Chapter 8
Circulation of the Atmosphere

Solar Radiation - initial source of energy to the Earth. It can be absorbed, reflected and reradiated. The redistribution of this energy controls the structure and dynamics of the Atmosphere and Oceans.

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Table 7.1 Composition of the Atmosphere

<table>
<thead>
<tr>
<th>Permanent Gases</th>
<th>Formulas</th>
<th>Percent by Volume</th>
<th>Molecular Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>78.08</td>
<td>28.01</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>20.95</td>
<td>32.00</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>0.93</td>
<td>30.95</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>1.8 x 10⁻²</td>
<td>20.18</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>5.0 x 10⁻²</td>
<td>4.00</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>1.4 x 10⁻²</td>
<td>2.05</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>9.0 x 10⁻⁹</td>
<td>131.30</td>
</tr>
</tbody>
</table>

Variable Gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>Formulas</th>
<th>Percent by Volume</th>
<th>Molecular Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water vapor</td>
<td>H₂O</td>
<td>≤ 4%</td>
<td>18.01</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>3.5 x 10⁻²</td>
<td>44.01</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>1.7 x 10⁻³</td>
<td>16.04</td>
</tr>
<tr>
<td>Nitrogen oxide</td>
<td>N₂O</td>
<td>3.0 x 10⁻³</td>
<td>44.01</td>
</tr>
<tr>
<td>Ozone</td>
<td>O₃</td>
<td>4.0 x 10⁻⁵</td>
<td>48.00</td>
</tr>
</tbody>
</table>

The Atmosphere Is Composed Mainly of Nitrogen, Oxygen, and Water Vapor

What are some properties of the atmosphere?

• The lower atmosphere is a fairly homogeneous mixture of gases.
• Water vapor occupies up to 4% of the volume of the atmosphere.
• The density of air is influenced by temperature and water content.

Ascending air cools as it expands. Cooler air can hold less water, so water vapor condenses into tiny droplets - clouds. Descending air warms as it compresses - the droplets (clouds) evaporate.

The Atmosphere Moves in Response to Uneven Solar Heating and Earth’s Rotation

An estimate of the heat budget for Earth. On an average day, about half of the solar energy arriving at the upper atmosphere is absorbed at Earth’s surface. Light (short-wave) energy absorbed at the surface is converted into heat. Heat leaves Earth as infrared (long-wave) radiation. Since input equals output over long periods of time, the heat budget is balanced.
Heat budget
- Solar input must balance solar output
- Temperature increases/decreases if input is greater/less than output
- Average Earth Temperature is 16°C
- Solar Energy is reradiated from the surface as a long wave.
- Surface of Earth (including oceans) is heated from above
- Atmosphere is heated from below

The Atmosphere
Vertical (thermal) structure of the atmosphere
- Troposphere: lowest layer 0-12 km, temperature decreases with altitude
- Tropopause: minimum temperature zone between the troposphere and stratosphere
- Stratosphere: layer above tropopause 12-50 km, temperature increases with altitude
- Mesosphere: layer above stratosphere 50-90 km, temperature decreases with height
- Thermosphere: layer above mesosphere >90 km, extends out to space

Density of air depends on temperature, water vapor and altitude
- Temperature decrease = density increase
- Water vapor increase = density decrease
- Altitude increase = density decrease

The Solar Heating of Earth Varies with Latitude
The atmosphere reflects, scatters and absorbs solar radiation. At high latitudes solar radiation travels a longer path through atmosphere.

How solar energy input varies with latitude.
Equal amounts of sunlight are spread over a greater surface area near the poles than in the tropics.
Ice near the poles reflects much of the energy that reaches the surface there.
The Solar Heating of Earth Varies with Latitude

Earth as a whole is in thermal equilibrium, but different latitudes are not. The average annual incoming solar radiation (red line) absorbed by Earth and the average annual infrared radiation (blue line) emitted by Earth. Polar latitudes lose more heat to space than they gain, and tropical latitudes gain more heat than they lose. The amount of radiation received equal the amount lost at about 38°N and S. The area of heat gained (orange area) equals the area of heat lost (blue areas) so Earth’s total heat budget is balanced.

What factors govern the global circulation of air?
- Uneven solar heating
- The Coriolis effect

Re-distribution of heat
- Heat gained at Equatorial latitudes
- Heat lost at higher latitudes
- Winds and ocean currents redistribute heat around the Earth

Oceans do not boil away near the equator or freeze solid near the poles because heat is transferred by winds and ocean currents from equatorial to polar regions.

The Seasons: solar heating varies with seasons

During the Northern Hemisphere winter, the Southern Hemisphere is tilted away from the sun and the Northern Hemisphere receives less light and heat. During the Northern Hemisphere summer, the situation is reversed.

The tilt (23½° inclination) causes the seasons
Earth's Uneven Solar Heating Results in Large-Scale Thermal Cell type of Atmospheric Circulation

A convection cell is driven by density differences.

A convection current forms in a room when air flows from a hot radiator to a cold window and back.

Air warms, expands, becomes less dense, and rises over the radiator. Air cools, contracts, becomes more dense, and falls near the cold glass window.

The Coriolis effect is the observed deflection of a moving object, caused by the moving frame of reference on the spinning Earth.

How does this apply to the atmosphere?

As air warms, expands, and rises at the equator, it moves toward the pole, but instead of traveling in a straight path, the air is deflected eastward.

In the Northern Hemisphere air turns to the right.

In the Southern Hemisphere air turns to the left.

What factors govern the global circulation of air?

- Uneven solar heating
- The Coriolis effect

The Coriolis effect deflects the path of moving objects.

As observed from space, cannonball 1 (shot northward) and cannonball 2 (shot southward) move as we might expect: that is, they travel straight away from the cannons and fall to Earth.

Observed from the ground, however, cannonball 1 veers slightly east and cannonball 2 veers slightly west of their intended targets.

The effect depends on the observer’s frame of reference.
The Coriolis Effect Influences the Movement of Air in Atmospheric Circulation Cells

Global air circulation as described in the six-cell circulation model. Air rises at the equator and falls at the poles, but instead of one great circuit in each hemisphere from equator to pole, there are three in each hemisphere. Note the influence of the Coriolis effect on wind direction. The circulation shown here is ideal – that is, a long-term average of wind flow.

Wind bands – Three convection cells in each hemisphere
- Trade winds = NE (30°N to 0°) and SE (30°S to 0°)
- Westerlies = 60°N to 30°N and 60°S to 30°S
- Polar easterlies = 90°N to 60°N and 90°S to 60°S
- Low pressure at 0°, 60°N, and 60°S
- Low pressure, ascending air, clouds, increased precipitation
- High pressure at 30°N, 30°S, 90°N, and 90°S
- High pressure, descending air, clear skies, low precipitation

The Coriolis Effect Influences the Movement of Air in Atmospheric Circulation Cells

A large circuit of air is called an atmospheric circulation cell.

Three cells exist in each hemisphere:
- Hadley cells are tropical cells found on each side of the equator.
- Ferrel cells are found at the mid-latitudes.
- Polar cells are found near the poles.

What are some of the wind patterns found between and within cells?
- Doldrums are calm equatorial areas where two Hadley cells converge.
- Horse latitudes are areas between Hadley and Ferrel cells.
- Trade winds are surface winds of Hadley cells.
- Westerlies are surface winds of Ferrel cells.

Monsoons Are Wind Patterns That Change with the Seasons

Monsoons are patterns of wind circulation that change with the season. Areas with monsoons generally have dry winters and wet summers.
- Sea breeze is cool air from over the water moving toward land. Sea breezes occur after sunrise.
- Land breezes occur after sunset when air warmed by the land blows toward the water.
In the Northern Hemisphere
Air flows clockwise around high pressure systems
Air flows counterclockwise around low pressure systems

Monsoons Are Wind Patterns That Change with the Seasons
A monsoon is a pattern of wind circulation that changes with the season. Locations where monsoons occur typically have wet summers and dry winters.

Monsoon patterns. During the monsoon circulations of January (a) and July (b), surface winds are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. (c) Detail of summer Asian monsoon, showing location of Cherrapunji, India, one of the world’s wettest places. Rainfall amounts there can exceed 10 meters (425 inches) per year!

Sea Breezes and Land Breezes Arise from Uneven Surface Heating
The flow of air in coastal regions during stable weather conditions.
(a) In the afternoon, the land is warmer than the ocean surface, and the warm air rising from the land is replaced by an onshore sea breeze.
(b) At night, as the land cools, the air over the ocean is now warmer than the air over the land. The ocean air rises. Air flows offshore to replace it, generating an offshore flow (a land breeze).

Storms Are Variations in Large-Scale Atmospheric Circulation
Storms are regional atmospheric disturbances. Storms have high winds and most have precipitation.
Tropical cyclones occur in tropical regions. These storms can cause millions of dollars worth of damage and endanger life.
Extratropical cyclones occur in Ferrel cells, and are winter weather disturbances. These storms can also cause extensive damage.
Both types of storms are cyclones, or rotating masses of low-pressure air.
Extratropical Cyclones Form between Two Air Masses

(a) The genesis and early development of an extratropical cyclone in the Northern Hemisphere

(b) How precipitation develops in an extratropical cyclone. These relationships between two contrasting air masses are responsible for nearly all the storms generated in the polar frontal zone and thus responsible for the high rainfall within those belts and the decreased salinities of surface waters below.

Tropical Cyclones Form in One Air Mass

The internal structure of a mature tropical cyclone, or hurricane. (The vertical dimension is exaggerated in this model of a hurricane.)

Tropical Cyclones Form in One Air Mass

The dynamics of a tropical cyclone, showing the influence of the Coriolis effect. Note that the storm turns the "wrong" way (that is, counterclockwise) in the Northern Hemisphere, but for the "right" reasons.
Tropical Cyclones Form in One Air Mass

The tracks of tropical cyclones. The breeding grounds of tropical cyclones are shown as orange-shaded areas. The storms follow curving paths: First they move westward with the trade winds. Then they either die over land or turn eastward until they lose power over the cooler ocean of mid-latitudes. Cyclones are not spawned over the South Atlantic or the southeast Pacific because their waters are too chilly; nor in the still air—the doldrums—within a few degrees of the equator.

Hurricanes

- Easterly waves = pressure disturbances resulting from variations in trade winds due to changing surface water temperature
- Critical sea surface temperature = 27°C
  - Decrease in atmospheric pressure
  - Increases evaporation rate
  - Increased wind speeds
- Energy from ocean fuels hurricanes
  - Water vapor extracted from warm sea surface
  - Energy released during condensation

- Heat capacity (review)
  - Heat capacity of ocean is greater than that of land
  - Ocean currents, wind and waves can transfer heat downward in summer and upward in winter
  - Larger seasonal variations of temperature over land
  - Oceans control surface temperatures in Southern Hemisphere
  - Land in the Northern Hemisphere influences the range in surface temperature
Chapter 8 - Summary

The interaction of ocean and atmosphere moderates surface temperatures, shapes Earth's weather and climate, and creates most of the sea's waves and currents.

Different amounts of solar energy are absorbed at different latitudes, and this makes the tropics warmer than the polar regions.

Uneven solar heating causes convection currents to form in the atmosphere and leads to areas of different atmospheric pressures. The direction of air flow in these currents is influenced by the rotation of Earth.

To observers on the surface, Earth's rotation causes moving air (or any moving mass) in the Northern Hemisphere to curve to the right of its initial path, and in the Southern Hemisphere to the left. This is known as the Coriolis effect.

Chapter 8 - Summary

The atmosphere responds to uneven solar heating by flowing in three great circulating cells over each hemisphere. The flow of air within these cells is influenced by Earth's rotation (Coriolis effect). Each hemisphere has three large atmospheric circulation cells: a Hadley cell, a Ferrel cell, and a polar cell (less pronounced over the South Pole).

Large storms are spinning areas of unstable air that develop between or within air masses. Extratropical cyclones originate at the boundary between air masses.

Tropical cyclones, the most powerful of Earth's atmospheric storms, occur within a single humid air mass.

Assigned Reading:

1. The Atlantic Hurricane Season of 2005 was the most Destructive ever Recorded

includes sections: 8.19, 8.20, 8.21, 8.22, 8.23, and 8.24 (5 pages)