Preface

A physical chill settled on the 14th century at its very start, initiating the miseries to come. The Baltic Sea froze over twice, in 1303, and 1306–7; years followed of unseasonable cold, storms and rains, and a rise in the level of the Caspian Sea. Contemporaries could not know it was the onset of what has since been recognized as the Little Ice Age ...

Barbara W. Tuchman, *A Distant Mirror*, 1978

George Santayana said that those who do not study history may be condemned to repeat it. Nowhere is this more true than in climate. Truly amazing data are now available—data that show that for most of the last million years the Earth has been in a colder state than now, with ice covering much of North America and Europe. This continuous ice age has been broken every 100,000 years or so by a brief "interglacial". We are in such an interglacial period now. It started about 12,000 years ago and, shortly afterwards, agriculture began and all of civilisation developed. History shows that such warm periods in the past lasted between 10 and 20 thousand years. Based on this, we should expect our present interglacial to end any millennium now.

That is, of course, unless human-caused global warming preempts it. But don't interpret this as an argument in favour of global warming. Many scientists believe that the enhanced greenhouse effect from fossil fuel emissions will yield a rise in temperature of 2–6°C in the first 30 years of the twenty-first century. Such rapid changes have never been experienced by humans, not even during the rapid terminations of the past ice ages. As fertile regions become arid, and arid regions fertile, our survival may depend on the maturity of our political institutions to handle the world-wide disruptions that, as history shows, result from climate shifts. Nobody who has studied history could be optimistic.

Ice or heat? Or somewhere in between? What is our future? The truth is, we don't know. Enormous research programmes are now under way to guide global climate models, the large computer-based programs that simulate the behaviour of the atmosphere, oceans and glaciers. It is hard to imagine a topic more important to the economy of the world. But the models are only as good as the information we base them on. Much of the best information is in the paleoclimate records of the past million years.

Fortunately, we are blessed with truly superb data. The history of climate has been preserved in ice, rock and in layers of sediment on the sea floor. In the last quarter of the twentieth century, these amazing records have been collected at great expense. The enormous Deep Sea Drilling Project, and its successor Ocean Drilling Program, have brought back thousands of cores of sediment from around the world, with data going back millions of years. The glaciers of Greenland and Antartica have been penetrated, as have mountain glaciers near the equator, and have given us truly detailed information on the last few hundred thousand years. Analysis of sedimentary rock shows not only the most recent ice ages, but patterns of glaciation that took place hundreds of millions of years ago.

In the 1970s and 1980s, scientists attempting to understand the phenomena of the ice ages reached a tentative conclusion: the driving mechanism for the cycles of glaciation was fundamentally understood. The key force, according to the theory, was insolation, the average amount of sunlight hitting the Earth. James Croll had proposed this idea in the 1860s, and Milutin Milankovitch had modified and extended it in the early and mid 1900s. He proposed that the insolation in the northern hemisphere, with its predominance of the land mass, was dominant. The theory did not account for all the details of the data, but was believed to explain the fundamental behaviour. It appeared to be time to accept the theory and use it as a framework for future analysis.

Now, at the beginning of the twenty-first century, it is a good time to take a new look at the subject. The enormity of new and excellent data has clarified many of the questions, if not the answers. Let us reexamine the data of the glacial cycles without prejudice—or, if that is impossible, at least minimum prejudice. The Croll/ Milankovitch theory has had remarkable success, but it also has remarkable problems. Can there be phenomena other than insolation that play central roles in climate? What are they? The key to understanding present climate may, indeed, lie in history.

The data are full of tantalising clues. If only we were smart enough, the complete mathematical theory of climate would be evident to us all. The goal of this book is to present the relevant techniques for analysing the data, and maybe to inspire the reader to help untangle the mystery. But there are also many established "facts" that mislead us. Mark Twain was once reputed to have said, "The trouble with most folks isn't so much their ignorance—it's knowing so many things that ain't so" (... including the authorship of this aphorism. It wasn't Mark Twain, but Josh Billings, another nineteenth century humorist.). Indeed, the published paleoclimate record is full of misinformation and error, and just one misleading or incorrect clue can derail an entire investigation. It is hard to solve a jigsaw puzzle when some pieces have previously been forced into wrong locations. The scientist must be adept at recognising false analyses and premature conclusions. More than most, this book will draw attention to the kinds of mistakes that permeate the field.

There is a problem. Many of the key breakthroughs in our understanding of climate depend on certain arcane areas of mathematics and physics that are difficult to master. These include solar system perturbation theory and spectral analysis. Not only are most geologists and climate scientists unfamiliar with these fields, but so are most physicists and mathematicians. Spectral analysis is particularly important, since it has played a key role in the elucidation of mechanisms. But it is full of traps and potential biases. There is a bad history of otherwise good scientists reporting cycles that later were shown not to be present, ranging from non-existent pulsars to claimed phenomena linked to the sunspot cycle. The whole field of finding and identifying cycles in geophysical data has a mixed reputation.

It is easy to do a Fourier transform, but trickier to know what to make of the results. There are numerous excellent books on spectral analysis, including *Spectral Analysis for Physical Applications*, (Percival and Walden, 1993) or *Spectral Analysis and Time Series* (Priestley, 1981). But most of these are books that assume a love of mathematics and prior expertise in statistics; they can be very difficult for the beginner. At the other extreme, there are books that emphasise practical approaches with minimum theoretical background. One of the best of these is *Numerical Recipes* (Press et al., 1993). But these books are too general to give details relevant to paleoclimate, and they are often misleading since the spectra available in paleoclimate are sufficiently unusual that they benefit from specialised methods. Our tone will be kept closer to that of *Numerical Recipes* than to Percival and Walden or Priestley. We will emphasise those techniques that are most applicable to paleoclimate data, but skip most of the proofs.

There are many important issues in the spectral analysis of paleoclimate that have not received direct treatment in the classic texts. Primary among these is the uncertainty in the time scale—not a problem for typical physics or engineering data. The paleoclimate signal is often measured vs. depth, but all the theories address the signal vs. time. To translate from depth to time requires assumptions that can have significant effects on the interpretation of the data. Another issue that is barely mentioned, if at all, in many standard texts is analysis of spectral shape. Rules, such as the Cramer-Rao limit, are designed to describe the regions when unbiased measurements are possible. But what can you do when the limit is not satisfied? Do you ignore the information contained in the spectral shape, or do you live with the bias and pull out useful information? Another topic frequently absent in the standard discussions of climate is the value of Monte Carlo simulations. This method has proved to be the most useful technique ever devised for understanding complex experiments in physics, and yet it has been little used in paleoclimate.

The study of the ice ages is remarkably interdisciplinary. To be an expert in this field, a scientist must have a comprehensive knowledge of geology, physics, glaciology, oceanography, atmospheric science, celestial mechanics, solar system astrophysics, cosmic rays, solar physics, interplanetary dust, climate modelling, spectral analysis and statistics. As a consequence, there are no real experts. Moreover, the subject matter is too diverse to allow a comprehensive treatment of the subject in any one text. This book, therefore, attempts to cover those aspects of the ice age that are critical in trying to deduce the origin of these climate events. A key issue is understanding how orbital changes of the earth relate to past climate.

Our emphasis will be on the information that we can glean from spectral analysis, and not on understanding the interplay of the oceans and atmosphere that turn a celestial force into a climate variation.

In fact, the evidence for the role of astronomy comes almost exclusively from spectral analysis. The seminal paper was published in 1976, titled, "Variations of the earth's orbit: pacemaker of the ice ages" (Hays et al., 1976). Their conclusions depended on spectral analysis, and yet spectral analysis is a discipline that makes many scientists uncomfortable. The strange result is the appearance of excellent books on paleoclimate, such as the recent (1999) book by Raymond Bradley, which are used as the basis for courses on paleoclimate—and yet spectral methods are not discussed at all in the text. The term "spectral analysis" is not listed in the index.

We will not try to cover the wealth of data that Bradley's book covers. Nor will we attempt to survey oceanography or its methods; for that see a text such as *The Sea Floor* (Seibold and Berger, 1996). Our emphasis instead will be to try to fill the gap, to try to give a working approach to the use of spectral analysis in paleoclimate data. Although we will touch on other climate indicators, our emphasis will be on oxygen isotopes, since those appear to give the most direct indication of the phenomenon known as the ice ages.

We believe that the current paradigms in climate theory owe too much to historical accident. Some features in early data that seemed to point the way to a theoretical understanding were not verified when subsequent higher-quality data became available. One example of this is the 19 kyr peak observed in the 1976 Pacemaker article. In subsequent oxygen isotope measurements, it has been very weak and, in many cases, completely absent. We will argue that its presence in the Pacemaker paper may have been no more than a statistical fluctuation.

As the century turns over, the authors of this book are known for taking an iconoclastic view of much climate research. We have proposed that the 100 kyr cycle of the ice ages is driven by orbital inclination, and not by eccentricity, the prevailing paradigm. The purpose of this book is not to present our viewpoint—although it certainly will creep through at various places, and will appear in more strength in Chapter 7—but we hope it will prove useful even to those who completely disagree with this theory. Our goal is to present the methods of analysis so that they can be used by anybody, particularly by those who have little prior experience in the spectral analysis of paleoclimate data.

If Sherlock Holmes were around today, and if he had an interest in science (according to Arthur Conan Doyle, he did not), would the wealth of clues we have available now point him clearly to the answer? Would he say, "It's elementary, Dr Watson," as he often did in the movie (but not the book) versions of his work? We don't know. But we think it is time to look at the data again, with open minds, as if for the first time.

Foreword

This is an interdisciplinary book, lying at the intersection of geology and paleoclimatology with physics, mathematics and astronomy. Great advances in science often come from interdisciplinary frontiers, but this work is difficult because it requires that specialists in one field learned the concepts, accumulated knowledge and ways of thinking of a different speciality. The study of the climate of the glacial Earth over the last couple of million years is one of the most active interdisciplinary frontiers of the present time, with discoveries and data pouring forth. Yet the significance of these discoveries is not always clear, particularly their implications for global climate change in the near future.

In order for the implications of paleoclimatology to be clearly understood, the emerging data must be carefully analysed with sophisticated mathematical techniques, properly applied, and interpreted in terms of the underlying physics and the astronomical driving forces. This requires that geologists and paleoclimatologists have or acquire an understanding of these very different but relevant fields of science. In this book, Richard Muller and Gordon MacDonald set out to provide the understanding of mathematics and solar-system astronomy that paleoclimatologists must have.

In a widely held if rather unsophisticated view, the sciences should be arranged in a hierarchical order of merit, depending on the degree to which their subject matter can be treated mathematically. However, it is more useful to see the sciences as occupying a spectrum, with the simple but quantitative at one end and the complex but qualitative at the other. The difference results from the nature of the subject matter, not the merit of the approach. Rigorous mathematical treatment is possible only in the absence of historical complications. In a physics experiment, it makes no different what the electron of interest was doing the day before yesterday; it always behaves as an electron should. At the other extreme, in sociology, history is almost everything; people behave in complex ways conditioned by millions of years of contingent, unpredictable and unrepeatable events.

By dealing with individual particles, idealised objects and experiments sensitive to a single variable, physicists have come to the extraordinary realisation that Nature behaves according to mathematical laws of the most exquisite elegance. Are we seeing deep into the very heart of Nature? Or is mathematics simply the best tool we have so far for approximating a still more subtle and sophisticated reality?

Scientists long believed that the physical laws of Nature controlled everything in the Universe so completely that the future is predetermined and free will is an illusion. This concept has been overturned in the last decade or so by the emerging understanding of chaos, complexity and non-linear dynamics. It is appropriate that this new development began in ecology, a discipline well along towards the complex, qualitative, historical end of the spectrum.

Midway along the spectrum is a group of disciplines, with no unifying name, but sharing the characteristic that their subject matter has been shaped by history, but not to the extent that rigorous mathematical treatment is impossible. Geology, geophysics, geochemistry, astronomy, astrophysics and cosmology thus bridge the gap which makes it almost impossible for a psychologist and a physicist to have a fruitful conversation.

This book falls squarely in this bridging area of the sciences. Muller and MacDonald may be a uniquely qualified team for this effort. MacDonald is the coauthor (with Walter Munk) of the classic book *The Rotation of the Earth, A Geophysical Discussion*. He has been the editor of the Journal of Atmospheric Sciences, the Journal of Geophysical Research, and Science. Muller is a physicist whose interests have always extended into the study of the Earth and the heavens. This is shown by some of his major contributions—the discovery of the motion of the Solar System relative to the cosmic background radiation, the invention of accelerator mass spectrometry now routinely used in radiocarbon dating, the investigation of comet showers and periodicity in mass extinctions, and the recent determination of the history of cosmic bombardment by dating lunar impact-glass spherules. Each of these contributions clarifies some aspect of the history of Earth or the cosmos.

What kind of history has that been? Has history been characterised primarily by unidirectional trends, or mostly by repetitive oscillations? Most geologists and astronomers would agree that both are involved.

It may be more useful to add a third category, and see the history of the Earth as made up of sudden events, slow trends and cycles. In astronomy and cosmology we seen events such as the Big Bang and supernovas, trends like the cosmic expansion and the progressive conversion of light elements into heavier ones by fusion, and cydles like the rotation of galaxies and solar systems and the cycling of material through exploding and condensing stars. In geology, events include impacts, volcanic episodes, and jumps in plate configuration; trends include the extraction of crustal material from the mantle and the gradual production of an oxygen- rich atmosphere by photosynthesis; and cycles range from the daily rotation of the Earth to the repeated opening and closing of the Atlantic Ocean on a 500 million-year time scale.

How can these features of history be quantified? Events like impacts and volcanic eruptions can be characterised by the statistics of recurrent intervals and magnitudes, and their physics is best understood in mathematical terms. Trends lend themselves to the techniques of the calculus of rates. Cycles are, of course, best studied by the mathematical techniques of time-series analysis, going back to Fourier. The paleoclimatological literature is thus full of spectral plots, showing the importance of time cycles of different lengths observed in paleoclimate proxy data. The widely accepted Croll-Milankovitch theory that fluctuating climate conditions during the Quaternary glaciation have been driven by astronomical cycles is based entirely on time-series analysis of paleoclimatic and orbital data.

And yet, time-series analysis is subtle and full of traps. Considerable mathematical sophistication is required in order to apply it without reaching incorrect conclusions. This new book is exactly what is needed in paleoclimatology for the interpretations of data on ancient climates to be really valid. Combining a theoretical presentation of the techniques with practical instructions and many useful Matlab recipes, and augmented with a new hypothesis for an astronomical climate driver, the book should be of the greatest use to practising geologists and paleoclimatologists.

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