

# Fundamentals of Earth's Atmosphere

AOSC 433/633 & CHEM 433/633

Tim Canty

**Class Web Site:** <http://www.atmos.umd.edu/~rjs/class/spr2013>

## Notes:

- Ross, Tim, & Allison co-teach this class; please include all of us on class related email unless you are writing to set up a meeting with one of us
- Lectures are the “glue” that hold this class together: therefore, attendance is strongly encouraged
- We like to “ask questions” for many reasons: to get to know you, to keep you engaged, etc. Please participate at your own level of comfort
- Problem sets tend to be quantitative and exams tend to be qualitative: problem set #1, due 12 February

**We encourage students to start working on Problem Set #1 soon and not wait until the night before due date to get started**

## Lecture 3

31 January 2013

## Overview of fundamental atmospheric concepts

### Today's goals:

Review mathematical concepts that guide understanding the chemical and dynamical behavior of the atmosphere, such as:

- 1) Ideal Gas law
- 2) Atmospheric Pressure
- 3) Atmospheric Temperature
  - a) effective temperature
  - b) temperature profile
- 4) Coriolis Force

# Gas Laws

Let's review a few important laws that govern the relationship between the physical states of a gas:

## Boyle's Law

named after The Hon. Sir Robert Boyle  
(1627-1691)



## Charles' Law(s)

named after Jacques A.C. Charles  
(1746-1823) sometimes called  
Gay-Lussac's law



## Avogadro's Law (hypothesis)

named after Amedeo Avogadro  
(1776-1856)



# Gas Laws

Let's review a few important laws that govern the relationship between the physical states of a gas:

## Boyle's Law

$pV = \text{constant}$        $p = \text{pressure}$   
 $V = \text{Volume}$



## Charles' Law(s)

$V/T = \text{constant}$        $T = \text{temperature}$   
 $p/T = \text{constant}$



## Avogadro's Law (hypothesis)

$V = n \cdot \text{constant}$        $n = \# \text{ of moles}$



# Ideal Gas Law

Gas laws combine to form the *Ideal Gas Law*:

$$pV = nRT$$

$$R(\text{universal gas constant}) = 0.083145 \text{ m}^3 \text{ mbar mole}^{-1} \text{ K}^{-1}$$

Can be written several different ways

– relates changes in temperature to changes in pressure and volume.

Most convenient to use Ideal Gas Law in this form:

$$p = Nk_b T$$

**Pressure units = mbar**

**N(number density) units = molecules / cm<sup>3</sup>**

**Temperature units = Kelvin**

**k<sub>b</sub>(Boltzmann's constant) units = 1.38 x 10<sup>-19</sup> mbar • K<sup>-1</sup> • cm<sup>3</sup>**

*From this equation, can you determine the number density of air at Standard Temperature and Pressure (STP) (273 K, 1000 mbar)?*

# Dalton's Law of Partial Pressures

Total pressure exerted by mixture of non-interacting gases is equal to sum of the partial pressures of the gases.

$$p_{\text{tot}} = p_1 + p_2 + \dots$$

For a given volume and temperature,

$$p_1 V = n_1 RT$$

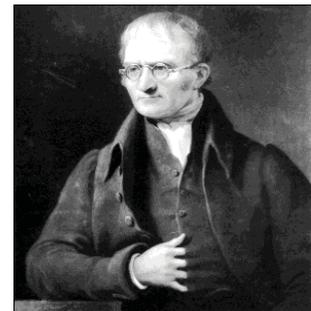
$$p_2 V = n_2 RT$$

$$(p_1 + p_2)V = (n_1 + n_2)RT$$

$$\text{If, } n = n_1 + n_2$$

$$\text{Then } p_1 = (n_1/n)p$$

$$\text{or } p_1 = (N_1/N)p$$



John Dalton

*What is the number density of ozone (O<sub>3</sub>), if it has a partial pressure of 0.0001 mbar? (again, assume STP conditions)*

# Mixing Ratio

**Volume mixing ratio** of a gas is the ratio of number density of a gas to the number density of dry air (or the ratio of partial pressure to total pressure) and is independent of atmospheric density.

$$\text{M.R.} = N_{\text{gas}}/N_{\text{air}} = p_{\text{gas}}/p_{\text{air}}$$

Can be expressed as:

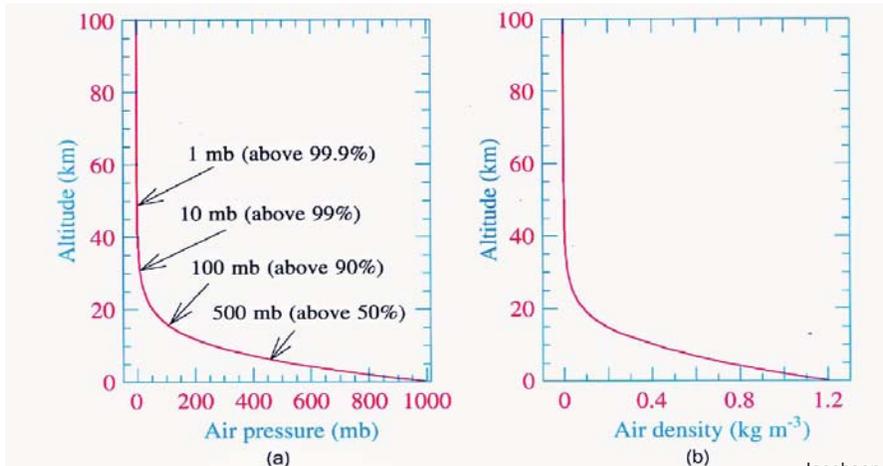
$$\text{Parts per million (ppmv or simply ppm)} = \text{M.R.} \cdot 1 \times 10^6$$

$$\text{Parts per billion (ppbv or simply ppb)} = \text{M.R.} \cdot 1 \times 10^9$$

$$\text{Parts per trillion (pptv or simply ppt)} = \text{M.R.} \cdot 1 \times 10^{12}$$

*What is the mixing ratio of ozone from the previous problem?*

## Pressure and Density vs. Altitude



**Figure 3.2.** (a) Pressure and (b) density versus altitude in the Earth's lower atmosphere. The pressure diagram shows that 99.9 percent of the atmosphere lies below an altitude of about 48 km (1 mb), and 50 percent lies below about 5.5 km (500 mb).

Jacobson, *Atmospheric Pollution*

Gravitational forces pull the atmosphere to the surface, increasing the density and pressure of the atmosphere, closer to the surface (i.e. air at the surface is supporting the weight of all of the air above).

Lower density air gets pushed away from layers of the atmosphere that have a higher density.

$$p = p_0 e^{-\frac{z}{H}} \quad H = \frac{RT}{g} \quad H = \text{scale height, } \sim 8.5 \text{ km for Earth}$$

# Role of the Sun

The Sun is the major source of energy input into the atmosphere.

At a very basic level, we're trying to understand the interaction between the atmosphere and the energy that the planet is receiving from the sun.

- How much solar energy is reaching the planet?
- How does temperature respond to this energy input?
- What factors determine how energy is distributed throughout the atmosphere?



Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

9

## Types of Radiation

All objects emit (radiate) energy continuously in the form of electromagnetic waves.

The type of radiation associated with the transfer of heat energy from one location to another is referred to as *infrared radiation*.

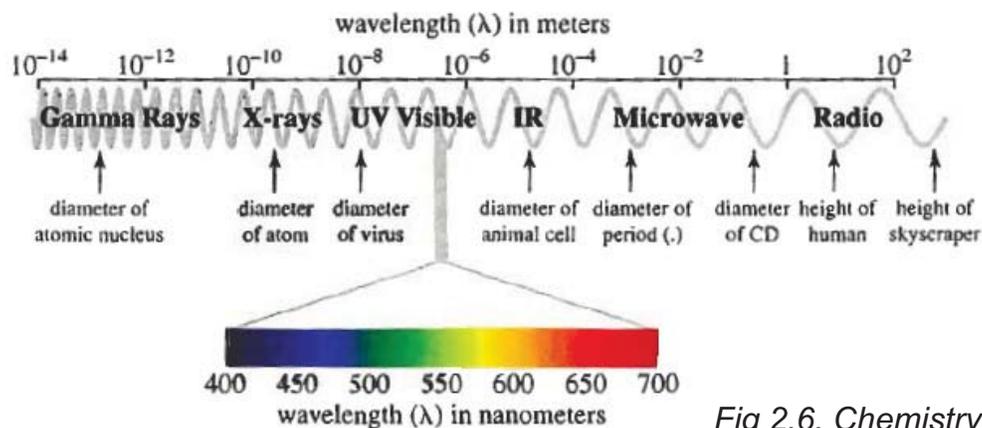


Fig 2.6, *Chemistry in Context*

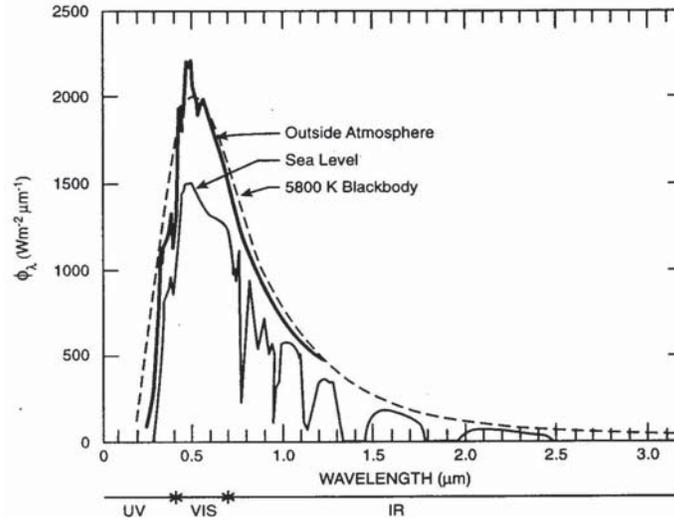
To help understand how energy is emitted, consider a theoretical abstraction called a “**blackbody**” which is both a perfect absorber (it absorbs all energy that hits it) and a perfect emitter (it re-emits all energy that it absorbs).

Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

10

# Energy flux as a function of wavelength



The wavelength at which the energy spectrum reaches maximum can be found from **Wien's Displacement Law**:

$$\lambda_{\max}(\mu\text{m}) = 2898(\mu\text{m K}) / T(\text{K})$$

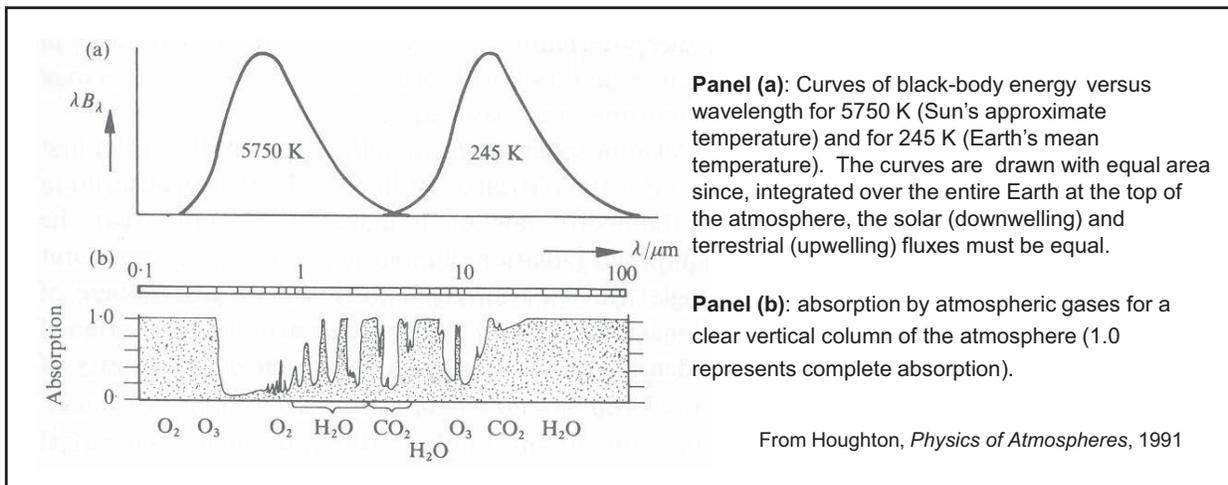
Total radiant energy emitted by a blackbody can be determined using the **Stefan-Boltzmann Law**:

$$E = \sigma AT^4$$

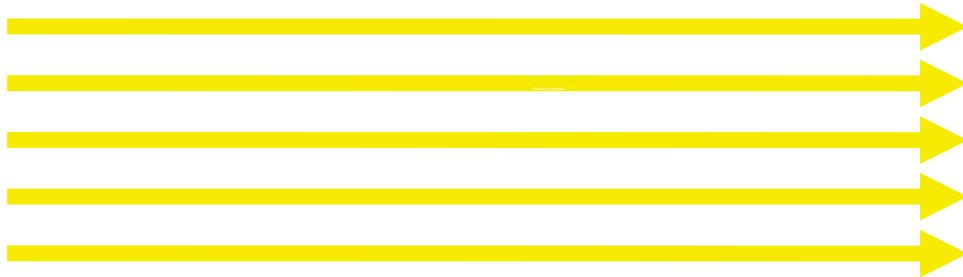
$$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}, A = \text{area}, T = \text{temperature}$$

# Atmospheric Radiation

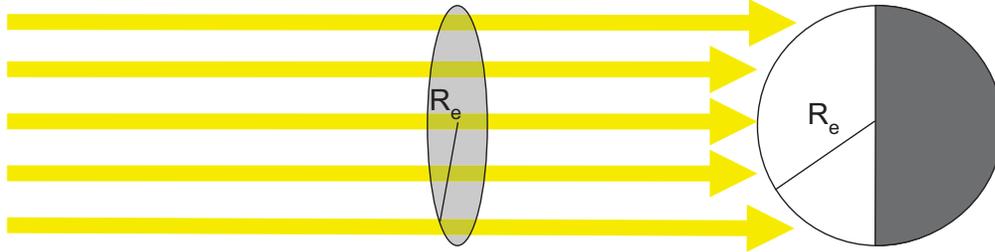
- Solar irradiance (downwelling) at top of atmosphere occurs at wavelengths between ~200 and 2000 nm (~5750 K "black body" temperature)
- Thermal irradiance (upwelling) at top of the atmosphere occurs at wavelengths between ~5 and 50 μm (~245 K "black body" temperature)



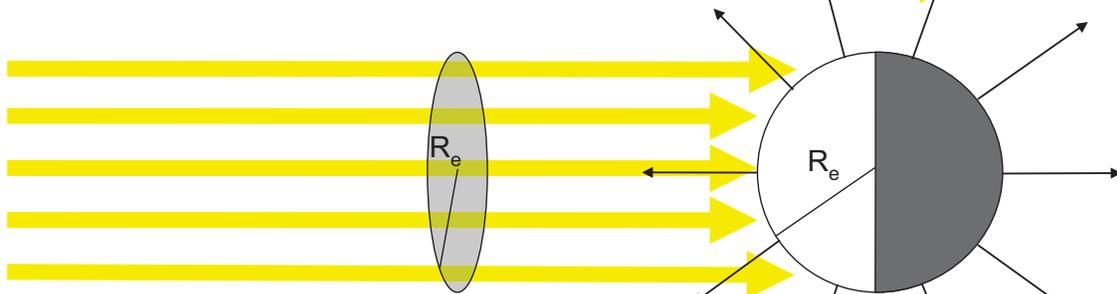
- Absorption and photodissociation in the UV occurs due to changes in the electronic state (orbital configuration) of molecules
- Absorption and re-emission in the IR occurs due to changes in vibrational and rotational states of molecules with electric dipole moments



At the Earth, the flux of Solar radiation (S)=1370 W/m<sup>2</sup>



Rate at which solar energy strikes the Earth =  $S\pi R_e^2$



The Earth emits energy in all directions, however.

# Effective Temperature of Earth

Using the Stefan-Boltzmann law, we can determine the temperature of the Earth (this is called the *effective temperature*).

$$S\pi R_e^2 = \sigma AT_e^4$$
$$T_e = \left[ \frac{S}{4\sigma} \right]^{\frac{1}{4}} \quad (\text{where did } \pi, R_e^2, \text{ and } A \text{ go?})$$

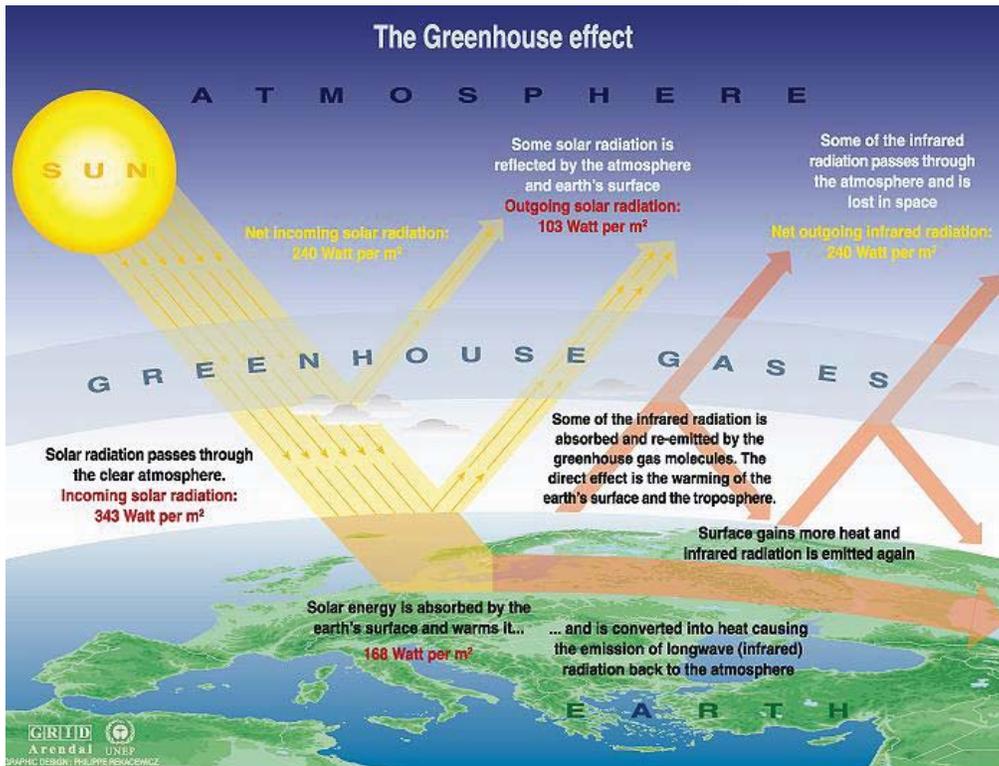
**Is this temperature hotter or colder than the temperature today?**

## Effective Temperature of other Planets

Planet	Distance from Sun	S	Albedo	Effective Temperature	Actual Temperature
Venus	108x10 <sup>6</sup> km	2643 W/m <sup>2</sup>	0.75	232 K	730 K
Earth	150x10 <sup>6</sup> km	1370 W/m <sup>2</sup>	0.30	255 K	288 K
Mars	228x10 <sup>6</sup> km	593 W/m <sup>2</sup>	0.25	210 K	218 K

You may hear people argue there is no greenhouse effect. Obviously, there is and without it life on this planet would be completely different.

What they are really arguing is the efficiency of the greenhouse effect and whether humans are influencing it.



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

See also, Slide 6, Lecture 2

<http://www.grida.no/publications/vg/climate/page/3058.aspx>

Copyright © 2013 University of Maryland

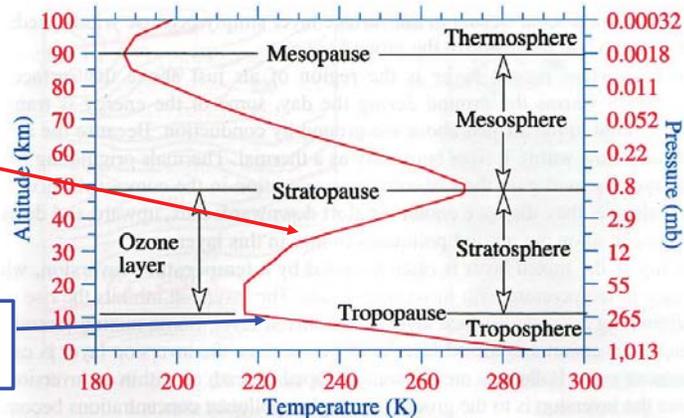
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

17

## Atmospheric Temperature Profile

Why does temperature increase with altitude in the stratosphere?

Why does temperature decrease with altitude in the troposphere?



**Figure 3.3.** Temperature structure of the Earth's lower atmosphere, ignoring the boundary layer.

Jacobson, *Atmospheric Pollution*

Does the change in slope of the temperature profile between the troposphere and the stratosphere have any affect on weather, distribution of pollutants, etc.?

Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

18

# How will temperature of an air parcel change with altitude?

To determine this, use the  
**1<sup>st</sup> Law of Thermodynamics:**

$$dQ = dU + dW$$

which we rewrite as:

$$dQ = C_p dT - V dP$$

$dQ$  = Heat added to air parcel

$C_p$  = specific heat

$dT$  = temperature change

$V$  = volume per unit mass

$dP$  = change in pressure

Assume an air parcel is adiabatic ( $dQ=0$ ),  $\therefore$  it does not mix with the air around it.

$$\frac{dT}{dP} = \frac{V}{C_p} \quad (1)$$

We also need to use the  
**hydrostatic equation:**

$$\frac{dP}{dZ} = -g\rho \quad (2)$$

Can derive this from first principles (anyone wishing to see the derivation, please contact Tim) but the main point is that this equation determines change in pressure as a function of height ( $Z$ ).

Combining eqns (1) and (2), we derive the change in temperature of an air parcel as a function of height ( $Z$ ), also known as the: **dry adiabatic lapse rate**

$$\frac{dT}{dZ} = -\frac{g}{C_p} = \Gamma$$

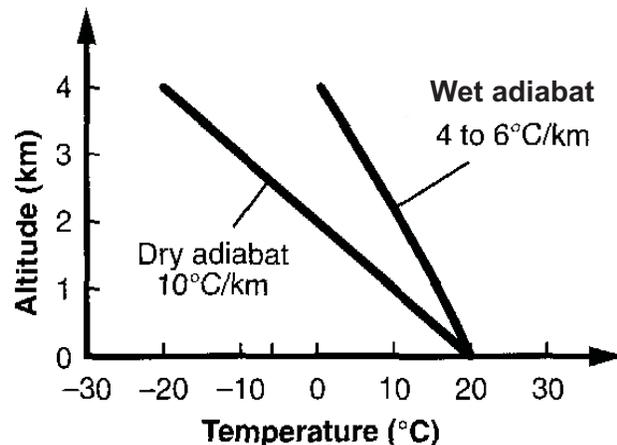
*"In this house, we obey the laws of thermodynamics."* - Homer Simpson

## Lapse Rate

**Dry adiabatic lapse rate:** describes change in temperature of air parcel as a function of altitude

$$\frac{dT}{dZ} = -\frac{g}{C_p} = \Gamma$$

If air is saturated, it follows a different lapse rate, the **wet adiabatic lapse rate**



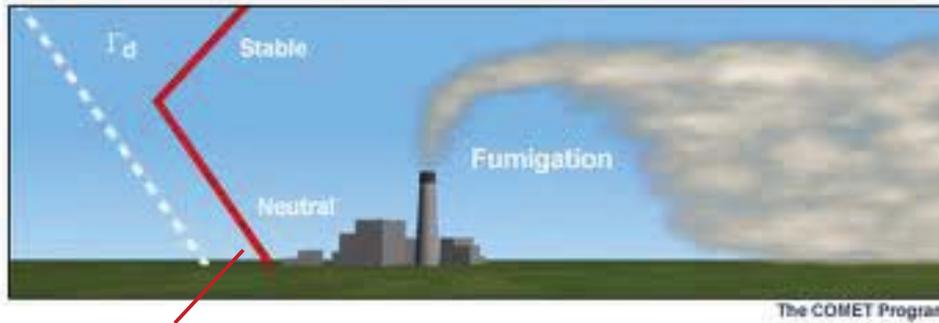
Actual rate of temperature change with elevation is the **ambient lapse rate**.

Different from adiabatic rate because of wind, sunlight, and water vapor.

Average global lapse rate is 6.5 °C/km.

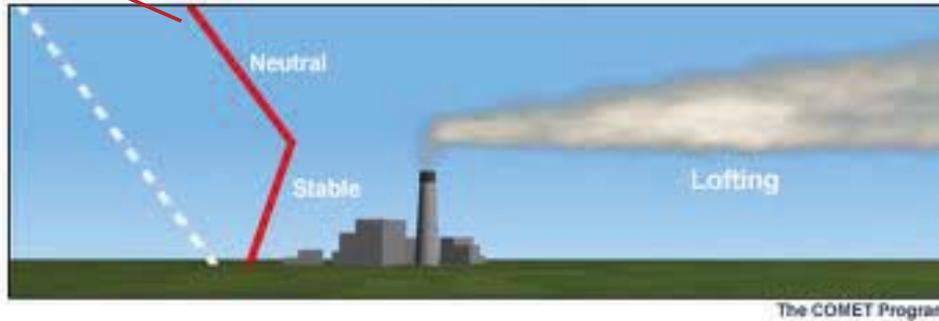
# Lofting and Fumigation

Fumigation Plume Type



Actual temperature profile

Lofting Plume Type



<http://www.comet.ucar.edu/>

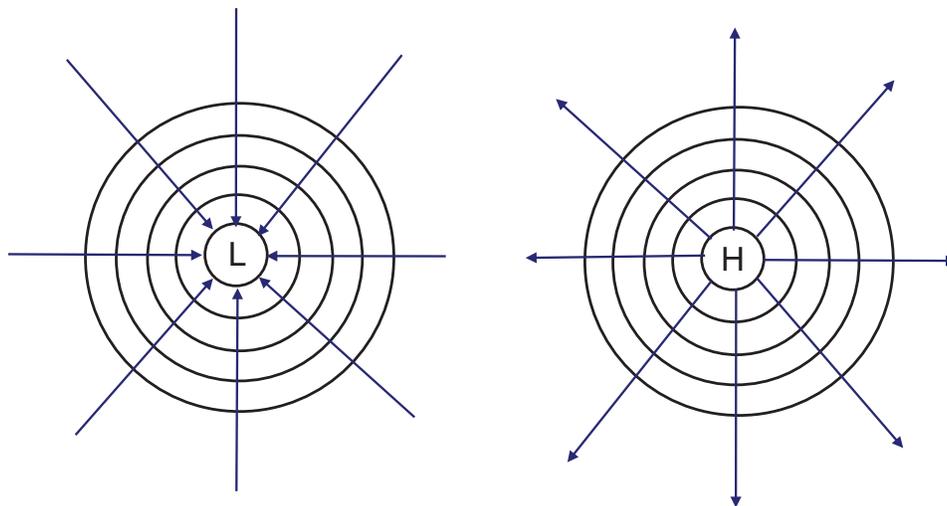
Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

21

# Coriolis Force

So far, we've reviewed temperature, pressure, and solar energy input in the atmosphere. There's one more piece of the puzzle that we need to be familiar with.



In general, wind moves from areas of high pressure to areas of low pressure. In the absence of external forces, wind will move in a straight line.

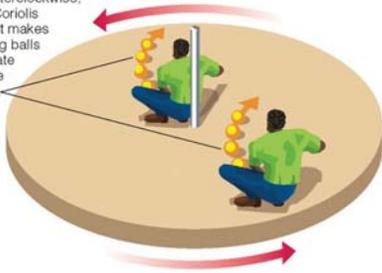
Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

22

# Coriolis Force

On a merry-go-round spinning counterclockwise, the Coriolis effect makes rolling balls deviate to the right.

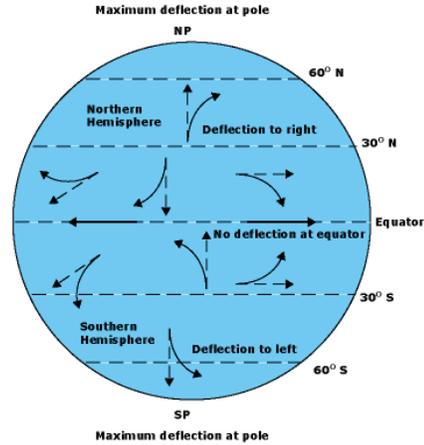


© 2005 Pearson Education, Inc., publishing as Addison Wesley

<http://lasp.colorado.edu/~bagenal/3720/CLASS15/15EVM-Dyn1.html>

Need to take into account the rotation of the Earth and the affect this will have on wind motion.

Earth's rotation will make it seem as if air is being deflected to the right (Northern Hemisphere).



<http://dcweather.blogspot.com/2005/12/sunday-to-enjoy.html>

Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

23

# Coriolis Force



Coriolis forces do not noticeably influence how water flows into a drain!

But, will affect large scale dynamics.

Horizontal Coriolis Force proportional to  $\sin(\text{latitude})$

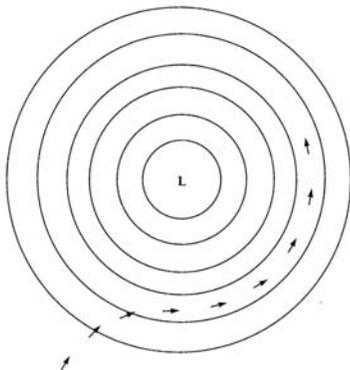


Figure 8.16 Track of an air parcel in the vicinity of a low pressure region in the Northern Hemisphere. The parcel is initially at rest but then adjusts to the pressure gradient force and the Coriolis force to achieve geostrophic balance.

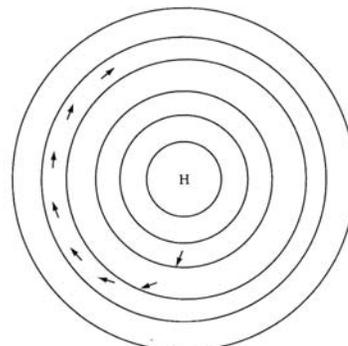


Figure 8.17 Same situation as in 8.16, except that the parcel is in the vicinity of a high pressure region in the Northern Hemisphere.

From "The Atmospheric Environment", M. B. McElroy

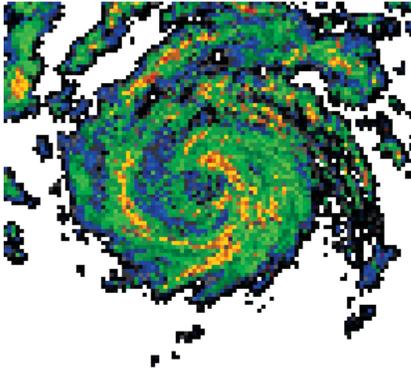
Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

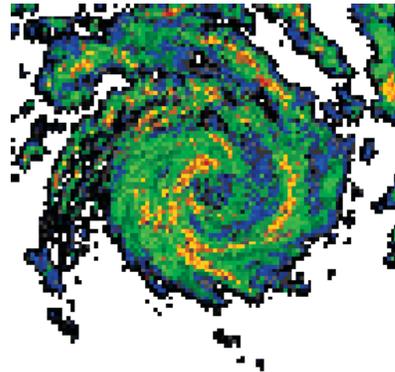
24

# Cyclonic Flow

## NH Weather System:



## SH Weather System:



**Cyclonic Flow:** when the wind swirls counter-clockwise in the NH or clockwise in the SH

**Hurricane:** Cyclonic flow that occurs in the N Atlantic Ocean, the NE Pacific Ocean east of the dateline, or the S Pacific Ocean.

**Typhoon:** The same type of storm occurring over the NW Pacific Ocean, west of the dateline

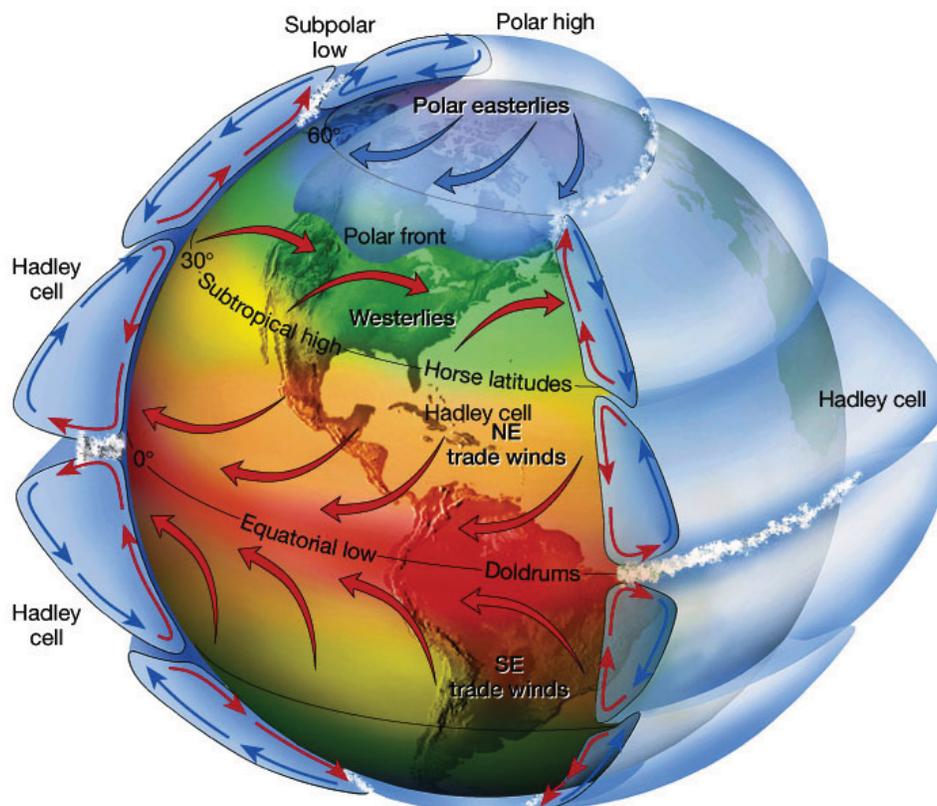
**Tropical Cyclone:** storm occurring over Australia and the Indian Ocean (winds rotate clockwise.)

Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

25

On a global scale, prevailing wind patterns can be better understood when Coriolis forces are considered.



<http://www.ux1.eiu.edu/~cfjps/1400/circulation.html>

Copyright © 2013 University of Maryland

This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty

26