Earth System Climatology (ESS220)

- **Course Time**
  Lectures: Tu, Th 9:30-10:50
  Discussion: 3315 Croul Hall

- **Text Book**
  *The Earth System*, Kump, Kasting, and Crane, Prentice-Hall

- **Grade**
  Homework (40%), Final (60%)

- **Homework**
  Issued and due every Tuesday

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**Course Description**

- This course offers an overview of Earth's climate system by describing the major climatological features in the atmosphere and oceans and by explaining the physical principals behind them.

- The course begins with an introduction of the global energy balance that drives motions in the atmosphere and oceans, then describes the basic structures and general circulations of the atmosphere and oceans, and finally look into major climate change and variation phenomena.

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**Syllabus**

| WEEK | 9/25 & 9/28 | Overview & Global Energy Balance
|      | 9/30 & 10/5 | Atmospheric Composition; Planetary Energy Balance; Greenhouse Effect; Role of Clouds
|      | 10/7 & 10/12 | Earth Climate System: Atmosphere, Ocean, Land
| Week 1 | 10/14 & 10/19 | Climate Variability
| Week 2 | 10/21 | East and Future Climate Changes
| Week 3 | Final | Earth System Climatology

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**Earth Climate System**

- **Solar forcing**
  - thousands of years
    - (23K, 41K, 100k)

- **Atmosphere**
  - days ~ weeks

- **Ocean**
  - months ~ 1000 years

- **Land**
  - 1-2 seasons

- **Solid Earth**
  - millions of years

- **Energy, Water, and Biochemistry Cycles**
The rising hot rocks and slid-away flows are thought to be the factor that control the positions of ocean basins and continents. The convection determines the shape of the Earth.

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 Composition**

- up to ~500km
  - Heterosphere
  - ~80km
  - Homosphere

- Dominated by lighter gases with increasing altitude, such as hydrogen and helium.
- This part of the atmosphere continually circulates, so that the principal atmospheric gases are well mixed.
- For most purpose, we consider the homosphere virtually the entire atmosphere.

**Composition of the Atmosphere**

*inside the DRY homosphere*

- Water vapor (0-0.25%)
- Carbon dioxide (CO₂) 0.04%
- Nitrogen (N₂) 78.06%
- Oxygen (O₂) 20.95%
- Argon (Ar) 0.93%
- Other gases, such as: Carbon monoxide (CO), helium (He), neon (Ne), krypton (Kr), xenon (Xe), nitrogen oxide (N₂O), hydrogen (H₂), and water vapor (H₂O).

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

(from The Blue Planet)

**Ionosphere and AM Radio**

- The D- and E-layers absorb AM radio, while the F-layer reflect radio waves.
- When night comes, the D-layer disappears and the E-layer weakens. Radio waves are able to reach the F-layer and get reflected further.
- The repeated reflection of radio waves between Earth surface and the F-layer allows them to overcome the effect of Earth’s curvature.

**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 (CH₄) and ammonia (NH₃).
  - 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 (CO₂) with some Nitrogen (N₂) and water vapor (H₂O), and trace amounts of other gases.
**What Happened to H₂O?**

- The atmosphere can only 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 oceans.

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

**Table 1.2**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage of mass of hydrosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>97%</td>
</tr>
<tr>
<td>Ice</td>
<td>2.4</td>
</tr>
<tr>
<td>Fresh water (underground)</td>
<td>0.6</td>
</tr>
<tr>
<td>Fresh water in lakes, rivers, etc.</td>
<td>0.02</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.004</td>
</tr>
</tbody>
</table>

*(from Atmospheric Sciences: An Introductory Survey)*

**Saturation Vapor Pressure**

- Saturation vapor pressure describes how much water vapor is needed to make the air saturated at any given temperature.

- Saturation vapor pressure depends primarily on the air temperature in the following way:

\[
\frac{dT}{dL} = \frac{L}{T(\alpha - \alpha_0)}
\]

- Saturation pressure increases exponentially with air temperature.

**Carbon Inventory**

**What happened to CO₂?**

- 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 process reduced CO₂ in the atmosphere and locked carbon in rocks and mineral.

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

**Table 1.3**

<table>
<thead>
<tr>
<th>Inventory of carbon near the earth’s surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biosphere marine</td>
</tr>
<tr>
<td>Nonmarine</td>
</tr>
<tr>
<td>Ocean (in dissolved CO₂)</td>
</tr>
<tr>
<td>Fossil fuels</td>
</tr>
<tr>
<td>Shales</td>
</tr>
<tr>
<td>Carbonate rocks</td>
</tr>
</tbody>
</table>

*(from Atmospheric Sciences: An Introductory Survey)*
What Happened to N₂?

- 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 O₂ Come from?

- 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 gas 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 most abundant gas in the atmosphere.

Formation of Ozone (O₃)

- With oxygen emerging as a major component of the atmosphere, the concentration of ozone increased in the atmosphere through a photodissociation process.
Ozone (O₃)

- "good" ozone: ~15ppm
- "bad" ozone: ~0.15ppm

Other Atmospheric Constituents

- **Aerosols**: small solid particles and liquid droplets in the air. They serve as condensation nuclei for cloud formation.

- **Air Pollutant**: a gas or aerosol produced by human activity whose concentration threatens living organisms or the environment.

Air Pressure Can Be Explained As:

- Weight of the air: due to Earth's gravity
- Motion of air molecules: due to motion

Air Pressure and Air Density

- Weight = mass x gravity
- Density = mass / volume
- Pressure = force / area
  = weight / area
How Soon Pressure Drops With Height?

- 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.

Ocean

Atmosphere

(from Is The Temperature Rising?)

One Atmospheric Pressure

- The average air pressure at sea level is equivalent to the pressure produced by a column of water about 10 meters (or about 76 cm of mercury column).
- This standard atmosphere pressure is often expressed as 1013 mb (millibars), which means a pressure of about 1 kilogram per square centimeter.

Units of Atmospheric Pressure

- **Pascal (Pa)**: a SI (Systeme Internationale) unit for air pressure.
  \[ 1 \text{ Pa} = \text{a force of 1 newton acting on a surface of one square meter} \]
  \[ 1 \text{ hectopascal (hPa)} = 1 \text{ millibar (mb)} \quad \text{[hecto = one hundred =100]} \]
- **Bar**: a more popular unit for air pressure.
  \[ 1 \text{ bar} = \text{a force of 100,000 newtons acting on a surface of one square meter} \]
  \[ = 100,000 \text{ Pa} \]
  \[ = 1000 \text{ hPa} \]
  \[ = 1000 \text{ mb} \]
- **One atmospheric pressure** = standard value of atmospheric pressure at sea level = 1013.25 mb = 1013.25 hPa.

Units of Air Temperature

- **Fahrenheit (°F)**
- **Celsius (°C)**
  \[ °C = (°F-32)/1.8 \]
- **Kelvin (K)**: a SI unit
  \[ K = °C+273 \]

1 K = 1 °C > 1 °F
**Vertical Thermal Structure**

**Standard Atmosphere**

- **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

**Mesosphere**

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

**Thermosphere**

- very little mass

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**Variations in Tropopause Height**

- From Understanding Weather & Climate

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**Dry Adiabatic Lapse Rate**

- From Meteorology: Understanding the Atmosphere

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**Moist Adiabatic Lapse Rate**

- From Meteorology: Understanding the Atmosphere
Stratosphere

Standard Atmosphere

- 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.

Ozone (O₃)

- "good" ozone ~ 15ppm
- "bad" ozone ~ 0.15ppm

Ozone Column Depths

- The greatest production of ozone occurs in the tropics, where the solar UV flux is the highest.
- However, the general circulation in the stratosphere transport ozone-rich air from the tropical upper stratosphere to mid-to-high latitudes.
- Ozone column depths are highest during springtime at mid-to-high latitudes.
- Ozone column depths are the lowest over the equator.

Mesosphere

- 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.
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.

lapse rate = 6.5 C/km

(from Understanding Weather & Climate)