Changes of state of water

- **Heat energy**
  - Measured in calories – one calorie is the heat necessary to raise the temperature of one gram of water one degree Celsius

- **Latent heat**
  - Stored or hidden heat
  - Not derived from temperature change
  - Important in atmospheric processes
Changes of state of water

❖ Three states of matter
  • Solid
  • Liquid
  • Gas

❖ To change state, heat must be
  • Absorbed, or
  • Released
Changes of state of water

Processes

• Evaporation
  • Liquid is changed to gas
  • 600 calories per gram of water are added – called latent heat of vaporization

• Condensation
  • Water vapor (gas) is changed to a liquid
  • Heat energy is released – called latent heat of condensation
Changes of state of water

Processes

- Melting
  - Solid is changed to a liquid
  - 80 calories per gram of water are added – called latent heat of melting

- Freezing
  - Liquid is changed to a solid
  - Heat is released – called latent heat of fusion
Changes of state of water

Processes

• Sublimation
  • Solid is changed directly to a gas (e.g., ice cubes shrinking in a freezer)
  • 680 calories per gram of water are added

• Deposition
  • Water vapor (gas) changed to a solid (e.g., frost in a freezer compartment)
  • Heat is released
Changes of state of water

**Figure 17.2**

- **Solid (ice)**: Heat absorbed (80 cal) when melting.
  - Heat released (80 cal) when freezing.
  - Releases latent heat to the environment.

- **Liquid (water)**: Heat released (~680 cal) when sublimation.
  - Heat absorbed (540–600 cal) when evaporation.
  - Heat released (540–600 cal) when condensation.

- **Gas (water vapor)**: Absorbs latent heat from the environment.

Copyright © 2006 Pearson Prentice Hall, Inc.
Humidity

- Amount of water vapor in the air
- Saturated air is air that is filled with water vapor to capacity
- Capacity is temperature dependent – warm air has a much greater capacity
- Water vapor adds pressure (called vapor pressure) to the air
Humidity

- **Measuring humidity**
  - **Mixing ratio**
    - Mass of water vapor in a unit of air compared to the remaining mass of dry air
    - Often measured in grams per kilogram
  - **Relative humidity**
    - Ratio of the air's actual water vapor content compared with the amount of water vapor required for saturation at that temperature (and pressure)
Humidity

- Measuring humidity
  - Relative humidity
    - Expressed as a percent
    - Saturated air
      - Content equals capacity
      - Has a 100% relative humidity
    - Relative humidity can be changed in two ways
      - Add or subtract moisture to the air
        - Adding moisture raises the relative humidity
        - Removing moisture lowers the relative humidity
Humidity

Measuring humidity

• Relative humidity
  • Relative humidity can be changed in two ways
    • Changing the air temperature
      • Lowering the temperature raises the relative humidity
  • Dew point temperature
    • Temperature to which a parcel of air would need to be cooled to reach saturation
Relative humidity changes at constant temperature

Figure 17.4

A. Initial condition
- Temperature 25°C
- 1 kg air
- 5 grams H₂O vapor
1. Water vapor needed for saturation at 25°C = 20 grams*
2. H₂O vapor content = 5 grams
3. Relative humidity = \( \frac{5}{20} = 25\% \)

B. Addition of 5 grams of water vapor
- Temperature 25°C
- 1 kg air
- 10 grams H₂O vapor
1. Water vapor needed for saturation at 25°C = 20 grams*
2. H₂O vapor content = 10 grams
3. Relative humidity = \( \frac{10}{20} = 50\% \)

C. Addition of 10 grams of water vapor
- Temperature 25°C
- 1 kg air
- 20 grams H₂O vapor
1. Water vapor needed for saturation at 25°C = 20 grams*
2. H₂O vapor content = 20 grams
3. Relative humidity = \( \frac{20}{20} = 100\% \)

*See Table 17.1
Relative humidity changes at constant water-vapor content

Figure 17.5

A. Initial condition 20°C

1. Water vapor needed for saturation at 20°C = 14 grams*
2. H₂O vapor content = 7 grams
3. Relative humidity = \( \frac{7}{14} = 50\% \)

*See Table 17.1

B. Cooled to 10°C

1. Water vapor needed for saturation at 10°C = 7 grams
2. H₂O vapor content = 7 grams
3. Relative humidity = \( \frac{7}{7} = 100\% \)

C. Cooled to 0°C

1. Water vapor needed for saturation at 0°C = 3.5 grams*
2. H₂O vapor content = 3.5 grams
3. Relative humidity = \( \frac{3.5}{3.5} = 100\% \)
Humidity

Measuring humidity

• Relative humidity

• Dew point temperature

• Cooling the air below the dew point causes condensation

• e.g., dew, fog, or cloud formation

• Water vapor requires a surface to condense on
Typical daily variations in temperature and relative humidity

Figure 17.6
Humidity

Measuring humidity

• Relative humidity

  • Two types of hygrometers are used to measure humidity
  
  • Psychrometer - compares temperatures of wet-bulb thermometer and dry-bulb thermometer
  
  • If the air is saturated (100% relative humidity) then both thermometers read the same temperature
  
  • The greater the difference between the thermometer readings, the lower the relative humidity
A sling psychrometer

Figure 17.8
Humidity

- Measuring humidity
  - Relative humidity
  - Two types of hygrometers are used to measure humidity
    - Hair hygrometer – reads the humidity directly
Adiabatic heating/cooling

- Adiabatic temperature changes occur when
  - Air is compressed
  - Motion of air molecules increases
  - Air will warm
  - Descending air is compressed due to increasing air pressure
  - Air expands
    - Air parcel does work on the surrounding air
    - Air will cool
    - Rising air will expand due to decreasing air pressure
Adiabatic heating/cooling

- Adiabatic temperature changes occur when
  - Adiabatic rates
    - Dry adiabatic rate
    - Unsaturated air
      - Rising air expands and cools at 1°C per 100 meters (5.5°F per 1000 feet)
      - Descending air is compressed and warms at 1°C per 100 meters
Adiabatic heating/cooling

- Adiabatic temperature changes occur when:
  - Adiabatic rates
    - Commences at condensation level
    - Air has reached the dew point
    - Condensation is occurring and latent heat is being liberated
    - Heat released by the condensing water reduces the rate of cooling
    - Rate varies from 0.5°C to 0.9°C per 100 meters
Adiabatic cooling of rising air

Figure 17.9
Processes that lift air

- Orographic lifting
  - Elevated terrains act as barriers
  - Result can be a rainshadow desert

- Frontal wedging
  - Cool air acts as a barrier to warm air
  - Fronts are part of the storm systems called middle-latitude cyclones
Processes that lift air

- **Convergence** where the air is flowing together and rising (low pressure)
- **Localized convective lifting**
  - Localized convective lifting occurs where unequal surface heating causes pockets of air to rise because of their buoyancy
Processes that lift air

Figures 17.10, 17.12, 17.13, & 17.14
Stability of air

Types of stability

- Stable air
  - Resists vertical displacement
  - Cooler than surrounding air
  - Denser than surrounding air
  - Wants to sink
  - No adiabatic cooling

Absolute stability occurs when the environmental lapse rate is less than the wet adiabatic rate
Figure 17.17

Absolute stability

Copyright © 2006 Pearson Prentice Hall, Inc.
Stability of air

Types of stability

• Stable air
  • Often results in widespread clouds with little vertical thickness
  • Precipitation, if any, is light to moderate

• Absolute instability
  • Acts like a hot air balloon
  • Rising air
    • Warmer than surrounding air
    • Less dense than surrounding air
    • Continues to rise until it reaches an altitude with the same temperature
Stability of air

- Types of stability
  - Absolute instability
    - Adiabatic cooling
    - Environmental lapse rate is greater than the dry adiabatic rate
    - Clouds are often towering
  - Conditional instability occurs when the atmosphere is stable for an unsaturated parcel of air but unstable for a saturated parcel
Absolute instability

Figure 17.18

Environmental lapse rate 12°C/1000 m

-8°C

3000 m

4°C

2000 m

16°C

1000 m

28°C

Surface

40°C

Wet rate 6°C/1000 m

Dry rate 10°C/1000 m

Tendency

Rising air 16° warmer than environment

Rising air 10° warmer than environment

Rising air 4° warmer than environment

Rising air 2° warmer than environment

Solar heating

Copyright © 2006 Pearson Prentice Hall, Inc.
Conditional instability

Figure 17.19
Stability of air

- Determines to a large degree
  - Type of clouds that develop
  - Intensity of the precipitation
How surface water evaporates to become clouds

- Sunlight turns surface water into invisible water vapor
- Heated moist air rises where it expands, cools, and condenses into liquid
- Cloud droplets are very tiny, made of liquid water
Condensation and cloud formation

Condensation

• Water vapor in the air changes to a liquid and forms dew, fog, or clouds

• Water vapor requires a surface to condense on
  • Possible condensation surfaces on the ground can be the grass, a car window, etc.
  • Possible condensation surfaces in the atmosphere are tiny bits of particulate matter
    • Called condensation nuclei
    • Dust, smoke, etc
    • Ocean salt crystals which serve as hygroscopic ("water seeking") nuclei
<table>
<thead>
<tr>
<th>Cloud Family and Height</th>
<th>Cloud Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>High clouds—above 6000 meters (20,000 feet)</td>
<td>Cirrus</td>
<td>Thin, delicate, fibrous, ice-crystal clouds. Sometimes appear as hooked filaments called “mares’ tails.” (Figure 17.21A)</td>
</tr>
<tr>
<td></td>
<td>Cirrostratus</td>
<td>Thin sheet of white, ice-crystal clouds that may give the sky a milky look. Sometimes produce halos around the Sun or Moon. (Figure 17.21B)</td>
</tr>
<tr>
<td>Middle clouds—2000–6000 meters (6500–20,000 feet)</td>
<td>Altocumulus</td>
<td>White to gray clouds often composed of separate globules; “sheep-back” clouds. (Figure 17.21D)</td>
</tr>
<tr>
<td></td>
<td>Altostratus</td>
<td>Stratified veil of clouds that are generally thin and may produce very light precipitation. When thin, the Sun or Moon may be visible as a bright spot, but no halos are produced. (Figure 17.21E)</td>
</tr>
<tr>
<td>Low clouds—below 2000 meters (6500 feet)</td>
<td>Stratocumulus</td>
<td>Soft, gray clouds in globular patches or rolls. Rolls may join together to make a continuous cloud.</td>
</tr>
<tr>
<td></td>
<td>Stratus</td>
<td>Low uniform layer resembling fog but not resting on the ground. May produce drizzle. (Figure 17.21F)</td>
</tr>
<tr>
<td></td>
<td>Nimbostratus</td>
<td>Amorphous layer of dark gray clouds. One of the chief precipitation-producing clouds.</td>
</tr>
<tr>
<td>Clouds of vertical development—500–18,000 meters (1600–60,000 feet)</td>
<td>Cumulus</td>
<td>Dense, billowy clouds often characterized by flat bases. May occur as isolated clouds or closely packed. (Figure 17.21G)</td>
</tr>
<tr>
<td></td>
<td>Cumulonimbus</td>
<td>Towering cloud sometimes spreading out on top to form an “anvil head.” Associated with heavy rainfall, thunder, lightning, hail, and tornadoes. (Figure 17.21H)</td>
</tr>
</tbody>
</table>
Condensation and cloud formation

❖ Clouds

• Made of millions and millions of
  • Minute water droplets, or
  • Tiny crystals of ice

• Classification based on
  • Form (three basic forms)
    • Cirrus – high, white, thin
    • Cumulus - globular cloud masses often associated with fair weather
    • Stratus – sheets or layers that cover much of the sky
Cirrus clouds

Figure 17.21 A
Altostratus clouds

Figure 17.21 E
Cumulus clouds

Figure 17.21 G
Low Altitude Cumulus Clouds
Condensation and cloud formation

Clouds

- Classification based on
  - Height
    - High clouds – above 6000 meters
      - Types include cirrus, cirrostratus, cirrocumulus
    - Middle clouds – 2000 to 6000 meters
      - Types include altostratus and altocumulus
    - Low clouds – below 2000 meters
      - Types include stratus, stratocumulus, and nimbostratus (nimbus means "rainy")
Condensation and cloud formation

Clouds

- Classification based on
  - Height
    - Clouds of vertical development
    - From low to high altitudes
    - Called cumulonimbus
    - Often produce rain showers and thunderstorms
Classification of clouds according to height and form

Figure 17.20
Classification of clouds according to height and form (continued)

Figure 17.20
Cumulonimbus clouds feature lightning, heavy rain, strong winds.
Fog

- Considered an atmospheric hazard
- Cloud with its base at or near the ground
- Most fogs form because of
  - Radiation cooling, or
  - Movement of air over a cold surface
Fog at San Francisco-Oakland Bay Bridge
Types of fog

• Fogs caused by cooling
  • Advection fog – warm, moist air moves over a cool surface
  • Radiation fog
    • Earth's surface cools rapidly
    • Forms during cool, clear, calm nights
• Upslope fog
  • Humid air moves up a slope
  • Adiabatic cooling occurs
Types of fog

- Evaporation fogs
  - Steam fog
    - Cool air moves over warm water and moisture is added to the air
    - Water has a steaming appearance
  - Frontal fog, or precipitation fog
    - Forms during frontal wedging when warm air is lifted over colder air
    - Rain evaporates to form fog
Precipitation

- Cloud droplets
  - Less than 20 micrometers (0.02 millimeter) in diameter
  - Fall incredibly slow

- Formation of precipitation
  - Bergeron process
    - Temperature in the cloud is below freezing
    - Ice crystals collect water vapor
    - Large snowflakes form and fall to the ground or melt during descent and fall as rain
<table>
<thead>
<tr>
<th>Type</th>
<th>Appropriate Size</th>
<th>State of Matter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mist</td>
<td>0.005 to 0.05 mm</td>
<td>Liquid</td>
<td>Droplets large enough to be felt on the face when air is moving second.</td>
</tr>
<tr>
<td></td>
<td>1 meter/</td>
<td></td>
<td>Associated with stratus clouds.</td>
</tr>
<tr>
<td>Drizzle</td>
<td>Less than 0.5 mm</td>
<td>Liquid</td>
<td>Small uniform drops that fall from stratus clouds, generally for several hours.</td>
</tr>
<tr>
<td>Rain</td>
<td>0.5 to 5 mm</td>
<td>Liquid</td>
<td>Generally produced by nimbostratus or cumulonimbus clouds. When heavy, it</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>can show high variability from one place to another.</td>
</tr>
<tr>
<td>Sleet</td>
<td>0.5 to 5 mm</td>
<td>Solid</td>
<td>Small, spherical to lumpy ice particles that form when raindrops freeze while</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>falling through a layer of sub-freezing air. Because the ice particles are</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>small, damage, if any, is generally minor. Sleet can make travel hazardous.</td>
</tr>
<tr>
<td>Glaze</td>
<td>Layers 1 mm to</td>
<td>Solid</td>
<td>Produced when supercooled raindrops freeze on contact with solid objects.</td>
</tr>
<tr>
<td></td>
<td>2 cm thick</td>
<td></td>
<td>Glaze can form a thick coating of ice having sufficient weight to seriously</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>damage trees and power lines.</td>
</tr>
<tr>
<td>Rime</td>
<td>Variable</td>
<td>Solid</td>
<td>Deposits usually consisting of ice feathers that point into the wind. These</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>delicate, frostlike accumulations form as supercooled cloud or fog droplets</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>encounter objects and freeze on contact.</td>
</tr>
<tr>
<td>Snow</td>
<td>1 mm to 2 cm</td>
<td>Solid</td>
<td>The crystalline nature of snow allows it to assume many shapes including six-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>sided crystals, plates, and needles. Produced in supercooled clouds where</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>water vapor is deposited as ice crystals that remain frozen during their</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>descent.</td>
</tr>
<tr>
<td>Hail</td>
<td>5 mm to 10 cm</td>
<td>Solid</td>
<td>Precipitation in the form of hard, rounded pellets or irregular lumps of ice.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Produced in large convective, cumulonimbus clouds, where frozen ice</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>particles and supercooled water coexist.</td>
</tr>
<tr>
<td>Graupel</td>
<td>2 to 5 mm</td>
<td>Solid</td>
<td>Sometimes called soft hail, graupel forms when rime collects on snow</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>crystals to produce irregular masses of “soft” ice. Because these particles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>are softer than hailstones, they normally flatten out upon impact.</td>
</tr>
</tbody>
</table>
Particle sizes involved in condensation and precipitation

Figure 17.24
The Bergeron process

Figure 17.25
Formation of precipitation

- Collision-coalescence process
  - Warm clouds
  - Large hygroscopic condensation nuclei
  - Large droplets form
  - Droplets collide with other droplets during their descent
  - Common in the tropics
The collision-coalescence process

Figure 17.26
Rainfall Gauge

Collecting funnel

Measuring scale

Measuring tube (1/10 area of funnel)

1 inch of rain

10 inches

Copyright © 2006 Pearson Prentice Hall, Inc.
Precipitation

Forms of precipitation

• Rain and drizzle
  • Rain – droplets have at least a 0.5 mm diameter
  • Drizzle – droplets have less than a 0.5 mm diameter

• Snow – ice crystals, or aggregates of ice crystals

• Sleet and glaze
  • Sleet
  • Wintertime phenomenon
  • Small particles of ice
Precipitation

Forms of precipitation

• Sleet and glaze
  • Sleet
    • Occurs when warmer air overlies colder air
    • Rain freezes as it falls
  • Glaze, or freezing rain – impact with a solid causes freezing
Precipitation

Forms of precipitation

• Hail
  • Hard rounded pellets
  • Concentric shells
  • Most diameters range from 1 to 5 cm
• Formation
  • Occurs in large cumulonimbus clouds with violent up- and down drafts
  • Layers of freezing rain are caught in up- and down drafts in the cloud
  • Pellets fall to the ground when they become too heavy
Hail stones can fall at over 100 miles per hour
Softball-sized Hail Stone
Precipitation

Forms of precipitation
- Rime
- Forms on cold surfaces
- Freezing of
  - Supercooled fog, or
- Cloud droplets
Rime
Very cold window panes can turn indoor water vapor into ice crystals
Precipitation

- Measuring precipitation
  - Rain
    - Easiest form to measure
  - Measuring instruments
    - Standard rain gauge
      - Uses a funnel to collect and conduct rain
      - Cylindrical measuring tube measures rainfall in centimeters or inches
The standard rain gauge

Figure 17.31
Precipitation

Measuring precipitation

- Snow has two measurements
  - Depth
  - Water equivalent
    - General ratio is 10 snow units to 1 water unit
    - Varies widely
    - Radar is also used to measure the rate of rainfall
End of Chapter 17