"The Natural Climate System"
Notes for Lectures 3-4 of AOS/IES 171   Fall 2003
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L3. ATM/OCN Evolution and Composition

The Big Bang theory, Solar System, the Sun and Volcanoes as Climate Control. The laws of physics and inherent chaotic qualities emerged very early. It takes a supernova to make the higher elements upon which life is based. "Gentle life" is very much a byproduct of violent explosions in the hearts of stars. Our solar system condensed out of a rotating disc of stardust about 5 billion years ago (5 x 10^9 ybp or 5 Ga). The originally molten earth cooled, forming moving crustal plates. We are utterly dependent on the sun for maintaining liquid water and to see and to grow food. The yellow photosphere of the sun radiates at a temperature of ~6000 K, the electromagnetic energy that keeps the earth warm and the biosphere alive. The sun is a highly dynamical entity which has changed and will change our climate.

Volcanic Emission versus Present Composition - How can we explain the discrepancies? Volcanoes emit 85% H_2O, 10% CO_2, and a trace of sulfur and nitrogen, while the air we breathe is 78% N_2, 21% O_2, and 1% Ar, (also including a few minor trace gases that act as important "trim-tabs" on the trajectory of our global climate by being greenhouse gases). Why is there so much N_2? Where did the O_2 come from? Where did the H_2O and CO_2 go? To understand these discrepancies, we need to consider interaction among the spheres of the earth system over a long time scale. Their relative masses are: atmosphere (1), hydrosphere (300), lithosphere (5000), biosphere (0.0002), where the mass of the atmosphere is 5x10^{18} kg. Significant processes which account for the discrepancies include: 1) Precipitation created the oceans and removed S and CO_2 in the form of sulfuric and carbonic acids (H_2SO_4 and $CaCO_3$), which became incorporated into rocks; 2) Photosynthesis created fossil fuels and oxygen, and removed CO_2 (see equation (1a)); 3) N_2 doesn't react readily or dissolve in raindrops, so it simply built up over time.

Crustal plates move around on overturning circulations in the asthenosphere at a speed similar to how fast your fingernails grow. The edges of thinner oceanic plates subduct underneath thicker continental plates, where the material melts, giving rise to volcanoes and emissions of trapped gases into the atmosphere. Associated earthquakes have a noumenal essence which has a profound effect on the psychology of living in certain areas of the world. On a geologic time scale, the atmosphere, ocean, and earth's crust exchange molecules quite readily.

Figure 3.1 shows the main atmospheric changes over the last 5 billion years. It is believed that the solar luminosity was much less than at present, so why don't we see evidence of an early frozen planet? This is the "faint young sun paradox". We think that there must have been a lot more CO_2 back then, with the increased greenhouse effect compensating for reduced solar heating. Periods of more active crustal plate recycling, associated volcanism, mountain building and rock weathering led to greater atmospheric CO_2 and warm periods, while reduced activity may explain the lower CO_2 and cold periods.

Summary points include: 1) Energy comes from a *variable* sun, which controls our climate and causes considerable natural variability; 2) Memory of the "local" cosmic dust's angular momentum explains the sense of rotation of the sun, the orbit of planets about the sun, the rotation of most planets, orbits of most moons, defines the plane of the ecliptic and hence which way "north" is, and the "right hand rule" in mathematics; 3) The early atmosphere was blown away by drastic solar variability; 4) Crustal plates recycling on a liquid core allow for exchange of constituents with the atmosphere and ocean; 5) The rotating molten metal core is a geodynamo which provides for a magnetic shield from the solar wind and other particles from outer space; 6) The present atmosphere was outgassed; 7) Rain, photosynthesis and rock formation account for our current air mixture.

L4. ATM/OCN Composition and Structure: Trace Gases, A Breath of Air, Temperature

1. Trace gases - the actors in our climate play. Ne, He, Kr, H_2 are fairly inert (very small loss rates from chemical reactions). Here is a list of climatically important trace gases, with their symbol, concentration, sources, and lifetime. Chemical lifetime is defined to be the total number of that kind of molecule divided by the loss rate. H_2O is the most important greenhouse gas, but is left off of this table because its concentration varies a great deal in space and time.

Carbon dioxide, CO_2: 360 ppmv; fossil fuel and deforestation; > 100 years
Methane, CH_4: 1.7 ppmv; agriculture, cattle, termites; 10 years
Nitrous Oxide, N_2O: 0.3 ppmv; fertilizer, deforestation; 170 years
Carbon Monoxide, CO: 0.1 ppmv; combustion, biomass burning; months
Ozone, O_3: 1 - 50 ppbv troposphere, 10 ppmv stratosphere; in sunlight; hours - days
Odd Nitrogen ("NO_x" = NO_2 and NO); 0 - 50 ppbv; burning; days
Sulfur Dioxide, SO_2; 0 - 50 ppbv; burning; days to weeks
Chlorofluorocarbons; 3 ppbv; spray cans, refrigerant, cleanser; $\sim$80 years
Hydroxyl Radical, OH; 10^{-5} ppbv; tropospheric cleanser; microseconds

Long-lived gases are most relevant to the greenhouse effect and to the Ozone Layer: CO_2, CH_4, N_2O, O_3, CFCs. Acid Rain is due to NO_x and SO_x, while smog is a mixture of NO_x and O_3. The tropospheric cleansing capability of OH is reduced by CO and CH_4.

2. A Breath of Air
One breath $\sim$ 1 liter $\sim 10^{22}$ molecules
Volume of Atmosphere $\sim 10^{21}$ liters
Tropospheric Mixing Time $\sim$ 1 year
Therefore, each time you breathe out, 1 year later each breath you take contains about 10 molecules from every breath you let out!

Each time you breathe in now you take in 10 molecules from every breath by every person on the planet. We all partake of the same molecules within a year or so. This includes everything from tadpoles to the Pope. Here is an example of our inter-connectedness, or web of life, a major component of the climate system. It has been said that 50% of the molecules in our bodies are replaced each year. It makes me wonder how we keep our shape and appearance from year to year!

3. Temperature - a measure of how fast molecules are moving, how much kinetic energy they have. If heat is added, temperature increases. If you remove as much heat as theoretically possible one reaches "absolute zero", or 0 K (zero Kelvins). Most forms of energy

end up as thermal energy, random molecular motions. At room temperature molecules travel at about 500 m/s in all directions. Coincidentally, this is similar to the eastward speed of the earth's surface at the equator.

Daniel Fahrenheit (1700): 0°F (ice, water, salt - road, ice cream), freezing (32°F), boiling (212°F), 180 divisions or degrees

Anders Celsius (late 1700s): freezing (0°C), boiling (100°C), 100 divisions

Lord Kelvin (late 1800s): No thermal motion (0 K), freezing (273 K), boiling (373 K)

$°F \approx 2 \times °C + 30, \quad K = °C + 273$

Compare the temperatures of the sun's photosphere (6000 K), Venus' surface (750 K), Earth's surface (288 K), and Mars' (213 K) Can you account for the differences among the temperatures of these three planets?

4. Figure 4.1 shows the globally averaged vertical temperature structure and the kinds of solar radiation which warm each region. Electromagnetic energy can be absorbed by the atmosphere (making it warmer) or emitted (making it cooler). Sunlight (short wave radiation) warms the ocean and land surface, which cools by radiating infrared (long wave radiation) back toward space. The "turning sphere" or troposphere is heated from below, boiling like a pot of water. The upward temperature decrease pauses at the tropopause. Ozone absorbs ultraviolet light in the stratosphere, where the upward temperature increase pauses at the stratopause. Up there in the middle, air molecules radiate infrared to space but absorb very little from the sun. This upward temperature decrease in the mesosphere pauses at the mesopause. Above that is the wildly variable and hot thermosphere, where the most intense photons of all are trapped, breaking apart molecules. The three warm layers occur from the absorption of different solar wavelength bands, with the most intense, shortest wavelengths being absorbed highest up: xuv in thermosphere, uv in stratosphere, visible at the surface.