ATOC 3500
Factors that contribute to pollution buildup and dispersal

Objective – to describe the variation of pressure and temperature with altitude in the lower atmosphere

Reading – Chapter 3

Additional material on hydrostatic balance – see web site

Motivation – although the atmosphere rids itself of harmful pollutants by a series of reactions that eventually produce compounds that rain out or are deposited on surfaces, it does so on finite timescales. That is, the pollutants can spend long periods of time in the atmosphere, anywhere from hours to days or weeks, even years and centuries (recall the Junge relationship).

Question – what processes determine the rates at which pollutants are dispersed in the atmosphere?

Pollutants released at the ground or by elevated sources (smokestacks or aircraft) are transported by winds and gradually mixed with ‘clean’ air by processes such as turbulence and diffusion – the combination of which we refer to as *dispersion*. These processes are studied in the field called *fluid dynamics* (or *fluid mechanics)*.

First we need to examine the forces that determine the vertical variation of pressure

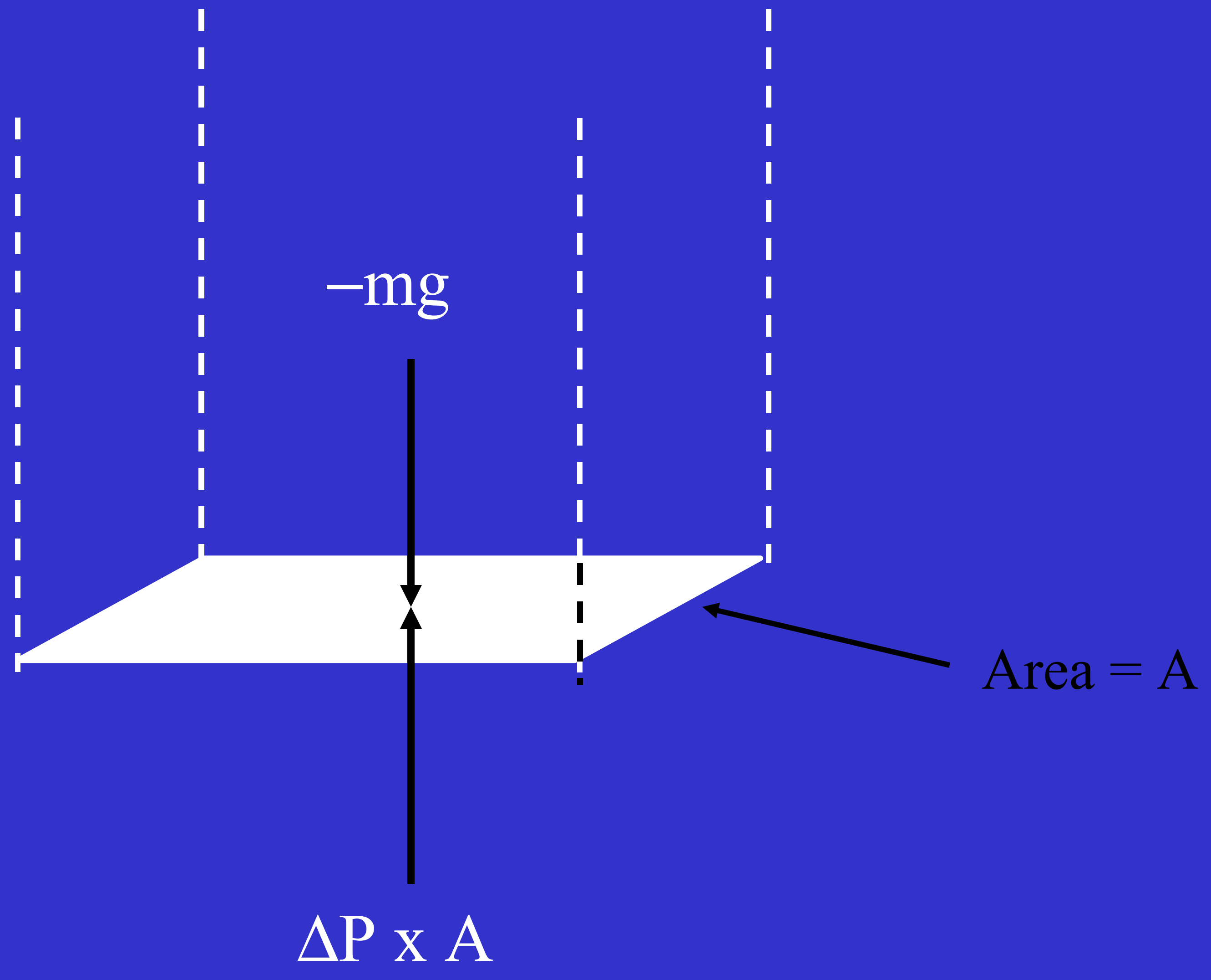
Pressure is defined as *force per unit area*

$$P = \text{force/area}$$

The vertical force acting on air is gravity (g)

$$F = m\,a$$
$$= m\,g$$

Hydrostatic balance – balance downward force due to weight of air (F = mg) with the upward force due to pressure gradient force, ΔP x Area



Assume a thin layer of gas. The pressure change across this layer is:

$$A \Delta P = -mg = -\rho g (A \Delta z)$$

Change finite difference (Δ) to infinitesimal (d) (I.e. ‘calculus’)

$$dP = -g\rho \, dz$$

Remember that density (ρ) is related to pressure by the ideal gas law

$$P = \rho RT$$

Substituting the ideal gas law into the hydrostatic balance equation:

$$dP = -g(P/RT) \, dz$$
$$dP/P = -g(1/RT) \, dz$$

Assuming that g and T are approximately constant with altitude (a good assumption for g, but a slight bit of a stretch for T, which varies by ~30% with altitude, as we have seen in class)

$$P/P_o = exp\ [-gz/RT]$$

Where z = 0 at sea level

The exponent is typically simplified by substituting H = RT/g, which is known as the "scale height", yielding the barometric law:

$$P = P_o\ exp[-z/H]$$

The value of H is about 7 km in the troposphere and stratosphere.

Problem: An airplane typically flies at 10 km (33,000 ft) altitude. What is the approximate pressure there?

$$P = P_o \exp(-z/H) = 1013 \text{ mb} \bullet \exp(-10/7) = 240 \text{ mb}$$

Note – this is about ¼ the pressure at sea level

On your own – repeat the calculation for the summit of Mt. Everest, which is at 29,000 feet. Why do you suppose most climbers use bottles of pure O_2?

How temperature varies with altitude

In the troposphere, the average temperature structure is determined by ideal gas behavior

($p = \rho RT$). But in the atmosphere, density and pressure both decrease with altitude, so we need a more sophisticated picture to calculate magnitude of change.

Consider a thermodynamic situation called *adiabatic*, meaning that when a process occurs there is no gain or loss of heat (expressed in thermodynamics as the identity $dQ = 0$) .

Temperature, T, is related to heat energy, but does that mean for an adiabatic process where there is no change in T?

$\Rightarrow$ If volume stays constant, YES! That is, if you don't put in any heat or take any out, there will be no change in temperature – pretty logical. But when air moves up or down in the atmosphere, pressure changes.

ENN FULL STORY
Honda Shows Cleaner Next-Generation Diesel, Streamlined Fuel Cell Car

September 25, 2006 — By Yuri Kageyama, Associated Press
HAGA, Japan — Diesel engines deliver great mileage but emit polluting gases. Fuel cell vehicles are zero-emission but look bulky. Honda's latest innovations counter the stereotypes. The latest fuel cell vehicle from the Japanese automaker, planned for limited marketing in Japan and the U.S. in 2008, has a slick, streamlined, close-to-the-ground look. Honda Motor Co.'s next-generation diesel engine delivers as clean a drive as a low-emission gas engine of comparable size. Honda's showcased its latest developments in clean driving to reporters recently at its research facility north of Tokyo. In a test drive, the FCX Concept fuel cell vehicle zipped quietly and effortlessly on a course at about 100 miles per hour. Honda declined to give a price for the vehicle. Like other fuel cell vehicles, the new model runs on the power produced when oxygen in the air combines with hydrogen that's stored in the fuel tank -- producing only harmless water vapor.

Old-style fuel cell stacks, the main part of the fuel cell vehicle, are usually placed under the floor of a car, making for thick floors and a box-like look. Honda's new fuel cell stack is 20 percent smaller than the one it developed in 2003, and can sit in between the driver and passenger's seats in the front, where the stick shift lies in a regular car. It weighs 67 kilograms (148 pounds), or about two-thirds of the 96-kilogram (213-pound) 2003 version, and far lighter than the one released in 1999, which weighed 202 kilograms (445 pounds). But it produces more power. Another innovation in the works at Honda is the next-generation diesel car -- planned for the U.S. market within three years.

Diesels are growing in popularity in Europe and some other parts of the world because of their fuel efficiency, and automakers have been working on technology to reduce diesel emissions as nations toughen environmental standards. Honda said its new engine meets standards applied in the U.S. state of California, the world's most stringent. The key to Honda's diesel innovation is the catalytic converter attached to the engine. Honda used an ingenious way to generate ammonia -- a substance that can turn harmful nitrogen oxide into harmless nitrogen.

Diesel engine systems already use ammonia to reduce nitrogen oxide emissions. But Honda's system is self-sustaining and more efficient than others, company officials said. Honda President Takeo Fukui said Honda is serious about fighting global warming and reducing pollution. "Honda believes in the importance of keeping a creative spirit and upholding high ideals," he told reporters.

Imagine a balloon filled with air in Boulder and released. As the balloon rises, what happens?

The balloon expands and the air inside it cools.

If the balloon were filled on the top of Long's Peak and forced down to Boulder, what would happen?

The balloon is compressed and the air inside warms.

In both cases, the volume changes, so WORK is done.

Pressure-volume work: $dW = -PdV$

One measure of the total energy of a system is called enthalpy, H:

$$dH = dQ + dW$$

"change in elthalpy" equals "change in heat" plus "change in work"

Under adiabatic conditions, $dQ = 0$, so $dH = 0 - pdV$. That is, if an air parcel moves up or down adiabatically, the change in enthalpy is related simply to the change in what is called "PV work" – work due to a change in volume.

So, as volume grows for an air parcel that rises, the molecules inside the parcel do work – specifically, they push external molecules away. They are able to do this by using some of their internal energy (i.e. enthalpy), and do their temperature drops, and the parcel gets colder.

Alternatively, if the volume of an air parcel decreases, work is done on the parcel by external molecules, so the parcel gets warmer.

Expansion: A can of Dust-off

Compression: Filling a bike tire

⇒ Thus, in the troposphere, temperature decreases with increasing altitude due to expansion, so long as that process occurs on relatively short (e.g. hours-days) time scales, which are typical of most convective situations.

What about other regions of the atmosphere? We cannot always assume adiabatic conditions.

In the stratosphere, ozone absorbs sunlight, breaks apart and releases energy to the surroundings, heating them. Thus, as one moves upward in the stratosphere into regions with more UV light, the temperature gets warmer. This is a situation called an “inversion” – rather than a decrease in temperature with altitude, there is an increase.

Why is an inversion important? Air below is trapped – it can’t rise because if it were to rise, it would cool because of expansion into a region of lower pressure, but we know that cold air is more dense than the warmer surrounding air, so the cooler air would sink…I.e. it can’t rise because it isn’t buoyant!

The same thing happens near the ground when the surface cools at night due to radiation (especially true where the climate is very dry, like a desert).

Back to temperature change in the troposphere.

Called the "lapse rate" (Γ):

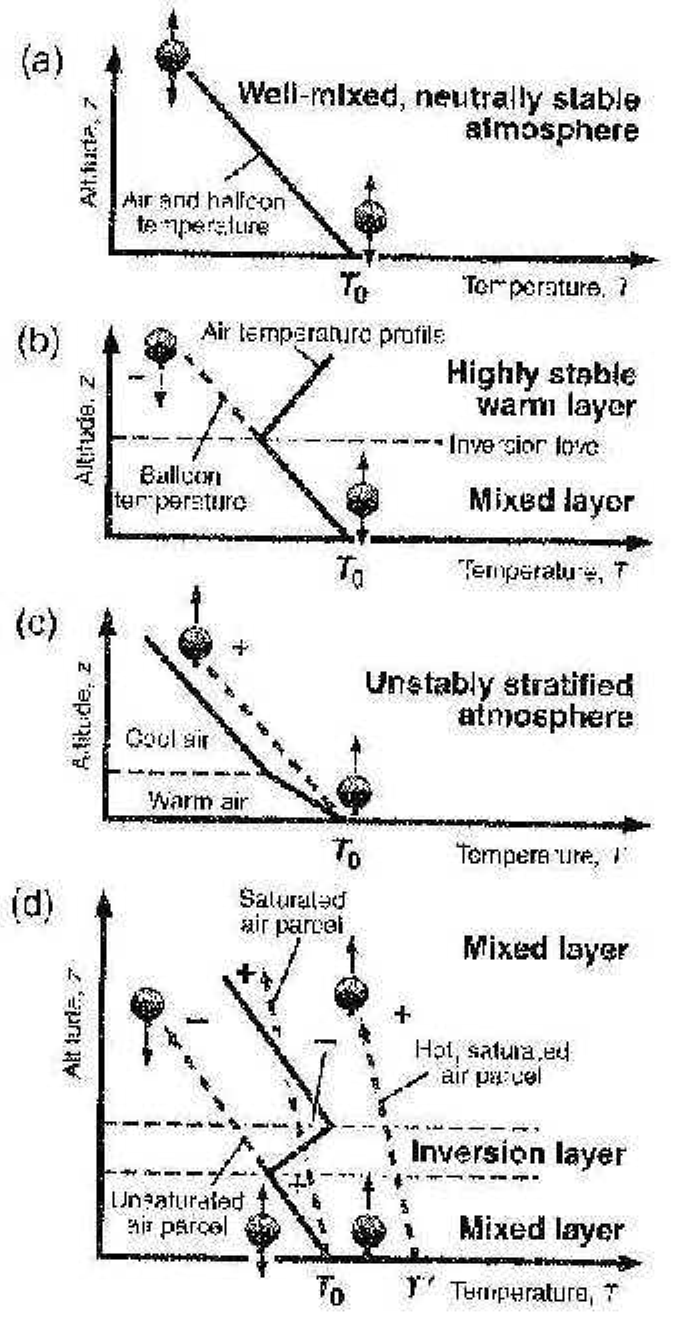
Environmental lapse rate (Γ_e): Actual change of temperature with altitude

Adiabatic lapse rate: Idealized change of temperature with altitude

In dry air (i.e., no condensed water present), the temperature change is controlled by heat capacity of air:

Dry adiabatic lapse rate (Γ_d) ≈ -10^{o}C/km

Now we can understand section 3.1.3 “Atmospheric Stability!”



(a)
Well-mixed, neutrally stable atmosphere
Altitude, z
Air and balloon temperature
T_0
Temperature, T
(b)
Air temperature profile
Highly stable warm layer
Inversion level
Balloon temperature
Mixed layer
T_0
Temperature, T
(c)
Unstably stratified atmosphere
Altitude, z
Cool air
Warm air
T_0
Temperature, T
(d)
Saturated air parcel
Mixed layer
Altitude, z
Hot, saturated air parcel
Inversion layer
Unsaturated air parcel
Mixed layer
T_0
Temperature, T