Physical Oceanography: A short course for beginners

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Smithville Crescent Publishing House

Smithville Crescent Publishing House
St. John's, Newfoundland, Canada
http://www.physics.mun.ca/~yakov/

ISBN-13: 978-1535312387
ISBN-10: 1535312386

Cover image: The main image shows an iceberg carried by the Labrador Current past St. John's, Newfoundland as viewed from Cape Spear (photograph by Y. D. Afanasyev). The inset image shows an "ocean in the laboratory" where the surface of water in a rotating tank is visualized by optical altimetry (image by Y. Sui and Y. D. Afanasyev). The flow in the tank is a laboratory model of zonal jets occuring in the Earth's oceans and the atmosphere and in the atmospheres of Jupiter and Saturn.

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Chapter 4

Climate change

Climate can be defined as the state of the Earth's atmosphere and the ocean averaged over a period of several years or several decades in order to eliminate seasonal cycle, or relatively short-term, year to year (interannual) variations. Climate studies have become a significant part of physical oceanography and there are reasons for that. Climate is changing and the change is due to human activity, so-called *antropogenic* factors. This can lead to instability and natural disasters and it can even threaten the very existence of humans as a species. Climate changes in the past, even the relatively short-term ones caused by a collision with an asteroid, have caused several mass extinctions. It is very important therefore, to understand the dynamics of the climate system. This is not an easy task, however. The system includes the Earth's ocean, atmosphere, land and biosphere and there are may different factors affecting the system including astronomical ones. In this chapter we briefly review the basics of climate dynamics.

The main human activity affecting climate is the emission of carbon dioxide (CO_2) due to the burning of fossil fuels. Why is this gas so important for climate? In order to understand this we need to consider the so-called *greenhouse effect*.

4.1 Greenhouse effect

The Earth receives its energy from the Sun and radiates the equal amount back to space so that the planet is in equilibrium; it neither loses nor accumulates energy. To study this balance we need to know a few things about how energy is radiated by bodies. The Stefan-Boltzmann law states that the energy radiated from a unit area of a body is proportional to the fourth power of the absolute temperature of the body:

$$E = \sigma T^4, \tag{4.1}$$

where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant. Here W is the power in watts, 1 W = 1 J/s, and K is the absolute temperature, K= °C + 273.15.

Consider now the Earth without its atmosphere. We can write the balance of energy at the Earth's surface in the following form:

$$E_S = E_p = \sigma T_p^4, \tag{4.2}$$

where E_S and E_p are the energy coming from the Sun (and absorbed by the planet) and the energy radiated back by the planet respectively and T_p is the temperature of the planet's surface. Note that a part of the incoming solar energy is reflected back and is not absorbed by the Earth: snow and ice are very effective reflectors. The reflected fraction,α_p, is called the *planetary albedo* and is about one third, that is $\alpha_p \approx 0.3$. The remaining 70 % of the energy is absorbed. E_S only includes the absorbed fraction. Measurements give $E_S \approx 240$ W/m^2; this is the mean value over the entire surface of the planet. Substituting this number into (4.2) we find the mean temperature of the Earth to be

$$T_p = (E_S/\sigma)^{1/4} \approx 255 \text{ K} \ = \ -18° \text{ C}. \tag{4.3}$$

This seems a bit low, doesn't it? This is how cold our planet would be in the absence of its atmosphere.

In order to consider the effect of the atmosphere we need to know at what wavelengths the Sun and the Earth radiate energy. A body at a given temperature gives off energy with a specific spectrum which is determined by the temperature of the body. The spectrum is given by the law of the *black body radiation* or Plank's law. The Sun with its 6000 K surface temperature radiates mostly in the visible spectrum with maximum energy at a relatively short wavelength corresponding to green light. The Earth is much cooler with an observed average temperature of about 288 K = 15° C and so its spectrum is much redder at relatively long wavelengths. This radiation is not visible to human eyes but can be felt as heat and is in the part of the spectrum called infrared (IR).

The Earth's atmosphere is quite transparent to the incoming solar radiation and it lets it through to reach the surface of the planet. However, the atmosphere is quite opaque in the infrared where the Earth radiates. This opacity is due to the presence of certain gases in the atmosphere including water vapor (H_2O) and carbon dioxide (CO_2). They are called greenhouse

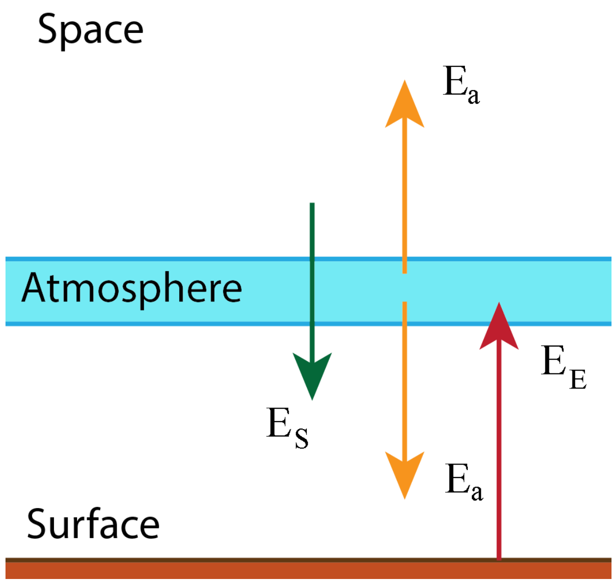

Figure 4.1: Greenhouse model.

gases. Both gases absorb infrared radiation because their molecules have three atoms which can vibrate and rotate at a frequency corresponding to infrared. Let us consider now a simple model which includes the atmosphere (Figure 4.1).

At the top of the atmosphere the energy radiated into space is E_a; it is determined by the temperature of the atmosphere. It must be equal to the incoming energy E_S in order to balance the overall planetary energy budget:

$$E_S = E_a = \sigma T_a^4. \tag{4.4}$$

This equation is the same as (4.2) so that $T_a = T_p$ which we have already calculated to be 255 K. But the atmosphere radiates energy in all directions, so that while it is radiating an amount E_a into space, it is also radiating the same amount down to the surface of the Earth. Thus at the surface, the balance is:

$$E_E = E_a + E_S = 2E_S, \tag{4.5}$$

where E_E is the energy radiated by the Earth's surface. Thus the surface under the cover of the atmosphere receives twice the solar energy. The temperature of the surface is then:

$$T_E = (2E_S/\sigma)^{1/4} = 2^{1/4}T_p. \tag{4.6}$$

The temperature is increased by a factor of $2^{1/4}$ or about 1.2 such that T_E is not 255 K but 303 K = 30° C. This is a bit hotter than it actually is. The reason is the oversimplification of our model. We assumed here that the atmosphere absorbs all of the IR radiation from the surface. Real atmosphere is not perfectly opaque. More detailed greenhouse models can give better predictions of the Earth's temperature.

The high temperature prediction that we obtained in our simple model is not that far off if conditions are close to the perfect greenhouse. In fact, something approaching this happened during the *Cretaceous period* between 145 and 66 million years ago when the concentration of CO_2 was believed to be very high because of the volcanic activity. The temperature was about 15°C higher than today with average temperature of about 30°C. The sea level was about 100 - 200 m higher because all ice sheets were melted. Continents were partially covered with vast shallow seas. Temperature was very uniform around the Earth because of the damping effect of the vast ocean and the inland seas.

Thus, the effect of the atmosphere is similar to that of the glass or plastic film covering a greenhouse. The atmosphere lets through solar radiation but its greenhouse gases absorb the IR radiation from the surface. The concentration of the greenhouse gases increases, the atmosphere becomes more opaque to Infrared Radiation and the surface temperature increases. Even though the concentration of CO_2 is small compared to other gases in the atmosphere its effect is significant.

4.2 Climate history

If we want to choose a single characteristic that describes climate, the best one is, perhaps, temperature. We can find an average temperature of the atmosphere or the average sea surface temperature. Subtracting a constant value which corresponds to temperature over a few recent years, we can find the *temperature anomaly* a term commonly used to describe climate. Temperature anomaly data going back millions of years can be found in databases. Researchers have used considerable ingenuity in establishing this data. One of the methods involves measuring the ratio of the concentrations of the heavy isotope of oxygen ^{18}O and "regular" oxygen ^{16}O. It turns out that this ratio in the molecules of water in the ancient ocean depends on temperature. It takes more energy to evaporate heavier water molecules from the surface and, as a result, in colder climates more ^{18}O remains in the ocean. Shells of *foraminifera* which are made of calcium carbonate, $CaCO_3$ can be used to measure the ratio. The shells can be dated,