Part I: The Natural Climate System

1. Introduction to the Earth System and Global Change

1.1. Spheres of the Earth System

Life on earth is sustained by the atmosphere, which provides oxygen, O_2, for animals and carbon dioxide, CO_2, for plants. The interaction of the atmosphere with *electromagnetic radiation* controls the *heat budget* of the earth. The *general circulation* of the atmosphere rapidly communicates water, chemical constituents, particles, heat, and momentum among the spheres of the earth system. Since the atmosphere is so thin, it is perhaps surprising how much it can accomplish. More than 99% of the mass of the atmosphere lies between the surface and ~50 km altitude. Relative to the size of the earth, the atmosphere is thinner than the skin of an apple. Yet the atmosphere protects life from harmful *ultraviolet radiation* (UV), allows visible light to heat the surface, and absorbs and re-emits enough outgoing *infrared radiation* (IR) to keep the planet from freezing. The ocean, being 1000 times denser than air, lies under the atmosphere and is 300 times more massive. The ocean contains most of the water on earth, the *hydrosphere*. It stores more heat than the atmosphere and introduces an interesting array of long time scales into climate change. It is harder to observe and simulate the state of the ocean since it is opaque (only the surface can be seen from satellite). Furthermore, in situ oceanic observations are sparse compared to radiosondes. Finally, characteristic motion scales in the ocean are almost two orders of magnitude smaller than in the atmosphere, requiring a finer network of observations in the ocean to adequately represent transport and mixing.

Ice, the *cryosphere*, plays a major role in the heat budget of the earth, participating in (and recording) glacial and interglacial cycles, and in weather systems. The *lithosphere* includes the oceanic and continental crustal plates, fossil fuel, and other mineral resources. The *asthenosphere*, or mantle, slowly overturns on geological time scales, causing continental drift. It also causes volcanic eruptions and earthquakes, which can be taken as a sign that things are working correctly for our ultimate safety! Our rotating liquid metal core generates a *magnetosphere* around our planet, which shields us from the solar wind and from cosmic rays, protecting life on earth. Although the mass of the *biosphere* is quite small, life exerts a surprising degree of control over the properties of the atmosphere and ocean and the climate system. The high oxygen content and the existence of ozone and fossil fuels are due to life on earth. Vegetation exerts a very strong influence on the planet's albedo, carbon cycle, hydrologic cycle, and general circulation. On long time scales, life has co-evolved with a chemical and climatic environment that is self-consistent with the success of life. We are now in the process of trying to understand the degree to which we are stretching this principle.

The atmosphere may be divided into layers according to its vertical temperature structure. Temperature decreases upward in the *troposphere*, which is heated from below by sunlight reaching the surface, increases upward in the *stratosphere*, which is heated from the absorption of UV by ozone (O_3), decreases upward in the *mesosphere*, and increases upward into the *thermosphere*, which is heated by extreme UV (XUV). The atmosphere gradually thins out and blends into the solar wind. The *exosphere* contains the moon, sun, other planets, and the rest of the universe, including asteroids that occasionally hit the earth.

The sun is the source of energy for life on earth. The biological *carrying capacity* of the earth is limited by how much energy it can receive from the sun. There is significant exchange of molecules and energy among the different spheres of the earth system. The fact that these spheres are inextricably intertwined motivates the emerging field of *earth system science*. A fundamental principle that we will return to often is the connectivity and interdependence among all phenomena and between the smallest and largest scales. We now introduce two prominent examples of global change issues: the anthropogenic ozone hole, and the relationship between glacial/interglacial cycles and greenhouse gases. This is followed by a brief discussion of changes in population and global change issues in the past 100 years. Finally, a brief history of changes in atmospheric composition and the relationship between photosynthesis and oxidation are introduced.

1.2. Examples of Global Change

1.2.1. The ozone hole and anthropogenic chlorofluorocarbons

Figure 1.1 shows the minimum amount of *column ozone* found during springtime over Antarctica from 1979 to 2021. If you take an average air column, extending from the surface to space, remove all molecules besdies ozone, and compress the ozone molecules to sea level pressure, the resulting layer will be about 3 mm thick, as thick as a dime, or 300 Dobson units (DU). The column ozone amount over Antarctica in October is normally ~250 DU. In the mid-1980s the British Antarctic Survey noticed that column ozone amounts during October over Halley Bay, Antarctica were dropping sharply. Over the past 15 years October column ozone amounts have been below 100 DU, with the area of the ozone hole regularly exceeding the size of North America. This profound ozone minimum lets more damaging UV from the sun reach organisms at the earth surface, harming phytoplankton in the circumpolar Antarctic Ocean. Scientists with the British Antarctic Survey correctly diagnosed that it was caused by long-lasting chemical compounds generated by humans far away from Antarctica.

This observation raised a red flag in the minds of scientists worldwide. It is an alarming example of climate change on a global scale caused by our activities that was not predicted by scientists. It suggests that we should expect other unpredictable results from our current and future activities. Yet this historical example of international cooperation in recognizing a problem and laying the groundwork for its solution provides a model for success. First, scientists diagnosed the cause: industrial manufacturing of *chlorofluorocarbons* (CFCs). Then the international political community responded by creating and enforcing treaties which regulate the manufacture and use of CFCs. CFCs have lifetimes on the order of 50-100 years. Since regulation, the atmospheric concentration of CFCs has stopped increasing. The anthropogenic ozone hole is still near its extreme, but with continued international cooperation scientists anticipate that conditions will gradually return to normal in about 50 years, as the existing CFCs gradually decline.

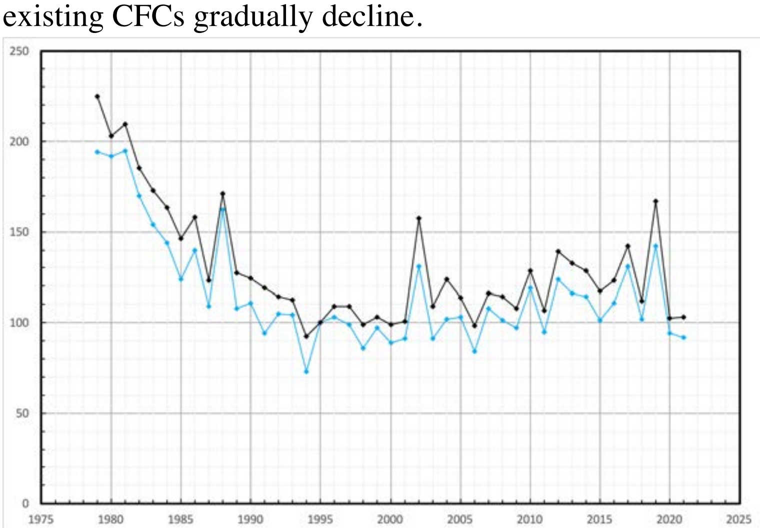

Figure 1.1. Annual minimum column ozone (DU) south of 60°S during 1979 – 2021 for (black) time mean and (blue) daily minimum ozone observed during 21 Sept. – 16 Oct. Data sources: 1978-1992 Nimbus 7 TOMS, 1993-1994 Meteo-3 TOMS, 1995 no data, 1996-2004 Earth Probe TOMS, 2006-present OMI. [http://ozonewatch.gsfc.nasa.gov/].

1.2.2. Greenhouse gases and glacial/interglacial cycles

Focus on Isotopes

An element is defined by its number of protons, but the number of neutrons can vary, giving different isotopes for that element. Most hydrogen molecules have one proton (and one very light electron), with an atomic weight of 1 kg/kmol (Fig. 1.2). But 0.015% of naturally-occurring hydrogen molecules also have a neutron, giving an atomic weight of 2 kg/kmol, making them twice as heavy. This *isotope* of hydrogen, ^{2}H, is called deuterium, D (Fig. 1.2). Oxygen molecules usually have 8 protons and 8 neutrons (and 8 electrons), with an atomic weight of 16 kg/kmol (Fig. 1.2). But 0.2% of naturally occurring oxygen molecules have 2 extra neutrons, with an atomic weight of 18 kg/kmol. A water molecule bearing either D or ^{18}O will be heavier than normal water. It takes more energy for D_2O or DOH or $H_2{}^{18}O$ molecules to leap into the vapor phase, compared to $H_2{}^{16}O$. When sea surface temperatures are colder, it is even harder for water molecules with heavy isotopes to evaporate. In 1938 Harold Urey recognized the usefulness of this principle of isotopic fractionation through evaporation, diffusion, and condensation. D_2O or DOH or $H_2{}^{18}O$ molecules will condense sooner into droplets and fall out along the path, especially when it is colder, leaving snowfall on the surface of Greenland and Antarctic glaciers diminished in D and ^{18}O during cold times.

This principle provides us with an extremely useful proxy for temperature variations in the ancient past, through variations in the abundances of D and ^{18}O trapped in deep sea sediments and continental glaciers. Each year a new layer of snow falls on Greenland and Antarctica and buries the layer below. Each year a new layer of organic material settles to the bottom of the ocean. During cold times, more snow with H and ^{16}O in it falls on glaciers, leaving the ocean enriched in D and ^{18}O, with life forms taking up relatively more D and ^{18}O, and falling to the sea floor. During warm times, more snow with D and ^{18}O in it falls on glaciers, leaving the ocean depleted in D and ^{18}O. Variations of D and ^{18}O have been calibrated with known temperature variations. This technique allows us to estimate earth temperatures back more than 420,000 years in ice cores and more than 1 million years in sea sediment cores.

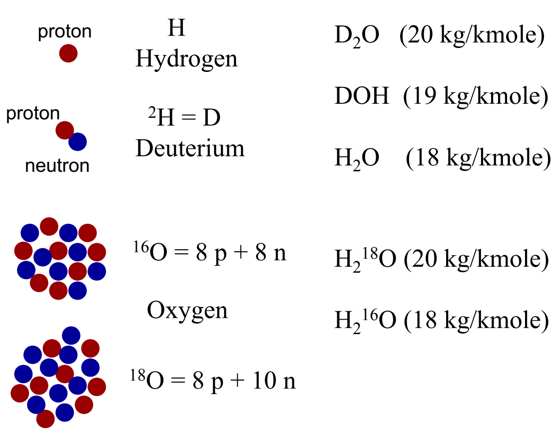

Figure 1.2. Isotopes of hydrogen and oxygen in ice sheet and ocean sediment cores are useful proxies for ancient earth temperatures. When the earth is colder, relatively fewer of the water molecules containing heavier isotopes evaporate and fall onto ice sheets, leaving sediment cores enriched.

Figure 1.3a shows an estimate of the variation of deuterium, a proxy of globally-averaged surface temperature, over the past 420,000 years made from the Vostok, Antarctica ice core (Petit et al., 1999). This curve shows the past four glacial-interglacial cycles, the variation between glacial states, such as the *Wisconsin ice age* peaking 20,000 years ago, and interglacial states, such as the *Eemian interglacial* 130,000 years ago. Deuterium anomalies show the departure from standard mean ocean water in parts per thousand. Variations in deuterium anomaly in snowfall over Antarctica of -490 to -410 ppt correspond to global temperature variations from 10 K cooler than now to 2 K warmer than now.

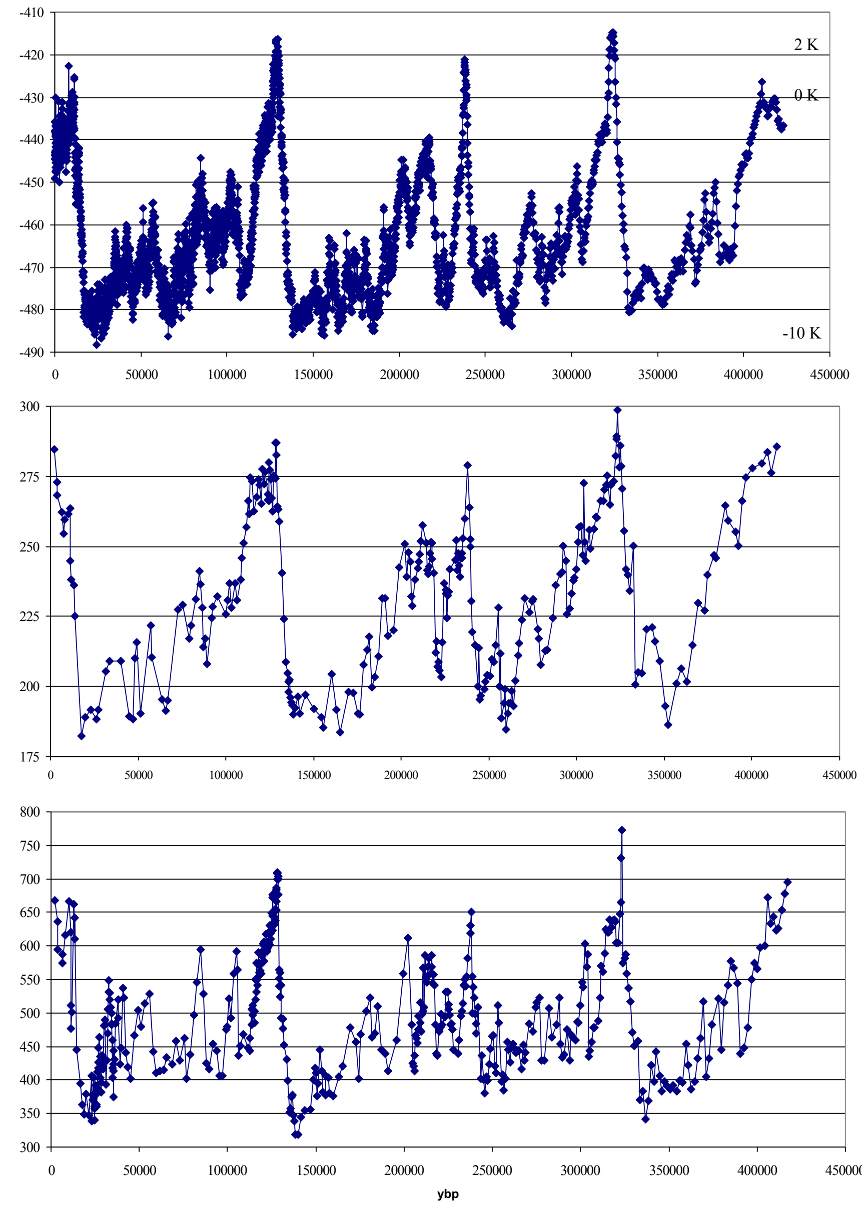

Figure 1.3. Variations over the past 420,000 years in the 3200-m deep ice core from Vostok, Antarctica [Petit et al. 1999, 2001] of a) Deuterium anomaly (pptv, left axis), with estimated global temperature anomaly (Kelvins, right axis), b) carbon dioxide (ppmv), and c) methane (ppbv) [from www.ncdc.noaa.gov/paleo].

Perhaps the most striking (and perhaps reassuring) aspect of this curve is that, while climate has always been in a state of change, it is within stable bounds. The range of global average surface temperatures of ~12 K (12°C or 22°F) may not seem very large, especially compared with typical daily temperature variations. Yet a range of 10 K in global average temperature represents the difference between a thick glacier 20,000 ypb (years before present) and the present oak savanna (corn fields) near Madison, WI.

During the past million years, our planet was generally much colder than at present (Fig. 1.3a). The last time it was warmer was ~130,000 ypb, during the Eemian Interglacial when half of Greenland was melted and sea level was ~6 m higher. The temperature was about 2 K warmer than at present. It is likely that we will see temperatures similar to the Eemian Interglacial by the end of this century. Most climate scientists believe that these cyclical changes are related to when and where sunlight falls on the planet, which is determined by slow changes in the tilt of the earth's axis, degree of ellipticity of the earth's orbit, and the timing of winter relative to the earth's position in its orbit. This is called the *Milankovich theory* of climate change. These orbitally-induced warming and cooling tendencies are augmented by natural positive feedbacks in the earth system, including the responses of ice, vegetation, and *greenhouse gases*.

Greenhouse gases absorb and emit infrared radiation, and so act to keep the surface of our planet warmer than it would be without them. During glacial times, more of these gases are found in the ocean and in the land surface, consistent with a colder state. During interglacial times these gases enter the atmosphere, consistent with a warmer state. Since successive layers of snow trap atmospheric gases in spaces between the ice crystals, ice cores can also tell us about variation in the average concentration of greenhouse gases in the past.

Figures 1.3b, c show variation of carbon dioxide (CO_2) and methane (CH_4) over the last 420,000 years in the Vostok Antarctic ice core. These quantities co-evolved with each other, consistent with what we know about the feedback nature of greenhouse gases. Ranges were -10 to +2 K relative to present temperatures, 180-290 ppmv for CO_2, and 300-700 ppbv for CH_4. These ranges mean that, in the past, if you had sampled one million air molecules (10^6), 180-290 of them would have been CO_2 (parts per million by volume, ppmv), and if you had sampled one billion molecules (10^9), 300-700 of them would have been CH_4 molecules (parts per billion by volume, or ppbv). Current CO_2 concentrations exceed 420 ppmv, which is 50% more than in the past, while CH_4 has passed 1700 ppbv, about ~3 times more than in the past (Fig. 1.3). The strong co-variation of temperature, CH_4 and CO_2 in the geologic record, and the large recent increases, raise the serious question of whether the temperature will rise out of the range seen in the previous million years.

We are putting a lot of greenhouse gases into the atmosphere. Will warming due to our activities take us to a climate regime warmer than any seen in the past million years or will the natural tendency to return to a glacial climate win out? Most climate scientists expect that it will continue to warm for the next several hundred years, and then cool off after a few thousand years.

Figures 1.4a, b show the observed changes in globally-averaged surface temperature and sea level over the past 130 years. Since 1880, the global average temperature has risen by ~1.1 K (2°F) and sea level has risen ~25 cm. Since 1980 global average temperatures have risen by 0.7 K (1.3°F). The Intergovernmental Panel on Climate Change (IPCC, 2007) recently released its summary for policy makers. In addition to these changes, they note that since 1980, Northern Hemisphere snow cover has diminished by ~10%.

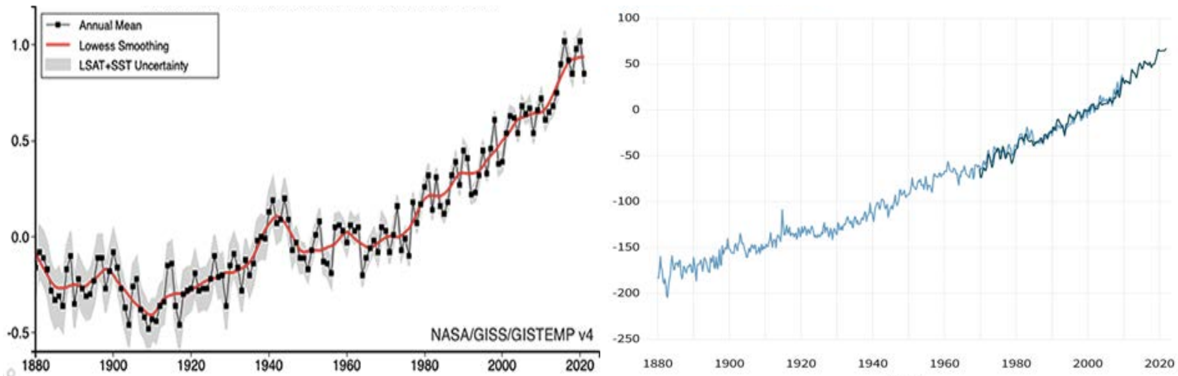

Figure 1.4. Departures of a) the global average surface temperature (K) during 1880-2021 from the average of 1951-1980 [http://www.nasa.giss], and b) sea level (mm) during 1880-2021 from the average of 1993-2008 [http://www.climate.gov].

Figure 1.5 shows a numerical prediction made in 1980 for the vertical profile of temperature change expected for increased CO_2 alone, and for all trace gases, by the year 2030. It suggested a surface warming of 1.8 K, and cooling of 10 K or more in the upper stratosphere. The stratopause region has cooled by ~5 K, while the surface has increased by 0.7 K since 1980. One of the most fascinating scientific pursuits at present is to take into account the interaction among the oceans, vegetation, ice, clouds, and other parts of the earth system in making quantitative forecasts of global climate change.

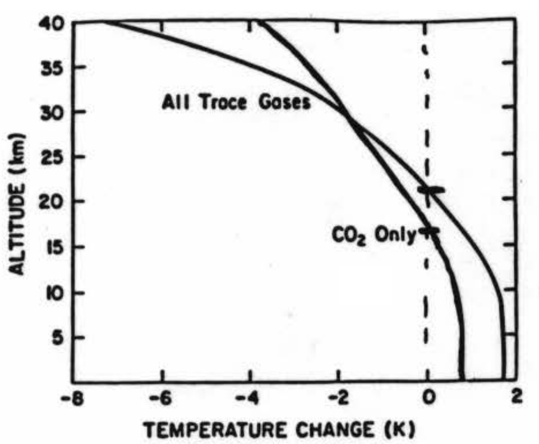

Figure 1.5. Change in global average temperature profile from 1980-2030 for anticipated increases in CO_2 only and including all other trace gases. [Ramanathan et al., 1979].

1.2.3. Human population increase and species loss

Our effect on biodiversity is similar to the effect of a massive bolide impact on our planet. Figure 1.6 shows the upward struggle of life toward ever-increasing *biodiversity*, termed "biodiversity rising" by Edward Wilson (1988), punctuated by cataclysmic losses, marking the boundaries of major geological ages.

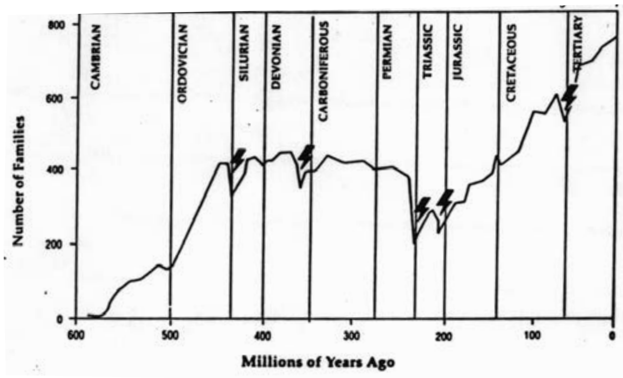

Figure 1.6. An estimate of the number of families of prehistoric species over the past 600 million years. Note the rise of biodiversity in spite of major losses due to impact by extraterrestrial objects [from Gore, 1992].

Figures 1.7a, b show the estimated variation in human population for the period 10,000 B.C. to 1800 A.D. (12,000 ybp to 200 ybp) and from 1800 to 2050 (United Nations 1999, U.S. Census Bureau 2008). Uncertainties in population estimates are of the order 100% for 10,000 B.C., tapering to less than 25% in the Middle Ages, to about 10% by 1900. The population growth rate peaked at 2% in the early 1960s and has declined gradually to ~1.2% per year. Figure 1.7b includes a best-guess extrapolation of global population to the year 2050. It is difficult to estimate the rate of species loss due to human encroachment on natural habitats. Some estimates suggest that we are now exceeding a loss rate of 10,000 species per year (Gore 1992).

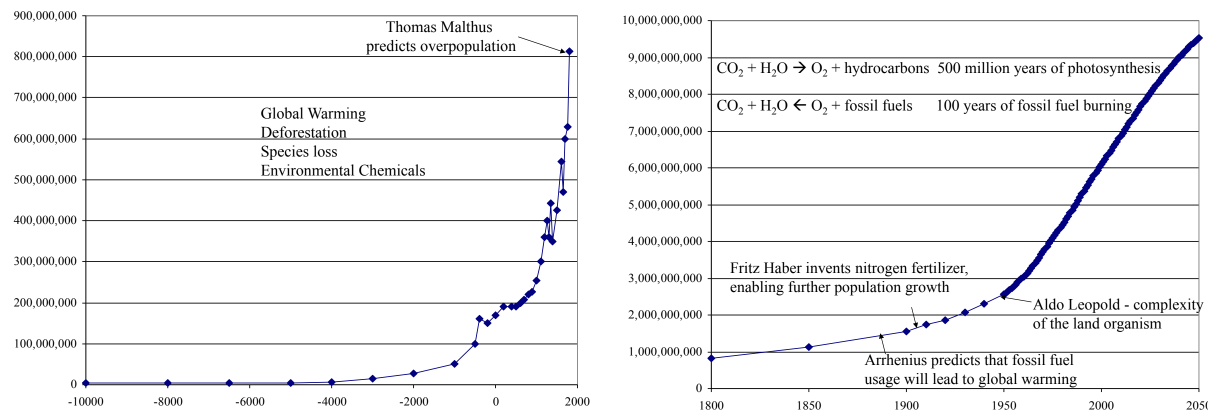

Figure 1.7. Estimated global human population a) from 10,000 BC to 1800 AD, (12,000 ypb to 200 ybp) and b) from 1800 to 2050 (predicted after 2008) [data from United Nations 1999 and U.S. Census Bureau 2008].

The ozone hole is an example of global-scale anthropogenic change which was not predicted. Warming of the earth is occurring, consistent with the predictions of Arrhenius in 1890 (Fig. 1.7b) regarding the rise of anthropogenic greenhouse gases. Scientists are now focusing on how the earth system functions as a whole. They are attempting to predict future climate to the best of their abilities. But our understanding always seems to lag behind the changes that we have wrought. For example, the modern study of ecology began in the 1930s, but human-induced ecological changes have occurred for millennia. The ideas were also present before the 1930s. Many cultures having traditional, close relationships with the earth have a world view of interdependency and the intrinsic worth of nature. The Russian philosopher Peter

Ouspensky wrote that "there can be nothing mechanical or dead in nature. A mountain, a tree, a river, the fish in the river, drops of water, rain, a plant, fire – each possesses a *noumenal essence* of its own." An appreciation of this concept is similar to "thinking like a mountain". In 1949 Aldo Leopold (Fig. 1.7b) wrote that "All ethics rest upon a single premise, that the individual is a member of a community of interdependent parts". He felt that the "complexity of the *land organism* is the outstanding scientific discovery of the 20th century." Perhaps what we are really doing with earth system science is re-discovering what we have forgotten, but from a more systematic and technological point of view.

1.3. Changes in Atmospheric Composition

1.3.1. How life "bootstrapped" its way onto the land surface

There is an intimate link between life on earth, the protective ozone layer, and greenhouse gas concentrations. Reductions in the diversity of life and changes in atmospheric composition are linked to the rise in human population. Global human population is thought to have been less than ~200 million people until the rise of industry. About 200 years ago the economist Thomas Malthus predicted that the world would experience exponential population growth. About 100 years ago the chemist Fritz Haber (Fig. 1.7b) discovered how to use fossil fuels to create nitrogen fertilizer, transforming agriculture. Since 1800 the population has grown from ~800 million to ~8.2 billion (Fig. 1.7b). This spectacular success as a species comes at the expense of reduced *biodiversity*, deforestation, fossil fuel burning, and the broad increase of anthropogenic chemical compounds, the metabolic byproducts of society. We have changed the composition of the air that we breathe. We are mining eons of ancient fossil fuels and burning it in a century. We are even eroding the protective ozone layer, which allowed life to colonize the land in the first place.

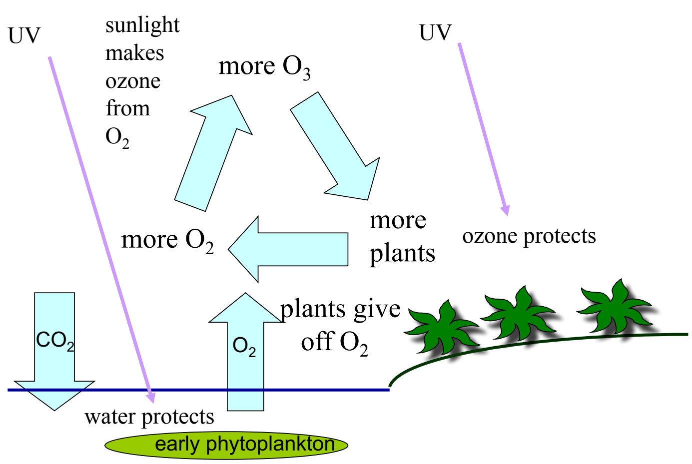

Figure 1.8. Life colonized the land surface via the positive feedback among photosynthesis, ozone, and UV protection.

Figure 1.8 illustrates the story of how life bootstrapped its way onto the land surface through the positive feedback among photosynthesis, oxygen and protective ozone. The early atmosphere was blown away by the highly variable solar wind. The outgassed water vapor (H_2O) rained and made the oceans. Carbon dioxide (CO_2) concentrations were much higher than at present, compensating for a weaker solar output. At first there was no protective O_3 to shield organisms from damaging UV radiation, because there was very little molecular oxygen (O_2) from which to make O_3. The sea surface provided a shield for photosynthetic organisms, which took up solar energy, CO_2, and H_2O, and gave off O_2, which enriched the atmosphere (Fig. 1.8), and created biomass, which sequestered carbon in sediments:

$$\textit{Photosynthesis}$$

$$sunlight + H_2O + CO_2 \rightarrow O_2 + hydrocarbons \qquad (1.1)$$

At the end of their life cycle, organisms settled to the bottom of the sea, an effective *biological pump* of carbon dioxide out of the atmosphere and oxygen into the atmosphere. Some of the O_2 was broken apart by intense photons of ultraviolet light, creating atoms of oxygen (O), some of which then combined with O_2 to make O_3. The life-protecting quality of O_3 is its excellent capability to absorb ultraviolet light from the sun. With a growing protective ozone layer, life was able to colonize the land, with land plants making more oxygen, hence more ozone (Fig. 1.8). We were able to succeed because of the positive feedback among photosynthesis, oxygen, and ozone, yet now we are making chlorine and bromine compounds which destroy ozone! It took several hundred million years of photosynthesis to build up breathable O_2 and to create fossil fuels via (1.1). But it is only taking us on the order of a century to mine these fossil fuels and burn them (Fig. 1.7b), putting hundreds of millions of years of sequestered carbon back into the air, driving the equation to the left instead, releasing the stored solar energy for our contemporary energy needs:

$$\textit{Oxidation (combustion)}$$

$$energy + H_2O + CO_2 \leftarrow O_2 + hydrocarbons\ (fossil\ fuels) \qquad (1.2)$$

The industrial revolution is putting a substantial amount of CO_2 into the atmosphere over a relatively short period of time. An initial flame starts the combustion, then the reaction with oxygen releases the energy bound in the hydrocarbons. The energy can be used to make fertilizer, power cell phone batteries, and drive cars. Reactions (1.1) and (1.2) also represent the food that plants create and their consumption by animals. In an organism, reaction (1.2) happens at a controlled rate. The heat given off by the human body from eating food is about the same as a 100 W light bulb.

1.3.2. Recent trends in atmospheric trace gases

Trends in trace gases at sites far from industrial centers are clear evidence that we are altering the global atmospheric composition. The upward trend in CO_2 (Fig. 1.9) is about 0.4% per year, which is less than what we would expect by considering the rate of fossil fuel usage, deforestation, and cement making. The remainder is going into the ocean and land biosphere. The annual cycle in CO_2 shows how the planet breathes (Fig. 1.9). Since most of the land mass is in the northern hemisphere, the annual cycle of the northern vegetation dominates the global mean cycle. CO_2 is lowest at the end of the northern summer growing season, having been taken up by plants. (Trees are indeed made from gaseous CO_2, but the resulting hydrocarbons can be painfully solid to run into! Turf grows over the edges of sidewalks because the mass of atmospheric carbon that is taken up adds to the mass of the soil.) Soil microbe and animal combustion of plant material continues after photosynthesis ceases, so the atmospheric CO_2 concentration maximum occurs at the end of winter. The annual range in CO_2 is about 6 ppmv, much less than the upward trend since 1958. This highlights the dominant role that fossil fuel burning has over the land biosphere, suggesting that massive tree planting cannot counteract the release of hundreds of millions of years of photosynthesis.

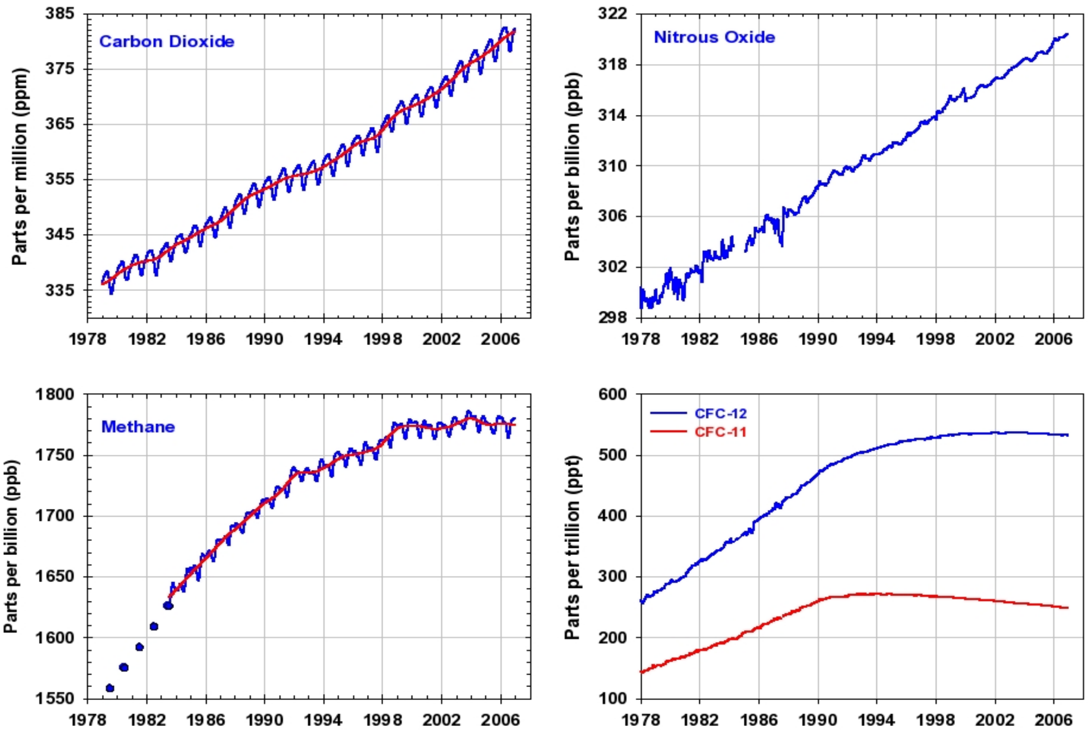

Figure 1.9. Changes in the atmospheric concentrations of carbon dioxide, methane, nitrous oxide, CFC-11 and CFC-12 during 1978-2007 [Dlugokencky et al., 2005].

Methane (CH_4) and nitrous oxide (N_2O) are also increasing (Fig. 1.9). Methane increases at ~1% per year, due to human encroachment on natural ecosystems: rice paddies, cattle, and termite colonies in cleared tropical forests. The increase has leveled off for a while, but now it is increasing again. The output of CH_4 from boggy soils increases with increasing temperature, suggesting that warming of cold or frozen high latitude soils would lead to more CH_4, amplifying its greenhouse effect further (a *positive feedback*). Another concern is that there is a large amount of methane in the form of frozen methane hydrates in sediments, largely on the continental slope under the ocean. If these are mined and used as fossil fuel, or if more evaporated in a warming scenario, there would be a marked amplification of global warming. Nitrous oxide is increasing at ~0.3% per year and is linked intimately with our food production, hence this greenhouse gas is inexorably tied to human population increase. Hundreds of other compounds act as greenhouse gases. One infamous class, the chlorofluorocarbons (CFCs; Fig. 1.9), increased rapidly in concentration during 1970-1990. Due to international treaties, total atmospheric chlorine loading has begun to decrease slightly. Since CFCs destroy ozone, we have hope that the ozone layer will return to normal by ~2060. However, the proliferation of the substitutes, HCFCs, contribute increasingly toward greenhouse warming.

1.3.3. Role of volcanic eruptions in climate

When considering atmospheric constituents relevant to climate change, one cannot overlook volcanic eruptions, which decrease the average temperature of the planet, catalyze ozone loss, and change the atmospheric circulation. Volcanic eruptions inject sulfur dioxide (SO_2) into the stratosphere, which condense into sulfuric acid droplets after a few months, creating a haze of aerosols that scatter sunlight and make sunsets red. Clusters of volcanic eruptions cool the planet, while a lack of eruptions for a few years allows more sunlight to reach the surface, tending to warm the planet. A major volcanic eruption cools the planet by ~0.5-2 K for 1-2 years. Figure 1.10 shows the variation of sunlight reaching the earth's surface during 1880-1980, expressed as aerosol *optical depth*. Note the eruptions of Krakatoa (1883), Pelee (1903), and Katmai (1915). It is interesting that the warm 1930s were relatively devoid of volcanic eruptions. Note also the increasing opacity of the atmosphere through 1980, referred to as the *global dimming*. It is believed to have been due to an increase in tropospheric sulfate aerosol haze related to fossil fuel burning. It occurs primarily in and downstream of urban regions. Since implementation of cleaner air standards in the U.S., Europe, and Japan, there has been a "brightening", allowing the solar radiation to return to normal at the surface. The rapid increase in global surface temperature since 1980 is consistent with anthropogenic greenhouse gas forcing emerging in the absence of counteracting aerosol cooling.

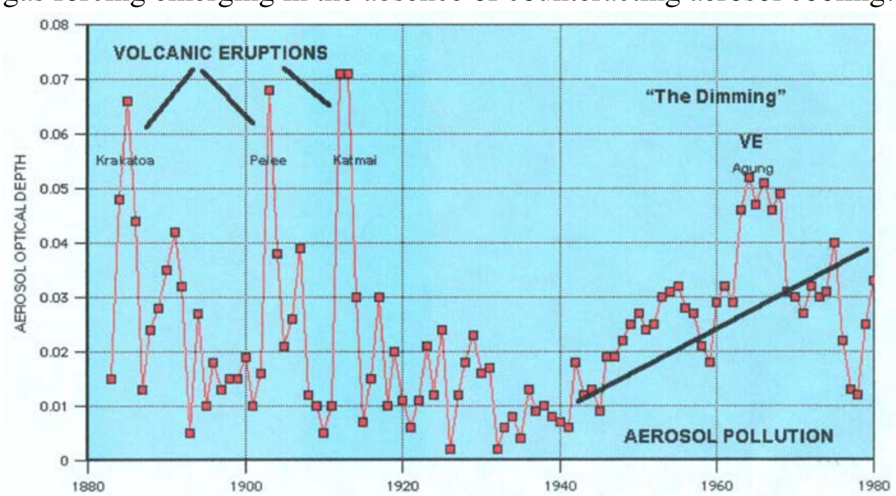

Figure 1.10. Aerosol optical depth from pyrheliometer data, a direct measure of the amount of sunlight reaching the ground, during 1880-1980 [Goodman 1984].

Figure 1.11 shows the variation with time of the occurrence of *polar stratospheric clouds (PSCs)* and their enhancement after the eruptions of El Chichon (1984) and Mt. Pinatubo (1991). PSCs are crystals made of frozen sulfuric acid, nitric acid, and water that occur in patches in the very cold polar lower stratosphere. The surfaces of stratospheric aerosols act to convert chlorine compounds to forms that destroy ozone in catalytic cycles. The rapid ozone loss over Antarctica during September and October occurs precisely in the layer 14-23 km, where PSCs occur (Fig. 1.12).

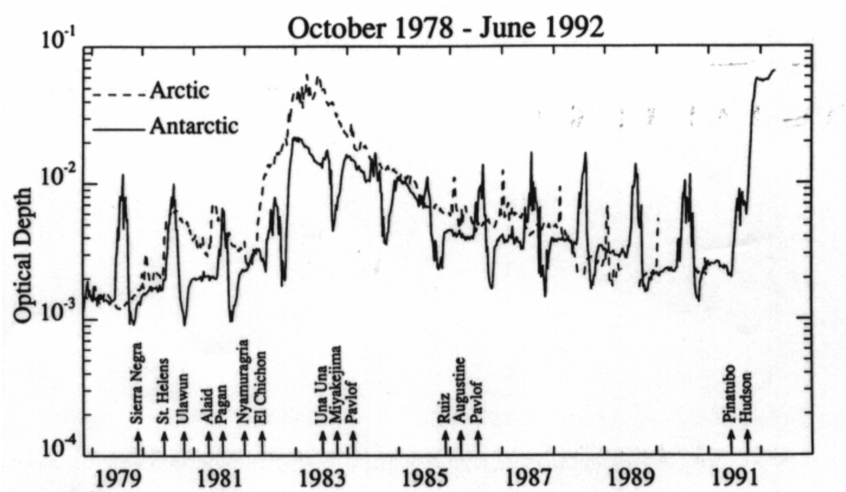

Figure 1.11. Variation of aerosol optical depth for the arctic (dashed) and antarctic (solid) from satellite solar extinction measurements during October 1978 - June 1992 [courtesy of Chip Trepte and Pat McCormick].

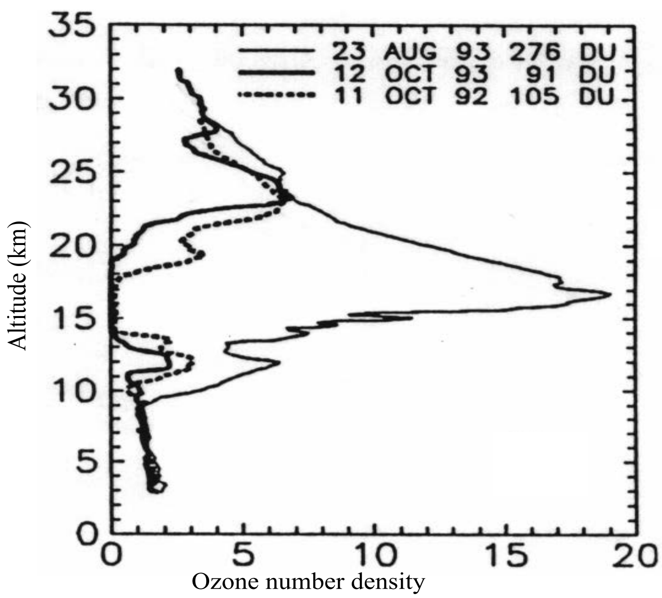

Figure 1.12. Profiles of ozone concentration (10^{18} molecules m^{-3}) over McMurdo, Antarctica during the polar night (23 August 1993, thin line) and after the sun comes up (11 October 1992, dashed line; 12 October 1993, thick solid line).

Tropospheric clouds play primary roles in the heat budget and chemistry of the atmosphere. Together with water vapor, clouds are the primary infrared trapping agent, keeping the earth's surface some 35 K warmer than it would be without this natural greenhouse effect. The future state of the planet will depend on how clouds respond to increasing surface temperatures. There is significant observational uncertainty about the present distribution of cloud amounts and types, with different measurement techniques giving substantially different answers [Wylie et al. 2006]. The proper treatment of clouds in climate simulations is one of the most difficult challenges facing scientists today. It is safe to say that future changes in the distribution of cloudiness and associated precipitation are even more uncertain. This uncertainty regarding the magnitude of cloud feedback for global warming scenarios provides a strong basis for legitimate argument regarding the magnitude of anticipated global warming.

1.4. Evolution of the Earth System and Natural Climate Control

Astronomy, geology, and biology inform us of the role that the sun, volcanoes, and life have played as natural climate controls during the evolution of the earth system. The prevailing scientific explanation for how the universe came into being is the "Big Bang" theory, where the laws of physics and inherent chaotic qualities emerged shortly after all of known matter exploded from an infinitesimal point some 16 billion years before present (14.3×10^9 ybp). Chaotic, irregular patches of mass gathered together by mutual gravitation, causing inward pressure sufficient to fuse hydrogen into helium, giving off light. When the outward force exerted by the light balances the force of gravity, then a star is born. When the hydrogen is used up, another gravitational collapse occurs, which can lead to massive explosions, seen as new stars in the sky, or supernovas. It takes the intensity of a supernova to create the higher elements upon which life is based. "Gentle life" is very much a byproduct of violent explosions in the hearts of stars. We are animated stardust.

Our solar system condensed out of a rotating accretion disc of stardust about 5×10^9 ybp. Rotation can be characterized by angular momentum per unit mass, the distance from the center of rotation times the speed around the center. The original angular momentum of the accretion disk, a relic chaotic swirl, is preserved in the "right hand" rotation of the sun, the orbits of each planet in the plane of the ecliptic, the sense of rotation of almost all of the planets and of the moons about their planets. This noumenal essence perhaps informs our mathematical "right hand rule" and the notion that the north pole is "up".

1.4.1. Effects of the sun on climate

The original molten earth cooled, forming moving crustal plates, the lithosphere, on top of the slowly overturning plastic asthenosphere. We are utterly dependent on the sun, which controls our climate and how much food we can grow. The distance to the sun is ~150,000,000 km. One prominent variation in the sun is called the solar cycle (Fig. 1.13). The solar cycle varies from 8 to 13 years, averaging 11 years, and is characterized by a variation in *sunspots*, solar flares, coronal mass ejections, x-rays, radio waves, and aurorae. When the sun has more sunspots, its "fevery" surface emits some ~0.1% more total solar energy. Sunspots are massive magnetohydrodynamic disturbances, one of a collection of other modes of solar variability, including spherical waves, spicules, faculae, and granules. During the Maunder minimum of 1615-1715 there were almost no sunspots. Most of the energy is emitted from the *photosphere* of the sun at ~6000 K. The expanding solar wind outside of the photosphere, the corona, glows at more than 20,000 K. NASA's Parker Solar Probe was launched in 2018 and is currently doing solar fly-bys to try to find out more about how the corona works.

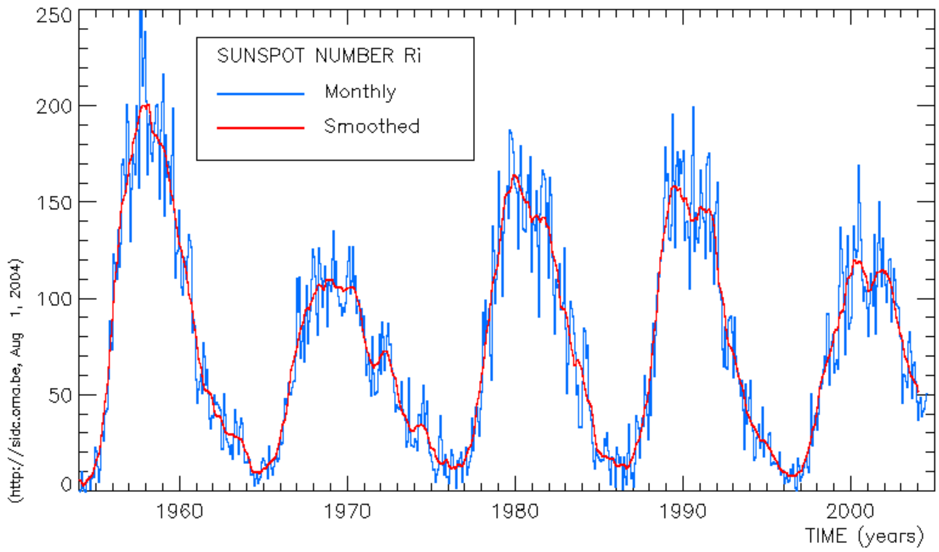

Figure 1.13. Sunspot number during 1954-2009, solar cycles 19-23 [http://sicd.oma.be].

Prominences and solar flares of the photosphere, with larger ones leading to *coronal mass ejections*, are more likely at solar maximum. Two outstanding flares were observed on October 28 and November 4, 2003. Luckily the larger one on November 4 (Figs. 1.14, 1.15) was aimed perpendicular to the earth and the polarity of the magnetic field associated with these coronal mass ejections happened to be opposite to that of the earth.

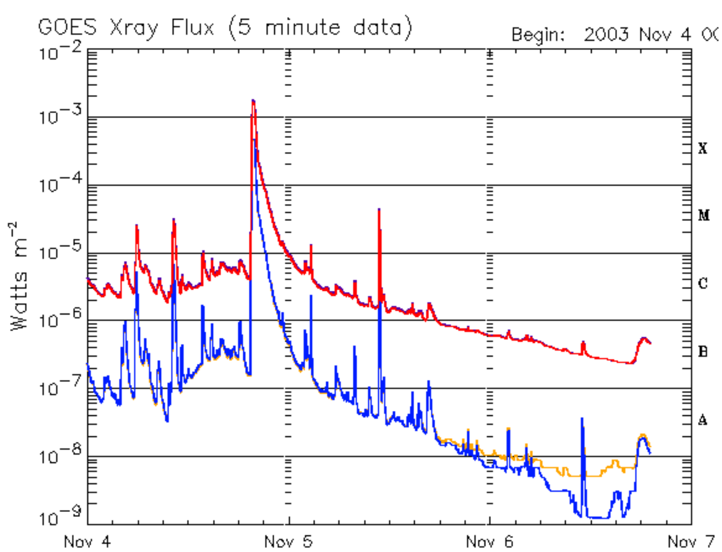

Figure 1.14. X-ray intensity showing the massive coronal mass ejection on 4 November 2003 [http://www.noaa.gov].

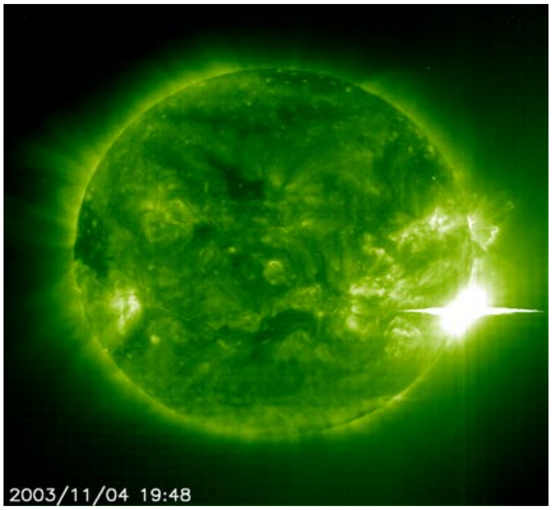

Figure 1.15. The solar flare of November 4, 2003, as seen by the SOHO satellite, located at the sunward libration point from earth [http://www.noaa.gov].

Outward pulses of solar protons carry solar magnetic field lines toward earth, interacting with the earth's magnetosphere, which acts as a protective blanket from energetic solar and cosmic particles. Coronal mass ejections cause the solar wind to deform the earth's magnetosphere. This disturbs the charged particles in the Van Allen belts near 500 km altitude, causing them to spiral down the earth's magnetic field lines over the poles into the thermosphere. These particles collide with N_2 and O_2 molecules in the altitude range 100-300 km, stimulating them to emit red and green light. The resulting auroral displays (Fig. 1.16) are evidence that the earth's magnetic field is doing its job. During times of very weak magnetic fields, such as a reversal, the earth is more at risk of bombardment by the solar wind. Since the earth's rotating, molten metallic interior involves accelerating electrons, it generates the magnetic field that creates the magnetosphere.

Figure 1.16. Green aurora over Fairbanks, Alaska [Geophysical Institute, University of Alaska - Fairbanks].

1.4.2. Role of plate tectonics

We are quite at the mercy of the variable output from the sun. It exerts an order-one control over the energy budget of the planet. If its output declined or increased significantly in the future, it would control the climate trajectory of our planet. During the first $500x10^6$ years rapid changes in the solar output blew away the earliest gaseous envelopes of the inner planets, and then settled into a steady output that was only ~75% that of today. For the vast majority of the earth's history, there is little evidence that the earth was ever entirely covered in ice. This suggests that, in the past, the greenhouse effect due to much larger CO_2 concentrations must have compensated for a weaker sun. Periods of more active crustal plate motion, associated volcanism, mountain building, and rock weathering may have led to increased atmospheric CO_2 and warm periods, while reduced activity may explain lowered CO_2 and colder periods. Crustal plates move around on the overturning circulations in the asthenosphere at a speed similar to how fast your fingernails grow, ~1 cm/yr (Fig. 1.17). The edges of the thinner oceanic plates subduct beneath thicker continental plates, where the material melts, giving rise to volcanoes and emissions of trapped gases into the atmosphere. Although living on a molten earth implies earthquakes, fissures, fumaroles, and volcanic eruptions, which are potent noumenal essences, it also protects us from the solar wind through its *geodynamo*.

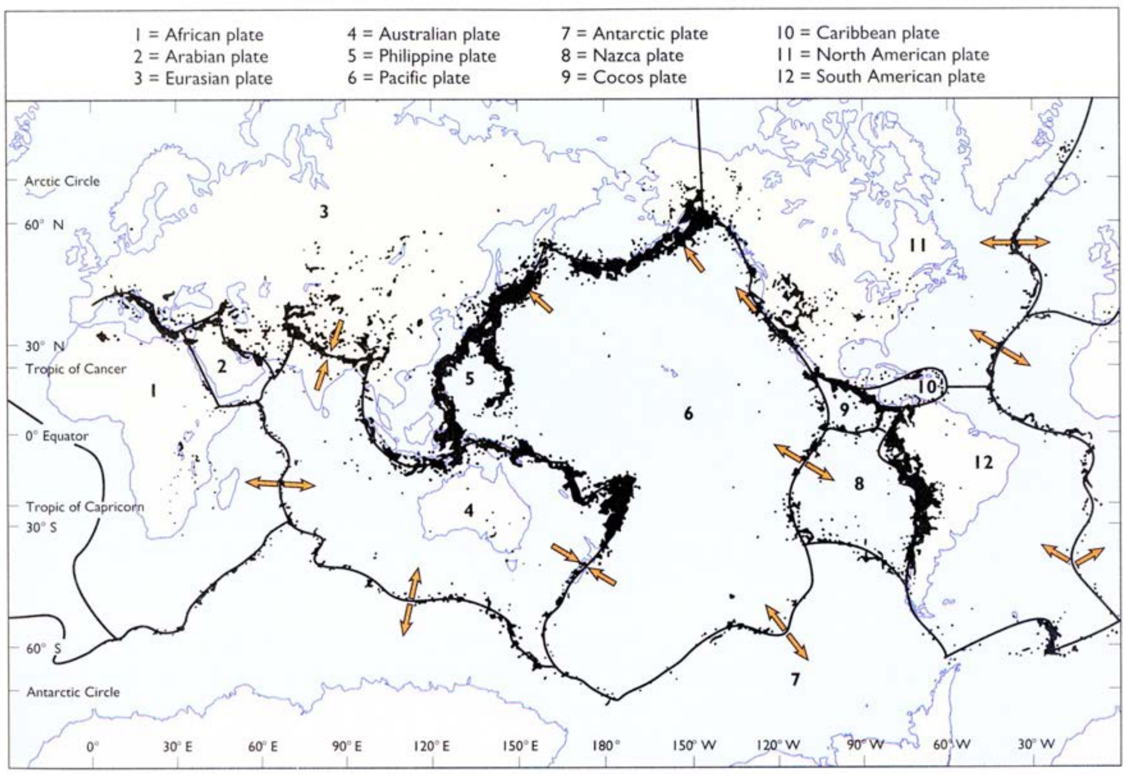

Figure 1.17. Lithospheric plates and earthquake occurrence [Fig. 3-7, Pinet, 2003].

On a geological time-scale, the atmosphere, ocean, and earth exchange molecules quite readily. Since the present atmosphere was outgassed, maybe we can understand the present composition of the atmosphere by looking at what comes out of volcanoes. If we compare observations of the composition of volcanic emissions with that of the air we breathe (Table 1.1), we find that an apparent paradox is turned to insight into the major processes which led to the current atmospheric composition.

Present Atmospheric Composition	Volcanic Emissions
78% N_2	Trace N_2
21% O_2	Trace O_2
1% Ar	Trace Ar
Trace S	Trace S
0.041% CO_2	10% CO_2
0-4% H_2O	85% H_2O

Table 1.1. A comparison of the concentrations of gases in the present atmosphere and in modern volcanic emissions.

A cursory inspection of Table 1.1 shows that, except for S, these are very different. There is hardly any N_2 and O_2 coming out of volcanoes, but air is mostly made of these two molecules. Volcanic emissions are mostly H_2O and CO_2, in much greater concentrations than in the air. To understand these discrepancies, we need to consider interaction among the spheres of the earth system over a long time-scale. The mass of the atmosphere is 5×10^{18} kg. Compared with the atmosphere, the hydrosphere is 300, the lithosphere is 5000, and the biosphere is 0.0002 times as massive. Over the ages, precipitation created the oceans and removed sulfuric acid (H_2SO_4) and carbonic acid ($CaCO_3$), which became incorporated into rocks. Despite the small mass of the biosphere, over time photosynthesis gradually created fossil fuels and oxygen, and removed CO_2 via (1.1). Photodissociation of H_2O at high altitudes, with escape of the lighter H to space, probably helped "top off" the oxygen to 21%. Finally, N_2 does not react or dissolve readily, so it simply built up over time to 78%.

Summary points

1) Energy comes from a variable sun, which controls our climate and causes natural variability.
2) Memory of the "local" cosmic dust's angular momentum explains the sense of rotation of the solar system.
3) The early atmosphere was blown away by strong solar variability.
4) Crustal plates recycling on a liquid core allow for exchange of constituents with the atmosphere and oceans.
5) The rotating molten 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, with rain, photosynthesis, and rock formation accounting for our current mixture.

Discussion Questions (with suggested articles)

Q1: Are tropical cyclones getting more numerous and dangerous?

Goldenberg, S. B., C. W. Landsea, A. M. Maestas-Nunez, and W. M. Gray, 2001: *Science*, **293**, 474-479.

Webster, P. J., G. J. Holland, J. A. Curry, and H. -R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309**, 1844-1846.

Q2: Are tornadoes in the Great Plains becoming more numerous and dangerous?
Diffenbaugh, N. S., and R. J. Trapp, 2008: Does global warming influence tornado activity? *EOS Transactions*, **89**, 553-554.

Q3: What is happening to Arctic sea ice?
Stroeve, J., and M. Serreze, 2008: Arctic sea ice extent plummets in 2007. *EOS Transactions*, **89**, 13-14.

Key Terms

angular momentum – the product of mass times distance times speed for circular motion
asthenosphere – the molten layer of the earth between the crust and core
biodiversity – variety of different species in an ecosystem
biological pump – phytoplankton sequestering carbon in sea sediments
biosphere – component of the earth system comprising all life forms
carrying capacity – limit to the biosphere by available energy
chlorofluorocarbons (CFCs) – human-created compounds which can destroy stratospheric ozone
column ozone – amount of ozone in a column of air compressed to sea level pressure
coronal mass ejections – massive outflowing of mass from the outer regions of the sun
cryosphere – component of the earth system comprising all frozen water
earth system science – study of the physical earth as interacting components or "spheres"
Eemian interglacial – last previous interglacial period, about 130,000 years ago
electromagnetic radiation – the spectrum of "light" from extreme ultraviolet to radio waves
exosphere – the universe outside of the earth's atmosphere
general circulation – the totality of all atmospheric and oceanic motions
global dimming – reduced solar radiation at the surface in the mid-1900s related to air pollution
greenhouse gases – trace gases which absorb and emit infrared radiation
heat budget – uses conservation of energy to determine thermal properties of a system
hydrosphere – component of the earth system comprising all liquid water
infrared radiation (IR) – electromagnetic radiation with wavelengths ~4-100 microns
isotopes – types of an element defined by the numbers of neutrons, for a given number of protons
land organism – totality of physical and noumenal properties of an ecosystem
lithosphere – component of the earth system comprising the crust
magnetosphere – protective shield from the solar wind caused by the earth's geodynamo
mesosphere – layer of atmosphere above the stratosphere where temperature decreases upward
Milankovich theory – theory of glacial cycles based on long-term changes in orbital parameters
noumenal essence – an aspect of something which cannot be sensed directly
optical depth – nondimensional ratio of incident to transmitted radiation for a layer of material
ozone hole – pronounced ozone minimum over the Antarctica
polar stratospheric clouds (PSCs) – patches of crystals which form in the cold lower stratosphere
stratosphere – layer above the troposphere where temperature increases with height
sunspots – magnetic disturbances on the sun
thermosphere – layer above the mesosphere, where temperature increases upward
troposphere – layer near the surface, where temperature decreases upward
ultraviolet radiation (UV) – electromagnetic radiation with wavelengths 0.2 - 0.3 microns
Wisconsin ice age – the most recent glacial period, peaking at ~20,000 years ago

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