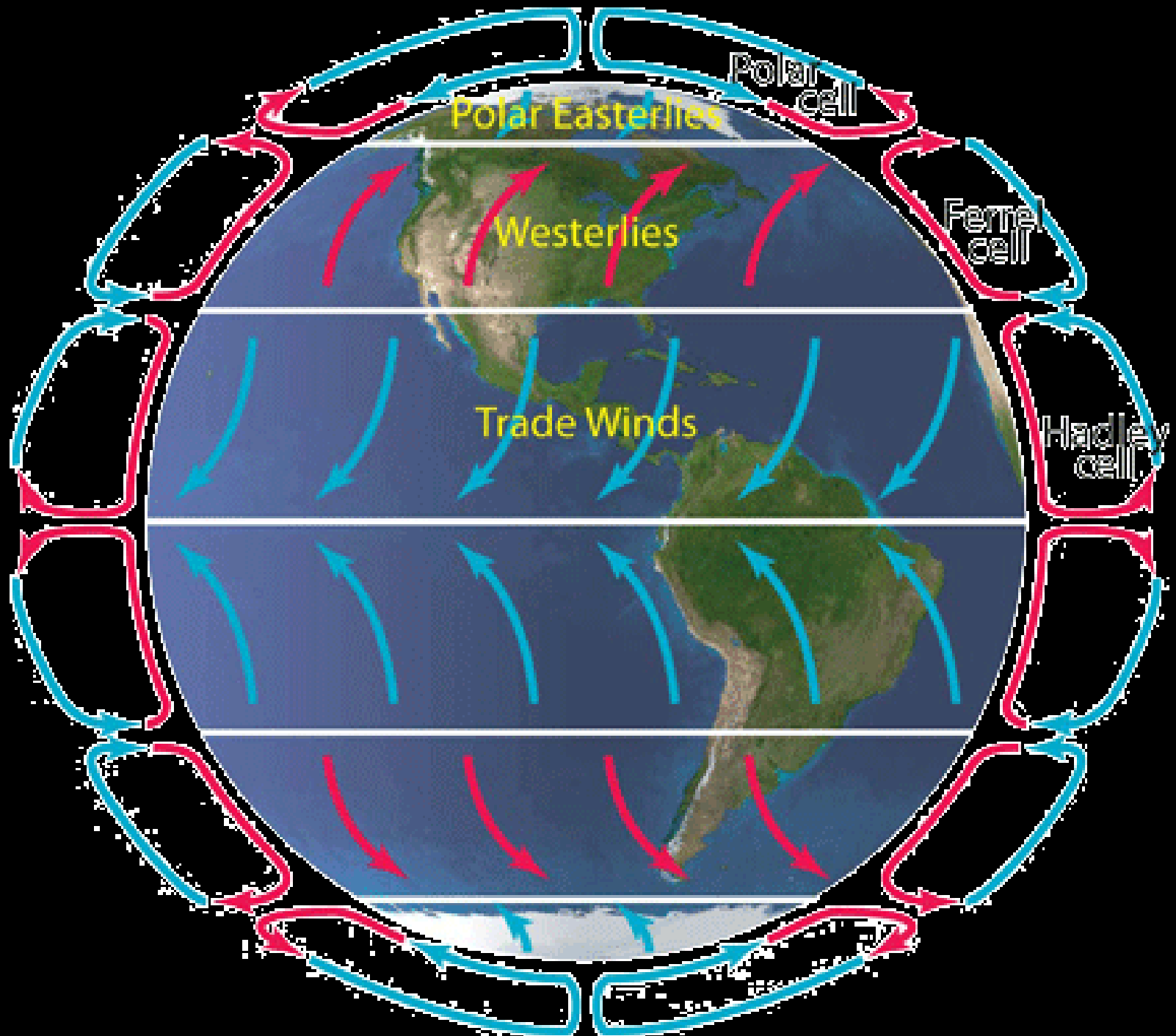
- [6 min YouTube](#) (start 1 min in for merry-go-round demo)



As winds move towards either pole, winds veer to the right relative to the underlying ground, due to the Coriolis Force:  
The velocity of the ground goes from 25,000 mi/day at the equator, down to zero at the pole; winds moving across this differentially rotating landscape will appear to veer to the right for someone riding with the wind.

wind.







# The Hadley Cell (Sometimes called the Tropical Cell)

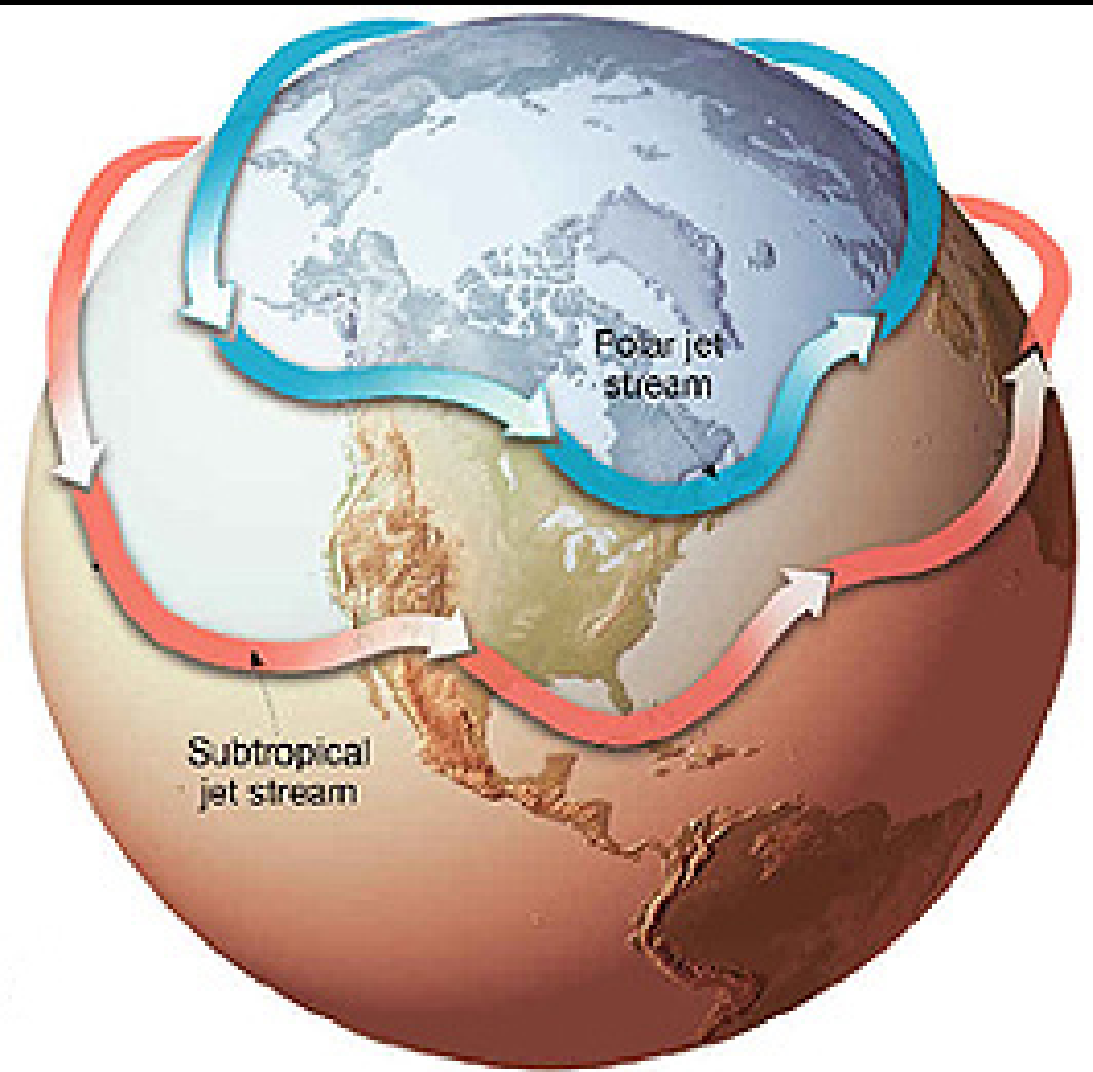
- Solar heating at the equator is strongest, causing rising convective air which is pushed north and south at the tropopause = troposphere/stratosphere boundary.
- At ~30 deg latitude it has deflected enough by the Coriolis force to be moving almost due east. Here, it meets air moving down from the north (Ferrel Cell air) and both meet and descend, warming and drying
- The return of the air, now a surface wind, to the equator is called the “trade winds”.

# Mid-latitudes - The Ferrel Cell

- Convective rising air near 60 deg latitude arrives at the tropopause, moves (in part) to the south, deflecting by Coriolis to the west, till it meets the northerly moving air from the tropical Hadley cell, forcing both to descend
- These are the “Horse Latitudes” at +/-30 deg latitude. Descending air dries. Deserts here (e.g. Sahara, Mojave/Sonora, Gobi)
- Northerly moving surface winds deflected east - “the Westerlies” - carrying heat from the lower latitudes to higher mid-latitudes
- The primary circulation on Earth is driven by the equatorially heated Hadley Cell, and the polar cooled Polar Cell.
- **The Ferrel cell is a weaker intermediate zone**, in which weather systems move through driven by the polar jet stream (boundary between Ferrel and Polar cell, at the tropopause) and the tropical jet stream (boundary between Ferrel and Hadley cells, at the tropopause). Think of it as a ball bearing between the more forcefully driven Polar and Hadley cells.

# The Polar Cell

- Easiest of the cells to understand – rising air from the 60 degree latitude area in part moves north to the pole, where it's cold enough to densify, converge with other northerly winds from all longitudes, and descend.
- This descending air makes a “desert” at the north and south poles.
- It's a strong temperature gradient, again, that drives the circulation of the Polar Cell, but this time it's COLD at the pole that does it



The Boundaries between Cells where air pressure differences can drive fast winds, are called the “Jet Streams”. If the winds are fast, they streams tend to be straighter-going west-to-east. If they weaken, they can meander north and south more (as seems to be happening with current climate change)

# The Boundary Between the Polar Cell and the Ferrel Cell is the Polar Jet Stream

- The steep temperature gradient between these cells means a steep pressure gradient (density difference between cold dense air and warmer less dense air)
- This causes high winds in the upper troposphere – the Jet Stream ([short video animation](#))
- The jet stream guides mid-latitude low-pressure (storm) systems.

# If the temperature gradient between the Polar and Ferrel cells decreases

- ... it makes for a weaker Polar Cell
- ... which makes for a weaker Polar Jet Stream, which then meanders more in latitude, but on average to migrates poleward.
- It would also be expected to cause the tropical cell to expand (more heating) and the desert bands to migrate northward in the Northern Hemisphere.
- We'll come back to this in "Current climate change" PowerPoint.

# Hadley Cells and the Rising Temperature of the Oceans

- Rising ocean temperatures is raising the power of the Tropical Cell by 570 billion watts per year, since 1979 ([Huang & McIlroy 2014](#))
- Combined with the weakening cold of the Arctic polar cell, this is causing the polar cell boundary (polar jet stream) to migrate poleward
- But the jet stream guides storms, which now are also migrating northward, so that the “horse latitudes” deserts are migrating north, (in California too)

# Expansion of the Hadley Tropical Cell

- At this early stage of climate change, the natural variations are hard to separate from the secular climate change component, but a doubling of CO<sub>2</sub> (from 280ppm to 560ppm, which seem virtually unavoidable) in a wide variety of climate models ([Barnes and Polvani 2013](#), [Bengtsson et al. 2005](#)) indicates the northern hemisphere jet stream boundary migrates north by 1 degree (112 km), and twice that in the Southern Hemisphere.
- Currently, at 410 ppm, we're 46% of the way towards a doubling of pre-industrial level CO<sub>2</sub> concentrations, suggesting **we have already migrated the jet stream boundary by ~50 km or 30 miles.**



# Key Points – K32: Structure of Earth's Atmosphere

- 78% Nitrogen which is fairly inert. 21% oxygen, 1% Argon, 0.04% CO<sub>2</sub>
- Troposphere – heated from sun-warmed ground, Temp falls with height
- Stratosphere, heated from above by UV absorbed by ozone; Temp rises with height
- Troposphere can have convection = weather; stratosphere cannot
- Mesosphere; where meteors burn up. Ionosphere (=thermosphere), heated by solar wind, aurorae. Top two layers almost no mass, little influence on climate
- Hadley/Ferrel/Polar cells. Their general circulation
- Ferrel cell is weakest; having neither a strong heat source nor sink
- Coriolis force stronger with more rapid rotation, and this with larger planet size makes more cells
- Jet streams – tropical and polar – boundaries between the cells at the tropopause have lots of shear, guide low pressure storm systems
- Weaker temp gradient at poles causes a weaker and meandering polar jet stream on average migrating north, and an expanding Hadley Cell migrating northern hemisphere deserts northward