# Lecture 1: Introduction to the Climate System

- Chapter 1: Introduction to the Climate System
  - Abstract
  - 1.1. Atmosphere, ocean, and land surface
  - 1.2. Atmospheric temperature ⟶ T
  - 1.3. Atmospheric composition ⟶ mass (& radiation)
  - 1.4. Hydrostatic balance ⟶ T & mass relation in vertical
  - 1.5. Atmospheric humidity ⟶ mass (& energy, weather..)
  - 1.6. Atmospheric thermodynamics, vertical stability and lapse rate ⟶ Energy ➔ T ➔ vertical stability ➔ vertical motion ➔ thunderstorm
  - 1.7. The world ocean
  - 1.8. The cryosphere
  - 1.9. The land surface

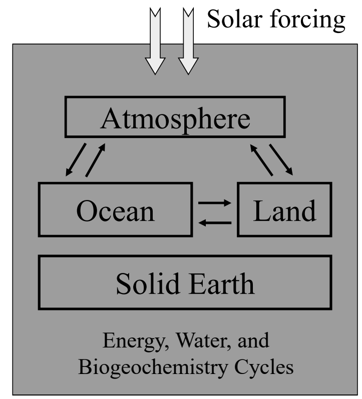
❑ What are included in Earth's climate system?

❑ What are the general properties of the Atmosphere?

❑ How about the ocean, cryosphere, and land surface?



# Earth's Climate System




❑ The ultimate driving force to Earth's climate system is the heating from the Sun.

❑ The solar energy drives three major cycles (energy, water, and biogeochemisty) in the climate system.

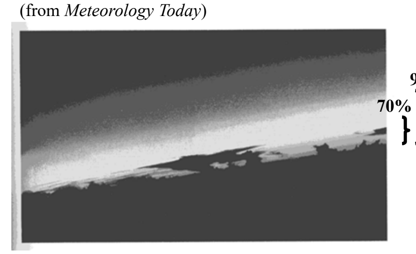


# Atmosphere



# Thickness of the Atmosphere

(from *Meteorology Today*)




❑ The thickness of the atmosphere is only about 2% of Earth's thickness (Earth's radius = ~6400km).

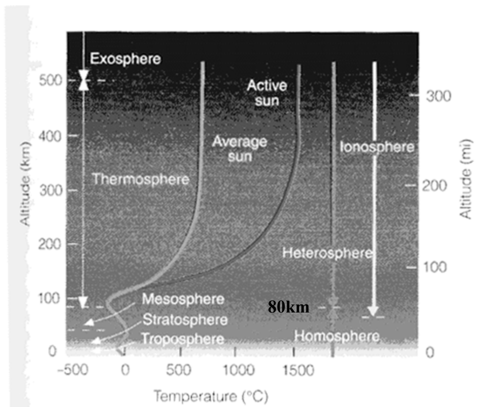
❑ Most of the atmospheric mass is confined in the lowest 100 km above the sea level.

❑ Because of the shallowness of the atmosphere, its motions over large areas are primarily horizontal.

➔Typically, horizontal wind speeds are a thousands time greater than vertical wind speeds.

(But the small vertical displacements of air have an important impact on the state of the atmosphere.)

# Vertical Structure of the Atmosphere




composition

temperature

electricity

(from *Meteorology Today*)

ESS200
Prof. Jin-Yi Yu

# Composition of the Atmosphere

(inside the DRY homosphere)

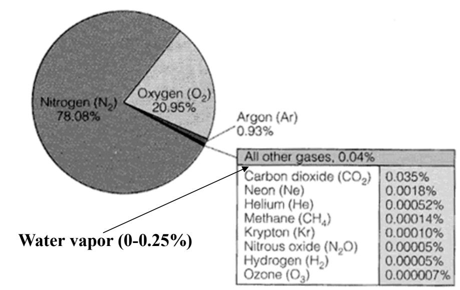



*Figure 12.2* Composition of dry, aerosol-free air in volume percent. Three gases—nitrogen, oxygen, and argon—make up 99.96 percent of the air.

(from *The Blue Planet*)

ESS200
Prof. Jin-Yi Yu

# Origins of the Atmosphere

- ❑ When the Earth was formed 4.6 billion years ago, Earth's atmosphere was probably mostly hydrogen (H) and helium (He) plus hydrogen compounds, such as methane ($CH_4$) and ammonia ($NH_3$).

➔ Those gases eventually escaped to the space.

- ❑ The release of gases from rock through volcanic eruption (so-called **outgassing**) was the principal source of atmospheric gases.

➔ The primeval atmosphere produced by the outgassing was mostly carbon dioxide (**$CO_2$**) with some Nitrogen (**$N_2$**) and water vapor (**$H_2O$**), and trace amounts of other gases.

ESS200
Prof. Jin-Yi Yu

# What Happened to $H_2O$?

**Table 1.2**
An inventory of the hydrosphere[a,b]

| Component | Percentage of mass of hydrosphere |
|---|---|
| Oceans | 97. |
| Ice | 2.4 |
| Fresh water (underground) | 0.6 |
| Fresh water in lakes, rivers, etc. | 0.02 |
| Atmosphere | 0.001 |

[a] Total mass $= 1.36 \times 10^{21}$ kg $= 2.66 \times 10^{6}$ kg m$^{-2}$ over surface of earth.
[b] Based on data given in H. H. Lamb, "Climate: Present, Past and Future," Methuen Co. Ltd., London, 1972, p. 482.

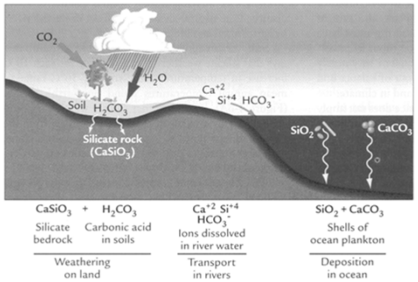
(from *Atmospheric Sciences: An Introductory Survey*)

- ❑ The atmosphere can only hold small fraction of the mass of water vapor that has been injected into it during volcanic eruption, most of the water vapor was condensed into clouds and rains and gave rise to rivers, lakes, and oceans.

➔ The concentration of water vapor in the atmosphere was substantially reduced.

ESS200
Prof. Jin-Yi Yu

# What happened to $CO_2$?




(from *Earth's Climate: Past and Future*)

- ❑ Chemical weather is the primary process to remove CO2 from the atmosphere.
- ➔ In this process, CO2 dissolves in rainwater producing weak carbonic acid that reacts chemically with bedrock and produces carbonate compounds.
- ❑ This biogeochemical process reduced CO2 in the atmosphere and locked carbon in rocks and mineral.



# What Happened to $N_2$?

❑ Nitrogen (N2):
(1) is inert chemically,
(2) has molecular speeds too slow to escape to space,
(3) is not very soluble in water.

➔ The amount of nitrogen being cycled out of the atmosphere was limited.

➔ Nitrogen became the most abundant gas in the atmosphere.



# Where Did $O_2$ Come from?

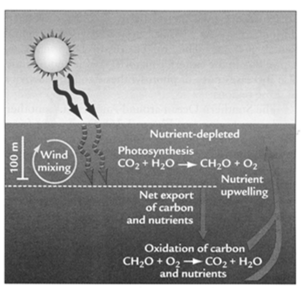



**FIGURE 2-35 Photosynthesis in the ocean** Sunlight penetrating the surface ocean causes photosynthesis by microscopic plants. As they die, their nutrient-bearing organic tissue descends to the seafloor. Oxidation of this tissue at depth returns nutrients and inorganic carbon to the surface ocean in regions of upwelling.

(from *Earth's Climate: Past and Future*)

- ❑ Photosynthesis was the primary process to increase the amount of oxygen in the atmosphere.
- ➔ Primitive forms of life in oceans began to produce oxygen through photosynthesis probably 2.5 billion years ago.
- ➔ With the concurrent decline of CO2, oxygen became the second most abundant atmospheric as after nitrogen.



# Where Did Argon Come from?

❑ Radioactive decay in the planet's bedrock added argon (**Ar**) to the evolving atmosphere.

➔ Argon became the third abundant gas in the atmosphere.

# Composition of the Atmosphere

*important for physical climate !*

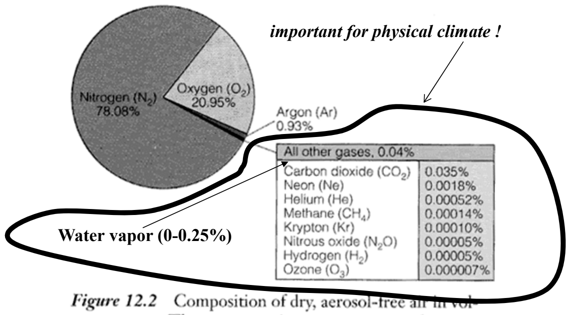



*Figure 12.2* Composition of dry, aerosol-free air in volume percent. Three gases—nitrogen, oxygen, and argon—make up 99.96 percent of the air.

(from *The Blue Planet*)

ESS200
Prof. Jin-Yi Yu

# Key Atmospheric Properties

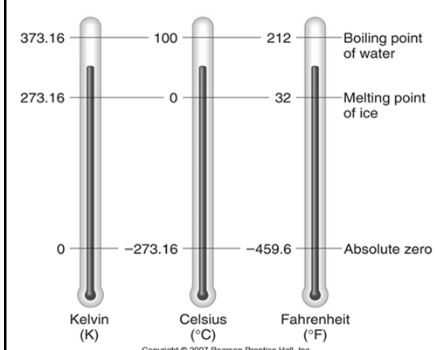
**T** **P** **q** **U, V, ω**

ESS200
Prof. Jin-Yi Yu

# Temperature

ESS200
Prof. Jin-Yi Yu

# Units of Air Temperature



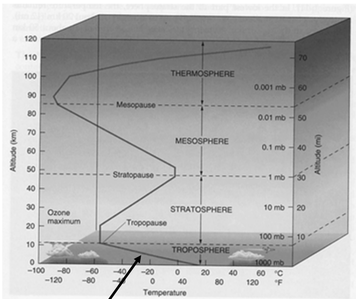

- Fahrenheit (ºF)
- Celsius (ºC)
  ➔ ºC = (ºF-32)/1.8
- Kelvin (K): a SI unit
  ➔ K= ºC+273

$\boxed{1\ K = 1\ ^\circ C > 1\ ^\circ F}$

ESS200
Prof. Jin-Yi Yu

# Vertical Thermal Structure

**Standard Atmosphere**




**(from *Understanding Weather & Climate*)**

lapse rate = 6.5 C/km

Troposphere ("overturning" sphere)
- contains 80% of the mass
- surface heated by solar radiation
- strong vertical motion
- where most weather events occur

Stratosphere ("layer" sphere)
- weak vertical motions
- dominated by radiative processes
- heated by ozone absorption of solar ultraviolet (UV) radiation
- warmest (coldest) temperatures at summer (winter) pole

middle atmosphere

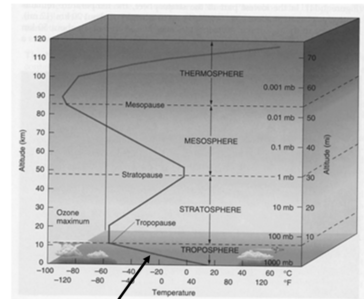
Mesosphere
- heated by solar radiation at the base
- heat dispersed upward by vertical motion

Thermosphere
- very little mass

**ESS200**
**Prof. Jin-Yi Yu**

# Stratosphere

**Standard Atmosphere**




**(from *Understanding Weather & Climate*)**

lapse rate = 6.5 C/km

❑ The reasons for the inversion in the stratosphere is due to the ozone absorption of ultraviolet solar energy.

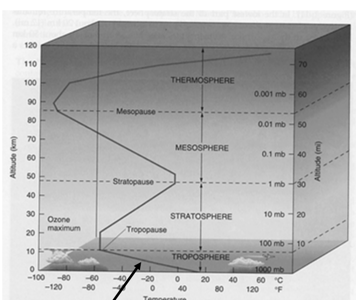
❑ Although maximum ozone concentration occurs at 25km, the lower air density at 50km allows solar energy to heat up temperature there at a much greater degree.

❑ Also, much solar energy is absorbed in the upper stratosphere and can not reach the level of ozone maximum.

**ESS200**
**Prof. Jin-Yi Yu**

# Mesosphere

**Standard Atmosphere**




**(from *Understanding Weather & Climate*)**

lapse rate = 6.5 C/km

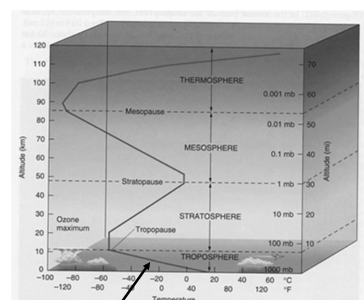
❑ There is little ozone to absorb solar energy in the mesosphere, and therefore, the air temperature in the mesosphere decreases with height.

❑ Also, air molecules are able to lose more energy than they absorb. This cooling effect is particularly large near the top of the mesosphere.

**ESS200**
**Prof. Jin-Yi Yu**

# Thermosphere

**Standard Atmosphere**




**(from *Understanding Weather & Climate*)**

lapse rate = 6.5 C/km

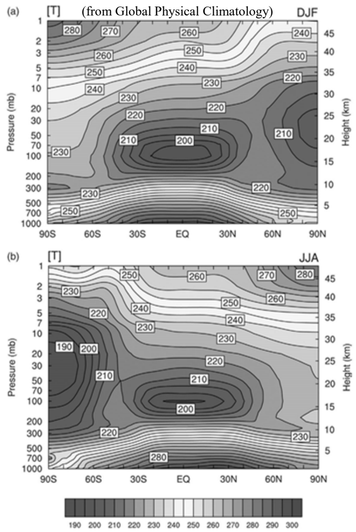
❑ In thermosphere, oxygen molecules absorb solar rays and warms the air.

❑ Because this layer has a low air density, the absorption of small amount of solar energy can cause large temperature increase.

❑ The air temperature in the thermosphere is affected greatly by solar activity.

**ESS200**
**Prof. Jin-Yi Yu**

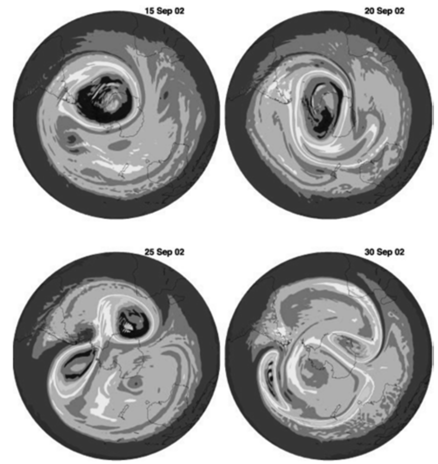
## Vertical Cross-Section of Atmospheric Temperatures




- ❑ The global average temperature at the surface of Earth is about 288 K, 15°C, or 59°F.
- ❑ In Southern Hemisphere winter, the polar stratosphere is colder than 180 K, and is the coldest place in the atmosphere, even colder than the tropical tropopause.
- ❑ The Northern Hemisphere stratosphere does not get as cold, on average, because planetary Rossby waves generated by surface topography and east–west surface temperature variations transport heat to the pole during sudden stratospheric warming events.

ESS200
Prof. Jin-Yi Yu

## Sudden Warming




- ❑ Every other year or so the normal winter pattern of a cold polar stratosphere with a westerly vortex is interrupted in the middle winter.
- ❑ The polar vortex can completely disappear for a period of a few weeks.
- ❑ During the sudden warming period, the stratospheric temperatures can rise as much as 40°K in a few days!

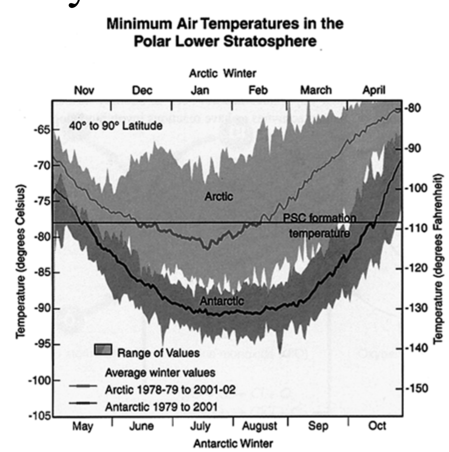
ESS200
Prof. Jin-Yi Yu

## Why Sudden Warming?

- ❑ Planetary-scale waves propagating from the troposphere (produced by big mountains) into the stratosphere.
- ❑ Those waves interact with the polar vortex to break down the polar vortex.
- ❑ There are no big mountains in the Southern Hemisphere to produce planetary-scale waves.
- ❑ Less (?) sudden warming in the southern polar vortex.

ESS200
Prof. Jin-Yi Yu

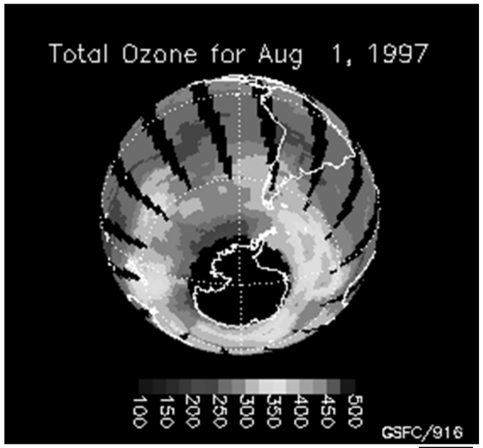
## Why No Ozone Hole in Artic?




(from WMO Report 2003)

ESS200
Prof. Jin-Yi Yu

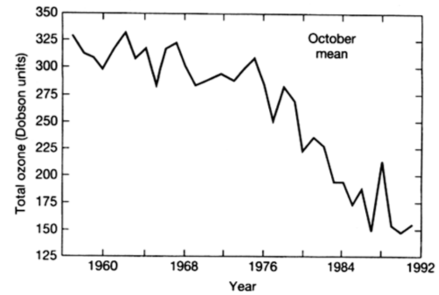
# The 1997 Ozone Hole




ESS200
Prof. Jin-Yi Yu

# Antarctic Ozone Hole

**Mean Total Ozone Over Antarctic in October**




(from *The Earth System*)

- ❑ The decrease in ozone near the South Pole is most striking near the spring time (October).
- ❑ During the rest of the year, ozone levels have remained close to normal in the region.

ESS200
Prof. Jin-Yi Yu

# Polar Stratospheric Clouds (PSCs)

(Sweden, January 2000; from NASA website)

- ❑ In winter the polar stratosphere is so cold (-80°C or below) that certain trace atmospheric constituents can condense.
- ❑ These clouds are called “polar stratospheric clouds” (PSCs).
- ❑ The particles that form typically consist of a mixture of water and nitric acid (HNO3).
- ❑ The PSCs alter the chemistry of the lower stratosphere in two ways:

  (1) by coupling between the odd nitrogen and chlorine cycles

  (2) by providing surfaces on which heterogeneous reactions can occur.

ESS200
Prof. Jin-Yi Yu

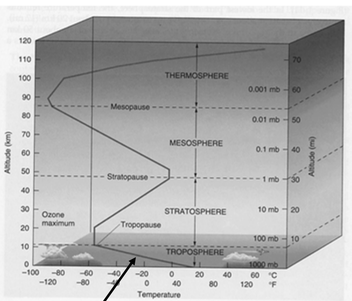
# Ozone Hole Depletion

- ❑ Long Antarctic winter (May through September)
- ➔ The stratosphere is cold enough to form PSCs
- ➔ PSCs deplete odd nitrogen (NO)
- ➔ Help convert unreactive forms of chlorine (ClONO2 and HCl) into more reactive forms (such as Cl2).
- ➔ The reactive chlorine remains bound to the surface of clouds particles.
- ➔ Sunlight returns in springtime (September)
- ➔ The sunlight releases reactive chlorine from the particle surface.
- ➔ The chlorine destroy ozone in October.
- ➔ Ozone hole appears.
- ➔ At the end of winter, the polar vortex breaks down.
- ➔ Allow fresh ozone and odd nitrogen to be brought in from low latitudes.
- ➔ The ozone hole recovers (disappears) until next October.

ESS200
Prof. Jin-Yi Yu

# Lapse Rates

**Standard Atmosphere**




(from *Understanding Weather & Climate*)

lapse rate = 6.5 C/km

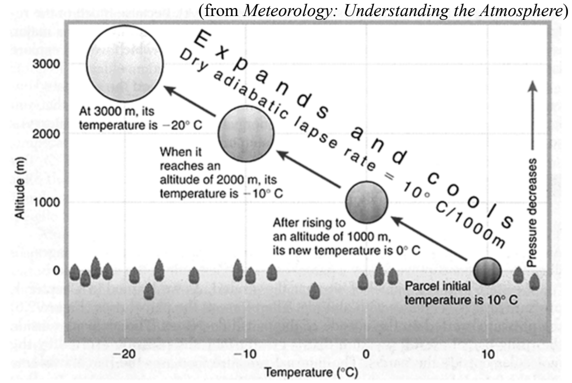
- An important feature of the temperature distribution is the decline of temperature with height above the surface in the lowest 10–15 km of the atmosphere.
- This rate of decline, called the lapse rate, is defined by $\Gamma \equiv -\frac{\partial T}{\partial z}$
- A lapse rate is the rate at which temperature decreases (lapses) with increasing altitude.
- Three different lapse rates we need to consider:

(1) dry adiabatic lapse rate
(2) moist adiabatic lapse rate
(3) environmental lapse rate

ESS200
Prof. Jin-Yi Yu

# Dry Adiabatic Lapse Rate

(from *Meteorology: Understanding the Atmosphere*)

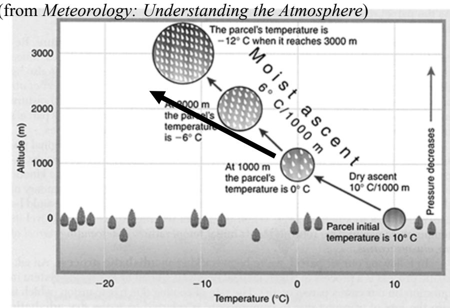



- Air parcels that do not contain cloud (are not saturated) cool at the dry adiabatic lapse rate as they rise through the atmosphere.
- Dry adiabatic lapse rate = 10°C/1km

ESS200
Prof. Jin-Yi Yu

# Moist Adiabatic Lapse Rate

(from *Meteorology: Understanding the Atmosphere*)

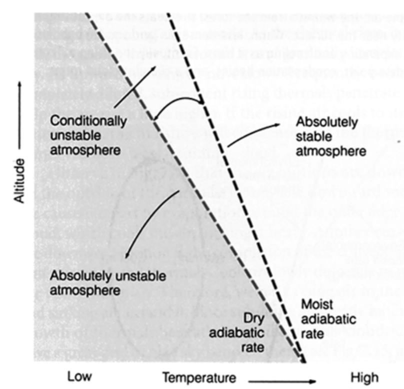



- Air parcels that get saturated as they rise will cool at a rate smaller than the dry adiabatic lapse rate due the heating produced by the condensation of water vapor.
- This moist adiabatic lapse rate is not a constant but determined by considering the combined effects of expansion cooling and latent heating.

- In the lower troposphere, the rate is 10°C/km – 4°C/km = 6°C/km.
- In the middle troposphere, the rate is 10°C/km – 2°C/km = 8°C/km.
- Near tropopause, the rate is 10°C/km – 0°C/km = 10°C/km.

ESS200
Prof. Jin-Yi Yu

# Static Stability of the Atmosphere



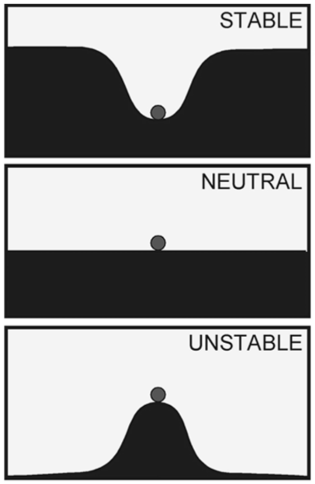

(from *Meteorology Today*)

$\Gamma e$ = environmental lapse rate
$\Gamma d$ = dry adiabatic lapse rate
$\Gamma m$ = moist adiabatic lapse rate

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

ESS200
Prof. Jin-Yi Yu

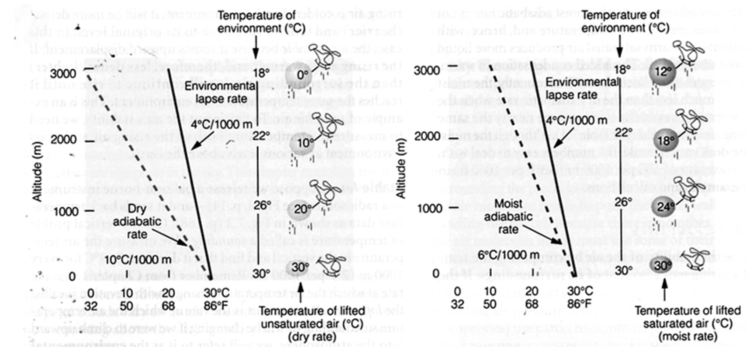
# Concept of Stability






ESS200
Prof. Jin-Yi Yu

# Absolutely Stable Atmosphere



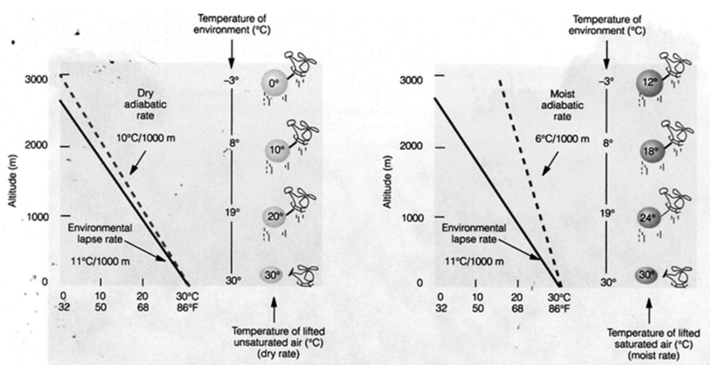

(a) Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position.

(b) Lifted, saturated air at each position is colder and heavier than the air surrounding it. If released, the parcel would return to its original position.

(from *Meteorology Today*)

ESS200
Prof. Jin-Yi Yu

# Absolutely Unstable Atmosphere



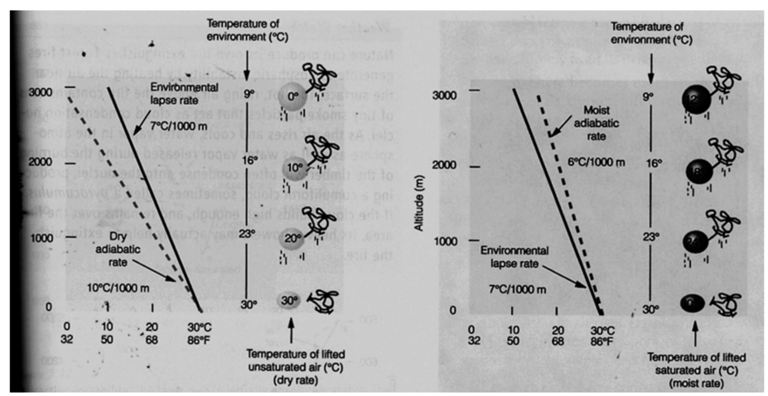

(a) The rising, unsaturated air parcel at each level is warmer and lighter than the air around it. If given the chance, the air parcel would accelerate away from its original position.

(b) The rising, saturated air parcel is warmer than its surroundings. If given the chance, it also would move away from its original position.

(from *Meteorology Today*)

ESS200
Prof. Jin-Yi Yu

# Conditionally Unstable Atmosphere



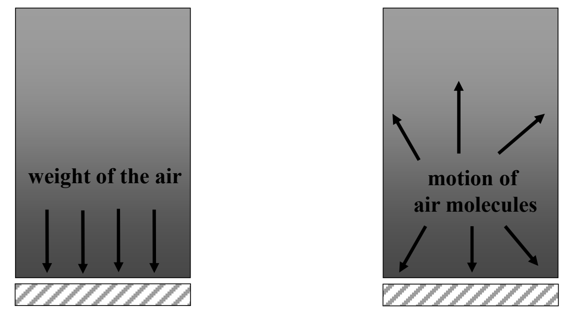

(from *Meteorology Today*)

ESS200
Prof. Jin-Yi Yu

# Pressure

ESS200
Prof. Jin-Yi Yu

# Air Pressure Can Be Explained As:

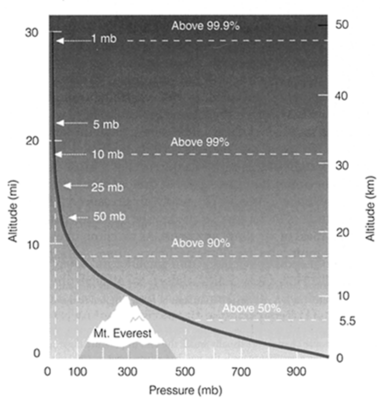



The weight of air above a surface (due to Earth's gravity)

The bombardment of air molecules on a surface (due to motion)

ESS200
Prof. Jin-Yi Yu

# Air Mass and Pressure

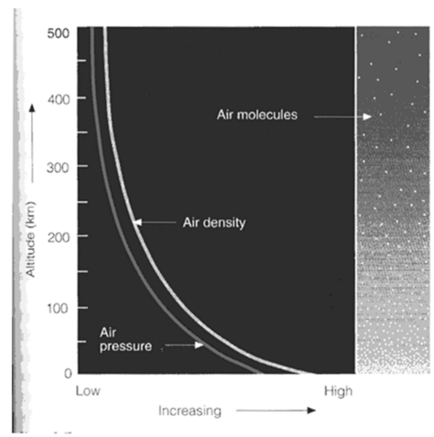



(from *Meteorology Today*)

- ❑ Atmospheric pressure tells you how much atmospheric mass is above a particular altitude.
- ❑ Atmospheric pressure decreases by about 10mb for every 100 meters increase in elevation.

ESS200
Prof. Jin-Yi Yu

# Air Pressure




(from *Meteorology Today*)

- ❑ Weight = mass x gravity
- ❑ Density = mass / volume
- ❑ Pressure = force / area
  = weight / area

ESS200
Prof. Jin-Yi Yu

# Units of Atmospheric Pressure

- **Pascal (Pa):** a SI (Systeme Internationale) unit for air pressure.

  *1 Pa = a force of 1 newton acting on a surface of one square meter*

  *1 hectopascal (hPa) = 1 millibar (mb)* [hecto = one hundred =100]

- **Bar:** a more popular unit for air pressure.

  *1 bar = a force of 100,000 newtons acting on a surface of one square meter*

  *= 100,000 Pa*

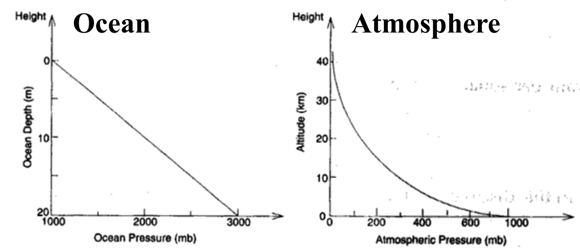
  *= 1000 hPa*

  *= 1000 mb*

- **One atmospheric pressure** = standard value of atmospheric pressure at lea level = 1013.25 mb = 1013.25 hPa.

ESS200
Prof. Jin-Yi Yu

# How Soon Pressure Drops With Height?

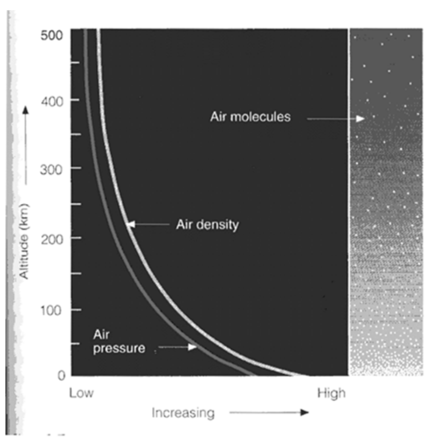



(from ***Is The Temperature Rising?***)

- In the ocean, which has an essentially constant density, pressure increases linearly with depth.
- In the atmosphere, both pressure and density decrease exponentially with elevation.

ESS200
Prof. Jin-Yi Yu

# Air Pressure




(from *Meteorology Today*)

- Weight = mass x gravity
- Density = mass / volume
- Pressure = force / area

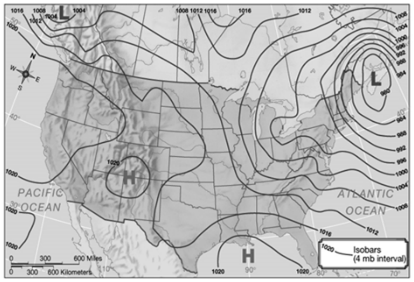
  = weight / area

ESS200
Prof. Jin-Yi Yu

# Pressure

# Winds

# Isobar




- ❑ It is useful to examine horizontal pressure differences across space.
- ❑ Pressure maps depict ***isobars***, lines of equal pressure.
- ❑ Through analysis of ***isobaric charts***, pressure gradients are apparent.
- ❑ Steep (weak) pressure gradients are indicated by closely (widely) spaced isobars.

**ESS200**
**Prof. Jin-Yi Yu**

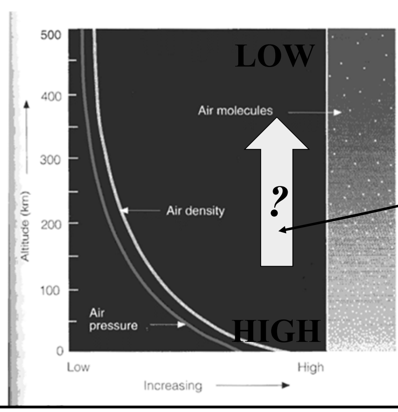
# Pressure Gradients

- Pressure Gradients
  - The pressure gradient force initiates movement of atmospheric mass, wind, from areas of higher to areas of lower pressure
- Horizontal Pressure Gradients
  - Typically only small gradients exist across large spatial scales (1mb/100km)
  - Smaller scale weather features, such as hurricanes and tornadoes, display larger pressure gradients across small areas (1mb/6km)
- Vertical Pressure Gradients
  - ***Average vertical pressure gradients are usually greater than extreme examples of horizontal pressure gradients*** as pressure always decreases with altitude (1mb/10m)

**ESS200**
**Prof. Jin-Yi Yu**

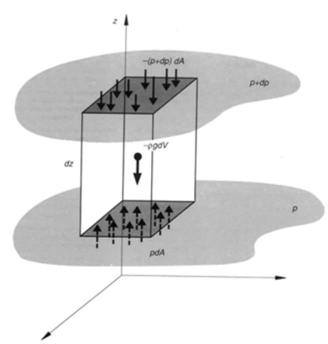
# Why is vertical wind so weak?

| | |
|---|---|
| $U \sim 10\,\mathrm{m\,s^{-1}}$ | horizontal velocity scale |
| $W \sim 1\,\mathrm{cm\,s^{-1}}$ | vertical velocity scale |




**ESS200**
**Prof. Jin-Yi Yu**

# 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 !!***

**ESS200**
**Prof. Jin-Yi Yu**

## 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 ($\rho$) times the acceleration of gravity (g)

ESS200
Prof. Jin-Yi Yu

## 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:

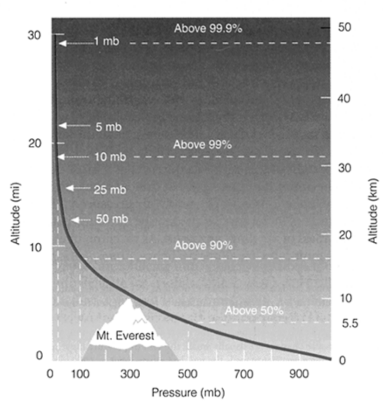
$$\boxed{P = \rho R T}$$

*pressure* *Density=m/V* *temperature* *(degree Kelvin)*

*gas constant* *(its value depends on the gas considered)*

ESS200
Prof. Jin-Yi Yu

### Hydrostatic Balance and Atmospheric Vertical Structure




(from *Meteorology Today*)

- Since $P= \rho RT$ (the ideal gas law), the hydrostatic equation becomes:

  $dP = -P/RT \times gdz$

➔ $dP/P = -g/RT \times dz$

➔ $\boxed{P = P_s \exp(-gz/RT)}$

➔ $P = P_s \exp(-z/H)$

- The atmospheric pressure decreases exponentially with height

ESS200
Prof. Jin-Yi Yu

## The Scale Height of the Atmosphere

"Scale height is a general way to describe how a value fades away and it is commonly used to describe the atmosphere of a planet. It is the vertical distance over which the density and pressure fall by a factor of 1/e. These values fall by an additional factor of 1/e for each additional scale height H. Thus, it describes the degree to which the atmosphere "hugs" the planet."

(from https://astro.unl.edu/naap/scaleheight/sh_bg1.html)

ESS200
Prof. Jin-Yi Yu

## 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*** (or ***7.6 km;*** for the mean temperature of Earth's atmosphere).
- 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.

ESS200
Prof. Jin-Yi Yu

## A Mathematic Formula of Scale Height

gas constant
temperature
gravity
scale height
molecular weight of gas

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

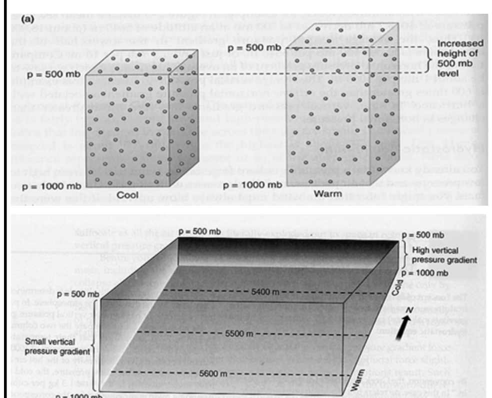
- The heavier the gas molecules weight (m) ➔ the smaller the scale height for that particular gas
- The higher the temperature (T) ➔ the more energetic the air molecules ➔ the larger the scale height
- The larger the gravity (g) ➔ air molecules are closer to the surface ➔ the smaller the scale height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

ESS200
Prof. Jin-Yi Yu

# Temperature

# Pressure

## Temperature and Pressure

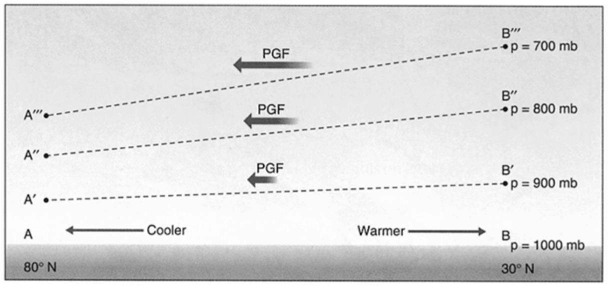



(from Understanding *Weather & Climate*)

- 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.

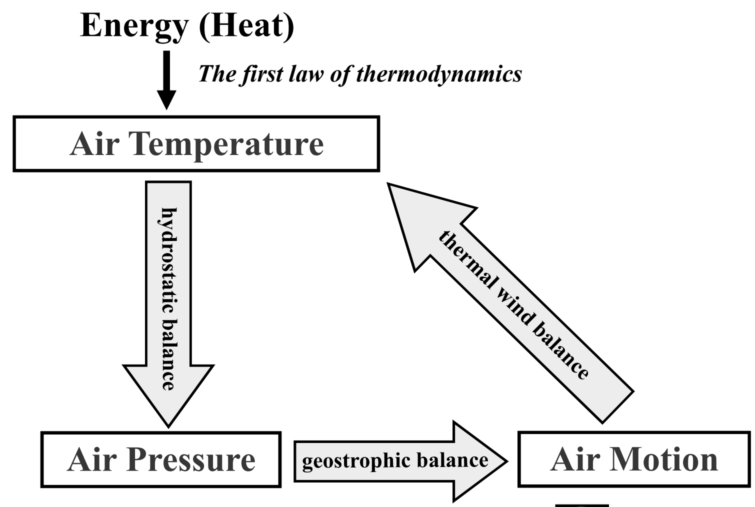
ESS200
Prof. Jin-Yi Yu

# Thermal Wind Relation




(from *Weather & Climate*)








# Humidity

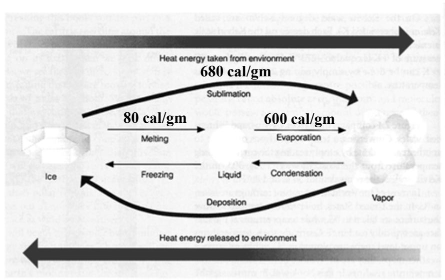
- ❑ Atmospheric humidity is the amount of water vapor carried in the air.
- ❑ Humidity = moisture in the air
- ❑ Atmospheric water vapor is also the most important greenhouse gas in the atmosphere.



# Why Is Water Vapor Important?

- ❑ Over 70% of the planet is covered by water
- ❑ Water is unique in that it can simultaneously exist in all three states (solid, liquid, gas) at the same temperature
- ❑ Water is able to shift between states very easily
- ❑ Important to global energy and water cycles

## Phase Changes of Water

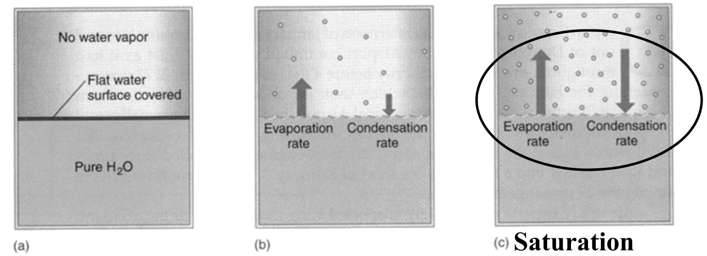



(from *Meteorology: Understanding the Atmosphere*)

- 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.



## 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 Humidity

- 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

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

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

relative humidity

in unit of %



# Specific .vs. Relative Humidity

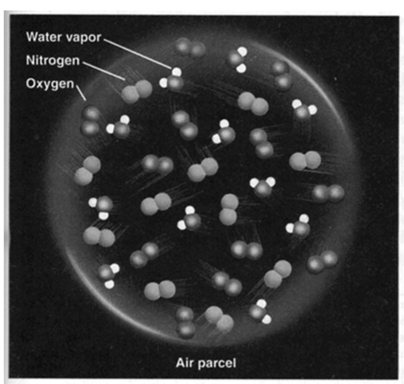
specific humidity 6 gm/kg → saturated specific humidity 10 gm/kg → Relative humidity 6/10 x 100%=60 %

specific humidity 6 gm/kg → 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.



# Observed Specific Humidity

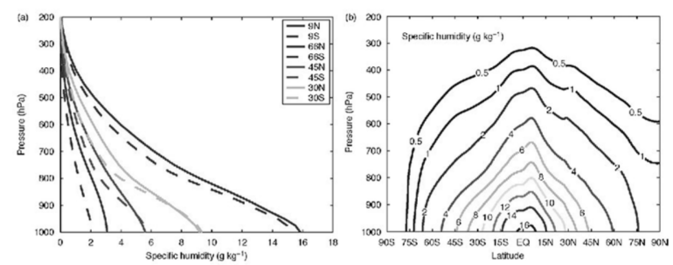
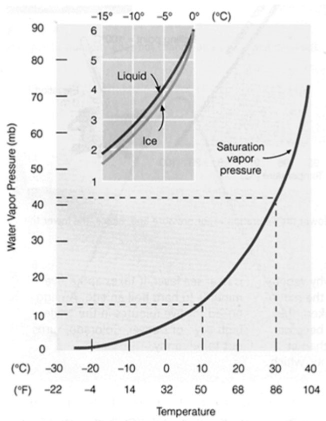



FIGURE 1.8 **Profiles of specific humidity as a function of pressure, for annual-mean conditions as (a) Line plots and (b) Contour plot.** *Data from ERA-Interim.*

(from *Global Physical Climatology)*

- The rapid upward and poleward decline in water vapor abundance in the atmosphere is associated with the strong temperature dependence of the saturation vapor pressure.

# Clausius–Clapeyron Relationship




- ❑ 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; $\alpha$: specific volume of vapor and liquid

ESS200
Prof. Jin-Yi Yu

---

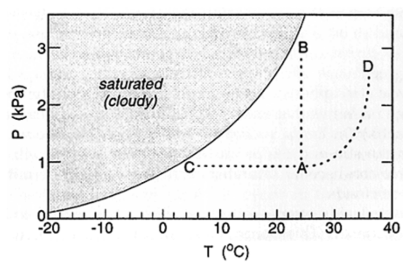
*Clausius–Clapeyron relationship tells us:*

If the relative humidity (the ratio of the actual specific humidity to the saturation specific humidity) remains fixed, then the actual water vapor in the atmosphere will increase by 7% for every 1 K temperature increase.

ESS200
Prof. Jin-Yi Yu

---

# How to Saturate the Air?




(from "*IS The Temperature Rising*")

- ❑ Two ways:

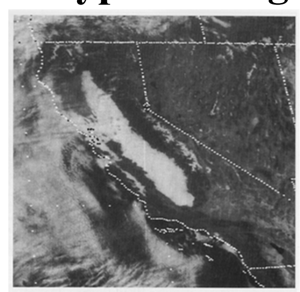
(1) Increase (inject more) water vapor to the air (A➔ B).

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

ESS200
Prof. Jin-Yi Yu

---

# Four Types of Fog



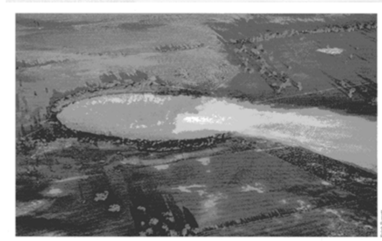
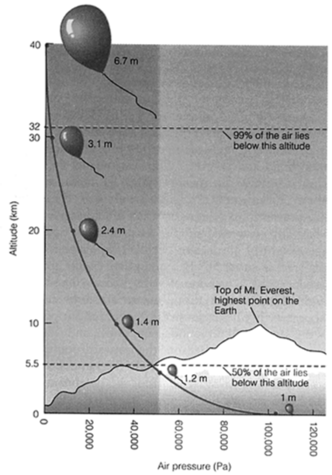


Figure 4.12
An aerial view of steam fog rising and moving downwind from a small lake in Australia. Using your knowledge of relative humidity plus the shadows in this photograph, can you determine what time of day this picture was taken?

- ❑ Radiation Fog: radiation cooling ➔ condensation ➔ fog
- ❑ Advection fog: warm air advected over a cold surface ➔ fog
- ❑ Upslope fog: air rises over a mountain barrier ➔ air expands and cools ➔ fog
- ❑ Evaporation fog: form over lake when colder air moves over warmer water ➔ steam fog

## 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*)

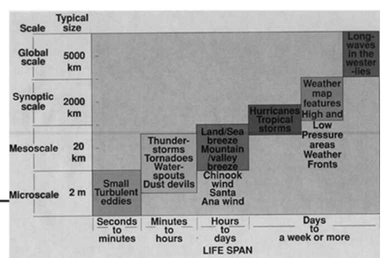
ESS200
Prof. Jin-Yi Yu

# Conservation Laws

ESS200
Prof. Jin-Yi Yu

## Basic Conservation Laws

| Type of motion | Horizontal scale (m) |
|---|---|
| Molecular mean free path | $10^{-7}$ |
| Minute turbulent eddies | $10^{-2} - 10^{-1}$ |
| Small eddies | $10^{-1} - 1$ |
| Dust devils | $1 - 10$ |
| Gusts | $10 - 10^{2}$ |
| Tornadoes | $10^{2}$ |
| Cumulonimbus clouds | $10^{3}$ |
| Fronts, squall lines | $10^{4} - 10^{5}$ |
| Hurricanes | $10^{5}$ |
| Synoptic cyclones | $10^{6}$ |
| Planetary waves | $10^{7}$ |




- Conservation of Momentum
- Conservation of Mass
- **Conservation of Energy**

ESS200
Prof. Jin-Yi Yu

## 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**

ESS200
Prof. Jin-Yi Yu

# 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:

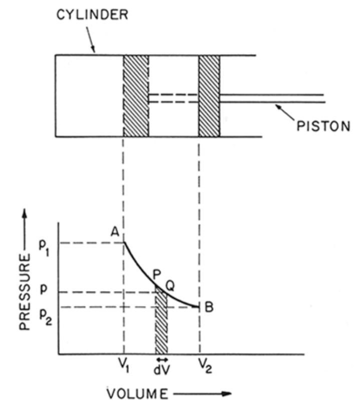
$$\boxed{Q = c*m*\Delta T}$$

Heat added — Mass — Temperature changed

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



(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

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

volume change of the gas — specific heat at constant volume



# 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*)



# Entropy Form of Energy Eq.

$$c_v \frac{DT}{Dt} + p\frac{D\alpha}{Dt} = J$$

***P α = RT***

***Cp=Cv+R***

$$c_p \frac{DT}{Dt} - \alpha\frac{Dp}{Dt} = J$$

***Divided by T***

$$c_p \frac{D\ln T}{Dt} - R\frac{D\ln p}{Dt} = \frac{J}{T} \equiv \frac{Ds}{Dt}$$

- The rate of change of entropy (s) per unit mass following the motion for a thermodynamically *reversible* process.
- A reversible process is one in which a system changes its thermodynamic state and then returns to the original state without changing its surroundings.

# Potential Temperature (θ)

- For an ideal gas undergoing an *adiabatic process* (i.e., a reversible process in which no heat is exchanged with the surroundings; $J=0$), the first law of thermodynamics can be written in differential form as:

$$c_p D \ln T - R D \ln p = D\left(c_p \ln T - R \ln p\right) = 0$$

$$\rightarrow \boxed{\theta = T\,(p_s/p)^{R/c_p}} \qquad \rightarrow \boxed{c_p \frac{D \ln \theta}{Dt} = \frac{J}{T} = \frac{Ds}{Dt}}$$

- Thus, every air parcel has a unique value of potential temperature, and this value is conserved for dry adiabatic motion.
- Because synoptic scale motions are approximately adiabatic outside regions of active precipitation, θ is a quasi-conserved quantity for such motions.
- Thus, for reversible processes, fractional potential temperature changes are indeed proportional to entropy changes.
- A parcel that conserves entropy following the motion must move along an isentropic (constant θ) surface.

ESS200
Prof. Jin-Yi Yu

# 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

ESS200
Prof. Jin-Yi Yu

# 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.

ESS200
Prof. Jin-Yi Yu

# 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.

ESS200
Prof. Jin-Yi Yu

## Diabatic Process

- Involve the direct addition or removal of heat energy.
- Example: Air passing over a cool surface loses energy through conduction.



## Static Stability

If potential temperature is a function of height, the atmospheric lapse rate, $\Gamma \equiv -\partial T/\partial z$, will differ from the adiabatic lapse rate and

$$\frac{T}{\theta}\frac{\partial\theta}{\partial z} = \Gamma_d - \Gamma$$

If $\Gamma < \Gamma d$ so that θ increases with height, an air parcel that undergoes an adiabatic displacement from its equilibrium level will be positively buoyant when displaced downward and negatively buoyant when displaced upward so that it will tend to return to its equilibrium level and the atmosphere is said to be statically stable or *stably stratified*.

$d\theta_0/dz > 0$ statically stable,
$d\theta_0/dz = 0$ statically neutral,
$d\theta_0/dz < 0$ statically unstable.



## Skip Section 1.6.4 of GPC



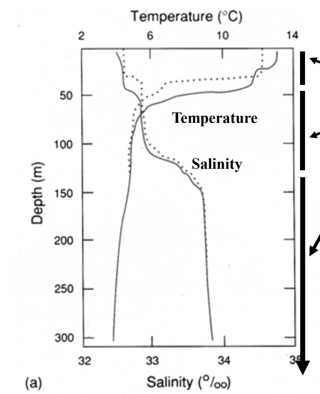
# Oceans

# Roles of the Word Ocean

- The world ocean is a key element of the physical climate system.
- Ocean covers about 71% of Earth's surface to an average depth of 3730 m.
- The ocean has tremendous capability to store and release heat and chemicals on time scales of seasons to centuries.
- Ocean currents move heat poleward to cool the tropics and warm the extratropics.
- The world ocean is the reservoir of water that supplies atmospheric water vapor for rain and snowfall over land.
- The ocean plays a key role in determining the composition of the atmosphere through the exchange of gases and particles across the air–sea interface.

ESS200
Prof. Jin-Yi Yu

# Vertical Structure of Ocean




**Mixed Layer:** T and S well mixed by winds

**Thermocline:** large gradient of T and S

**Deep Ocean:** T and S independent of height
cold
salty
high nutrient level

(from *Climate System Modeling*)

ESS200
Prof. Jin-Yi Yu

# Ocean Temperature

(from *Global Physical Climatology)*

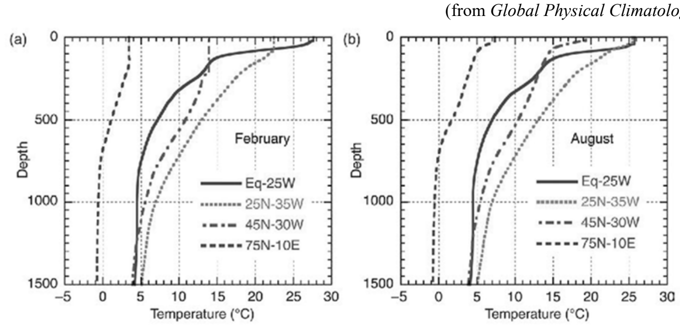
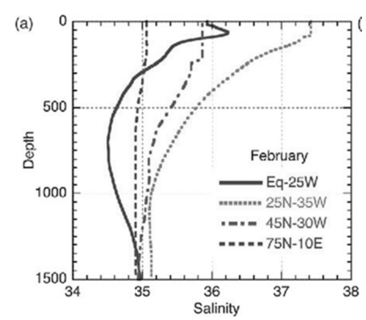



FIGURE 1.11 **Annual-mean ocean potential temperature profiles for various latitudes and as a function of depth in meters for (a) February and (b) August.** *MIMOC data.*

Temperature in the ocean generally decreases with depth from a temperature very near that of the surface air temperature to a value near the freezing point of water in the deep ocean

# Ocean Salinity

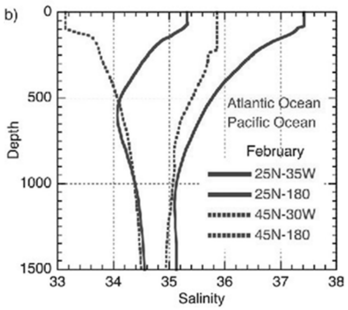
(from *Global Physical Climatology)*

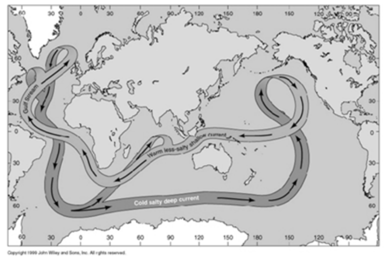



- ❑ Salinity of seawater is defined as the number of grams of dissolved salts in a kilogram of seawater.
- ❑ Salinity in the open ocean ranges from about 33 g/kg to 38 g/kg.
- ❑ Salinity is an important contributor to variations in the density of seawater at all latitudes and is the most important factor in high latitudes and in the deep ocean, where the temperature is close to the freezing point of water.
- ❑ Salinity of the global ocean varies systematically with latitude in the upper layers of the ocean.
- ❑ In the deep ocean, salinity variations are much smaller than near the surface, because the sources and sinks of freshwater are at the surface and the deep water comes from a few areas in high latitudes.

# Ocean Salinity / Pacific vs. Atlantic

(from *Global Physical Climatology)*



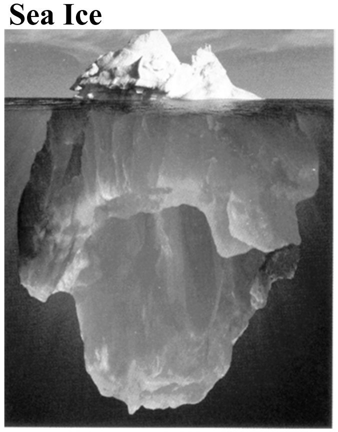
- ❑ The Atlantic is much saltier than the Pacific at nearly all latitudes.
- ❑ For this reason the formation of cold, salty water that can sink to the bottom of the ocean is much more prevalent in the Atlantic than the Pacific.

# Cryosphere



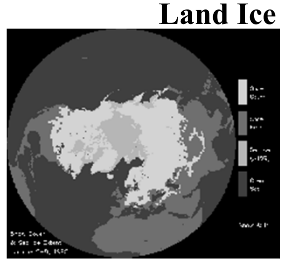
# Cryosphere

**Sea Ice**



(from *The Blue Planet*)

**Land Ice**



❑ The cryosphere is referred to all the ice near the surface of Earth: including sea ice and land ice.

❑ For climate, both the surface and the mass of ice are importance.

❑At present, year-round ice covers 11% of the land area and 7% of the world ocean.

# Land surface

# Climate Roles of Land Surface

- greenhouse gas emissions
  - ➔ affects global energy and biogeochemical cycles
- creation of aerosols
  - ➔ affects global energy and water cycles
- surface reflectivity (albedo)
  - ➔ affects global energy cycle
- impacts on surface hydrology
  - ➔ affect global water cycle

Vegetation

Soil Moisture

Snow/Ice Cover