brief introduction to

the history of climate

Beginning in the early 1900s, the climate of the world began to warm. This is evident in Figure 1-1, which shows the average Earth surface temperature from 1880 through 1999. The temperature is an area-weighted average over the land and ocean compiled by the National Oceanographic and Atmospheric Administration, using an averaging technique devised by Quayle et al. ; see also . In the plot, "zero" temperature is defined as the temperature in 1950. The fine line shows the monthly temperatures; the thicker line shows the 12 month yearly averages.

The figure shows that the 20th century had a temperature rise of nearly one degree Celsius. That may not sound like a lot, but its effects are quite noticeable. In Europe, the great glaciers of the Alps, such as the Mer de Glace near Chamonix, have been in retreat, and the canals of Holland almost never freeze over, as they did in an earlier era to allow Hans Brinker to silver skate into legend. The effects elsewhere on the globe are more severe, with large areas of Central Africa, once fertile, becoming arid and no longer capable of supporting a large population. Although the reason for this warming is not fully understood, many climate scientists think it is the result of the addition of carbon dioxide and other greenhouse gases into the atmosphere by humans.

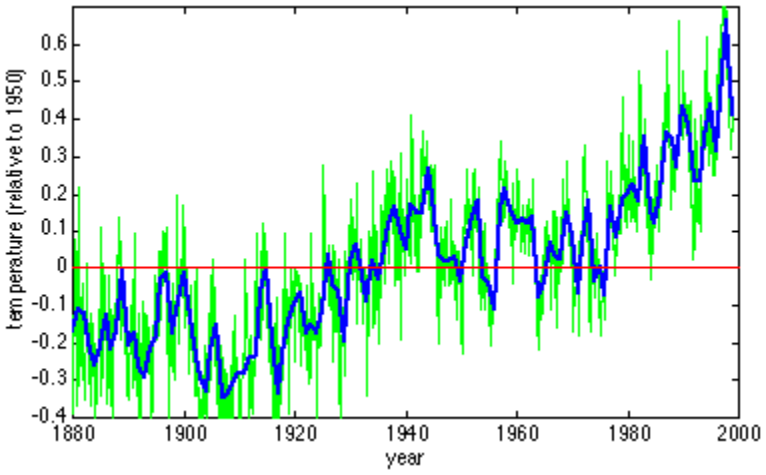

Figure 1-1 Global warming

As we go back in time in search of earlier records, the historical record becomes less reliable. Fortunately, Nature has provided its own recording mechanism. As we will explain in Chapter 4, measurements of oxygen isotopes yield an estimate of ancient temperatures combined with total global ice volume – a combination which is just as interesting as temperature alone, if not more so. Data from a kilometer long core taken from the Greenland glacier, as part of the Greenland Ice Sheet Project "GISP2" , are shown in Figure 1-2. For comparison purposes, the zero of temperature scale for this plot was set to match that of the previous plot. For historical interest, we marked some events from European history.

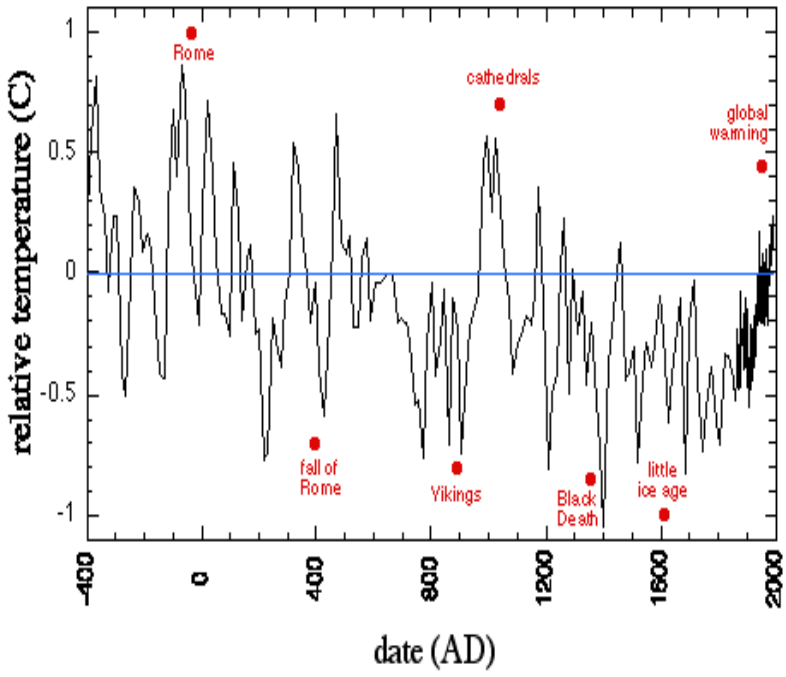

Figure 1-2 Climate of the last 2400 years

The cool period preceding the 20th century warming is now seen as a dip that lasted 700 years. This period is now referred to as "the little ice age." (The coldest periods, near 1400 and 1700, are sometimes called the *two* little ice ages.) In her popular account of the history of the 14th century, historian Barbara W. Tuchman, argues that the low temperatures triggered social conflict and poor food production, and was thus responsible for hunger, war, and possibly even pestilence . Just a few centuries prior, at the beginning of the second millennium, Europe had experienced the

"medieval warm period" . It was a time when civilization emerged from the Dark Ages, art and painting flourished, and the wealth and new productivity of Europe allowed it to build the great cathedrals. Some historians will attribute this flowering to great leaders, or to great ideas, or to great inventions, but it is foolish to ignore the changes in climate. Just prior to that, in the 900s, the Vikings were invading France, possibly driven from the more northern latitudes by the cold temperatures of that century. The height of the Roman republic and empire was reached during another time of unusual warmth – even higher than the warm period of today, if the ice-reckoned temperature scale is accurate.

The next plot (Figure 1-3) shows the data from the Greenland ice core back to 10,000 BC. Near the right hand side of this plot, the little dip of the little ice age is clear. Some scientists argue that global warming is not human caused, but is simply a natural return to the normal temperature of the previous 8,000 years. In fact, no one knows for sure if this is right or not. But the foundation for thinking that human effects will cause warming is substantial. Even if the recent rise in temperature is natural, human caused effects have a high probability of dominating in the near future, and within our lifetimes the temperature of the Earth could go higher than has ever seen previously by *Homo sapiens*.

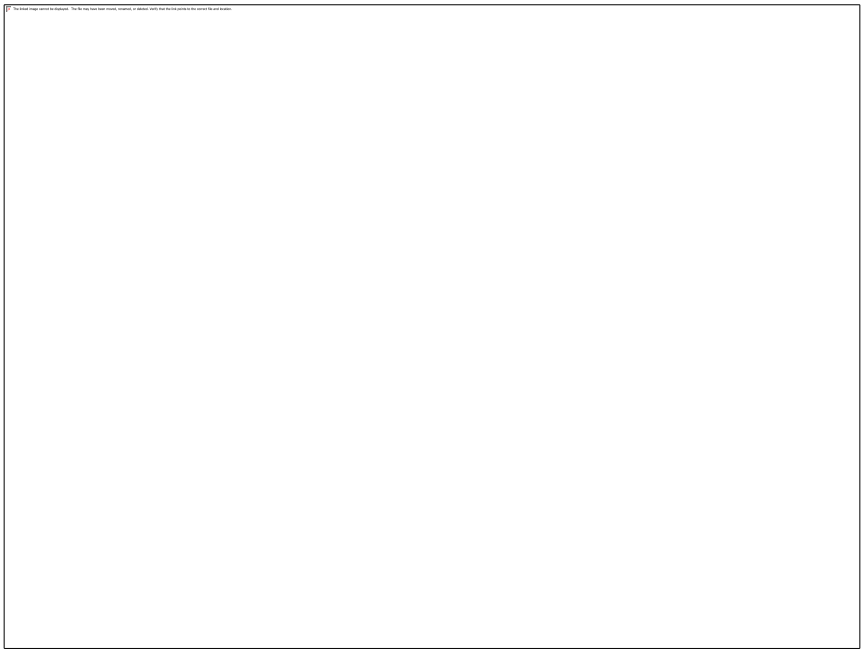

Figure 1-3 Climate of the last 12,000 years

The dip near 6000 BC is not understood. It actually appears to be coincident with a short term *increase* in temperature that took place in

Antarctica! So we can't easily interpret everything in these plots, at least not without studying other records. Fluctuations are evident all over the plot, and crying to be understood.

Agriculture began about 7,000 BCE, as marked on the plot. All of civilization was based on this invention. Agriculture allows large groups of people to live in the same location. It allows a small number of people to feed others, so that the others can become craftsmen, artists, historians, inventors, and scientists.

The sudden rise at the left side of the plot, at about 9,000 BCE (i.e. 11,000 years ago), was the end of the last ice age. The abruptness of the termination is startling. Agriculture, and all of our civilization, developed since this termination. The enormous glacier, several kilometers thick, covering much of North America and Eurasia, rapidly melted. Only small parts of this glacier survived, in Greenland and Antarctica, where they exist to this day. The melting caused a series of worldwide floods unlike anything previously experienced by *Homo sapiens*. (There had been a previous flood at about 120 kyr, but that was before *Homo sapiens* had moved to Europe or North America.) The flood dumped enough water into the oceans to cause the average sea level to rise 110 meters, enough to inundate the coastal areas, and to cover the Bering Isthmus, and turn it into the Bering Strait. The water from melting ice probably flooded down over land in pulses, as ice-dammed lakes formed and then catastrophically released their water. These floods left many records, including remnant puddles now known as the Great Lakes, and possibly gave rise to legends that persisted for many years. As the glacier retreated, it left a piles of debris at its extremum. One such pile is now known as New York's Long Island.

In the next plot, Figure 1-4, we show the Greenland ice data for the last 100,000 years. The very unusual nature of the last 11,000 years stands out in striking contrast to the 90,000 years of cold that preceded it. We now refer to such an unusual warm period as an interglacial. The long preceding period of ice is a glacial. During the last glacial, humans developed elaborate tools, and *Homo sapiens* migrated from Africa to Europe. But they did not develop civilization until the ice age ended.

During the glacial, not only was the temperature lower by 8 Celsius (and some estimates put it at more than 12 Celsius – the record is a superposition of ice volume and temperature), but the climate was extremely irregular. The irregularities in temperature during the glacials, the wild bumps and wiggles that cover much of Figure 1-4, are real, not an artifact of poor measurement. The same bumps and wiggles are seen in two separate cores in Greenland, and in data taken from sea floor records found off the California coast. The ability to adapt quickly during this wild

climate ride may have given a substantial advantage to adaptable animals, such as humans, and made it difficult for other large fauna to survive. Maybe it was these rapid changes, and not the rapaciousness of humans, that drove the mammoths, camels, giant ground sloths and giant beavers (the size of bears) of North America extinct. Recent global warming appears negligible on this plot. However, if predictions of climate modelers are correct, global warming temperature changes will be comparable those during the ice age.

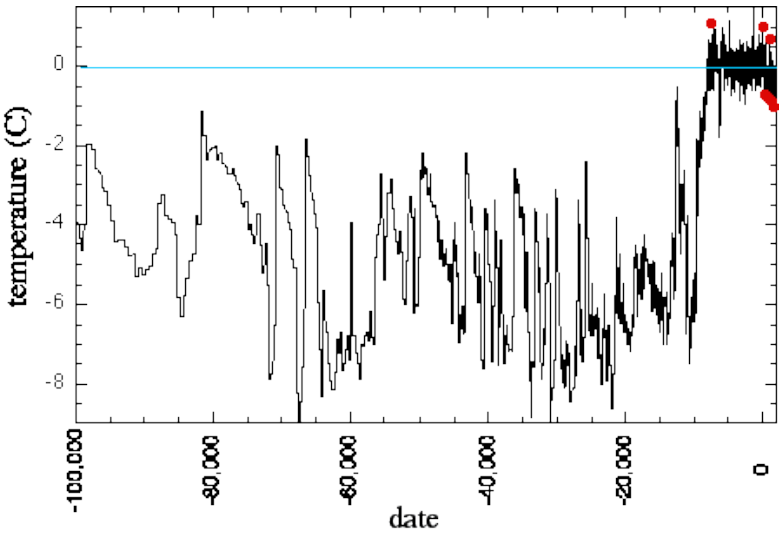

Figure 1-4 Climate of the last 100,000 years

The reliable data from Greenland go back only as far as shown in Figure 1-4. We can continue the climate plot further back by using the records from Vostok, the Russian base in Antarctica, where another ice core was drilled. The last 420 thousand years of a deuterium measurement at Vostok is shown in Figure 1-5, with the most recent 100 kyr appended from the Greenland record (which is more detailed). The temperature scale was adjusted to agree with the scale on the Greenland record.

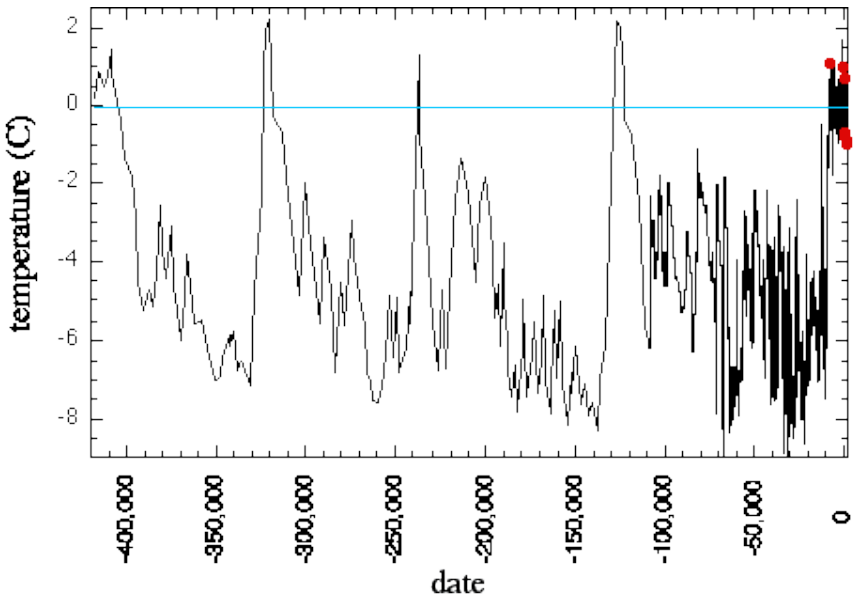

Figure 1-5 Climate for the last 420 kyr, from Vostok ice

From this plot, it is clear that most of the last 420 thousand years (420 kyr) was spent in ice age. The brief periods when the record peaks above the zero line, the interglacials, typically lasted from a few thousand to perhaps twenty thousand years.

These data should frighten you. All of civilization developed during the last interglacial, and the data show that such interglacials are very brief. Our time looks about up. Data such as these are what led us to state, in the Preface, that the next ice age is about to hit us, any millennium now. It does not take a detailed theory to make this prediction. We don't necessarily know *why* the next ice age is imminent (at least on a geological time scale), but the pattern is unmistakable.

The real reason to be frightened is that we really don't understand what causes the pattern. We don't know why the ice ages are broken by the short interglacials. We do know something – that the driving force is astronomical. We'll describe how we know that in Chapter 2. We have models that relate the astronomical mechanisms to changes in climate, but we don't know which of our models are right, or if any of them are. We will discuss these models in some detail in this book. Much of the work of understanding lies in the future. It is a great field for a young student to enter.

The ice records take us back only to 420,000 years in the past. However, oxygen isotope records in sea floor cores allow us to go further. One of the

best sets of data comes from a location in the northern Atlantic Ocean known as the Ocean Drilling Project Site 607 . This site has climate data going back three million years, and is shown in Figure 1-6. But before you look at the figure, let us warn you. In the paleoclimate community, there is a convention that time is shown *backwards*. That is, the present is plotted on the left-hand edge, and the past is towards the right. We are going to use this opportunity to change our convention, for the remainder of the book, so that you will have less trouble reading the literature. (The literature of "global warming" scientists, in contrast, follows the other convention, which we have used up until now.) We apologize for this change in convention, but we do not take blame for it.

In Figure 1-6, the 10 kyr years of agriculture and civilization appear as a sudden rise in temperature barely visible squeezed against the left hand axis of the plot. The temperature of 1950 is indicated by the horizontal line. As is evident from the data, civilization was created in an unusual time.

There are several important features to notice in these data, all of which will be discussed further in the remainder of the book. For the last million years or so (the left most third of the plot) the oscillations have had a cycle of about 100 kyr (thousand years). That is, the enduring period of ice is broken, roughly every 100 kyr, by a brief interglacial. During this time, the terminations of the ice ages appear to be particularly abrupt, as you can see from the sudden jumps that took place near 0, 120, 320, 450, and 650 thousand years ago. This has led scientists to characterize the data as shaped like a "sawtooth," although the pattern is not perfectly regular.

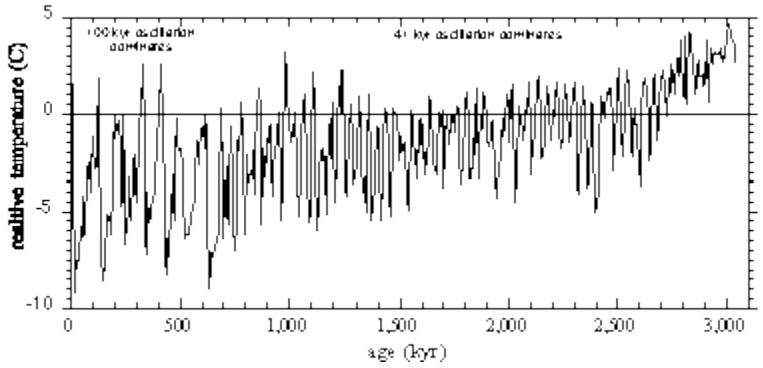

Figure 1-6 Climate of the last 3 million years

But as we look back beyond a 1000 kyr (1 million years), the character changes completely. The cycle is much shorter (it averages 41 kyr), the amplitude is reduced, the average value is higher (indicating that the ice ages were not as intense) and there is no evidence for the sawtooth shape. These are the features that ice age theories endeavor to explain. Why did the transition take place? What are the meanings of the frequencies? (We

will show that they are well-known astronomical frequencies.) In the period immediately preceding the data shown here, older than 3 million years, the temperature didn't drop below the 1950 value, and we believe that large glaciers didn't form – perhaps only small ones, such as we have today in Greenland and Antarctica.

As we end this brief introduction to the history of the ice ages, let's again look to the future. As soon as the cycle of the ice ages was known, scientists realized that the ice age would eventually return. Some of them enjoyed scaring the public about the impending catastrophe. In Figure 1-7 we show the cover from a magazine of the 1940s showing the consequences of the return of the ice age to New York City. (One of the authors of the present book, RAM, saw this image as a child, and it made a lasting impression.) Unfortunately, the art genre of returning ice has been superceded, in the public forum, by paintings of asteroids about to hit the Earth, usually with a curious dinosaur momentarily distracted by the unusual scene. But, as we mentioned earlier, the more likely scenario for the early 21st century, is the continued gradual growth of global warming.

Figure 1 -7 The Ice Age returns to New York City

You may continue in Chapter 1 to read A Brief Introduction to Ice Age Theories, or A Brief Introduction to Spectra.