ESCI 241 – Meteorology
Lesson 1 – Composition and Structure of the Atmosphere

References: ***Meteorology Today*, Ahrens**

Reading: MT – Chapter 1

GENERAL

- **Atmosphere is very thin compared to size of earth.**
    - **If earth were a basketball, our atmosphere would be as thick as a sheet of paper.**
    - **No defined upper limit to the atmosphere**
- **Energy source for the atmosphere is the Sun**
    - **Atmosphere is <u>not</u> heated due to heat in core of earth.**

IDEAL GAS LAW

- **Air behaves like an *ideal gas***
    - **No forces between molecules**
    - **Volume depends only on pressure, temperature, and number (not type) of molecules**
- **The *ideal gas law* (also known as the *equation of state*) relates pressure, temperature, and density (or volume).**
    - **In chemistry the ideal gas law is**

$$pV = nRT\,.$$

    - **In meteorology we use a different form, derived by**

$$p = \frac{n}{V}RT = \frac{Mn}{V}\frac{R}{M}T = \rho R'T$$
$$R' \equiv R/M$$

    - ***R′* is the *specific gas constant,* and *is different for different gases*.**
    - **For dry air, the specific gas constant is called *R_d*, and is 287 J-kg^{-1}-K^{-1}**

$$\boxed{\begin{aligned} p &= \rho R_d T \\ R_d &= 287 J - kg^{-1} - K^{-1} \end{aligned}}$$

Ideal Gas Law for Dry Air

COMPOSITION

- **Since air is an ideal gas, a volume percentage of its components is the same as a molecular percentage.**
- **Air is composed of fixed gases, variable gases, and aerosols**
- **Fixed gases**
    - **Nitrogen (N_2) - 78%**
    - **Oxygen (O_2) - 21%**
    - **Argon (Ar) - 0.9%**
    - **Carbon dioxide (CO_2) - 360 ppmv**
    - **Neon (Ne)**
    - **Helium (He)**
    - **Methane (CH_4)**
    - **Krypton (Kr)**
    - **Hydrogen (H_2)**
- **Variable gases**
    - **Water vapor (H_2O)**
    - **Ozone (O_3)**
- **Aerosols**

EVOLUTION OF THE ATMOSPHERE

- **Original atmosphere composed of gases from volcanoes (known as outgassing), and consisted of**
    - **Water vapor**
    - **Carbon dioxide**
    - **Nitrogen**
    - **Sulfur and others**
- **As earth cooled, water vapor condensed to form oceans, rivers, and lakes.**
- **Oxygen came from plants.**

PRESSURE AND DENSITY

- **Density is mass per volume**
    - **Density is determined by the mass, and number, of molecules.**
    - ***Air is compressible*, which means that you can squeeze the molecules closer together and increase density.**

  - **Air at the surface of the earth is compressed more than air at the top of the atmosphere (because of the weight of the air above it).**
    - **Therefore, density is greatest at the surface of the earth, and decreases as you go up.**
- **Pressure is force per area**
- **There are two types of pressure**
  - ***Hydrostatic pressure*, which is just due to the weight of the air above you**
  - ***Dynamic pressure,* which is due to the motion of the air**
- **In meteorology, dynamic pressure is usually very small, and we will assume for now that atmospheric pressure is solely due to hydrostatic pressure.**

HYDROSTATIC BALANCE

- **In an atmosphere at rest, there are three forces acting on an air parcel.**
  - **Gravity acting downward**
  - **Pressure force acting upward**
  - **Pressure force acting downward**
- **The difference between the upward and downward pressure gradient forces is known as the *pressure gradient force*.**
- **Since the net acceleration on an air parcel at rest is zero, the pressure gradient force must be balanced by the force of gravity.**
- **The balance between the pressure gradient force and gravity is known as *hydrostatic balance*.**
  - **Mathematically, hydrostatic balance is represented by the *hydrostatic equation***

$$\frac{dp}{dz} = -\rho g$$

Hydrostatic Equation

- **Integrating the hydrostatic equation would give an equation for how pressure changes with height. However, this is not straightforward for a real atmosphere.**

  - **For an isothermal atmosphere, however, this gives an equation that looks like**

$$p(z) = p_0 \exp\left(-\frac{g}{R_d T} z\right),$$

where p_0 is the pressure at the surface.

  - **Defining the *scale height* as**

$$H = \frac{R_d T}{g}$$

we get an equation for pressure versus height in an isothermal atmosphere as

$$p(z) = p_0 \exp(-z/H)$$ ***Pressure Change in an Isothermal Atmosphere***

- **Thought the actual atmosphere isn't isothermal, the pressure still changes somewhat exponentially with height, and to a first approximation we can use a scale height of $H \approx 8.1$ km (which corresponds to an average temperature of about 277 K).**
- **A rule of thumb…the pressure drops by ½ for every 5.6 km of altitude.**
- **Since density is related to pressure via the ideal gas law, we find that density also decreases exponentially with height according to**

$$\rho(z) = \rho \exp(-z/H)$$ ***Density Change in an Isothermal Atmosphere***

LAPSE RATE

- **The lapse rate indicates how rapidly the temperature decreases with height. Mathematically, it is defined as**

$$\boxed{\gamma = -\frac{dT}{dz}}$$ ***Definition of Lapse Rate***

  - **Lapse rate is defined with a negative sign. Thus, *if temperature decreases with height the lapse rate is positive*.**

THERMAL STRUCTURE OF THE ATMOSPHERE

- **The atmosphere can be divided into different layers based on its thermal (temperature) structure. These layers are differentiated by whether the lapse rate is positive or negative.**

- **The layers, from bottom to top, are:**

Layer	*Lapse rate*	*Mean Altitude*	*Remarks*
Troposphere	+	**0 – 11 km**	**- Contains majority of atmosphere.** **- Where most "weather" occurs.** **- Temperature decreases with height because heat source is at bottom (due to Sun's rays striking earth.** **- Thickness (height) varies with season and location. Higher in summer and in Tropics.**
Stratosphere	–	**11 – 47 km**	**- Contains ozone layer.** **- Temperature increases with height due to absorption of UV rays by ozone.**
Mesosphere	+	**47 – 85 km**	
Thermosphere	–	**> 85 km**	**- Temperature increases because heat source is at top (due to absorption of Sun's rays by molecular nitrogen and oxygen).** **- Temperature is hot, but it wouldn't feel hot. This is because there are so few molecules.**

- **The levels separating the layers are named by taking the prefix of the layer below and putting the suffix –*pause* with it.**
  - **Example – The top of the troposphere is the *tropopause*.**

HETEROSPHERE AND HOMOSPHERE

- **Lower part of atmosphere (below about 80 km) is well mixed (fixed gases are found in constant proportions).**
  - **The well-mixed layer is called the *homosphere*.**
  - **Above the homosphere is found the *heterosphere,* which is not well mixed. Lighter molecules found at higher altitudes.**

IONOSPHERE

- **The ionosphere is the region above about 60 km, where there are numerous ions and free electrons present.**
  - **Important for HF and AM radio propagation.**

EXERCISES

1. From the ideal gas law $pV = nRT$, calculate how many molecules are contained in a cubic centimeter (cm^3) of air at a pressure of 1013.25 mb and a temperature of 15 °C? ($R = 8.3145$ J-mol^{-1}-K^{-1}; $N_A = 6.022 \times 10^{23}$ molecules/mol)

2. How many oxygen molecules are there in a cm^3 of air at a pressure of 1013.25 mb and a temperature of 15 °C?

3. The table below gives the molecular weights and volume percentages for the standard atmosphere. Use them to show that the molecular weight of air is 28.964 g/mol.

Gas	M (g/mol)	% by volume
N_2	28.0134	78.084
O_2	31.9988	20.9476
Ar	39.948	0.934
CO_2	44.00995	0.0314

4. Show that the specific gas constant for dry air (R_d) is equal to 287.1 J-kg^{-1}-K^{-1}.

5. Levels of CO_2 in the atmosphere have been increasing since the industrial revolution. Is the specific gas constant for dry air larger or smaller now than it was in 1800?

6. Explain why moist air is lighter than dry air (at the same pressure and temperature).

7. Assuming a scale height of 8.1 km, how many molecules are in a cm^3 of air at the altitude where the air pressure is 500 mb? (Hint: density and the number of molecules per volume both decrease with height in the same way that pressure does)

8. How many oxygen molecules are there in a cm^3 of air at the altitude where the air pressure is 500 mb? Explain why airplane cabins are pressurized.

9. If the temperature at the ground is 15°C and the lapse rate is 4°C/km, what is the temperature at an altitude of 5000 m?

10. If the atmosphere was incompressible (density constant at all altitudes), 100 km thick, and had a surface pressure of 1000 mb, at what altitude would the pressure be 250 mb? Sketch the graph of pressure vs. altitude for this case and discuss how it compares with the real atmosphere.