

# GLOBAL CHANGE - A FIRST COURSE

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## Part I: The Natural Climate System

### 1. Introduction to the Earth System and Global Change

#### 1.1 *Spheres of the Earth System*

The earth's atmosphere is a gaseous envelope characterized by rapid mixing and dispersal of chemical constituents. It is a spritely medium for the exchange of energy, water, and other constituents among the spheres of the earth system. More than 99% of the mass of the earth's atmosphere lies between the surface and about 50 km altitude, hence, relative to the earth's radius ( $\sim 6367$  km), it is thinner than a layer of wax on an apple. Yet it provides oxygen and carbon dioxide for life to exist, protects us from harmful ultraviolet radiation, allows visible light to heat the surface, and traps enough outgoing infrared radiation to keep the planet from freezing. The ocean, being more dense, lies under the atmosphere, is 300 times more massive, and is characterized by more gradual mixing of properties. It contains much more heat and has a longer "memory" than the atmosphere. It composes most of the mass of water on the earth, the hydrosphere.

Other spheres of the earth system include the cryosphere (all of the ice), lithosphere (oceanic and continental crustal plates), asthenosphere (the slowly overturning mantle), and the biosphere (all of the living organisms). Although the mass of the biosphere is quite small, it exerts a surprising control on the properties of the atmosphere and ocean, and hence the climate system. The high oxygen content and the existence of ozone and fossil fuels are due to life on earth. The atmosphere may be divided according to its temperature structure into the troposphere (heated from below by sunlight reaching the surface), stratosphere (heated by ozone absorption of ultraviolet radiation, uv), mesosphere (few absorbing gases), and thermosphere (heated by extreme uv, xuv), which gradually thins out and blends into the solar wind. The exosphere contains the moon, sun, other planets, and the rest of the universe, including, notably, objects 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. The earth's asthenosphere, containing liquid metals rotating about the axis, generates a magnetosphere around our planet, which interacts with that of the sun and shields us from the solar wind. There is significant exchange of molecules and energy among the different spheres of the earth system. The fact that they 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 between the smallest and largest of phenomena.

#### 1.2 *Examples of Global Change*

Two salient examples of climate change are the appearance of the anthropogenic (human-caused) ozone hole over Antarctica every September and October, and the increase in average surface temperature over the past 100 years.

Figure 1.1 shows the minimum amount of column ozone during springtime over Antarctica from 1979 to 2006. If one takes an average air column, extending from the surface to

space, removes all molecules that aren't ozone, and compresses the ozone molecules to sea level pressure, it is normally about 3 mm thick, or 300 Dobson units, as thick as a dime. The British Antarctic Survey noticed in the mid-1980s that October ozone values over Halley Bay, Antarctica began to drop sharply in the 1970s. Over the past 10 years minimum column amounts regularly drop below 100 DU each October, with an area exceeding the size of North America. This profound ozone minimum, or ozone hole, lets more damaging uv from the sun reach organisms at the earth surface, harming phytoplankton in the circumpolar Antarctic Ocean. The British Antarctic Survey scientists argued that it was caused by long-lasting chemical compounds generated by humans, an anthropogenic ozone hole. But why over Antarctica, so far removed from industrial sources, and why so pointedly in October? These questions will be addressed in a later chapter. 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. By analogy, we should probably expect that there will be further surprises in the future.

It is also a useful historical example of how scientists diagnosed the cause, industrial manufacturing of chlorofluorocarbons (CFCs), and 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 ozone hole is hopefully at its worst over the past 5 years. Scientists anticipate that things will return to normal in about 50 years, as the existing CFCs gradually decline.

A useful proxy for temperature variation in the ancient past is variation in the ratio of two oxygen isotopes. 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. Most oxygen atoms in the earth system have 8 protons and 8 neutrons, for an atomic weight of 16, the normal isotope. A small percent have two extra neutrons, for an atomic weight of 18. Water molecules with  $O^{18}$  in them,  $H_2O^{18}$ , are heavier than regular water molecules,  $H_2O^{16}$ , and don't evaporate as easily. The effect increases as the ocean surface gets colder. During cold times, more snow with  $O^{16}$  in it falls on glaciers, leaving the ocean sediments enriched in  $O^{18}$ . This principle of isotopic fractionation upon evaporation was discovered by Harold Urey in the 1940s. The temperature proxy of interest here is the departure of the ratio of the two isotopes from the average, or "delta oh 18 ratio",  $\delta O^{18}$ . It allows us to estimate temperatures back more than 100,000 years in ice cores and almost 1 million years in sea sediment cores.

Figure 1.2 shows an estimate of the variation of globally-averaged surface temperature over the past 420,000 years in the Vostok Antarctica ice core. This curve shows 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. 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 only 6 K ( $6^{\circ}C$ ,  $\sim 11^{\circ}F$ ) may seem small, but this represents the difference between a thick glacier 20,000 ypb 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. 1.2). The last time it was

warmer than at present was  $\sim 130,000$  ypb, when more than half of Greenland was melted and sea level was 6 m higher. 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 position in orbit, 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 variations of greenhouse gases in the past. Figure 1.2 shows variation of temperature ( $\delta O^{18}$ ), carbon dioxide ( $CO_2$ ), and methane ( $CH_4$ ) over the last 160,000 years in Antarctic ice cores. These quantities clearly co-evolved with each other, consistent with what we know about the feedback nature of greenhouse gases. Ranges were  $-6$  to  $+2$  K relative to present temperatures, 180-290 ppmv for  $CO_2$ , and 300-700 ppbv for  $CH_4$ . This means 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) Currently, these values exceed 370 ppmv  $CO_2$  and 1700 ppbv  $CH_4$ , about 50% more  $CO_2$  and  $\sim 3$  times as much  $CH_4$  as typical values in the past (Fig. 1.3). Given the strong covariation of these three quantities, what do you think will happen to our planet's temperature?

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.

The Intergovernmental Panel on Climate Change (IPCC, 2007) recently released its summary for policy makers. Figure 1.4 shows the observed changes in global average surface temperature, sea level, and Northern Hemisphere snow cover during this time of rapidly increasing greenhouse gas concentrations. Over the past century temperatures rose  $\sim 1$  K, sea level rose  $\sim 20$  cm, and since  $\sim 1980$ , NH snow cover has diminished by  $\sim 10\%$ .

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 has already cooled 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.

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, punctuated by cataclysmic losses, marking the boundaries of major geological ages [Wilson

1988]. Human activities during the past century have caused a comparable reduction in the number of species on our planet comparable in magnitude to the effects of cataclysmic meteor impacts.

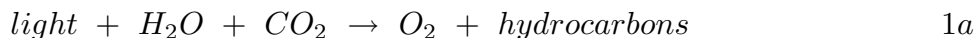
The ozone hole is an example of global-scale anthropogenic change which was not predicted. Warming of the earth is occurring, consistent with the predictions of Arrhenius in 1890 regarding the rise of anthropogenic greenhouse gases. Scientists are now focussing on how the earth system functions as a 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 millenia. 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 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*

There is an intimate link between life on earth, the protective ozone layer, and greenhouse gas concentrations. Reductions in the diversity of life and the rise in human population are linked to changes in atmospheric composition. Global human population is thought to have been less than  $\sim 200$  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 discovered how to use fossil fuels to create nitrogen fertilizer, transforming agriculture. Since 1800 the population has grown from  $\sim 500$  million to  $\sim 6.7$  billion. This spectacular success comes at the expense of reduced biodiversity, deforestation, fossil fuel burning, and the broad increase of anthropogenic 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.

The story of how life bootstrapped its way onto the land surface is the story of the positive feedback among photosynthesis, oxygen and protective ozone ( $O_3$ ). The early atmosphere was blown away by the highly variable solar wind. The outgassed water vapor ( $H_2O$ ) rained and made the oceans. The carbon dioxide ( $CO_2$ ) was in much larger concentrations than at present, compensating for a weaker solar output. At first there was no protective  $O_3$  to shield organisms from damaging ultraviolet 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  $H_2O$ , giving off  $O_2$  and creating hydrocarbons:

### *Photosynthesis*



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 oxygen atoms (O), which then combined with  $O_2$  to make some  $O_3$ . 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. We were able to succeed because of the 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 (1a). But it is only taking us on the order of a century to mine these fossil fuels and burn them, putting hundreds of millions of years of sequestered carbon back into the air, driving the equation to the left instead, yielding back some of the stored solar energy:

### *Combustion*



This represents a strong input of  $CO_2$  into the atmosphere in a 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. Equation (1) can also be used to represent the food that plants create and the oxidation by animals. In an organism, (1b) 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.

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. 1.7) 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. 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. It hurts when you run into trees, even though they are mostly made of air. Soil microbe and animal combustion of plant material continues after photosynthesis ceases, so the  $CO_2$  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.

Methane ( $CH_4$ ) and nitrous oxide ( $N_2O$ ) are also increasing (Fig. 1.7). Methane was increasing 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 over the past decade, a development which is not completely understood. The observed output of  $\text{CH}_4$  from boggy soils increases rapidly with increasing temperature, suggesting that warming of cold or frozen high latitude soils would lead to more  $\text{CH}_4$ , 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 for fossil fuel, or if more evaporated in a warming scenario, there could be a marked amplification of global warming. Nitrous oxide is increasing at  $\sim 0.3\%$  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 famous class, the chlorofluorocarbons (CFCs; Fig. 1.7), rose rapidly during 1970-1990, but then have begun to decrease slightly. Since CFCs also destroy ozone, we have hope that the ozone layer will return to normal by  $\sim 2060$ .

When considering atmospheric constituents relevant to climate change one cannot overlook the salient role of volcanic aerosol in both the temperature of the planet and in catalyzing ozone loss. Volcanic eruptions inject sulfur dioxide ( $\text{SO}_2$ ) into the stratosphere, which make sulfuric acid droplets after a few months, a haze of aerosols that reflect 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 1.8 shows the variation of sunlight reaching the earth's surface from 1880-1980, expressed as amount of non-transmitting material in the atmosphere. Note the eruptions of Krakatoa (1883), Katmai (1915), Agung (1963), El Chichon (1983), and Pinatubo (1991). It is interesting that the 1930s and the last 10 years were both relatively devoid of volcanic eruptions and both relatively warm periods. Note also the rise of the opacity of the atmosphere through 1980, referred to as the "global dimming". It is believed to be 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 a "brightening", which may have exacerbated surface temperature increases. An unsolved problem is how less sunlight reached the surface while greenhouse gases and surface temperatures rose.

Figure 1.9 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 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. A particularly noticeable response occurs in September and October over Antarctica, where column ozone decreases to less than 1/3 of what it used to be prior to the rise of anthropogenic CFCs. This ozone loss occurs precisely in the layer 14-23 km, where PSCs occur (Fig. 1.10).

Finally, 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 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 tem-

peratures. There is currently significant uncertainty regarding cloud fraction and type, with different measurement techniques giving substantially different answers. Treatment of clouds in current numerical climate simulations is one of the weakest links in depth of understanding. This implies that future changes in the distribution of cloudiness, and associated precipitation, are rather uncertain. This uncertainty regarding the magnitude of cloud feedback for global warming scenarios provides a 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 ( $16 \times 10^9$  ybp). Chaotic, irregular patches of mass gathered gravitationally to a pressure sufficient to fuse hydrogen into helium, giving off light. When the outward pressure exerted by the light balances the effect 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 stardust in the garden.

Our solar system condensed out of a rotating accretion disc of stardust about  $5 \times 10^9$  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 is perhaps remembered in our mathematical “right hand rule” and the notion that the north pole is “up”.

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  $\sim 150,000,000$  km. One prominent variation in the sun is called the solar cycle (Fig. 1.11). The solar cycle varies from 8 to 13 years, most commonly 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 fevered surface emits some  $\sim 1/2\%$  more total solar energy. Most of the energy is emitted from the photosphere of the sun at  $\sim 6000$  K. The expanding solar wind outside of the photosphere, the corona, glows at more than 20,000 K. During the Maunder minimum of 1615-1715 there were almost no sunspots at all. Sunspots are massive magnetohydrodynamic disturbances, one of a collection of other modes of solar variability, including spherical waves, spicules, faculae, and granules. Solar flares or prominences 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. 1.12, 1.13) 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.

Outward pulses of solar material 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. Rapidly moving charged particles in the Van Allen belts are disturbed during solar mass ejections, spiralling down the earth's magnetic field lines, and colliding with rarefied molecules of  $N_2$  and  $O_2$  in the altitude range 100-300 km, stimulating them to emit red and green light. These aurorae (Fig. 1.14) 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 radially accelerating electrons, it generates the magnetic field that creates the magnetosphere.

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  $500 \times 10^6$  years it is believed that 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  $\sim 75\%$  that of today. Since there is little evidence that the earth was ever entirely ice covered, it is likely that the greenhouse effect of much larger  $CO_2$  concentrations compensated for a weaker sun. Periods of more active crustal plate motion, associated volcanism, mountain building, and rock weathering may have led to greater 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,  $\sim 1$  cm/yr (Fig. 1.15). The edges of the thinner oceanic plates subduct underneath 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 and volcanic eruptions, potent noumenal essences, it also protects us from the solar wind with its geodynamo.

On a geological time scale, the atmosphere, ocean, and earth exchange molecules quite readily. We can look to observations of volcanic emissions, and their differences from the air that we breathe, for insight into the major processes which led to our current atmospheric composition. Volcanoes emit  $\sim 85\%$   $H_2O$ ,  $\sim 10\%$   $CO_2$ , traces of sulfur and nitrogen, and very little  $O_2$ . In contrast, the air that we breathe is  $\sim 78\%$   $N_2$ ,  $21\%$   $O_2$ ,  $1\%$  Ar, and a whole host of minor constituents which act as "trim-tabs" on the trajectory of our global climate system. To understand these discrepancies we need to consider interaction among the spheres of the earth system over a long time scale. The relative masses are atmosphere (1), hydrosphere (300), lithosphere (5000), biosphere (0.0002), where the mass of the atmosphere is  $5 \times 10^{18}$  kg. 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  $CO_2$  (1a). 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 include: 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.

### Figure Captions

Figure 1.1. The minimum in column ozone observed by satellite south of 60°S during each austral spring during 1979-2005. The minimum ozone amount in Dobson units, month, and date are shown for each year. Ozone was observed by a succession of satellites bearing intercalibrated Total Ozone Mapping Spectrometers (TOMS) instruments [NASA GSFC TOMS website].

Figure 1.2. Vostok Antarctica ice core time series for the past 423,000 years of a) carbon dioxide, b) isotopic temperature, c) methane, d)  $\delta^{18}\text{O}$  for trapped  $\text{O}_2$ , and e) mid-June solar radiation at 65°N. The time resolution is  $\sim 1000$  years. The accuracy is  $\sim 1\%$  for  $\text{CO}_2$  and  $\sim 4\%$  for  $\text{CH}_4$ . [Fig. 2 of Petit et al., 1999].

Figure 1.3. Atmospheric concentration of carbon dioxide, methane and nitrous oxide over the past 10,000 years and since 1750 (inset panels), and their corresponding radiative forcings (right scale). [Fig. SPM-1 from IPCC 2007].

Figure 1.4. Observed changes in a) global average surface temperature, b) global average sea level rise from tide gauge (blue) and satellite (red) data, and c) Northern Hemisphere snow cover for March-April. The left axis measures departures from the 1961-1990 averages. [Fig. SPM-3 from IPCC 2007].

Figure 1.5. Change in global average temperature profile from 1980-2030 for anticipated increases in  $\text{CO}_2$  only and including all other trace gases. [Ramanathan et al., 1980].

Figure 1.6. A comparison of prehistoric species loss due to impact by extraterrestrial objects and to human activities [Gore, 1992].

Figure 1.7. Changes in the atmospheric concentrations of carbon dioxide, methane, nitrous oxide, CFC-11 and CFC-12 during 1978-2007. [Dlugokencky et al. 2005].

Figure 1.8 Aerosol optical depth from pyrhelimeter data during 1880-1980. [Goodman 1984].

Figure 1.9. Polar stratospheric optical depth from satellite solar extinction measurements in the Arctic and Antarctic during October 1978 - June 1992. [McCormick et al. 1993].

Figure 1.10. Profiles of ozone concentration over McMurdo Antarctica during the polar

night (right curve) and after the sun comes up (left curves).

Figure 1.11. Sunspot number during 1954-2004, solar cycles 19-23. [<http://sicd.oma.be>]

Figure 1.12. X-ray intensity showing the massive coronal mass ejection on November 4 2003. [<http://www.noaa.gov>]

Figure 1.13. 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>]

Figure 1.14. Green aurora over Fairbanks, Alaska. [Geophysical Institute, University of Alaska - Fairbanks]

Figure 1.15. Lithospheric plates and earthquake occurrence. [Fig. 3-7, Pinet, 2003]