Lecture 2: Atmospheric Thermodynamics

- Ideal Gas Law (Equation of State)
- Hydrostatic Balance
- Heat and Temperature
- Conduction, Convection, Radiation
- Latent Heating
- Adiabatic Process
- Lapse Rate and Stability

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The Ideal Gas Law

- An ***equation of state*** describes the relationship among pressure, temperature, and density of ***any material***.
- All gases are found to follow approximately the same equation of state, which is referred to as the ***"ideal gas law (equation)"***.
- Atmospheric gases, whether considered individually or as a mixture, obey the following ideal gas equation:

$$\boxed{P = \rho R T}$$

pressure *Density=m/V* *temperature (degree Kelvin)*
gas constant (its value depends on the gas considered)

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Gas Constant

- The ideal gas law can be applied to the combination of atmospheric gases or to individual gases.
- The value of gas constant for the particular gas under consideration depends on its molecular weight:

  $\mathbf{R_{gas} = R^* / M_{gas}}$

  where R* = universal gas constant = 8314.3 J deg^{-1} kg^{-1}

- The gas constant for dry atmospheric air is:

  $R_{air} = R^* / M_{air} = 8314.3/28.97 = 287$ J deg^{-1} kg^{-1}

  ($M_{air} \cong 0.80 * M_{N2} + 0.20 * M_{O2} = 0.80*28 + 0.2*32 = 28.8$)

- The gas constant for water vapor is:

  $R_{vapor} = R^* / M_{vapor} = 8314.3/18.016$

  $= 461$ J deg^{-1} kg^{-1}

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Applications of the Gas law

Question: Calculate the density of water vapor which exerts a pressure of 9 mb at 20°C.

Answer:

Use the ideal gas law: $\mathbf{P_v = \rho R_v T}$

and $P_v = 9$ mb $= 900$ Pa (a SI unit)

$R_v = R^* / M_v = 461$ J deg^{-1} kg^{-1}

$T = 273 + 20$ (°C) $= 293$ K.

So we know the density of water vapor is:

$\rho = P_v / (R_v T) = 900 / (461*293) = 6.67 \times 10^{-3}$ kg m^{-3}

(from *Atmospheric Sciences: An introductory Survey*)

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Virtual Temperature

- ❑ Moist air has a lower apparent molecular weight that dry air.
- ➔ The gas constant for 1 kg of moist air is larger than that for 1 kg of dry air.
- ➔ But the exact value of the gas constant of moist air would depend on the amount of water vapor contained in the air.
- ➔ It is inconvenient to calculate the gas constant for moist air.

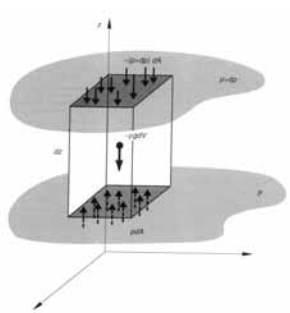
- ❑ It is more convenient to retain the gas constant of dry air and use a fictitious temperature in the ideal gas equation.
- ➔ This fictitious temperature is called “virtual temperature”.
- ➔ This is the temperature that dry air must have in order to has the same density as the moist air at the same pressure.
- ➔ Since moist air is less dense that dry air, the virtual temperature is always greater than the actual temperature.

How to Calculate Virtual Temperature?

$$\boxed{T_v = \frac{T}{1 - \left(\frac{e}{p}\right)(1-\varepsilon)}}$$

Where T: actual temperature
p: actual (total) pressure = $p_d + e$
p_d: partial pressure exerted by dry air
e: partial pressure exerted by water vapor
$\varepsilon = R_d/R_v = 0.622$

Hydrostatic Balance in the Vertical



(from *Climate System Modeling*)

❑ vertical pressure force = gravitational force

$$-(dP) \times (dA) = \rho \times (dz) \times (dA) \times g$$

$$dP = -\rho g dz$$

$$\boxed{dP/dz = -\rho g}$$

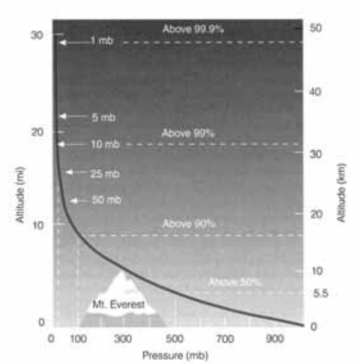
The hydrostatic balance !!

What Does Hydrostatic Balance Tell Us?

- ❑ The hydrostatic equation tells us how quickly air pressure drops wit height.

- ➔ The rate at which air pressure decreases with height ($\Delta P/\Delta z$) is equal to the air density (ρ) times the acceleration of gravity (g)

Hydrostatic Balance and Atmospheric Vertical Structure



- Since P= ρRT (the ideal gas law), the hydrostatic equation becomes:
  $dP = -P/RT \times g dz$
- ➔ $dP/P = -g/RT \times dz$
- ➔ $\boxed{P = P_s \exp(-gz/RT)}$
- ➔ $P = P_s \exp(-z/H)$

- The atmospheric pressure decreases exponentially with height

(from *Meteorology Today*)

The Scale Height of the Atmosphere

- One way to measure how soon the air runs out in the atmosphere is to calculate the scale height, which is about ***10 km***.
- Over this vertical distance, air pressure and density decrease by 37% of its surface values.
- If pressure at the surface is 1 atmosphere, then it is 0.37 atmospheres at a height of 10 km, 0.14 (0.37x0.37) at 20 km, 0.05 (0.37x0.37x0.37) at 30 km, and so on.
- Different atmospheric gases have different values of scale height.

A Mathematic Formula of Scale Height

gas constant

temperature

$$H = \frac{R^*T}{mg}$$

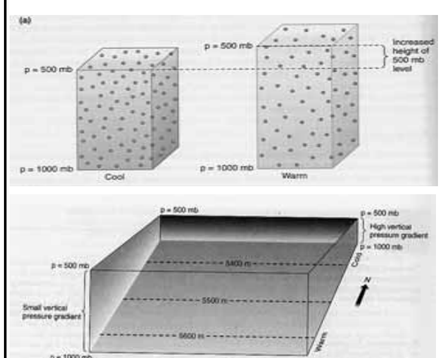
gravity

scale height

molecular weight of gas

- The heavier the gas molecules weight (m) ➔ the smaller the scale height for that particular gas
- The higher the temperature (T) ➔ the more energetic the air molecules ➔ the larger the scale height
- The larger the gravity (g) ➔ air molecules are closer to the surface ➔ the smaller the scale height
- H has a value of about 10km for the mixture of gases in the atmosphere, but H has different values for individual gases.

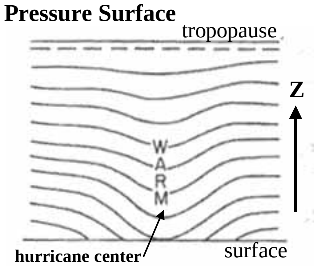
Temperature and Pressure



- Hydrostatic balance tells us that the pressure decrease with height is determined by the temperature inside the vertical column.
- Pressure decreases faster in the cold-air column and slower in the warm-air column.
- Pressure drops more rapidly with height at high latitudes and lowers the height of the pressure surface.

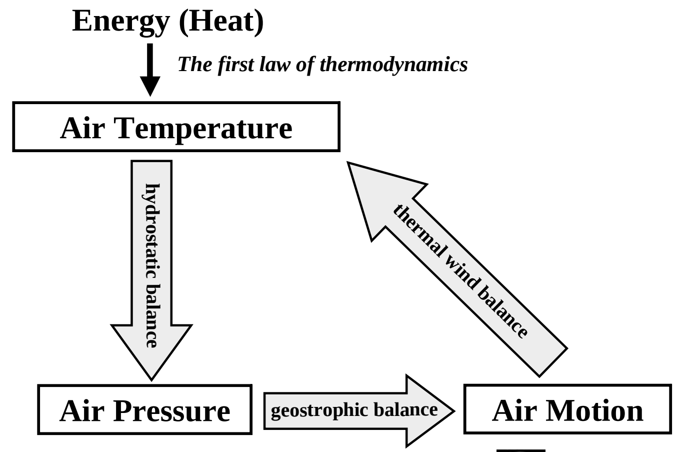
(from Understanding *Weather & Climate*)

Warm Core Hurricane

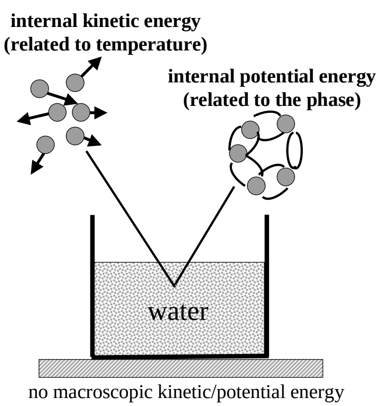


- ❑ The core of a hurricane is warmer than its surroundings.
- ❑ The intensity of the hurricane (as measured by the depression of pressure surface) must decrease with height.
- ❑ Thus, a warm core hurricane exhibits its greatest intensity near the ground and diminish with increasing height above ground.

(from *Understanding Weather & Climate and Atmospheric Sciences: An Intro. Survey*)



Heat and Energy



- ❑ Energy is the capacity to do work.
- ❑ Heat is one form of energy.
- ❑ Heat is one form of internal energy which is associated with the random, disordered motion of molecules and atoms.
- ❑ Internal kinetic/potential energy are different from the macroscopic kinetic/potential energy.

What Is Air Temperature?

- ❑ Air temperature is a measurement of the average internal kinetic energy of air molecules.
- ❑ Increase in internal kinetic energy in the form of molecular motions are manifested as increases in the temperature of the body.

The First Law of Thermodynamics

- This law states that (1) heat is a form of energy that (2) its conversion into other forms of energy is such that total energy is conserved.

- The change in the internal energy of a system is equal to the heat added to the system minus the work down by the system:

$$\boxed{\Delta U = Q - W}$$

change in internal energy (related to temperature) **Heat added to the system** **Work done by the system**

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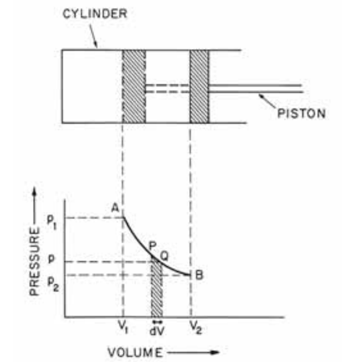
(from *Atmospheric Sciences: An Intro. Survey)*



- Therefore, when heat is added to a gas, there will be some combination of an expansion of the gas (i.e. the work) and an increase in its temperature (i.e. the increase in internal energy):

Heat added to the gas = work done by the gas + temp. increase of the gas

$$\Delta H = p\,\Delta\alpha + C_v\,\Delta T$$

volume change of the gas specific heat at constant volume

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Heat and Temperature

- Heat and temperature are both related to the internal kinetic energy of air molecules, and therefore can be related to each other in the following way:

$$\boxed{Q = c*m*\Delta T}$$

Heat added **Mass** **Temperature changed**

Specific heat = the amount of heat per unit mass required to raise the temperature by one degree Celsius

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Specific Heat

TABLE 2.1 The Specific Heat of a Substance is the Amount of Heat Required to Increase the Temperature of One Gram of the Substance 1° C

	Specific Heat	
Substance	*(cal/g/°C)*	*(J/kg/°C)*
Water	1.0	4186
Ice	0.50	2093
Air	0.24	1005
Sand	0.19	795

(from *Meteorology: Understanding the Atmosphere*)

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How to Change Air Temperature?

- **Add (remove) heat to (from) the air parcel (diabatic processes)**
  (1) Conduction: requires touching
  (2) Convection: Hot air rises
  (3) Advection: horizontal movement of air
  (4) Radiation: exchanging heat with space
  (5) Latent heating: changing the phase of water
- **Without adding (removing) heat to (from) the air parcel**
  (1) Adiabatic Process: Expanding and compressing air

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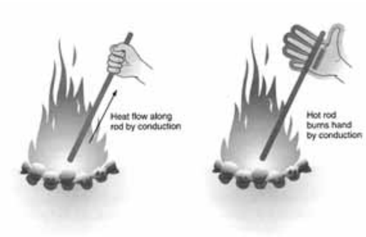
Conduction



(from *Meteorology: Understanding the Atmosphere*)

- Conduction is the process of heat transfer from molecule to molecule.
- This energy transfer process requires contact.
- Air is a poor conductor. (with low thermal conductivity)
- Conduction is not an efficient mechanisms to transfer heat in the atmosphere on large spatial scales.

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Convection

- Convection is heat transfer by mass motion of a fluid (such as air or water).
- Convection is produced when the heated fluid moves away from the heat source and carries energy with it.
- Convection is an efficient mechanism of heat transfer for the atmosphere in some regions (such as the tropics) but is an inefficient mechanism in other regions (such as the polar regions).

(from *Meteorology: Understanding the Atmosphere*)

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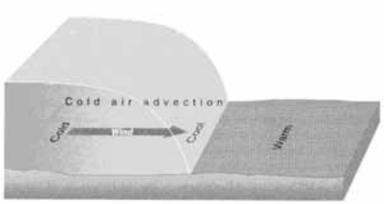
Advection



(from *Meteorology: Understanding the Atmosphere*)

- Advection is referred to the horizontal transport of heat in the atmosphere.
- Warm air advection occurs when warm air replaces cold air. Cold air advection is the other way around.
- This process is similar to the convection which relies on the mass motion to carry heat from one region to the other.
- Advection can be considered as one form of convection.

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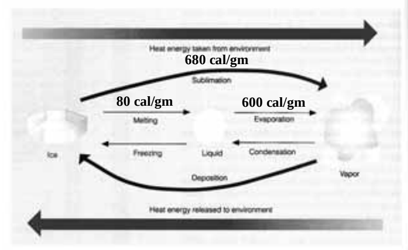
Radiation

- Radiation is heat transfer by the emission of electromagnetic waves which carry energy away from the emitting object.
- The solar energy moves through empty space from the Sun to the Earth and is the original energy source for Earth's weather and climate.

Latent Heating



(from *Meteorology: Understanding the Atmosphere*)

- Latent heat is the heat released or absorbed per unit mass when water changes phase.
- Latent heating is an efficient way of transferring energy globally and is an important energy source for Earth's weather and climate.

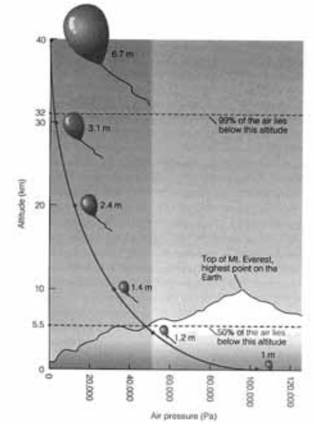
Latent Heat of Evaporation

- The latent heat of evaporation is a function of water temperature, ranging from 540 cal per gram of water at 100°C to 600 cal per gram at 0°C.
- It takes more energy to evaporate cold water than evaporate the same amount of warmer water.

Adiabatic Process

- If a material changes its state (pressure, volume, or temperature) without any heat being added to it or withdrawn from it, the change is said to be adiabatic.
- The adiabatic process often occurs when air rises or descends and is an important process in the atmosphere.

Air Parcel Expands As It Rises…



- ❑ Air pressure decreases with elevation.
- ❑ If a helium balloon 1 m in diameter is released at sea level, it expands as it floats upward because of the pressure decrease. The balloon would be 6.7 m in diameter as a height of 40 km.

(from *The Blue Planet*)

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What Happens to the Temperature?

- ❑ Air molecules in the parcel (or the balloon) have to use their kinetic energy to expand the parcel/balloon.
- ❑ Therefore, the molecules lost energy and slow down their motions

➔ The temperature of the air parcel (or balloon) decreases with elevation. The lost energy is used to increase the potential energy of air molecular.

- ❑ Similarly when the air parcel descends, the potential energy of air molecular is converted back to kinetic energy.

  ➔ Air temperature rises.

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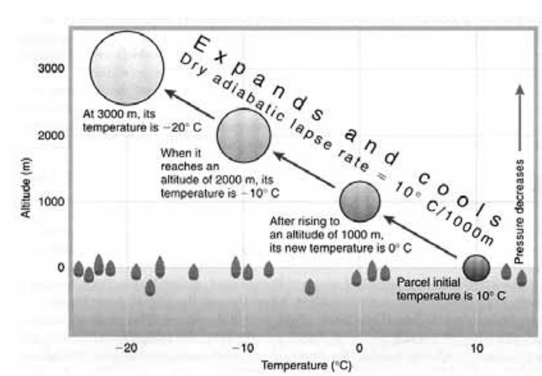
Dry Adiabatic Lapse Rate



(from *Meteorology: Understanding the Atmosphere*)

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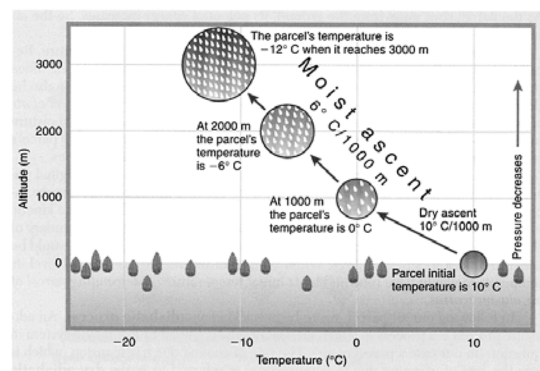
Moist Adiabatic Lapse Rate



(from *Meteorology: Understanding the Atmosphere*)

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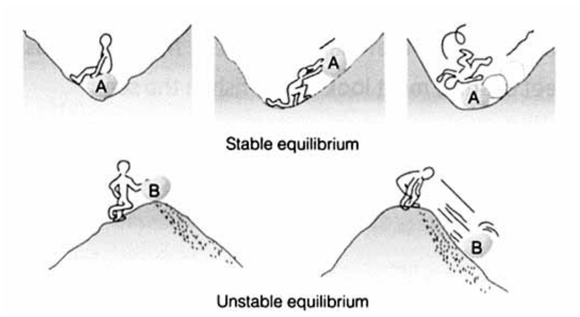
Concept of Stability



(from *Meteorology Today)*

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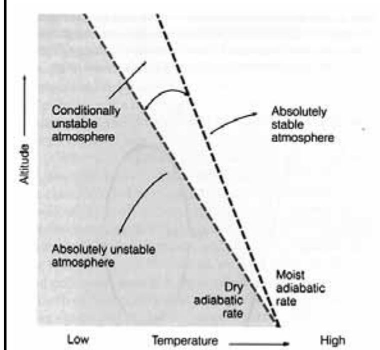
Static Stability



(from *Meteorology Today)*

- ❑ Static stability is referred as to air's susceptibility to uplift.
- ❑ The static stability of the atmosphere is related to the vertical structure of atmospheric temperature.
- ❑ To determine the static stability, we need to compare the lapse rate of the atmosphere (environmental lapse rate) and the dry (moist) adiabatic lapse rate of an dry (moist) air parcel.

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Environmental Lapse Rate

- ❑ The environmental lapse rate is referred to as the rate at which the air temperature surrounding us would be changed if we were to climb upward into the atmosphere.
- ❑ This rate varies from time to time and from place to place.

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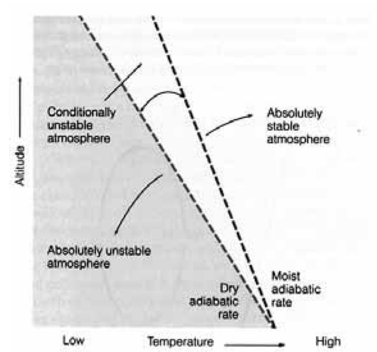
Static Stability of the Atmosphere



(from *Meteorology Today)*

Γe = environmental lapse rate
Γd = day adiabatic lapse rate
Γm = moist lapse rate

- ❑ Absolutely Stable
  $\Gamma e < \Gamma m$
- ❑ Absolutely Unstable
  $\Gamma e > \Gamma d$
- ❑ Conditionally Unstable
  $\Gamma m < \Gamma e < \Gamma d$

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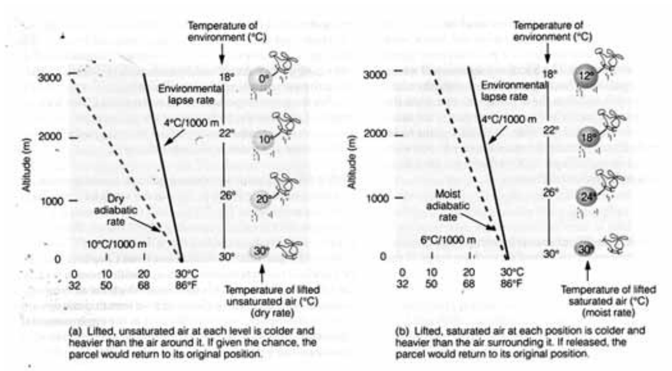
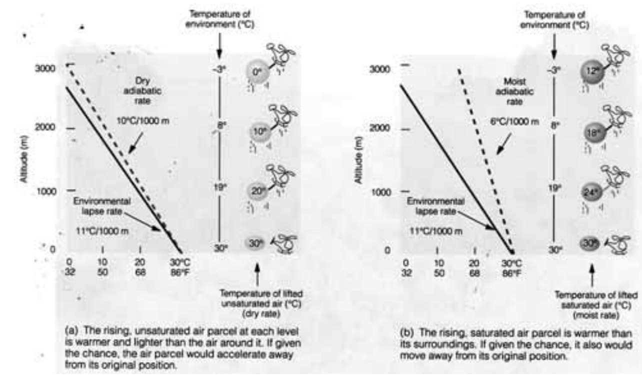
Absolutely Stable Atmosphere



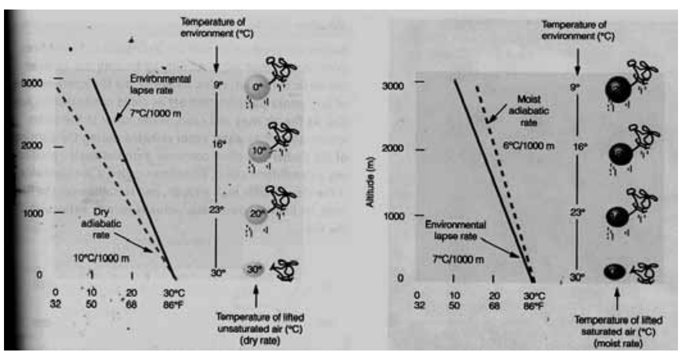
(from *Meteorology Today)*

Absolutely Unstable Atmosphere



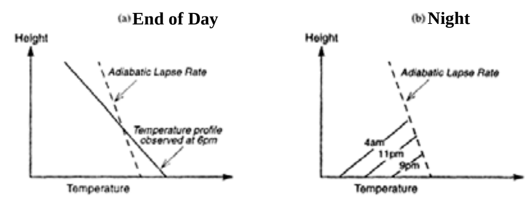
(from *Meteorology Today)*

Conditionally Unstable Atmosphere



(from *Meteorology Today)*

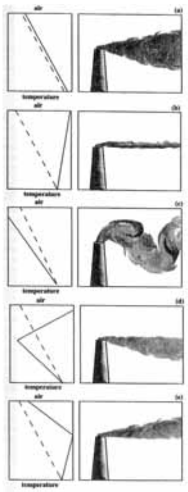
Day/Night Changes of Air Temperature



(from *Is the Temperature Rising?)*

- At the end of a sunny day, warm air near the surface, cold air aloft.
- In the early morning, cold air near the surface, warm air aloft.
- The later condition is called “inversion”, which inhibits convection and can cause sever pollution in the morning.

Stability and Air Pollution



Neutral Atmosphere (Coning)

Stable Atmosphere (Fanning)

Unstable Atmosphere (Looping)

Stable Aloft; Unstable Below (Fumigation)

Unstable Aloft; Stable Below (Lofting)

(from *Is the Temperature Rising?)*

Potential Temperature (θ)

- The potential temperature of an air parcel is defined as the the temperature the parcel would have if it were moved adiabatically from its existing pressure and temperature to a standard pressure P_0 (generally taken as 1000mb).

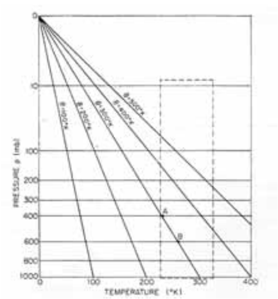
$$\boxed{\theta = T\left(\frac{P_0}{P}\right)^{\frac{R}{C_p}}}$$

θ= potential temperature
T = original temperature
P = original pressure
P_0 = standard pressure = 1000 mb
R = gas constant = R_d = 287 J deg^{-1} kg^{-1}
C_p = specific heat = 1004 J deg^{-1} kg^{-1}
R/C_p = 0.286

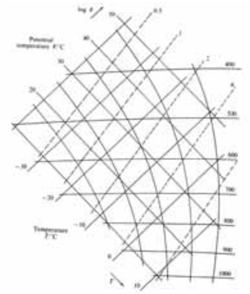
Importance of Potential Temperature

- In the atmosphere, air parcel often moves around adiabatically. Therefore, its potential temperature remains constant throughout the whole process.
- Potential temperature is a conservative quantity for adiabatic process in the atmosphere.
- Potential temperature is an extremely useful parameter in atmospheric thermodynamics.

Adiabatic Chart

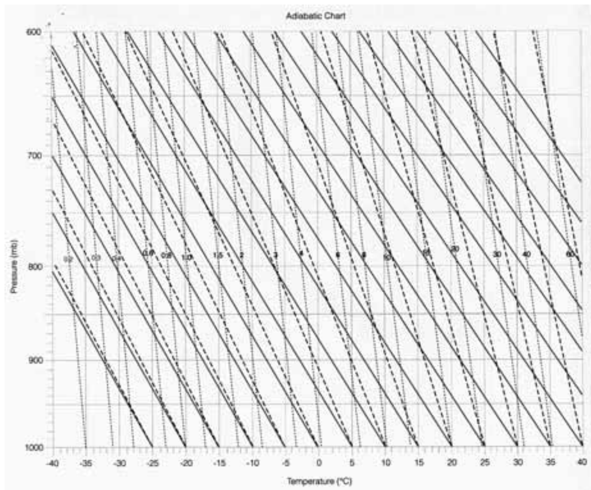


(from *Atmospheric Sciences: An Intro. Survey)*



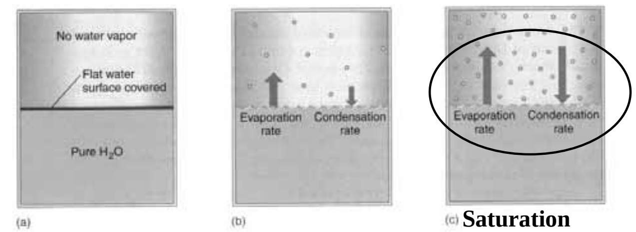
(from *The Physics of the Atmospheres)*

The expression of potential temperature can be modified into:
T = (constant * θ) P $^{0.286}$



(from *Meteorology Today)*

Water Vapor In the Air



(from *Understanding Weather & Climate*)

- **Evaporation:** the process whereby molecules break free of the liquid volume.
- **Condensation:** water vapor molecules randomly collide with the water surface and bond with adjacent molecules.

How Much Water Vapor Is Evaporated Into the Atmosphere Each Year?

- On average, 1 meter of water is evaporated from oceans to the atmosphere each year.
- The global averaged precipitation is also about 1 meter per year.

How Much Heat Is Brought Upward By Water Vapor?

- Earth’s surface lost heat to the atmosphere when water is evaporated from oceans to the atmosphere.
- The evaporation of the 1m of water causes Earth’s surface to lost 83 watts per square meter, almost half of the sunlight that reaches the surface.
- Without the evaporation process, the global surface temperature would be 67°C instead of the actual 15°C.

Measuring Air Moisture

- by mass

$$\text{Mixing ratio} = \frac{\text{mass of water vapor}}{\text{mass of dry air}}.$$

$$\text{Specific humidity} = \frac{\text{mass of water vapor}}{\text{total mass of air}}$$

in unit of g/kg

$$\text{Absolute humidity} = \frac{\text{mass of water vapor}}{\text{volume of air}}$$

in unit of g/m^3

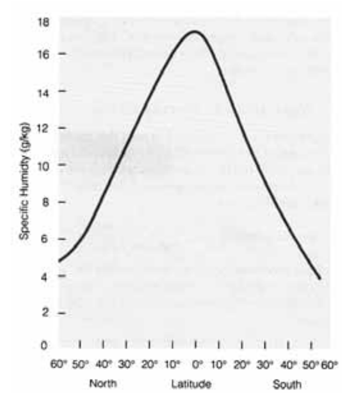
- by vapor pressure

$$\text{RH} = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} \times 100 \text{ percent.}$$

$$\text{RH} = \frac{\text{actual mixing ratio}}{\text{saturation mixing ratio}} \times 100 \text{ percent,}$$

in unit of %

Observed Specific Humidity



(from *Meteorology Today*)

Specific .vs. Relative Humidity

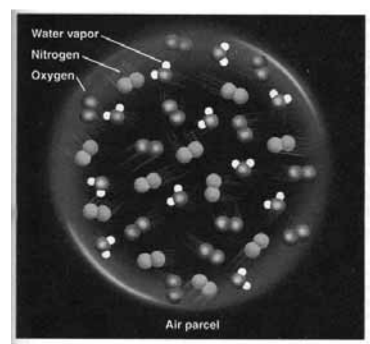
specific humidity 6 gm/kg

saturated specific humidity 10 gm/kg → Relative humidity 6/10 x 100%=60 %

saturated specific humidity 20 gm/kg → Relative humidity 6/20 x 100%=30 %

- Specific Humidity: How many grams of water vapor in one kilogram of air (in unit of gm/kg).
- Relative Humidity: The percentage of current moisture content to the saturated moisture amount (in unit of %).
- Clouds form when the relative humidity reaches 100%.

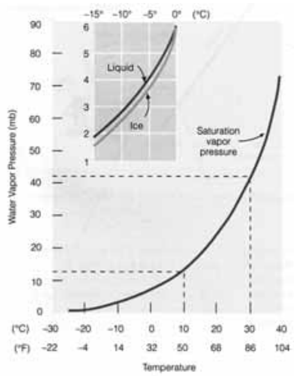
Vapor Pressure



(from *Meteorology Today*)

- The air's content of moisture can be measured by the pressure exerted by the water vapor in the air.
- The total pressure inside an air parcel is equal to the sum of pressures of the individual gases.
- In the left figure, the total pressure of the air parcel is equal to sum of vapor pressure plus the pressures exerted by Nitrogen and Oxygen.
- High vapor pressure indicates large numbers of water vapor molecules.
- Unit of vapor pressure is usually in mb.

Saturation Vapor Pressure



- Saturation vapor pressure describes how much water vapor is needed to make the air saturated at any given temperature.
- Saturation vapor pressure depends primarily on the air temperature in the following way:

$$\boxed{\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}}$$

The Clausius-Clapeyron Equation

➔ $$\boxed{e_s \cong 6.11 \bullet \exp\left\{\frac{L}{R_v}\left(\frac{1}{273} - \frac{1}{T}\right)\right\}}$$

- Saturation pressure increases exponentially with air temperature.

L: latent heat of evaporation; α: specific volume of vapor and liquid

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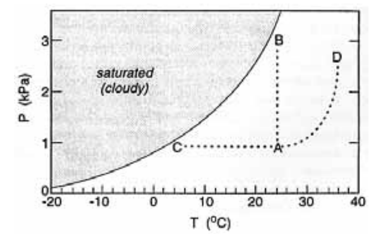
How to Saturate the Air?



(from "*IS The Temperature Rising*")

- Two ways:

(1) Increase (inject more) water vapor to the air (A→ B).

(2) Reduce the temperature of the air (A → C).

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"Runway" Greenhouse Effect

- If a planet has a very high temperature that the air can never reach a saturation point

➔Water vapor can be added into the atmosphere.

➔More water vapor traps more heat (a greenhouse effect)

➔The planet's temperature increases furthermore

➔ Ever more water evaporated into the atmosphere

➔ More greenhouse effect

➔ More warming

➔ More water vapor

➔ …..

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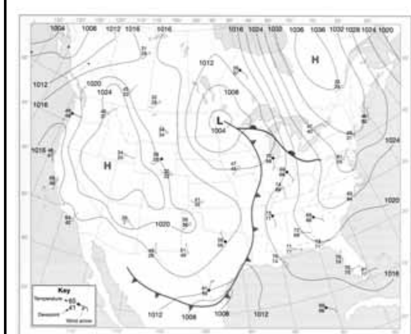
Dew Point Temperature



(from *The Atmosphere*)

- Dew point temperature is another measurement of air moisture.
- Dew point temperature is defined as the temperature to which moist air must be cool to become saturated without changing the pressure.
- The close the dew point temperature is to the air temperature, the closer the air is to saturation.

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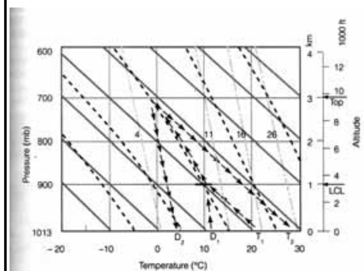
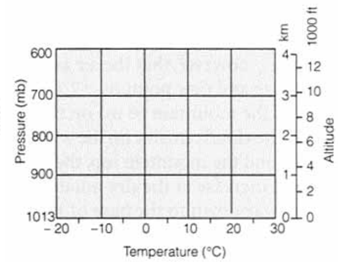
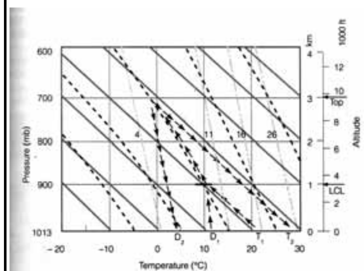
Adiabatic Chart: *P* and *T*

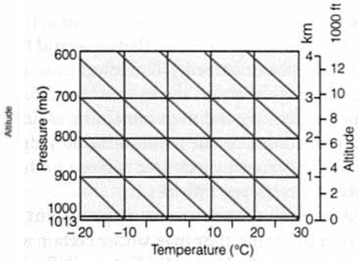




(from *Meteorology Today)*

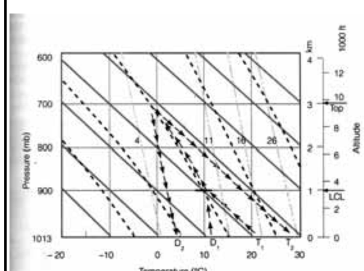
Adiabatic Chart: *Dry Adiabatic* / θ

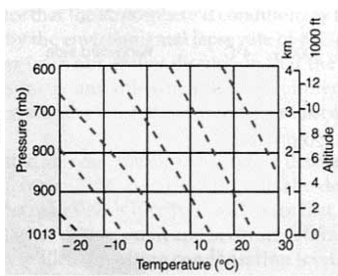




(from *Meteorology Today)*

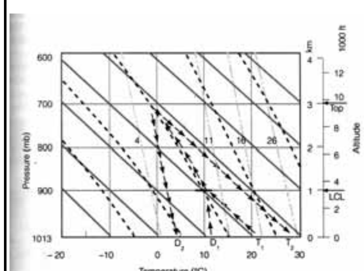
Adiabatic Chart: *Moist Adiabatic*

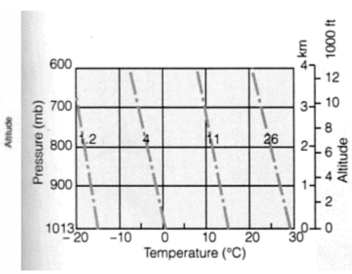




(from *Meteorology Today)*

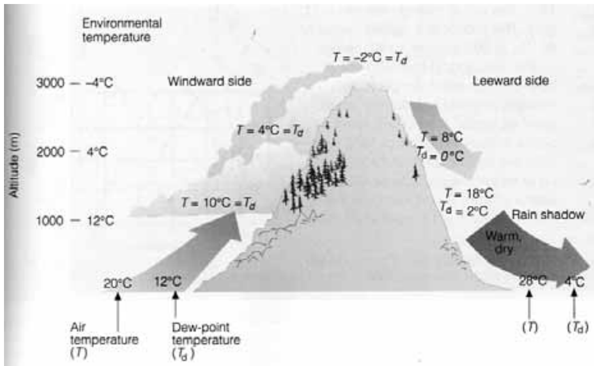
Adiabatic Chart: *Mixing Ratio*





(from *Meteorology Today)*

An Example



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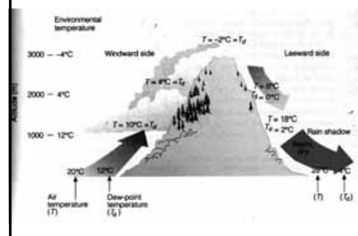
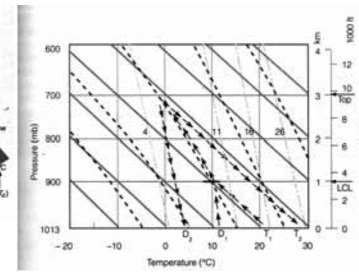
Applications of Adiabatic Chart



(from *Meteorology Today*)



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