MTO 412E Physics of Cloud and Precipitation

Atmospheric pressure, temperature, moisture and water

Units for Thermodynamic Quantities

- Heat (Q) and Work (Q) – Units of Energy
- Properties: p, V, T, E (KE, PE, U, H), S
- SI and USCS Units
  - Primary Dimensions: M, L, t, T, I, N, (F*)
  - Secondary Dimensions (Derived Quantities): F, E, W, Q, p, Power
- Units for the Thermodynamic Quantities

Two Important Intensive Thermodynamic Properties

- **Pressure = the force per unit area exerted by a fluid**
- **Temperature = a measurement of the internal energy of the fluid**

Atmosphere Structure

Fun facts

- Standard atmosphere
  - Very long term average for mid-latitudes
  - Average surface pressure **1013 mb**
  - Average surface temperature 15 ^oC (59 ^oF)
- 1/2 of the mass of the atmosphere (500 mb) below 6 km (3.7 miles)

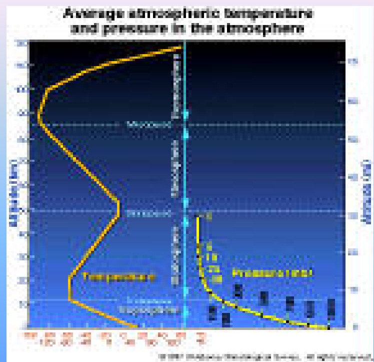
Atmosphere Structure

Fun facts

- Lapse rate (decrease in temperature in the vertical)

Troposphere:

+15 ^oC (atsfc) to ~ -50 ^oC (at 10 km) $\longrightarrow$ -6.5 ^oC / km



Atmospheric Pressure

Notes on Pressure

- Absolute Pressure (p)
- Atmospheric Pressure (p_{atm})
- Gage Pressure (p_{gage})
- Vacuum = Negative gage pressure
- $p = p_{atm} + p_{gage}$

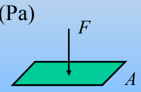
Another Question?

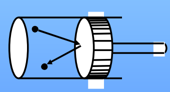
- What is the definition of "pressure"?
  - Pressure is defined as the force exerted on a unit area (F/A), where:
    F = mass x acceleration due to gravity
  - SI Unit: Pa (kPa)
  - Other Units: mmHg, atm
    - 760 mmHg = 1.01325 x 10^5 Pa = 1 atm

Pressure

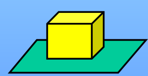
- **Pressure** - force per unit area
- It has units of N/m^2 or Pascals (Pa)

$$P = \frac{F}{A}$$





Impact

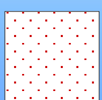


Weight

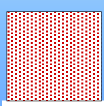
Density

- **Density** - mass per unit volume
- It has units of g/cm^3

$$\rho = \frac{M}{V}$$

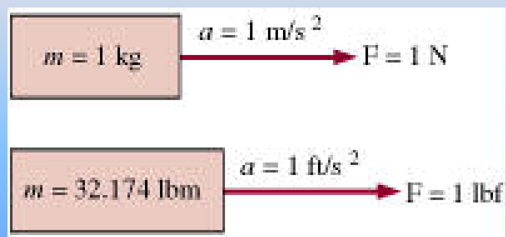


Low density



High density

Units of Force



Units of Pressure

- Force per unit area is called *pressure*, and its unit is the *Pascal*.
- 1 Pa = N/m^2
- 1 psi = Lbf/in^2

Pressure

- The pressure of a gas is equivalent to thinking about the concentration of a solute in a solution.

So....,

Air is 20% oxygen and 79% Nitrogen + other stuff. If the total pressure is one Atmosphere, then the "partial pressure" of oxygen is...

Dalton's Law of Partial Pressure.

The total pressure of a gaseous system is the sum of the pressures of each gas in the system.

$$P_T = P_1 + P_2 + P_3 + P_4 + \ldots + Pn$$

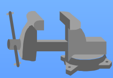
Example:

$$P_{N2} + P_{O2} + P_{(other)} = 1 \text{ atm.}$$

Pressure

- The SI Unit of Pressure is the Pascal (Pa)
  - Pressure = Force/Area
    - →Force = mass X acceleration... The SI unit of force is the *newton* (N). N = 1kg x m/s^2.
    - →The SI unit of area is the square meter (m^2).

∴ Pa = N/m^2 = kg/s^{2}m.

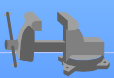


Practical Pressure

- The pascal (Pa) is not in common use.
- The unit of atmosphere (atm) is what is most commonly used. At 0°C and at sea level, the pressure of the earth's atmosphere is defined as "an atmosphere".
- STP = Standard Temperature (0°C) and Pressure (1atm)

Conversions

- 1 atm= 760 torr = 1.101325 X 10^2 kPa



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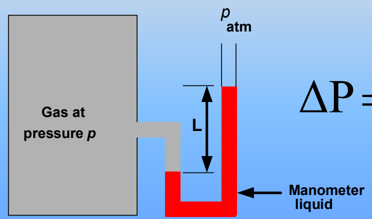
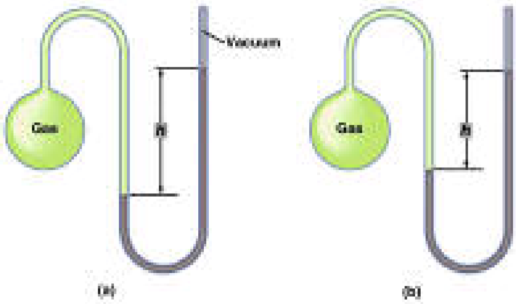
Pressure Measurement

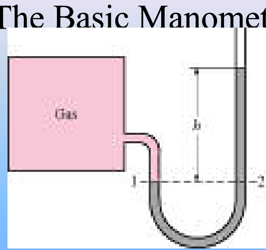


$$\Delta P = \rho g L$$

Manometers Used to Measure Gas Pressure

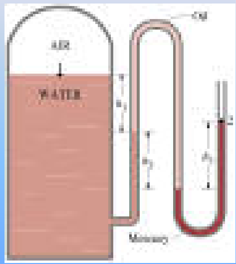


The Basic Manometer



$$\Delta P = \rho g h \qquad (kPa)$$

Schematic for Example 1.8



$P_{air} = f(P_{atm}, h_1, h_2, h_3, \rho_{water}, \rho_{oil}, \rho_{Hg})$

Concept of Atmospheric Pressure

- **We are surrounded by atmospheric gas which exerts a constant force on us due to its molecular motion**
- **At sea level,**

  P_{atm} = 101.325 kPa = 14.696 psi

Atmospheric Pressure

- P (atmospheric pressure): measured by the force of gravity due to the pressure of the atmosphere, divided by total area of the earth's surface

$$P^o = \frac{M_{atm}\, g}{4 r^2 \pi}$$

- P (sea level) = 101 325 Pa, M_{atm}=mass in kg of atmosphere, g=acceleration due to gravity=9.81ms^{-1}, r=radius of the earth=6.37x10^{6}m

Atmospheric Pressure

- **Pressure** = total weight of air above
- Air is compressible, so gravity concentrates most air molecules near the surface
- Atm pressure decreases with height ⟶

  rising air cools, sinking air warms
- Greatest pressure variation in vertical, but ***smaller horizontal variations produce winds and weather systems***

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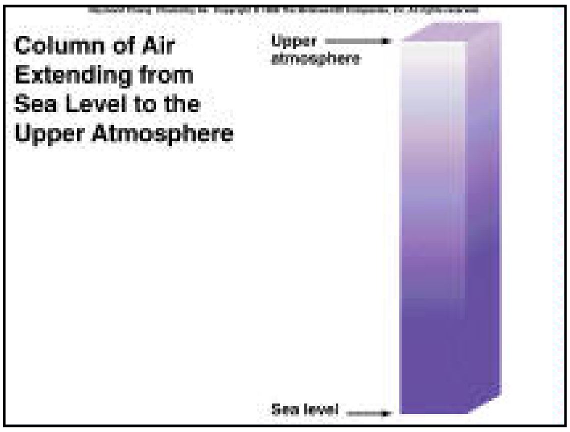
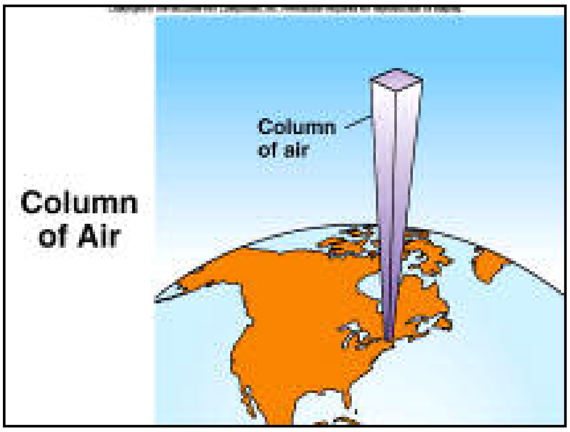
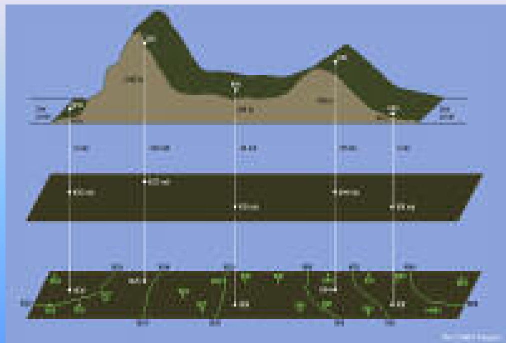
Atmospheric Pressure

- If all the known quantities are substituted in the equation it is possible to calculate the total mass of the atmosphere
- $M_{atm} = 5.27 \times 10^{18}$kg
- Useful quantity, referred to often

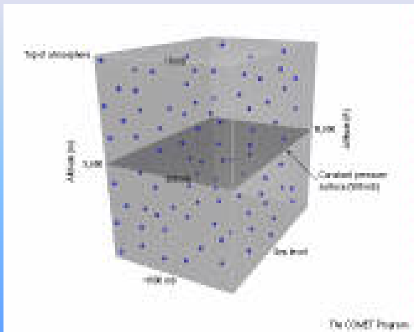




Pressure and terrain



Pressure and volume



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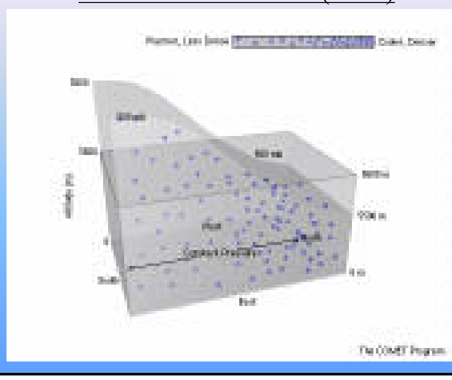
Pressure and volume (cont.)



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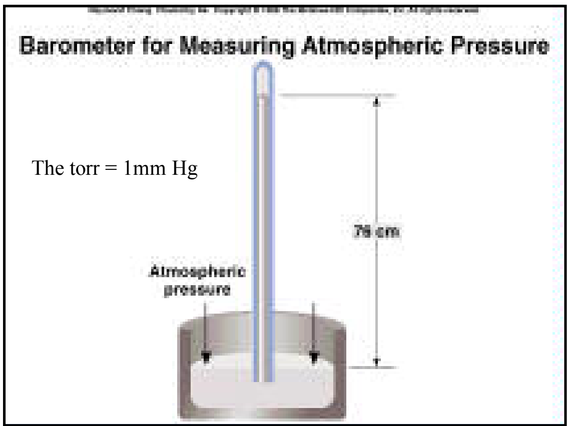
Measuring Air Pressure

- How do we measure air (gas) pressure?
- When using a manometer, we need to look at the difference in the levels of the Hg in the two arms
  - If the level of Hg in arm next to container is **lower**, the pressure inside is greater than atmospheric
  - If the level of Hg in arm next to container is **higher**, the pressure inside is less than atmospheric



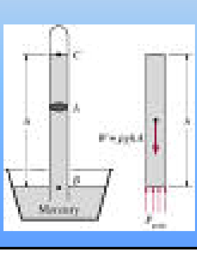
The torr = 1mm Hg

Measurement of Atmospheric Pressure

P_{atm} = ρgh (kPa)

At sea level,

P_{atm} = 101.325 kPa = 14.696 psi = 760 mm Hg (0° C)



Air Temperature

Thermodynamics

SOME DEFINITIONS:

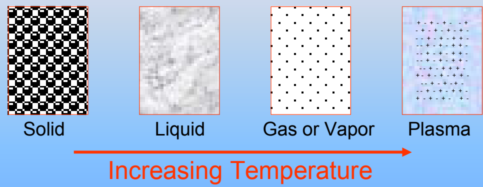
- THERMO – related to heat
- DYNAMICS – the study of motion
- SYSTEM – an object or set of objects
- ENVIRONMENT – the rest of the universe
- MICROSCOPIC – at an atomic or molecular level
- MACROSCOPIC – at a level detectable by our senses

THERMODYNAMICS

- is the study of the relationship between **heat** and **motion**.
- is a **macroscopic** description of the properties of a system using **state variables** (e.g. volume, temperature, pressure)

Atoms are in constant motion, which increases with **temperature**.

The Phases of Matter



Solids and **liquids** composed of atoms joined together at distances of about 10^{-10} m by attractive electrical forces. In **gases**, **vapors** and **plasmas**, the atoms, molecules or ions are in random motion.

Temperature

Temperature
- is a measure of how **hot** or **cold** an object is.
- is measured by a **thermometer**.

Thermometers are based on physical properties of objects that change with temperature, for example:
- volume of a liquid
- length of a solid
- pressure of a gas
- electrical resistance of a solid
- electrical potential difference between two solids.

Questions

- Is it possible for two objects to be in thermal equilibrium if they are not touching each other?
- Can objects that have different temperatures be in thermal equilibrium with each other?

Thermal Expansion

Most materials expand when heated:
- The average distance between atoms increases as the temperature is raised.
- The increase is proportional to the change in temperature (over a small range).

Consider an object of length L_i at temperature T_i
- If the object is heated or cooled to temperature T_f

$L_f - L_i = \alpha L_i (T_f - T_i)$ or $\Delta L = \alpha L_i \Delta T$

α = coefficient of linear expansion [°C^{-1}]

(α is a property of the material)

Thermal Expansion of Solids and Liquids

Material	α (°C^{-1})
Glass	9 x 10^{-6}
Concrete	12 x 10^{-6}
Copper	17 x 10^{-6}
Lead	29 x 10^{-6}
Mercury	1.8x 10^{-4}
Gasoline	3.2 x 10^{-4}

For the same temperature change, the thermal expansion of liquids is much greater than that of solids (> 10 times).

Area Expansion:

$\Delta A = 2\alpha A_i \Delta T$

Volume Expansion

$\Delta V = 3\alpha V_i \Delta T$

Thermal Stress

- Heat can stress materials if no allowance is made for thermal expansion:

$$\Delta L = \frac{1}{E}\frac{F}{A}L_0$$

E = Young's Modulus

$$\Delta L = \alpha L_0 \Delta T$$

Thermal Expansion

$$\frac{1}{E}\frac{F}{A}L_0 = \alpha L_0 \Delta T$$

$$\frac{F}{A} = \alpha E \Delta T$$

Thermal Stress

Equilibrium

- A system is in equilibrium if its properties are not changing at any given location in the system. This is also known as *thermodynamic equilibrium* or *total equilibrium*.
- Equilibrium implies balance – no unbalanced potentials (driving forces) in the system.

Four types of thermodynamic equilibrium:

- *Thermal equilibrium* – temperature does not change with time.
- *Mechanical equilibrium* – Pressure does not change with time.
- *Phase equilibrium* – Mass of each phase is unchanging with time.
- *Chemical equilibrium* – molecular structure does not change with time.

Forms of Energy

- Energy is usually symbolized by E, representing total energy

$$e = \frac{E}{m}$$

- e is energy per unit mass

Forms of Energy

- Macroscopic forms – possessed with respect to some outside reference frame.
  - Kinetic energy,

$$KE = \frac{1}{2} mV^2 \quad \text{or} \quad ke = \frac{1}{2} V^2$$

  - Potential energy,

$$PE = mgz \text{ or } pe = gz$$

Forms of energy

- Microscopic forms are called internal energy (internal to the molecule) and represent the energy a molecule can have as it translates, rotates, and vibrates. There are other contributors – nuclear spin, for example – as well.
- We will not concern ourselves with the details, but will use the symbols U and u.

Energy

- Now, we have

$$E = U + KE + PE$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

- For stationary, closed systems, ΔKE and ΔPE are 0.
- Therefore, $\Delta E = \Delta U$

Energy

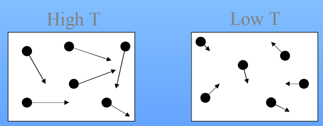
- Sensible energy – the portion of the internal energy associated with all forms of kinetic energy of the molecules.
- Latent energy – refers to internal energy associated with binding forces between molecules. Phase changes, such as vaporizing (boiling) water are latent energy changes.

Thermal Equilibrium

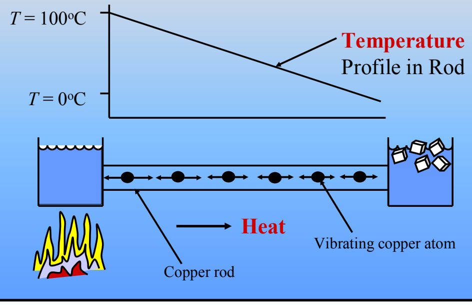
- Occurs when two bodies are at the same temperature T and no heat transfer can occur.

Temperature

- Rapidly moving molecules have a high temperature
- Slowly moving molecules have a low temperature



Example

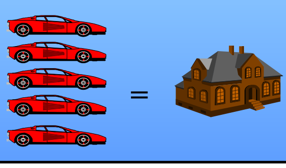


Heat

- **Heat** is the energy flow resulting from a temperature *difference*.
- NOTE: HEAT AND TEMPERATURE ARE **NOT** THE SAME!

Energy

- **Energy** is the capacity to do work, but work is a form of energy...
- It is easier to think of energy as a scientific and engineering “unit of exchange”, much like money is a unit of exchange.
- Example
  - 1 car = $20k
  - 1 house = $100k
  - 5 cars = 1 house



Question

You wake up at 6:00 AM on a winter morning, and go to the kitchen to make coffee. The air temperature is the same in all the rooms of your home. Which has a higher temperature, the carpet in your bedroom or the tiles on the kitchen floor?

1. Tiles
2. Carpet
3. They are at the *same* temperature.

Why do they *feel* different? Several reasons; one is that your feet are not good thermometers.

Measuring Temperature

Most objects change in some way as they get hotter or colder. Experimentally, some of the properties that change are

1. Volume of liquid.
2. Length of a solid.
3. Pressure of a gas at constant volume.
4. Volume of a gas at constant pressure.

Measurements of temperature are based on these changing physical properties.

Example: Liquid Thermometers

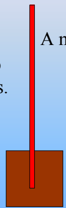
Alcohol thermometer

Mercury thermometer

The liquid expands when heated and flows up the capillary.

But before we can measure temperature, we have to have some idea of what it *is*.

What *is* temperature?



A mercury thermometer

The mercury rises up the tube as it expands. This is *movement*.

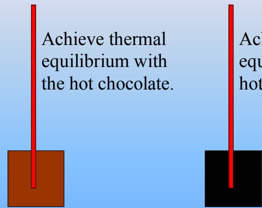
The mercury is gaining (internal) energy from the hot chocolate.

An object (say, a cup of hot chocolate)

This *transfer* of energy is what we call ***heat.***

When the transfer stops, the objects are in ***thermal equilibrium.***

What *is* temperature?

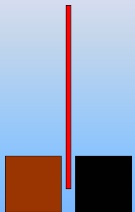


Achieve thermal equilibrium with the hot chocolate.

Achieve thermal equilibrium with hot coffee.

If the the mercury is at the *same height* in both cases → ***Zeroth Law of Thermodynamics*** The hot chocolate and the coffee are in ***thermal equilibrium.***

What *is* temperature?



Qualitatively: the hot chocolate, coffee, and thermometer are all in thermal equilibrium.

Quantitatively: the hot chocolate, coffee, and thermometer are all at the same ***temperature*** (defined, sort of).

The *value* of the temperature can be expressed as the height of the mercury in the column.

Putting a Number on Temperature

Alcohol thermometer

Mercury thermometer

The liquid expands when heated and flows up the capillary. The temperature is the reading on the scale.

We must pick the zero of temperature (recall picking the origin in mechanics problems).
Common choice: height of the mercury when in thermal equilibrium with ice-water (at atmospheric pressure). Call this temperature 0ºC.

Putting a Number on Temperature

Alcohol thermometer

Mercury thermometer

The liquid expands when heated and flows up the capillary. The temperature is the reading on the scale.

We must pick the *unit* of temperature as well (recall picking the unit of distance in mechanics problems). Common procedure: When in thermal equilibrium with boiling water (at 1 atm), the height is marked as 100ºC. The unit is now 1/100th of the distance between the marks.

Putting a Number on Temperature

Alcohol thermometer

Mercury thermometer

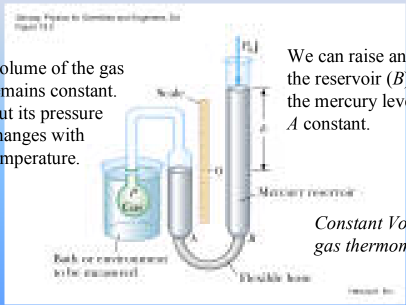
The liquid expands when heated and flows up the capillary. The temperature is the reading on the scale.

Problems: 1. Often agree only at the calibration points (0ºC and 100 ºC) since mercury and alcohol don't have the same thermal expansion properties.

2. Capillaries are not created equal. So two thermometers *with the same* liquid may disagree.

Building a Better Thermometer

Volume of the gas remains constant. But its pressure changes with temperature.



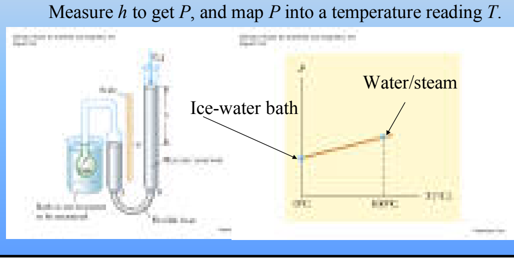
We can raise and lower the reservoir (*B*) to keep the mercury level in *A* constant.

Constant Volume gas thermometer.

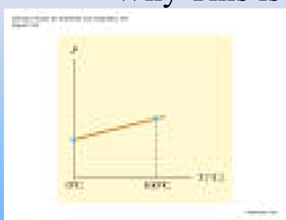
Using the Thermometer

$$P = P_{atm} + \rho g h$$

Measure *h* to get *P*, and map *P* into a temperature reading *T*.



Why This is So Cool



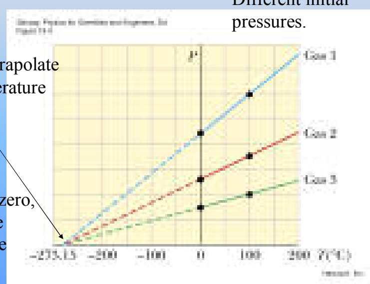
We get (nearly) the same curve regardless of the kind of gas used in the constant-volume gas thermometer, *IF* the pressure is low and we are not close to the temperature where the gas liquefies.

A Fundamental "Zero" for Temperature

Different initial pressures.

All the curves extrapolate to the same temperature for zero pressure- ***absolute zero.***

A new scale- zero at absolute zero, units same as the Celsius scale- the ***absolute scale.***



Temperature Scales

- Celsius
  - Zero defined by an ice-water bath at 1 atm.
  - Unit defined by water-steam (100ºC) at 1 atm.
- Kelvin (absolute)
  - Zero defined by absolute zero, but we cannot reach that temperature experimentally
  - 273.16 K defined by the *triple-point* of water (0.01ºC at 4.58 mm of mercury)
  - Unit is the same as the Celsius scale
- Fahrenheit
  - Zero and unit based on salt-water (?)

Converting Between the Scales

From Celsius to Kelvin:

$$T_C = T - 273.15$$

From Fahrenheit to Celsius:

$$T_F = \frac{9}{5}T_F + 32°\mathrm{F}$$

ConcepTest

*

Three objects are at the same temperature. Each object has its temperature increased. Object 1 increases by 10 K, Object 2 increases by 10°C, and Object 3 increases by 10°F.
The correct ordering of the final temperatures is

1. T1 = T2 = T3.
2. T1 = T2 > T3.
3. T1 = T2 < T3.
4. T1 > T2 = T3.
5. T1 < T2 = T3.
6. T1 > T2 > T3.
7. T1 < T 2 < T3.

Answer: 2. Degrees Kelvin and degrees Celsius are the same size so T1 = T2. Degrees Fahrenheit are smaller than degrees Cenlsius, so T3 < T1.

Zeroth Law of Thermodynamics

The zeroth law of thermodynamics states that two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact. Or,

- If two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other.

Zero'th Law of Thermodynamics

Our experience tells us that objects placed in contact will eventually reach the same temperature. We say that they are then in thermal equilibrium. This is the basis for

__The Zero'th Law of Thermodynamics:__

If two objects A and B are in thermal equilibrium with a third object C, then A and B are in thermal equilibrium with each other.

Objects or systems in __thermal equilibrium__ have the __same temperature__. This is the physical basis for the **definition of temperature.**

Common Temperature Scales

__Fahrenheit__:

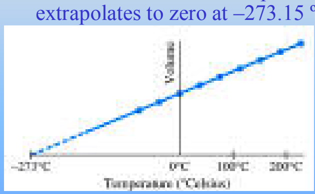
- Based on the ability of farm animals to survive without attention (0 ° F is the coldest and 100 ° F is the hottest).

__Celsius or Centigrade__:

- Based on the physical properties of water on the earth's surface at sea level (0 ° C is the freezing point and 100 ° C is the boiling point).
- T(° C) = (5/9)[T(° F) – 32]
  T (° F) = (9/5)T(° C) + 32

Absolute (Kelvin) Temperature Scale

The volume occupied by any gas at constant pressure is a linear function of temperature, which **always** extrapolates to zero at –273.15 ºC.



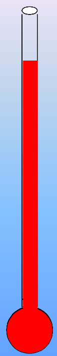
This is called **Charles's Law** and is the basis for the absolute or Kelvin temperature scale:

T(K) = T(ºC) + 273.15

Absolute or Kelvin Temperature Scale

- The absolute or Kelvin scale is the true physical temperature scale.
- T = -273.15 ºC = 0 K is the lowest temperature that can be defined for any physical system.
- Absolute zero of temperature (0 K) is a theoretical limit that can never be reached in a physical system.
  - *Experiments on Bose-Einstein Condensation in gases have reached the nano-Kelvin (10^{-9} K) range (1998, 2001 Nobel Prizes in physics)!*
- The degree steps in the Celsius and Kelvin scales are chosen to be the same: ΔT(ºC) = ΔT(K).

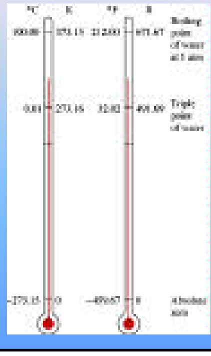
We Need to Work With Temperatures



	ºC	ºF	K	R
Boiling point	100	212	373.15	671.67
Triple point @ 0.006 atm, T = 0.01 ºC				
Ice point	0.00	32.00	273.15	491.67
Absolute Zero	-273.15	-459.67	0	0

1-10

Temperature Scales Comparison



$$T(K) = T(°C) + 273.15$$

$\Delta T(K) = \Delta T(°C)$

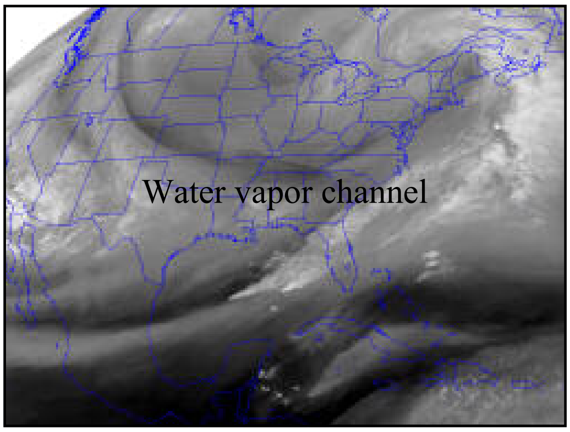
$$T(R) = T(°F) + 459.67$$

$\Delta T(R) = \Delta T(°F)$

Temperature relationships

- T (ºR) = T (ºF) + 459.67 [use 460]
- T (K) = T (ºC) + 273.15 [use 273]

Atmospheric Moisture



Introduction

First Step: What is the question?

- General weather conditions
- Support another activity, e.g. environmental monitoring
- Representative of specific area
- Vertical gradient (e.g. atmospheric stability or flux)
- Time average - mean and/or extreme

Humidity: Measures of Atmospheric Water Content

- Humidity – an expression of the amount of water vapor in the air.
- There are several ways to measure humidity:
  - Vapor Pressure
  - Absolute Humidity
  - Specific Humidity
  - Mixing Ratio
  - Relative Humidity
  - Dew Point Temperature
  - Depression of Wet-bulb Temperature

measures of atmospheric humidity

- Absolute humidity = mass H_2O/volume of air
- Specific humidity = mass H_2O /mass of air
- Mixing ratio = mass of H_2O /mass of dry air

I.Water vapor pressure

- Molecules in an air parcel all contribute to parcel pressure
- Each subset of molecules (e.g., N_2, O_2, H_2O) exerts a partial pressure
- The VAPOR PRESSURE, e, is the pressure exerted by water vapor molecules in the air
  - similar to atmospheric pressure, but due only to the water vapor molecules
  - often expressed in mbar (2-30 mbar common at surface)

Actual vapor pressure equals the partial pressure of water vapor in a parcel of air

Saturation vapor pressure is the maximum pressure that water molecules would exert if a parcel were saturated

Saturation vapor pressure is a function of temperature.

II. Absolute Humidity

- symbol: h_a
- h_a is the density of water vapour in the atmosphere
- units: kg m^{-3} or g m^{-3}

*****

Absolute Humidity

- Absolute Humidity – The density of water vapor (mass of water vapor in a volume of air).
- Dependencies: Volume of the air
- Not widely used.

  Because it varies with changes in pressure, thus not very useful in atmospheric sciences

Formula for Absolute Humidity

- h_a can be calculated from the formula

$$\boxed{h_a = 2.11 e_a / T_a}$$

where
h_a is the absolute humidity in g m^{-3}
e_a is the vapour pressure in Pa
T_a is the absolute temperature in K
*****

Calculation of Absolute Humidity

- example
- $T_a = 20\ ^oC$; $h_r = 0.5$
- therefore $e_s(T_a) = e_s(20\ ^oC) = 2340$ Pa
- therefore $e_a = 0.5*2340 = 1170$ Pa
- but $h_a = 2.11 e_a/T_a$
- therefore $h_a = 2.11 \times 1170/293 = 8.43$ g m^{-3}

*****

III. Specific Humidity

- Specific Humidity- The mass of water vapor per unit mass of air.
- Dependencies: Atmospheric pressure
- Units: grams per kilogram (g/kg)
- Widely used

$$q = \frac{m_v}{m} = \frac{m_v}{(m_v + m_d)}$$

  – q=specific humidity, m_v=mass of water vapor, m_d=mass of dry air

IV. Mixing Ratio

- Mixing Ratio - The mass of water vapor relative to the mass of the other gases.
- Offers same advantages as specific humidity

$$r = \frac{m_v}{m_d}$$

V. Relative Humidity

- Relative Humidity – The amount of water vapor in the air relative to the maximum amount possible.
- Dependencies: Temperature
- Unit: Percentage (%)
- Widely used, but not necessarily good

Relative Humidity

- Symbol: h_r
- h_r is the ratio of actual vapour pressure e_a to saturated vapour pressure $e_s(T_a)$ at that temperature
- $h_r = e_a/e_s(T_a)$
- $0 < h_r < 1$
- units: none

*****

Expressing the water vapor pressure

- Relative Humidity (RH) is ratio of actual vapor pressure to saturation vapor pressure
  - 100 * e/e_S
  - Range: 0-100% (+)
  - Air with RH > 100% is supersaturated
- RH can be changed by
  - Changes in water vapor content, e
  - Changes in temperature, which alter e_S

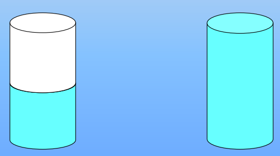
Relative Humidity

$$RH = \frac{\text{water vapor content}}{\text{water vapor capacity}} \times 100$$

$$RH = \frac{\text{Actual vapor pressure}}{\text{Saturation vapor pressure}} \times 100$$

RELATIVE HUMIDITY

T=75º



T = 75º

RH = 50% **RH = 100%**

©

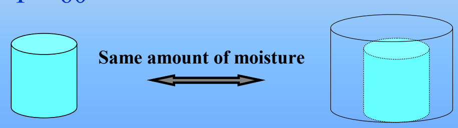
SATURATION AND SUPER SATURATION

SATURATED **SUPER-SATURATED**

© RH = 100% RH = 125%

RH CHANGES WITH VOLUME

T = 60º T = 95º



RH = 100% "A"

RH = 75% "B"

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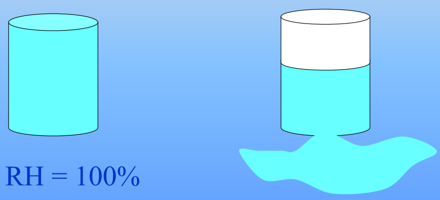
CHANGES IN AMOUNT OF WATER VAPOR

NEW RH = 75%

“A” “B”



RH = 100%

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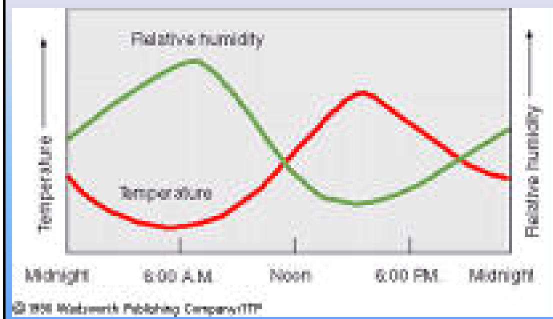
Relative Humidity

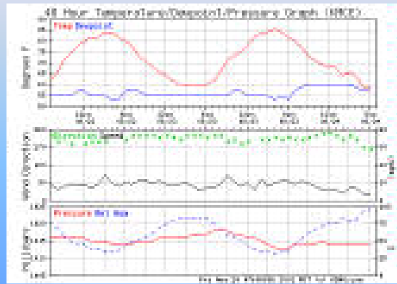


VI. Dewpoint Temperature

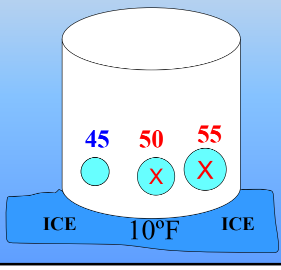
- symbol T_d
- Unit: °F, °C, K
- Widely used

is the temperature to which a parcel of air would have to be cooled with no change in pressure or moisture content for saturation to occur

Dew Point Vs. Relative Humidity



DEW POINT TEMPERATURE



Liquid water

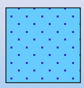
Water Vapor X

At a Dew point (Td)=45°, saturation occurs and the VAPOR X changes to a Liquid.

©

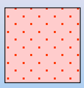
Relative Humidity and Dew Point

Parcel A



Pressure at 1000 mb

Parcel B



T = 10 °C (50 °F)
e_s = 12.3 mb
e = 12.3 mb

T = 20 °C (68 °F)
e_s = 23.7 mb
e = 12.3 mb

RH = (e_s / e) x 100 = 100%

RH = (e_s / e) x 100 = 52%

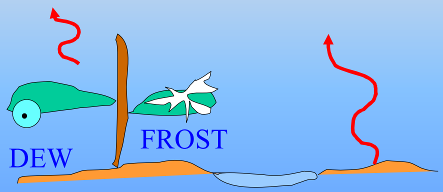
Therefore: T_d = 10 °C for Parcel B

Dew point = Temperature to which air must be cooled *at constant pressure* to reach saturation. It is a measure of the air’s actual water vapor content.

Relative Humidity is a measure of the degree of saturation of the air. 102

DEW & FROST

Early morning near minimum temperature time



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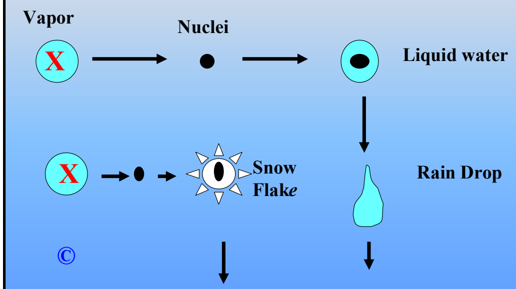
PRECIPITATION



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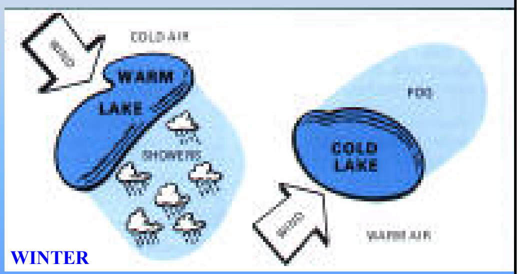
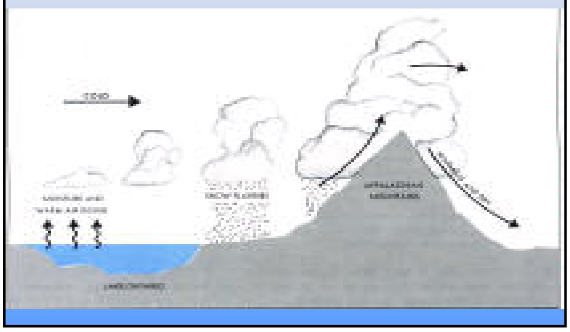
LAKE EFFECTS



LAND & WATER EFFECTS



How do we express the amount of water vapor in an air parcel?

- Absolute humidity
  - mass of water vapor/volume of air (g/m^3)
  - *changes when air parcel volume changes*
- Specific humidity
  - mass of water vapor/mass of air (g/kg)
- Mixing ratio
  - mass of water vapor/mass of dry air (g/kg)
- Specific humidity and mixing ratio remain constant as long as water vapor is not added/removed to/from air parcel
- Dew point temperature

Temperature Instruments

Electrical Thermometers

- Thermocouple
  - More commonly used in industrial applications
- Resistance temperature detector (RTD)
  - Good features, but can be sensitive to installation wiring
- Thermistor
  - Good answer for many applications

Temperature Instruments

Manual Thermometers and Thermographs

- Liquid in glass thermometers
  - Basic standard for many years
- Bi-metallic sensor
  - Mechanical link to pen for graphs
- Slower response times, less resolution, etc.
- Understand historical data limitations

Humidity Instruments

Electrical Hygrometers

- Hygroscopic films detect atmospheric moisture
- Dew point impedance from partial pressure of water vapor

Chilled mirror

- Optically sense presence of dew or frost on mirror
  - Measure temperature of mirror for dew point or frost point
  - Recent optical sensing improvements

Humidity Instruments

Manual hygrometers

- Psychrometer
  - Paired dry-bulb and wet-bulb thermometers
  - Manual and semi-automated

Hygrographs

- Hygroscopic material sensor (e.g. hair)
  - Mechanical link to pen

Field Measurement

Siting and Instrument Exposure

- Base on purpose of measurement and local logistics
- See monitoring guidance in text References
- Aspirated or naturally ventilated shields (important)
- Avoid local sources of heat and moisture

Field Measurement

Delta-temperature (vertical gradient)

- Choose levels, such as 2 to 10 meters agl for EPA stability
- Match sensors to optimize accuracy

Documentation

- Pictures worth many megabytes of words
- Geographic coordinates and reference system

Field Measurement

Measurement system and data collection

- Merge into total system requirements

On-site processing

- Time averages (fractional seconds to hour or daily)
  - Glass thermometer: approximately 1-min average
  - ASOS 5-min; ASTM 10-min; typical hourly
- Mean (true or median of range), extremes
- Other calculations

Field Checks and Calibrations

Routine checks

- External changes to sensor or shield (material, coating)
- Component checks (electronic)

Calibrations

- Determine accuracy and resolution requirements
- Place sensor in known environment
- Total system check - use normal readout in operating mode

Calculations

Measure temperature and relative humidity

- Calculate dew point directly, or
- Calculate dew point indirectly use vapor pressure
- Dew point is based on vapor pressure over water, by convention
- Calculation is sensitive to RH below about 40 percent

Calculations

Measure dry-bulb and wet-bulb temperatures

- To convert to dew point:
  - Calculate vapor pressure, then dew point
  - Calculate saturation vapor pressure from temperature
- Now you can worry about frozen bulbs

Calculate vapor pressure

Calculate saturation vapor pressure from temperature

Temperature: t, degrees Celsius

Saturation vapor pressure: e_s, millibars or hecto-Pascals

Reasonable option: Campbell Scientific P56 statement

Also to calculate vapor pressure from dew-point temperature

$$e_s(t) = 6.1121 \cdot \exp\left(\frac{17.502 \cdot t}{(240.97 + t)}\right)$$

Calculate dew point from vapor pressure

Dew point: T_d, degrees Celsius

Vapor pressure: e, millibars or hecto-Pascals

(hint: inverse of previous equation)

$$T_d = \frac{240.97 \cdot \ln(e/6.1121)}{17.502 - \ln(e/6.1121)}$$

Calculate dew point from temperature and relative humidity (1)

Intermediate calculated term A from:

Temperature: t, degrees Celsius

Relative humidity: RH, percent

$$A = [\ln(RH/100)] + \left[\frac{(17.502 \cdot t)}{(240.97 + t)}\right]$$

Calculate dew point from temperature and relative humidity (2)

Dew point: T_d, degrees Celsius

Intermediate term: A (see previous slide)

note: $T_d = 0\ °C$ for $RH = 100\%$ and $t = 0\ °C$

$$Td = \frac{240.97}{[(17.502/A) - 1]}$$

Calculate vapor pressure from wet-bulb and dry-bulb temperatures

Vapor pressure: e, millibars or hecto-Pascals

Dry-bulb temperature: t, degrees Celsius

Wet-bulb temperature: tw, degrees Celsius

Barometric pressure: p, millibars or hecto-Pascals

Then calculate dew point from equation on slide 15

$$e = e_s(tw) - \left[\left(6.6 \cdot 10^{-4}\right) \cdot (1 + 0.00115 \cdot tw) \cdot p \cdot (t - tw)\right]$$

Equipment

Relative humidity probe with built-in temperature sensor

Motor aspirated shield for temperature sensor

(courtesy Met One, Inc.)

psychrometer

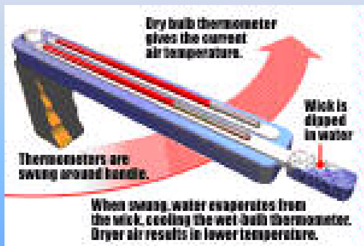
Dry-bulb temperature

Wet-bulb temperature

Wet-bulb depression

The Sling Psychrometer

Measures water vapor content of air



Equipment

Naturally ventilated shield

Wooden shelter for thermometers or hygrothermograph

(courtesy Nova Lynx, Inc.)

Equipment

Motor aspirated shield

Naturally ventilated shield

(courtesy R. M. Young, Inc.)

Equipment

Motor aspirated shield

(courtesy Climatronics, Inc.)

Water in the atmosphere

Properties of Water

- Physical States
  - only natural substance that occurs naturally in three states on the earth's surface
- Heat Capacity
  - Highest of all common solids and liquids
- Surface Tension
  - Highest of all common liquids
- Latent Heat of Fusion
  - Highest of all common substances
- Compressibility
  - Virtually incompressible as a liquid
- Density
  - Density of seawater is controlled by temperature, salinity and pressure
  - Liquid has maximum density at +4°C; solid phase has lower density!

Properties of Water (cont')

- Radiative Properties
  - transparent to visible wavelengths
  - virtually opaque to many infrared wavelengths
  - large range of albedo possible
    - water 10 % (daily average)
    - Ice 30 to 40%
    - Snow 20 to 95%
    - Cloud 30 to 90%
- Water Vapor - water in a gaseous form, not droplets.
- Water can also achieve solid and liquid phases on Earth
  - Temperature and pressure
- Saturation – The maximum amount of water that can exist in the atmosphere as a vapor.

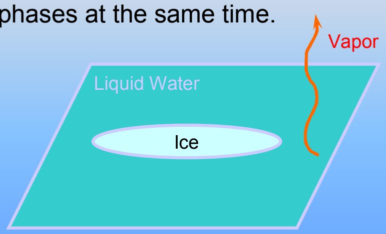
Water -- Funny Stuff

- Water has a very high boiling point (100 ° C at 1000 mb).
  - Normally the boiling point increases with increasing molecular weight. Chemically related substances have boiling points 100 to 150 °C.

Substance	Formula	Mol. Wt.	Boil Pt. (°C)
Water	H_2O	18	100
Methane	CH_4	16	-164
Ammonia	NH_3	17	-75
Iodine Chloride	ICl	162	97

Water -- Funny Stuff

- Water exists naturally in all three phases at the same time.

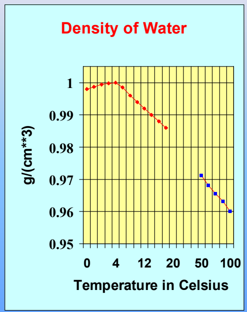


Water can exist in liquid form down to -40 °C.

Water -- Funny Stuff

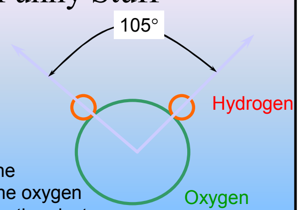
- Density decreases as water freezes.
  - Ice floats.
  - Lakes freeze from the top down.
  - Pipes burst in the winter.
- Latent heats of Fusion and Vaporization are unusually high.

Liquid water has an unusual property.



- Water **contracts** when heated from **0ºC to 4ºC**, then **expands** when heated from **4 ºC to 100 ºC**.
- Just above the freezing point, the coldest (and least dense) water rises to the surface, and lakes freeze from the surface downward.
- **This <u>unusual</u> property permits aquatic life on earth to survive winter!**

Water -- Funny Stuff

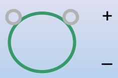


The three atoms share electrons. This is the “glue” that holds the molecule together.

The oxygen atom has 16 positively charged protons. The hydrogen atom has one. So the oxygen nucleus exerts a greater pull on the electrons than does the hydrogen atoms. The electrons tend to spend more time closer to the oxygen nucleus than to the hydrogen atoms. The oxygen atom becomes slightly negatively charged and the hydrogen atoms become slightly positively charged.

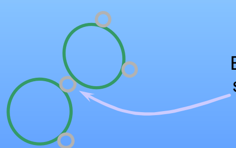
Water is a <u>dipole</u> molecule.

Water -- Funny Stuff

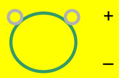


Water: A polar molecule.

Water molecules, in liquid, can get together and share electrons between molecules. This is a form of bonding of molecules together called <u>hydrogen bonding</u>.



Water -- Hydrogen Bonding



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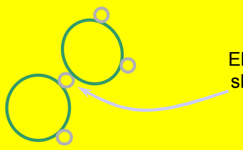


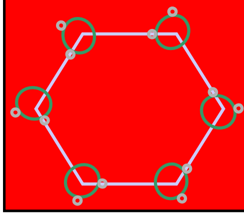
Water -- Hydrogen Bonding

- Hydrogen bonds are not permanent.
  - Some groups of water molecules have more energy than others and can move more freely about the liquid.
  - Some of these molecules have so much energy that they can escape the liquid and become vapor.

- Liquid: Order with some chaos.
- Vapor: Pandemonium!

Ice

- A "black tie" affair.
- Molecules are organized in a hexagonal lattice.
- Lower kinetic energy than liquid or gas.

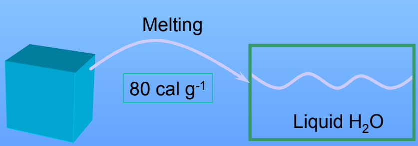


- Six-sided snow flakes.
- Ice is less dense than the liquid. Ice floats!
  A few molecules may still escape into the atmosphere -- Sublimation
- Ice in a frost-free freezer will eventually get smaller.

Phase Change

The tea is too hot to drink!
Add an ice cube to cool the tea down.

The melting of the ice requires energy.
Need to break up the lattice.
The molecules acquire more kinetic energy.

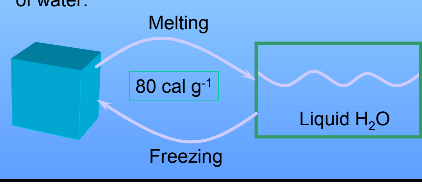


Phase Change

Since it takes energy to melt ice, energy is released when liquid water freezes.

Conservation of Energy
Energy can neither be created nor destroyed.
Ideally, the same amount of heat is released during freezing as was used to melt the same amount of water.

80 cal g^{-1} Latent heat of Fusion.



Salt on the Highways

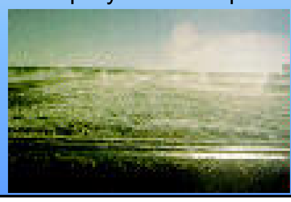
- If all water freezes at 0 °C, why do we salt the roads in the winter?

- Not all water freezes at 0 °C, so 0 °C is the **melting point** for pure water.

- Salt does not melt the ice
  - Need to mix the salt into a solution.
  - The salt solution prevents the ice lattice from forming until a lower temperature.

Save Our Strawberries!!!

- Plant damage occurs at about -3 °C.
- Temperature sensors are placed near the plants.
- If the temperature is too low, a fine mist of water is sprayed on the plants.

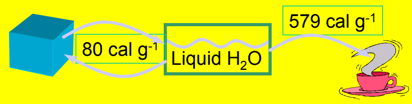


Save Our Strawberries!!!

- The water freezes, releasing latent heat, keeping the plants' temperature above the critical level.
- After the water freezes, the plants' temperature can fall below the critical temperature. The ice does not act as a blanket.
- More water is added as needed to protect the plant.

Phase Change 2

It takes much more energy to break the hydrogen bonds in liquid water in order for molecules to escape into vapor. This energy is called the Latent Heat of Vaporization = 579 cal g^{-1}

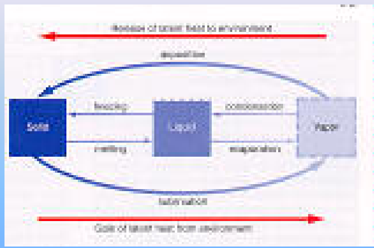


Upon condensing, heat is released: This energy is called the Latent Heat of Condensation = 579 cal g^{-1}.

Associated with local warming in clouds.

Transport of heat: Condensation is usually far from the source of evaporation.

Phase Change 3



Two other phase change processes involve a transformation between the vapor and solid phase.

Deposition: Vapor to Solid

Sublimation: Solid to Vapor (Recall the freezer)

Low Level Saturation Processes

We have seen that when the temperature falls to the dew point, the vapor pressure is the same as the saturation vapor pressure. At saturation, the net number of water vapor molecules enter the air as leave it.

Consider a clear, calm night…….

The earth radiates.

The earth cools and will cool the objects near the earth as well.

Dew

The temperature of the objects cool to or slightly below the dew point -- no longer an equilibrium situation.

Water molecules leave the vapor phase and condense on objects near the ground. This condensation is dew and shows up on blades of grass, your car, etc.

Not all dew is dew!!!!

Dew is deposited on all parts of the plant.

<u>Guttation</u>

The process in which liquid water is removed from the plant at the tips of the leaves.

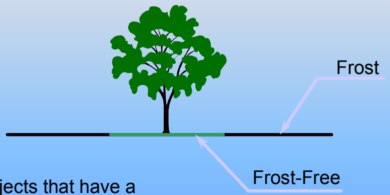
Not Dew!!!!!

Frost

- Ice that has been deposited from atmospheric water vapor on a subfreezing surface.
- <u>Frost Point</u>: The temperature at which air must be cooled, at constant pressure, to reach saturation with respect to ice.

Frost Under Your Tree?

Sometimes frost will <u>not</u> form underneath a tree.



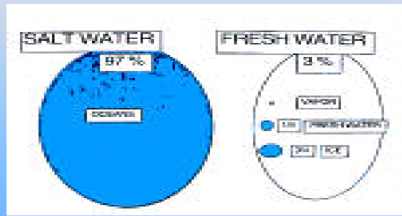
All objects that have a temperature will radiate. The tree will radiate in all directions, including toward the ground. In some situations, the downwelling radiation from the tree is enough to keep the grass below the tree above the frost point.

Which environment has higher water vapor content?

Water vapor is distributed throughout the atmosphere

- Generally largest amounts are found close to the surface, decreasing aloft
  - Closest to the source - evaporation from ground, plants, lakes and ocean
  - Warmer air can hold more water vapor than colder air

Fresh vs. salt water



- Most of the earth's water is found in the oceans
- only 3% is fresh water and 3/4 of that is ice
- The atmosphere contains only ~ 1 week supply of precipitation

The Earth's Hydrologic Cycle

a model of the movement and exchanges of water amongst the earth, atmosphere and oceans

Why is the southwest coast of the US hot and dry while the Gulf coast is hot and moist?

- Both are adjacent to large bodies of water
- Both experience onshore wind flow on a regular basis
- Why does one have a desert like climate and the other ample moisture and rainfall?

Can we explain the hot dry southern California climate based upon the proximity of a cold ocean?

The cold water temperatures typically found off the west coast of continents are a result of oceanic upwelling which ocean currents typically cause in these locations

REVIEW QUESTIONS

1. **Water, in the form of a gas, is called________**
   - a. air
   - b. nitrogen
   - c. water vapor
   - d. snow

2. **Two common terms used to describe the amount of water vapor present in the air are_____ and ________.**
   - a. humidity / moisture
   - b. relative humidity/water
   - c. dew point / saturation
   - d. relative humidity / dew point

3. **The amount of water vapor in the air is largely determined by the _____ of the air.**
   - a. temperature
   - b. pressure
   - c. density
   - d. condensation constant

4. **Relative humidity depends on how ___ the air is and how much _____ is present.**
   - a. dry/density
   - b. wet/density
   - c. dense/water
   - d. warm/water vapor

5. **Virtually all of the atmospheric water vapor exists below the_____.**
   - a. Ionosphere
   - b. Thermosphere
   - c. Tropopause
   - d. Troposphere

6. **The air is said to become saturated when the relative humidity reaches______.**
   - a. 80%
   - b. 85%
   - c. 90%
   - d. 100%

7. **The surface temperature-dew point spread is useful for predicting ______.**
   - a. sky condition
   - b. snow
   - c. rain
   - d. fog

8. **The process whereby water vapor changes directly to a solid form (ice), or vice versa, is called_________.**
   - a. fusion
   - b. vaporization
   - c. freezing
   - d. sublimation

9. **Fog, rain and snow are usually heavier on the _____ side of a water body.**
   - a. colder
   - b. leeward
   - c. warmer
   - d. windward

10. **________ precipitation can be expected from cirrus clouds.**
    - a. Showery
    - b. No
    - c. Steady
    - d. Freezing

11. The conversion of ice directly into water vapor.
   a. Releases thermal energy
   b. Requires thermal energy
   c. Is known as sublimation
   d. Is not physically possible without first going through the melting process
   e. Both b and c

12. Air cools when it rises because.
   a. The temperature of the environment decreases with height
   b. Water within the parcel evaporates
   c. The pressure of the environment decreases with height
   d. Both a and c
   e. a, b, and c

13. Suppose two columns of air have identical depth. The column of air having a greater density will
   a. Have a higher surface pressure
   b. Have a higher surface temperature
   c. Have more air molecules per cubic centimeter
   d. Have the same number of air molecules per cubic centimeter
   e. Both a and c.

14. Temperature is
   a. The average speed of atoms and molecules
   b. A byproduct of sensible heating
   c. A byproduct of latent heating
   d. Always transferred from hot objects to cold ones
   e. Both a and b.

15. Which requires more energy to complete the stated phase transition?
   a. Ice to liquid water
   b. Ice to water vapor
   c. Liquid water to water vapor
   d. Liquid water to ice
   e. Liquid water to slush

16. Relative humidity (RH) is NOT a good measure of the amount of moisture in the air because
   a. RH depends upon the vapor pressure
   b. RH depends upon the temperature
   c. Cold air can hold far less moisture than warm air at the same pressure
   d. The RH is a function of the dew point
   e. None of the above

17. Which of the following is/are independent of air parcel volume
   a. Relative humidity
   b. Mixing ratio
   c. Dew point
   d. Specific humidity
   e. Both b and d

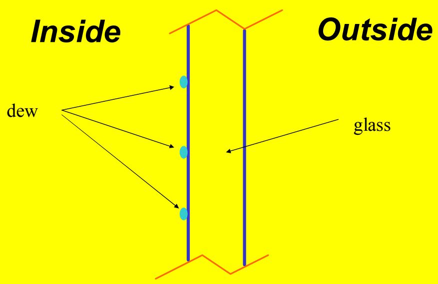
18. Relative humidity is
   a. The saturation vapor pressure divided by the vapor pressure
   b. The saturation mixing ratio divided by the mixing ratio
   c. The vapor pressure divided by the dew point
   d. The temperature divided by the dew point
   e. None of the above

19. The saturation vapor pressure depends primarily upon temperature.
   a. True
   b. False

20. Thunderstorms are unable to penetrate very far into the stratosphere because, above the tropopause, the temperature of the atmosphere increases with height.
   a. True
   b. False

Explain Dew on Your Window

Why does dew (or frost) form in winter on the inside of windows in your house?



Explain: Why Ice Cubes Shrink in the Freezer?

Usually an important guest is visiting when you discover that the ice cubes are rattling around in the bottom of their trays like contact lenses...