4. Paleoclimate and Climate Dynamics

4.1 Introduction

People have been anxious to anticipate droughts or floods for at least 10,000 years. Many fascinating examples show how climate events have helped shape the course of civilization [e.g., Chapter 3, Gore 1992]. Consider the waning of the Anasazi in the American Southwest near 1150 during a prolonged drought, or the duration of Viking occupation of Greenland during 970-1400, the North Atlantic Medieval Optimum. Large volcanic eruptions or clusters of them have been repeatedly linked with colder summers and crop failures, together with warmer and wetter winters in Eastern North America and Eurasia. There is significant evidence for a synergy among climate change, food supply, and outbreaks of disease. Paleoclimate is intrinsically interesting to many of us, presenting a deep mystery. An investigation of paleoclimate and speculation about possible causes sheds light on how the climate system works (*climate dyanamics*), and therefore provides some guidance regarding what might happen in the future. Since climate change has had a large effect on humans in the past, we should expect that any anthropogenic climate change could also affect us significantly.

During this brief overview specific named events become our focus, as examples of different types of climate dynamical mechanisms. The western linear tradition of thinking has enjoyed success with the identification of cause and effect. "All one has to do is know the initial conditions and the laws of physics, and then the evolution is determined." This is *determinism.* A newer idea is that there is chaos inherent to the natural world, and that even simple systems have inherent significant unpredictability, as well as processes which keep the system within bounds, attracted to an attractor. This is *chaos theory* [Gleick 1990]. One wondrous problem is how the earth goes into ice ages and back into interglacial times, such as the one we are in now (the Holocene). The *Milankovich theory* of climate change is fundamentally deterministic, but is compatible with chaos theory, and the climate system exhibits elements of both. Ruddiman [2001] provides a detailed account of paleoclimate.

4.2 The Paleoclimatic Record

Paleoclimatic events to be discussed include the faint young sun paradox (4.5 Bybp), Hot Houses and Ice Houses (100s of M yr variability), continental drift (M y variability), impacts by extraterrestrical object (any time), the Oort cloud (a 27 M yr periodicity), the Cretaceous warm period (100 M ybp), Antarctica (10 M ybp), ice age /interglacial cycles (last 1 M yr), Eemian interglacial (130 kybp), Wisconsin glacial maximum(20 kybp), Younger Dryas event (11 kybp), Dansgaard-Oeschger events (hundreds of years), Holocene maximum (4-8 kybp), Medieval Optimum (600-1000 ypb; 1000-1400 A.D.), Little Ice Age (120-600 ybp; 1400-1890 A.D.), Dust Bowl Years (1930s), End of Millenium Warming (1990-present). Factors to be examined in accounting for these events include the sun, asteroids, plate tectonics, the Milankovich theory of orbital parameters, ice albedo, vegetation, and greenhouse gas feedbacks, the North Atlantic Thermohaline Oscillator theory, volcanism, humans, and chaos theory.

Astronomy informs us that our sun is rather typical of a large number of similar stars in the universe, whose evolution is always rather similar. Our sun was likely to have been rather variable in its output during the first few 100 M yr, with more intense outflow blowing the early atmospheres of the inner planets away from the sun. The atmospheres that developed later were outgassed from liquid interiors, on earth being primarily water vapor and carbon dioxide. Within 1 B yr the sun probably equilibrated to a solar output that was ∼75% of its current output. The equation for radiative equilibrium with A=0.3 gives $T_{re} = 202$ K, far below the freezing point of water. You may wonder whether the earth was ever entirely covered by ice. Ice ball earths have been speculated about now and again, but the preponderance of evidence suggests that there never was a time when the earth was covered by ice. This would seem to pose a paradox. One factor that may have helped is that the suns rays in the tropics would still have been intense, keeping ice from forming in the tropics. The leading explanation, however, is that there was much more CO_2 in the atmosphere, perhaps 20-30 times as much, with the strong greenhouse effect compensating for the *faint young sun*. If this is the case, then there has been a serendipitous gradual decline in atmospheric greenhouse constituents over geologic time to roughly compensate for the gradually strengthening solar output.

The rise of biodiversity has been punctuated by abrupt, cataclysmic species loss, demarcating the end of major geological periods and the beginning of new ones. It is believed that most of these are caused by impacts of objects from outer space. Whether they are comets or asteroids or large meteors, these bolide impacts have exerted an order-one influence on our planet and they will happen in the future. The impact which resulted in the end of the Cretaceous period and beginning of the Tertiary period at 65 Mybp, or “KT boundary”, occurred near the north tip of the Yucatan peninsula. It most likely lobbed sheets of flaming earth over forests, caught them on fire, encased the planet in a debris cloud that shut off photosynthesis, and many forms of life became extinct. Mammals had been outcompeting the dinosaurs for millions of years, and this was the final straw.

One very uncomfortable theory is that there is something about the way the solar system goes through space that yields an apparent periodicity of extinctions every 27 M yr. The idea is that every 27 M yr our solar system passes near something that gravitationally perturbs the numerous but distant cloud of objects, called the Oort cloud, that weakly orbits the sun far beyond Pluto. These objects then have a greater likelihood of hitting the earth and fostering climate change.

Over 100s of millions of years the earth moved gradually into and out of warmer and colder periods. A primary theory for explaining this is that convection in the earth’s mantle varies in strength at these time scales. When overturning is faster, oceanic plates are subducted under continental plates more vigorously, with more volcanic emission of CO_2. There would also be more mountain range building, hence enhanced limestone rock weathering, which would add to the CO_2 in the atmosphere.

Figure 4.1 presents an overview of paleoclimatic globally averaged temperature estimates, starting from 180 Mybp and successively zooming in on higher temporal resolutions starting at 1 Mybp, 160 kybp, 18 kybp, 900 A.D., and 1870 A.D. One of the most recent hot house periods was during the Cretaceous (Fig. 4.1a), when the global mean temperature was at least 10 K warmer and sea level was 300 m higher. It is likely that there was 10-20 times as much CO_2 in the atmosphere as at present. Cool-blooded dinosaurs roamed the earth. The arctic was inhabited by plants and animals normally associated with warm climates. This Cretaceous warm period gradually gave way to a fourth ice house period, as Antarctica gradually drifted toward the South Pole, arriving there some 10 Mybp. In this position Antarctica anchors the climate in an ice house, acting as a giant solar reflector and planetary refrigerator.

During the past million years (Figure 4.1b) there have been at least 7 major cycles of glacial and interglacial times, with the Laurentide Ice sheet advancing out of Canada all the way to Illinois 170 kybp and to Southern Wisconsin 20 kybp. To find times as warm as the present, one would have to return to the Eemian interglacial of 130 kybp, when half of the Greenland ice sheet was melted and sea level was 6 m higher than at present. The CO_2 concentration back then never exceeded 300 ppmv (Fig. 1.2). It seems likely that, by doubling or tripling CO_2 in this century, there will be significant melting of Greenland.

The last 100,000 years have been characterized by a variable, but downward trend in temperature toward the Wisconsin Ice Age maximum 20 kybp (Fig. 4.1c). The descent toward a glacial state typically occurs in a series of sawtooth declines, while warming to an interglacial state occurs comparatively quickly. This provides clues for distentangling the various feedbacks within the system. An especially cold time along the way occurred about 70 kybp, coinciding with the eruption of Mt. Toba in Sumatra, which left a lake 70 km long. During this time Neanderthals spread throughout Africa and Eurasia, with commingling Cro-Magnons beginning ∼40 kybp. Whether they were truly distinct we may never know, but by 40 kybp humans were creating art preserved in caves that strikes us as pleasingly adept.

Figure 4.2 shows that prior to 20kybp the climate record was characterized by rapid oscillations in ice volume and global temperature. These events have come to be called *Dansgaard-Oeschger events.* These climate oscillations are of much shorter duration than the glacial-interglacial cycles, with time scales on the order of hundreds to a few thousand years. These Dansgaard-Oeschger events have been remarkably rare since the Wisconsin glacial maximum. An exception is 12-10 kybp, when the gradual warming was interrupted by a pronounced cooling and subsequent warming, with multiple oscillations (Figs. 4.1d, 4.2). The most pronounced cooling period was near 10,600 ybp and is called the Younger Dryas event, named after the white Dryas flower which grew plentifully across northern Europe at this time, but is normally confined to the Arctic. We will return to the Younger Dryas event when discussing the North Atlantic oscillator theory of climate change.

At the Wisconsin glacial maximum sea water was stored in the form of compacted snow on land surfaces, primarily in North America and northern Eurasia (Figs. 4.3 and 4.4). Figure 4.5 shows radiocarbon isochrones of retreat of the Laurentide ice sheet. The ice edge retreated northward past the St. Lawrence river around 12 kybp. When Stonehenge and the pyramids were being built about 5 kybp there was still significant ice remaining in Labrador and west of Hudson Bay. Some time during this last ice age humans made their way from Asia to North America via the exposes land bridge of Beringia. Some probably made their way down the west coast in primitive boats, while others made their way into the interior east of the Cordilleran Ice sheet anchored in the Canadian Rockies. By 14 kybp a distinctive weapon making culture, the Clovis people, were found all throughout the Americas. By 12 kybp all of the megafauna were hunted to extinction, including the Giant Deer, Woolly Mammoth, and the Cave Bear. Some trees that have remained as relict partners with these megafauna include the anomalously large-fruited osage orange and catalpa trees. The last Woolly Mammoth lived on Wrangell Island, northeast of Siberia, until about 3 kybp. It was a smallish variety. Perhaps the smaller ones were able to survive on the more limited food of the island, away from people.

Around 7 kybp the Mediterranean broke through the Dardanelles, spilling into and filling the Black Sea. This may have contributed toward the oral tradition of a great flood prevalent among ancient tribes in the Middle east. By 8 kybp the earth was getting warm enough to favor the rise of large scale farming across both the Old and New Worlds (Fig. 4.1d). During 900-1400 the earth was warm enough for the Vikings to negotiate the North Atlantic more safely and grow food in Greenland. But then they were frozen out. An alternative theory holds that they may have been victims of the slave trade [Prytz, 1991]. The Little Ice Age was ∼0.6 K cooler than the 1900s on the global average, with much more severe winters in Eurasia and North America (Fig. 4.1e). The Thames used to freeze on a regular basis and perhaps wolves would come ravening out of the north. On occasion an Eskimo kayak would appear on the shores of Scotland and black vultures would show up on dreary Dutch snowscapes. The earth warmed significantly from ∼1900 to 1940, then leveled off, and then began warming again ∼1980 (Fig. 4.1f). The last few years have been the warmest on record (Fig. 1.4).

It is useful to first briefly consider some of the evidence which provides us information about the past, then we will consider climate theory in an effort to explain what has occurred in the past.

4.3 Evidence of Past Change

Wherever an insightful thinker has achieved a new understanding about the relationship between information available to us now and the state of the past, one is likely to find a new way of knowing about the past. Proxy data include records of life forms, isotopic chemical methods, and physical methods. Interpretation of tree rings (dendrochronology) provides an absolute time scale, often specifying to the year, for an event in the distant past, hundreds or even thousands of years ago. Warm rainy years foster large growth rings and small growth rings are indicators of drought. A unique tree ring pattern for a given region can be constructed by finding live, dead, and fossil tree trunks that overlap but are successively older in age. One sequence of oak has been extended back 10,000 yr. Some fossil tree sequences go back to 40 kybp. Dendochronology sequences are useful for calibrating radiocarbon dates.

Lichens provide another interesting means of dating objects. They are symbiotic combinations of algae and fungus, perhaps somewhat analogous to the mycorrhizal association for trees and the algal coral symbiont, zooxanthellae. Lichens festoon trees in damp environs and form thick carpets on tundra for the caribou to eat. Lichens are useful in cleaning the environment of pollutants, but are especially sensitive to acid rain. As an infusion in tea, usnea or Old Man's Beard, is said to be helpful with lung ailments, as well as being part of the lungs of the planet. The growth rate of each lichen species helps us relate their size to their age. Their size on the sides of boulders is useful for dating the advance and retreat of glaciers.

Since vegetation type is closely linked to climate, it is very useful to have information about the mix of plants and how they varied with time. One handy recording mechanism is provided by the annual signal in lake sediments. Each spring high flow will bring pollen from a drainage basin into a lake, where it settles into the bottom, leaving annual layers, or varves. By taking a core at the lake bottom one may determine the mixture of plants that grew in the drainage basin back in time. The Dryas flower pollen, favoring cold climates, was found over a much more widespread area of northern Europe near 10,600 ybp than several thousand years before and after that.

Fossil animals and plants are also useful in determining paleoclimate. Subarctic islands bear fossils of alligator-like and palm tree-like species from the Cretaceous. Certain radiolarians, a type of phytoplankton, have a threshold temperature above and below which they coil in a right or left-handed sense. By examining a deep sea sediment core, one may determine when the sea surface waters overhead were above or below the threshold. Since corals can grow only in the temperature range $\sim$24-30^{o}C, the record of fossil corals, in conjuntion with chemical dating techniques, informs us of when it was warm and when it was not so warm in the world's oceans.

For land samples with organic material emplaced less than 40,000 yr ago, it may be possible to tell its age by analyzing the amount of C^{14} relative to C^{12}. C^{14} is a heavy isotope of carbon that is radioactively unstable, decaying with a half-life of 5400 yr. It is hard to predict when a single C^{14} nucleus will spontaneously emit 2 neutrons and decay to C^{12}, but with a large enough sample of molecules, the decay follows a well-known exponential shape. The original amount of C^{14} will decay to 1/2 of its original value in 5400 yr, to 1/4 at 10,800 yr and to 1/8 at 17,200 yr. Thus, material in sediments sequestered for a long time contains only C^{12}. C^{12} has 6 electrons, 6 protons and 6 neutrons, while C^{14} has 2 extra neutrons. C^{14} is created when cosmic rays from outer space strike a nitrogen molecule in the atmosphere. N^{14} has 7 electrons, 7 protons, and 7 neutrons. But when a cosmic ray strikes it, one proton is converted to a neutron, making it C^{14}! There is a distinct variation in the amount of cosmic rays reaching earth on 1000 yr time scales and this signal must be accounted for in estimating age with the C^{14} technique. A live organism either photosynthesizes C^{14} or eats the plants. If it is buried by sediment when it dies and is cut off from the atmosphere, then the C^{14} starts decaying to C^{12} at an inexorable, predetermined rate.

Another useful isotope is O^{18}. Since the earth was formed its oxygen has been made up of 99.756% O^{16} (8 electrons, 8 protons, and 8 neutrons), 0.039% O^{17}, (1 more neutron), and 0.205% O^{18} (2 more neutrons). The heavier isotopes are not unstable; they are not radioactive nuclei. O^{18} is 10% heavier than O^{16}. Evaporation is a process by which the fast tail in the Maxwell-Boltzmann distribution of molecules has enough energy to leave the liquid phase and enter the solid phase. It is harder for a H_2O^{18} molecule to evaporate than for a H_2O^{16} molecule. When the water surface is colder, there are even fewer H_2O^{18} molecules that have enough energy to evaporate. The ones that do tend to be H_2O^{16} during cold times, with relatively more H_2O^{18} evaporating during warm times. In regions of perpetual annual snowfall, such as Antarctica and Greenland, a higher amount of H_2O^{18} in the snow core indicates a warmer planet, while higher amounts of H_2O^{16} indicate a colder planet. Due to the sequestration of H_2O^{18} in glaciers on land, relatively less of it is left in the ocean, so a deficit will be found for O^{18} in a sea organism that settled to the bottom of the ocean during warm times. Deep sea cores and ice cores exhibit the same patterns of δ O^{18} into the past, but excursions are in the opposite sense, compatible with the mechanism of the temperature dependence of isotopic separation upon evaporation first noted by Harold Urey in 1938.

Once large land glaciers melt, the ice no longer weighs down the crust. By Archimedes buoyancy principle, the elastic asthenosphere will help push the lightened crust upward, yielding isostatic rebound. Rebound of the Gulf of Bothnia has closed the eastward-flowing ice age mountain glaciers in northern Sweden and made them into lakes. If Greenland melts slowly enough then isostatic rebound may help keep it above water, for if the ice were removed now, it would appear as a giant ring atoll filled with sea water. The rate of isostatic rebound can be measured and extrapolated backward into the past to give corroborating evidence regarding the mass of glacial overburden. It also helps us understand the elastic properties of the asthenosphere.

The action of waves on the shores can scoop material away and transport it offshore, making for shelf-like structures. When ice builds up on land during an ice age there is less and less in the ocean, so sea level goes down. As sea level falls shelves are made at lower and lower levels on the shoreline. Submerged shorelines are evidence of melting glaciers and rising sea levels. Since the Wisconsin Ice Age sea level has risen $\sim$120 m in $\sim$20,000 yr, an average of 6 m per 1000 yr. Oral tradition in Cornwall, United Kingdom, holds that the land used to extend far out to sea and that St. Michael's Mount, a beautiful island that one may wade to at low tide, used to be a curious hill in the woods. Indeed there is evidence of submerged habitation relics under some 6 m water on the way to the Scilly Isles.

Cold times greatly favor transporting rocks and dirt around. Lateral and terminal moraines tell us about the advance and retreat of glaciers. Continental glaciers exhibit a slow plastic flow, with downward flow in the snow accumulation zone in the center, then flowing out to the sides. At the bottom the glacier can pluck rocks from the substratum and carry them long distances to the edge of the continental glacier. Calving ice bearing these rocks can float out to sea where they eventually melt, letting the rock debris sink to the bottom of the ocean and become incorporated into the sediment record. Ice-rafted rock debris from the central Canadian shield of pre-Cambrian pink granite can be found in deep sea cores throughout the North Atlantic. Piecing together when ice-rafting occurred off the coast of Portugal helps pin down climate changes such as the Younger Dryas event.

Cold times also favor the transportation of windblown, or aolean, dust. Central Asia is far from the oceans. During the Ice Ages not much snow fell on norhtern Siberia and the ice masses were small compared with the Laurentide ice sheet, with a source for snowfall in the nearby Atlantic. Central Asia became very cold and dry. Winds easily picked up sand and dust from the dry desert steppes across Asia and spread it around the world, settling noticeably across the Pacific basin. This type of dust reflects sunlight and cools the planet, constituting a positive feedback to change during transition to or from a glacial state. Aolean dust plays a major role in providing mineral nutrients so that phytoplankton and island plants can grow.

4.4 Climate Theory and Ice Age / Interglacials

We now consider how our planet seems to vacillate back and forth between glacial and interglacial states on time scales of 10,000-100,000 yr. One of the consequences of Kepler's laws is that a planet receives the same amount of sunlight each year (given a constant solar output), regardless of what the axial tilt is or how elliptical the orbit is. Copernicus, Kroll, and more recently, Yugoslavian mathematician Milutin Milankovich, have each speculated on the notion that the manner in which the earth goes around the sun may, through concentrating rays in certain configurations and rarefying them in others, act to grow or melt continental glaciers. Since most of the land is in the northern hemisphere, the reflective quality of ice will amplify the signal, affecting the average surface temperature of the whole planet.

The equations of motion for bodies orbiting the sun under gravitational attraction have been known since Isaac Newton. Attraction among the planets complicates things, giving minor but significant changes in motion that can accumulate over millenia. Calculation of the motion of objects in the solar system is called celestial mechanics. Over the centuries observations of planetary motion have improved in accuracy, and so has the ability to extend diagnosis of planetary motion into the distant past and into the future. In 1930 Milankovich published an extensive volume which tabulated the intensity of sunlight as a function of latitude and time of year, extending back several hundred thousand years.

The three orbital parameters in the Milankovich theory of climate change are tilt of earth's rotation axis, precession of the axis, and ellipticity of the orbit (Fig. 4.6). When a top spins its axis tilts somewhat off vertical and this pointing direction will gradually rotate around in a circle: its axis will precess. Axial tilt is also known as the obliquity with respect to the plane of the ecliptic. The planets orbit the sun in nearly the same plane, and may eclipse each other in the plane of the ecliptic. A rotation axis that is normal to the plane of the ecliptic would have $0o$ tilt. Each planet's rotation axis tilts somewhat from the normal, and is oblique with respoct to the plane of the ecliptic. Earth's is about $23\frac{1}{2}^o$ at present and varies from 22^o to $24\frac{1}{2}^o$ and back again on a 41,000 year cycle.

The eccentricity of the earth's orbit is about 5% at present, implying a 7% variation in solar power around the orbit. The eccentricity varies from 3% to 9% and back again on a 100,000 yr cycle. At 9% eccentricity the solar strength would vary by 20% throughout the year.

The pointing direction of the earth's axis precesses on a cycle of 22,000 yr. At present the summer sun is in the constellation Aquarius and the axis is pointed toward the star Polaris. Some 11,000 yr from now the axis will be pointed such that the sun will be in the constellation Leo at the summer solstice.

If an orbiting planet has non-zero axial tilt then it will have seasons. When a given hemisphere is tilted toward the sun, that hemisphere will have summer because the sun's rays are concentrated. When that hemisphere is tilted away from the sun it will have winter because the sun's rays are spread over such a large surface area. This aspect of spherical geometry wins over whether the planet is at a point in its orbit that is farthest or closest to the sun. The precession factor determines where in the orbit northern winter occurs. For example, at present the least sunlight falls on the northern hemisphere on December 21, which is fairly close to the time of perihelion, or closest approach to the sun, on January 4. Right now NH winter occurs close to the sun, NH summer far from the sun. 11,000 yr from now NH winter will occur near aphelion, far from the sun.

To understand how the orbital parameters can build up an ice age, we need to consider two aspects of snow accumulation. Firstly, if one assumes that 1 more foot of extra snow is left at the end of each summer, it would take 3000 yr to build up an ice sheet 3000 feet thick. This means that there will be a time delay of several thousand years from when optimal orbital parameter configurations begin to generate an ice age and when the ice will be the thickest. The second consideration is that the capacity of air to hold vapor and make more snow depends strongly on temperature. If air temperatures over a glacier are extremely cold, not much snow can fall. If air temperatures are warmer but still below freezing, more snow can fall. This is the key to why a weak axial tilt favors growth of a glacier.

When axial tilt is weak, seasonal differences are weaker: NH winters are cool and snowy and summers are cool and not much snow is melted. These aspects foster glacial growth. When axial tilt is strong NH winters are cold and dry, while summers are hot and a lot of snow is melted. Thus, paradoxically, milder seasons favor an ice age!

Figure 4.7a shows the variation of these three orbital parameters during the past 250 ky and the next 100 ky. By considering these parameters alone in a heat balance model for continental glaciers, an ice volume curve such as the upper curve in Fig. 4.7b would be anticipated. The periodicities agree fairly well with the observed climate record (lower curve). The 100,000 year ellipticity and 41,000 year obliquity periods are compatible with the primary features in the record. More advanced models which include positive feedbacks by greenhouse gases yield a more favorable comparison.

The Wisconsin Ice Age began on the heels of a prolonged period of weak axial tilt centered at 25 kybp. We are now entering a similar period of weak axial tilt centered at 5 ky in the future (Fig. 4.7a). With the time lag for building up the glacier, a reasonable forecast is an ice age in the 5-10 ky time frame.

The Milankovich theory of climate change requires amplification of tendencies from orbital parameter variations in order to work. Climate theory allows us to consider idealized states of equilibrium, where there is no net forcing of the climate system to change. A ball-bearing analogue serves to illustrate the types of equilibrium that can exist. On a flat surface the ball will roll along for a while unchaged. This system is near neutral in stability. At the bottom of a bowl, the shape of the bowl ensures that any perturbation will be opposed and the ball will return to the bottom. This is a stable equilibrium. In the climate system friction, turbulence, and exchange of infrared photons all act to relax the system, to oppose perturbations. Since these factors will oppose a perturbation in the positive or negative direction, they are called negative feedbacks. Negative feedbacks act like stabilizers in the climate system, with a tendency to stay near attractors in climate system phase space. On a hilltop a perturbation in any direction will cause it to accelerate down the hill. This is an unstable equilibrium. Factors which amplify a perturbation act to destabilize a system. Since these factors act in the same direction as a perturbation, whether it is in the positive or negative sense, they are called positive feedbacks. Positive feedbacks are responsible for wrenching the climate out of its same old state and pushing it toward a different state.

Positive feedbacks that amplify Milankovich orbital parameters include greenhouse gases, the ice albedo feedback, the boreal forest feedback, and the high latitude soil feedback. As temperatures increase more water and carbon dioxide evaporate from the oceans, and more methane comes out of the high latitude soils, all creating a stronger greenhouse effect, leading to further temperature increases. As temperatures decrease water vapor and carbon dioxide condense into the oceans and more methane is frozen into high latitude tundra, weakening the greenhouse effect, leading to further temperature decreases. Meanwhile, a temperature increase will melt snow and ice, allowing more sunlight to be absorbed, warming the periphery further, making things still warmer. A temperature decrease will encourage snow and ice growth, reflecting sunlight, cooling the planet further. Forests trap air and photons, so that if the boreal forest grows farther north, it will trap more heat, further warming high latitudes. If it gets too cold and they die off, their heat retaining properties will be absent, and the planet will get colder.

Positive feedbacks act as amplifiers that help the planet go from one climate state to another. The climate record suggests that glacial and interglacial states represent the extremes of climate, that there may be internal negative feedbacks sufficient to keep the planet within these bounds. To the extent that the complexity of the earth underlies this stabilizing thermoregulatory capability, it seems unwise to continue with massive destruction of ecosystems. By reducing the complexity of the earth organism through species destruction, we may be reducing its resiliency. Some scientists are concerned that with the unprecedented loading of fossil fuel CO_2 in the atmosphere, that we will be forcing the climate system, like pushing the ball bearing up and over the hill, into a new climate state, a superinterglacial that has not been seen in the past million years.

But what if these orbital parameters don't actually matter all that much? Isn't the climate system sufficiently complex that one might expect the climate to wander around, with variability at all time scales, including 10,000-100,000 yr time scales? Maybe the transitions into or out of an ice age are random, with periodicities emerging by chance. This is an argument in favor of internal variability as a source of variation in paleoclimate and future climate, an element of Chaos Theory. Chaos Theory was pioneered by Meteorologist Ed Lorenz in 1960. A stimulating synopsis of this young and rapidly evolving field is provided by Gleick [1987].

One aspect of chaos theory is often referred to as the butterfly effect. Lorenz found in his initial numerical weather forecast experiments that, if he changed one input value an apparently insignificant amount, it eventually led to the new forecast diverging hopelessly from the original forecast. Intuitive aspects of this come from folklore regarding the consequences of one minor change, such as not being able to shoe a horse, being unexpectedly large. The sensitivity of outcome to uncertainty in initial conditions is a central aspect of chaos theory. The ability to forecast the weather will eventually be compromised by whether it is known at the outset that a butterfly in Brazil flapped its wings or not. Jonathan Swift wrote in the 1700s that "Big dogs have little fleas, That feed on 'em and bite 'em, But the little fleas are plagued by lesser bugs, And so on, ad infinitum, So are the greater poets bit, By the lesser that come behind 'em." An application by L. F. Richardson in 1922 to the atmosphere goes: "Bigger whirls have smaller whirls, That feed on their velocity, And small whirls have still lesser whirls, And so on, to viscosity." This represents another aspect of chaos theory, that the smallest of phenomena are linked to the largest. It's a two-way street. The distribution of large-scale structure helps determine what happens to individual molecules, while each molecule's behavior determines the whole, not just by additive effect, but by cascade across scale. A butterfly flapping its wings can influence minor zephyrs, which subtly influence larger and still larger zehpyrs, eventually making a slight difference over the whole globe. One may consider the interdependency of civilization and microorganisms in light of chaos theory.

The chaotic nature of even very simple systems is illuminated by Lorenz' simple analog, the water wheel (Fig. 4.8). Imagine a set of leaky buckets mounted in a ferris wheel configuration, with a water spigot filling them as they pass the top. If the wheel begins to rotate clockwise, more buckets on that side will fill, accelerating the wheel in a clockwise sense. But if it spins fast enough so that the next few buckets don't fill much and the fuller buckets are found on the left side, the wheel may slow down and start rotating the other way. It turns out that it is devilishly hard to predict when the water wheel will reverse its course. It has two states of rotation, clockwise and counterclockwise (two attractors in phase space), but one cannot predict when the transition from one to the other will occur; it is chaotic.

Fundamental aspects which contribute toward a lack of predictability, or precise determinism, include Heisenberg's uncertainty principle, phase transitions, advection, hydrodynamic instabilities, and other nonlinear processes. The fact that we cannot determine the precise speed and position of each molecule that makes up the earth system contributes a certain lack of predictability due to the butterfly effect cascading up from the molecular level. If a raindrop forms and falls, it cannot go back again to where it was. Very subtle things may determine whether or not a given raindrop forms. Whether it forms or not represents a great amplification of a small difference. If wind speed varies in space it will self-advect in a way that changes the distribution. Momentum advection takes the form $u\ \partial u/\partial x$, is quadratically dependent on speed, so is fundamentally nonlinear, a quality that can amplify initial uncertainties. Flow field instabilities include those due to shear and to curvature, which contribute to the chaotic nature of von Karman vortex streets, eddy shedding, energy conversion among eddies, and amplification of waves. Instabilities that seek to lower the center of mass include convective and baroclinic instability associated with growth of synoptic scale storms. Each of these will amplify initial uncertainties, leading to chaotic aspects of weather and climate.

To explore a little further into chaos theory, consider a simple pendulum that is displaced or swung in a circle. Eventually air friction will cause it to come to rest hanging straight down. If you plotted the position of the pendulum in two dimensions on the page it would spiral gradually into the middle. Each perturbation eventually ends up there. The origin is called an attractor in phase space. It is a stable attractor because every perturbation eventually ends up there; Every orbit gradually tends toward that point. It exists due to the negative feedback of friction on the pendulum. In the much more complex climate system negative feedbacks provide regions where the climate spends most of its time. The upper and lower temperatures embodied in glacial and interglacial states represent attractors that arise from friction and infrared emission. The attractors in the climate system are strange, however, because the orbit in phase space is irregular and impossible to predict. They are thus called strange attractors.

Lorenz boiled down the climate system into a simple set of three coupled equations governing Rayleigh convection, with three variables being the vertical temperature gradient, horizontal temperature gradient, and amplitude of eddy motion. The famous result from plotting the climate state of this three-variable system in Cartesian coordinates is called the Lorenz butterfly, due to its shape. It features a trajectory around two strange attractors and unpredictable transitions from one to the other. If one substituted equator to pole temperature difference, ice amount, and strength of poleward heat transport, and plotted their variation over geologic time, one would see a pattern emerge that clusters around glacial and interglacial times, with transitions between the two taking a while but being unpredictable.

Since elements of determinism and chaos were both present in the initial moments after the Big Band, it makes sense to describe climate dynamics as having a healthy mixture of both. Milankovich theory goes a long way toward describing the fundamental climate signal over the past million years, but the detailed evolution of the earth's climate has chaotic qualities to it. One aspect of the climate signal that begs explanation is the fact that Dansgaard-Oeschger events are conspicuously absent during the past 10,000 years. Even during the Emian interglacial there were chronic rapid oscillations, near the bottom of the ice core in Fig.4.2. What is the secret to the stability of the late Holocene?

4.5 Climate Dynamics Since the Last Ice Age

The rise out of the Wisconsin Ice Age was rudely interrupted by the Younger Dryas event around 11,000 yr ago. Figure 4.9 shows the co-evolution of δO^{18} in northern European lakes, a Greenland ice core, and corresponding CO_2 variations. From 13,000 ybp to 10,600 the climate cooled considerably, with notable swings in temperature. One theory for how this could have occurred starts with the retreat of the Laurentide ice sheet, which allowed water from Lake Agassiz in south central Canada to flow out the St. Lawrence river. This influx of fresh, light water may have been sufficient to stop the formation of North Atlantic bottom water and redirect the Gulf stream on a less northward trajectory. This could have led to cooling of the North Atlantic and subsequent regrowth of the Laurentide Ice sheet. Strong evidence to support this includes ice-rafted rocks from central Canada found in the sea floor sediments off the coast of Spain during 20-13 kybp, their absence during 13-11 kybp, and reappearance during 11-10 kybp. The timing of release of stored greenhouse gases from various ecosystems may have contributed to these oscillations.

The idea that changes in the Gulf stream and bottom water formation can exert a strong control over climate underpins the movie Day After Tomorrow, in which global warming all of a sudden induces an ice age. The primary difference between the current situation and that of 11,000 years ago is that the Laurentide ice sheet was still large and ready to grow but today it is gone. Moreover, the Gulf stream strength is controlled primarily by by the pattern of wind stress over the Atlantic basin, so it is not clear that the Gulf stream would weaken significantly if the formation of deep water ceased. Nevertheless, if the Gulf stream penetrates farther north, as it does now, it is consistent with a warm arctic. When the Gulf stream landfalls in southern Europe it is consistent with a cold arctic. Because of the proximity of the Canadian shield, which can build up snow, the North Atlantic is the seat of powerful climate change. The interaction among the atmosphere, ocean, and cryosphere is subtle and not well understood, yet it may be the key to the Dansgaard-Oeschger events which have dominated the climate record prior to 10 kybp.

Consistent with Milankovich theory, the Holocene Maximum began around 8 kybp, at a time when Northern Hemisphere summer occurred at perihelion. The hot land in the summer mass-wasted the remaining glaciers and it got pretty warm. Interglacials never last very long (Fig. 1.2). One might have expected the climate to begin to cool around 4 kybp. Instead it has wandered around, then gotten hotter.

During the past few thousand years temperature variations on the order of 0.5 K have occurred. The Medieval optimum during 950-1400 A.D. was warmer, coinciding with a period of fascinating, but sporadic cultures in the southwestern U.S. which succumbed to various phases of a megadrought. It also coincided with expansion of the Vikings into Greenland and parts of North America, with extensive trade for 500 years. Both are consistent with a warmer global climate.

The Little Ice Age lasted from ∼1400 to 1890, which was bad for Greenland and the new world all around, due to European expansion. Although such a time may be viewed as due to internal variability, one can never rule out variations in solar output. Shortly after Galileo documented spots on the sun that changed over the years, a remarkable period of almost no sunspot activity occurred, the Maunder minimum of ∼1620-1715. Given that the sun emits ∼0.5% less sunlight during solar minimum compared to solar maximum, this would have contributed toward making the 1600s somewhat cooler. Although this is an interesting theory and probably a contributing factor, the Little Ice Age lasted almost 500 years, including 200 years before and after the Maunder minimum. Variability of volcanic eruptions can operate on almost any time scale. A contributing deterministic factor in this case is their degree of clustering by decade and century. The acidity of Greenland ice cores is a good proxy for global volcanic activity, being more acidic when more sulfuric acid droplets are incorporated into snowflakes. The period 1000-1250 was fairly light in volcanic activity, while the period 1300-1900 was rather robust in volcanic activity. Intercentury variability in volcanic aerosol loading may have contributed to the Medieval optimum and Little Ice Age (Fig. 4.1e).

Trends during the past century include warmer times during the 1930s, followed by little increase, then pronounced warming since the 1980s (Figs. 1.4a, 4.1f). During the 1930s and 1980s there were relatively few volcanic eruptions, contributing somewhat to warmer temperatures. The eruption of Mt. Pinatubo cooled the planet by ∼0.5 K for 1-2 yr, but since then there have been no major eruptions and the planet has been getting warmer. The length of the solar cycle has also varied over the past century, with cycles being ∼8 yr in the 1930s and 1990s, and ∼12 yr in other decades. The sun appears to be slightly stronger when the solar cycle is faster, but the most recent solar cycle was fairly normal and temperatures continue to rise.

There is currently a decadal drought in the U.S. southwest that is similar to the prolonged drought that brought about the demise of the Anasazi culture in the 1100s (Fig. 4.10). We are also witnessing a remarkable period of rapid arctic sea ice loss, primarily during the summer (Fig. 4.11). With increasing summer temperatures and urban populations there is increasing risk that heat waves will cause serious loss of life (Fig. 4.12). We will return to this topic in discussing climate prediction for the next century.

4.6 Volcanoes and Climate

Volcanic eruptions can cool the planet for several years, lead to more PSCs and cirrus, exacerbate ozone depletion, and can change weather patterns. Figure 4.13 (Robock 1990) summarizes the primary effects of small tropospheric eruptions and of large volcanic eruptions that reach the stratosphere. Eruptions can consist of an array of ash particles, with smaller particles carried farther by the wind. On geological time scales, wind-borne volcanic ash is a significant source of mineral nutrients for islands far out at sea. The primary gaseous emissions are H_2O (85%), CO_2 (15%), and trace amounts of N_2, HCl, H_2S, and SO_2. The sulfur gases from minor tropospheric eruptions become oxidized into sulfuric acid, incorporated into liquid sulfate aerosol and precipitate out within 1-3 weeks. This is similar to the fate of fossil fuel sulfur and acid rain.

A large eruption can inject gases directly into the stratosphere, where it takes about 6 months for sulfur compounds to form the characteristic volcanic stratospheric sulfate aerosol, with bright orange sunsets. This stratospheric aerosol layer is known as the Junge layer, with a maximum mixing ratio near 21 km in the tropics (Fig. 4.14). Volcanically-enhanced sulfate aerosol can remain for 1-3 years, with an exponential decay rate of $\sim 1/e$ in 22 months. The dominant effect of stratospheric volcanic aerosol is backscattering of solar visible and uv to space, cooling the surface of the planet, on average. The aerosol layer acts as a greenhouse agent, absorbing upwelling surface infrared, heating the bottom half of the aerosol layer. This can lead to lofting in the tropics and an enhancement of the overturning Brewer-Dobson circulation.

One primary way that we know about volcanic eruptions in the past is by quantifying acidity in ice cores. Large volcanic eruptions cause snow layers rich in sulfuric acid to be deposited in for several years. This can also happen from local large sources such as Icelandic volcanoes and Greenland ice cores, so care must be taken in interpreting them. Nevertheless, they are quite valuable in helping us understand the history of volcanic eruptions. Volcanic eruptions provide unique insights into the general circulation of the stratosphere and troposphere. They are also harbingers of changing weather, notably warmer winters in the interiors of the continents of North America and Eurasia. Let us explore some historic eruptions to gain some insight into their effects.

Volcanic eruptions have always had the knack for grabbing our attention. A massive eruption of Mt. Toba in Sumatra some 70 kybp left a crater 70 km long, possibly aiding in the descent toward the last ice age. It probably caused massive destruction in Southeast Asia, and global cooling with reduced food supply. How the Neanderthals coped is beyond understanding. Large eruptions in the Mediterranean have shaped the evolution of civilizations in the regions. Sometimes a distinctive volcano can be a vital geographical marker. According to Herodotus, in 600 B.C. Pharoah Necho II sent ships clockwise around Africa and back through the Straits of Gibraltar to the Nile (Hermann, 1932). On a similar circumnavigation in 500 B.C. Captain Hanno commented specifically on the location of Mt. Cameroon near the equator on the west side of Africa. Francis Drake mentioned that Mt. Cameroon was erupting when he passed by to harrass the Spanish on the west coasts of the Americas in 1587, then exploring the Pacific Northwest for the fabled Northwest Passage. If only he had been born today he could have realized his dream.

Pesky Icelandic volcanoes have been the bane of agriculture and cause of famine many times. In 1150 B.C. Hecla 3 erupted and the population of Scotland dropped 90% due to failed crops (Gore 1992). Chinese scholars noted at the time that “it rained dust at Po”.

Again in 208 B.C. an Icelandic volcano caused the scholars to write “stars were not seen for 3 months” and there was a great famine in China the next year.

Around 1783 there were multiple eruptions of Mt. Asama in Japan and furious fumigations from Loki in Iceland. Icelandic eruptions do not generally reach the stratosphere by direct injection. Yet material can be transported into the lower stratosphere near weather systems. Moreover, it has been realized recently that particles can absorb infrared, maker the air warmer and lighter, and loft, making its way into the stratosphere. Forest fire smoke in Canada has been observed to self-loft into the summer stratosphere. It is likely that some of the Loki material made its way into the stratosphere. This was followed by 6 years of crop failures in Europe. It may have fostered unrest and contributed toward conditions leading to the French Revolution.

Mt. Tambora erupted in 1815. The next year has gone down in history as “the year without a summer”. It snowed in New England in July. There was a famine in Europe in 1817 and 1818. The result has been called “the last great subsistence crisis in the Western World”.

Then on August 27, 1883 Krakatoa erupted, sending enormous tsunamis that killed 35,000 people. For several hundred years passersby would refer to Krakatoa as “an island with a pointy mountain” (Winchester 2002). In 1858 Alfred Russell Wallace was in the vicinity, documenting an astounding 125,660 new species in Indonesia. He had great insights into the idea of survival of the fittest, a driving force in evolution, and sent a formal manuscript on the subject to his mentor Charles Darwin to deliver to the Royal Society. Darwin was far into writing his Origin of the Species and felt quite discomfitted. In the end he presented both works to the society and the rest is history. Wallace didn’t seem to mind the early lack of recognition of this contribution, preferring to continue collecting new species anyway. He also had astounding early insight into the idea of continental drift. He knew that there must be some way to explain the abrupt juxtaposition of Eurasian species and Australian species across a deep north-south channel near Bali. This line has come to be known as the Wallace Line. His fame has gradually grown to this day. It wasn’t until the end of the century that famed meteorologist and geologist Alfred Wegner posed his theory of continental drift. Now we know that the oceanic plates diving under Indonesia make for an unusually explosive brand of volcanic eruption.

On August 27, 1883 Captain Thompson of the British ship Medea measured the height of the volcanic cloud to be no less than 17 miles or 27 km, well into the stratosphere. As the sun never set on the British empire, Royal society observers reported brilliant orange sunsets in a pattern spreading westward from Indonesia in the tropics. Scientists concluded that stratospheric winds were westward, and referred to them as the “Krakatoa easterlies”. After a few months northern winter began setting in, and the eruption cloud began to transported northward into the winter westerlies, with orange sunsets arriving from the west over Britain some 3 months later. This informs us that volcanic aerosol tends to be confined to the tropics, and will spread poleward by planetary scale wavy motions during winter.

People were content with the volcanically-informed notion of “Krakatoa easterlies” for several years. Then in August of 1908 Arthur Berson made careful measurements of winds and temperatures at Dar es Salaam at 6.30^{o}S and Shirati at 1^{o}S, using radiosonde balloons that could reach the tropical lower stratosphere. That is hard to do, since the tropopause is quite high over tropical Africa. On August 30 at Shirati the coldest temperature was -84.3^{o}C (188.7 K) at 19,330 m. Much to everyone's consternation, Berson found weak westerly winds in the layer 19-20 km. The new view became a layer-cake, with steady deep Krakatoa easterlies topping a thin layer of Berson westerlies.

It wasn't until Reed (1961) and Veryard and Ebdon (1961) discovered a most interesting phenomenon that all was revealed. By systematically examining long time series of radiosonde observations in tropical stations they were able to deduce that westerly and easterly wind regimes formed and descended in time, to be repeated again in a cycle taking 24-32 months (Fig. 3.32). A most fascinating geophysical phenomenon, this quasi-biennial oscillation (QBO) is not driven by the annual solar cycle. Instead it is driven by the upward transport of momentum by tropical waves above deep convection. The QBO exerts a strong influence on stratospheric circulation and has an influence on tropospheric weather as well. It turns out that a volcanic eruption serves as a perfect dye for illuminating the circulations associated with the QBO.

There are various ways of estimating the magnitude of influence of volcanic eruptions, including a severity index, a volcanic explosivity index, and aerosol optical depth observed at the surface. Table 4.1 shows the major eruptions of the past 150 years. Figure 4.15 shows an estimate of aerosol optical depth during that time, based on severity and explosivity indices (Sato et al. 1993). Ground-based pyrheliometers provide a more direct means of estimating volcanic eruptions (Fig. 1.8). Note the huge eruption of Krakatoa (1883) and the clustering of eruptions in 1880-1915 in both data sets, a period when the earth was fairly cold. The 1930s and 40s were fairly devoid of eruptions and these were warm decades. In the pyrheliometer data of Goodman (1980) a gradual rise in aerosol optical depth occurred from 1940-1970. This is referred to as the global dimming, and may be related to the sulfate aerosol produced by burning ever-increasing amounts of fossil fuel (see section 6.3).

The eruption of Mt. Agung in 1963 ushered in another few decades of moderate volcanic activity, including Mt. St. Helens in 1980, El Chichon in 1982, and Mts. Pinatubo and Hudson in 1991. These years were not particularly hot years. Since Mt. Pinatubo there has not been a major eruption and it has gotten warmer. It seems likely that some of the record high temperatures in the last decade can be attributed to the lack of volcanic eruptions.

Living in Seattle in 1980 I used to go sailing on Lake Washington and watch Mt. St. Helens send up big clouds of material. A fellow graduate student used to go down to a ridge north of Mt. St. Helens each weekend between classes and take pictures. Inclinometers showed that the north face was bulging outward and that something interesting might happen. He felt fairly safe 20 miles away. At 9 o'clock on the morning of May 19 people started screaming, so he scrambled out of his tent and took a few pictures (Fig. 4.6a). Then he dove in his pickup truck and headed north down the logging roads away from the debris cloud, which was advancing at 150 mph. Luckily he got behind a ridge, but it kept getting closer and closer (Fig. 4.6b), until he was enveloped in falling ash and it became completely dark. The ash kept building up, 6", 8", 10", until he thought he would suffocate. Then a knock in the dark produced a logging truck with three men, one to drive, and one each to feel for the ditch with their feet in the dark. He got in right behind them and could see their bumper when about 1' away and followed them out to the town of Randle.

Figure 4.17 shows a latitude-time section of stratospheric aerosol showing the eruptions of Mt. St. Helens, Ruiz, El Chichon, Hudson, and Pinatubo. Extratropical eruptions tend to be cleansed fairly rapidly by the Brewer-Dobson circulation transporting the aerosol poleward and downward, where it is lost in the troposphere. This is why Mt. St. Helens didn't have much of a cooling effect planet-wide. As the plume made its way across the U.S., wherever the cloud was thickest, the daytime maximum temperature was reduced by a few degrees, due to solar reflection, and the nightime minimum was also reduced, due to infrared trapping.

One may also see that aerosol tends to come out of the tropics during winter and during the westerly phase of the QBO. Figure 4.14 shows the mean distribution of aerosol. It peaks near 21 km altitude in the tropics. Within a year after an eruption the pattern looks very similar to this. Note the poleward and downward extension from the tropical aerosol reservoir in the lowest stratosphere.

Figure 4.18 shows how the Pinatubo cloud spread westward, making a ribbon shape in the tropics. It was confined to the tropics until winter set in. Figure 4.19 shows that the arrival of volcanic aerosol in the lower stratosphere over Colorado (from the west again) didn't occur until October of 1991, but the eruption was in June.

The effects of volcanic eruptions on PSCs (see section 5.3) is very noticeable in Fig. 1.9, which shows the evolution of optical depth in the Arctic and Antarctic. After the eruption of El Chichon there was much more aerosol mass in the Arctic, and the PSCs in the southern winter began much earlier in the year.

Eruptions heat the tropical stratosphere by 1-4 K, causing an acceleration of the Brewer-Dobson circulation. By cooling the troposphere, the tropical tropopause will not be forced by convection to be so high and cold, allowing more water vapor to enter the stratosphere, further changing the radiative budget.

An interesting result from the tropical stratosphere warming more than high latitudes is that a stronger westerly jet results In winters following a major eruption, instead of the jet stream getting set up into large poleward excursions into Alaska around a ridge, and an equatorward excursion from Canada across the east coast of the U.S., the subtropical westerly jet is stronger and comes from the Pacific ocean right into the Midwest, while the Atlantic jet stream goes right across Europe into Russia. The result is to bring warm air from over the North Pacific and Atlantic into the interiors of continents, keeping them warm. Thus, while the globe cools generally after an eruption, during the winter the interiors of continents are warmer.

A volcanic eruption can also excite the NAM and the SAM (section 3.9), since a stronger westerly vortex favors the high index phase of each. We now know that a strong vortex regime in the northern winter stratosphere is a good predictor of a strong westerly vortex in the troposphere over the next several weeks (Thompson and Wallace, Baldwin and Dunkerton 2000). This may be the mechanism by which warm continental winters are obtained (Fig. 3.29).