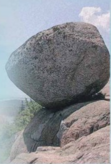
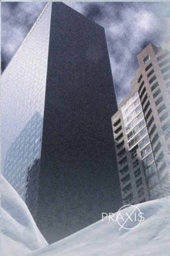


ICE AGES AND INTERGLACIALS

Measurements, Interpretation and Models

Donald Rapp



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Preface

The typical description of the past million years would be that the Earth has experienced about ten major periods of glaciation (“ice ages”) spaced at roughly 100,000-year intervals. This presupposes that ice ages are unusual departures from normalcy. Actually, it appears as if the natural state of the Earth during this period was an ice age, but there were about ten interruptions during which the climate resembled something like today’s for perhaps 10,000 years or so. Each ice age required several tens of thousands of years to develop to its maximum state of glaciation.

During the last glacial maximum, some 20,000 years ago, Canada and the northern U.S. were blanketed by huge ice sheets, up to 4 km in thickness. In addition, there was a large ice sheet covering Scandinavia that reached down into northern Europe. The Antarctic ice sheet was somewhat more full than today. Local glaciations existed in mountainous regions of North America, Europe, South America, and Africa driving the treeline down by up to 700 m to 800 m. The temperature of Greenland was lower by up to 20°C, but the climate was only a few degrees colder than normal in the tropics.

These ice sheets tied up so much of the Earth’s water that the oceans were as much as 120 m shallower. As a result, the shorelines of the continents moved outward by a considerable distance. The Beringia land bridge from Siberia to Alaska was created, allowing animals and humans to cross from one continent to the other. In the upper latitudes to mid-latitudes, climates were semi-Arctic and the flora shifted to tundra. Humidity was reduced and many lands dried out. The sharp temperature discontinuity at the edges of the ice sheets generated violent winds that swept up dust and dirt from dry regions, filling the atmosphere with dust. This ice age began to wane around 15,000 years ago, and dissipated through a series of gyrating climate oscillations, ending in a comparatively benign period that has lasted for the past $\sim$10,000 years, called the *Holocene*.

A few geologists of the 19th century were perceptive enough to read the signs in the rocks and formations, and concluded that the Earth must have once (or more) been heavily glaciated with massive ice sheets that generated the markings and rock depositions that they observed. They eventually overcame the initial resistance to this new (and shocking) concept in the geological community. But it wasn't until the 1970s that extensive studies of marine sediments (followed by polar ice core studies in the 1980s and 1990s) demonstrated the existence, amplitude, and recurrent chronology of multiple ice ages.

During the 19th century, several scientists proposed that ice ages could have resulted from semi-periodic variability in the Earth's orbital parameters, which change relative solar energy input to higher latitudes. As the theory goes, when solar energy input to higher northern latitudes drops below a critical threshold range, ice and snow can survive the summer, and thus a runaway expansion of ice sheets develops over many millennia. James Croll formulated this concept in 1875. In the first several decades of the 20th century, Milutin Milankovitch quantified this theory by carrying out extensive calculations by hand in the pre-computer age. Nevertheless, in the absence of long-term data over many ice ages, astronomical theory remained an abstract concept. Furthermore, there were no credible mechanistic models that described how changing solar energy inputs to higher latitudes led to alternating ice ages and deglaciations.

With the advent of marine sediment data in the 1970s, it became possible to compare astronomical theory with data over many glacial cycles. John Imbrie was a pioneer in this regard. He created the SPECMAP "stack" of ocean sediment data from several sites to reduce noise, and devised models with which to compare climatic time series with solar variations. In doing this, he "tuned" the chronology of the SPECMAP using solar variability as a guide. He also used spectral analysis to show that some of the prominent frequency components of SPECMAP variability were in consonance with known frequencies of solar variation. From this, he concluded that the astronomical model explained much of the ice age record—at least for the past ~650,000 years. However, there seems to be some circular reasoning involved, and one could construe his procedure to involve curve fitting as well as physics. More importantly, when a dispassionate comparison of data and theory is made today, the results are not so convincing.

As ocean sediment data were extended backward in time, it became apparent that some features of the sediment record did not fit astronomical predictions. Of greatest importance was the fact that the period from about 2.7 million years before the present (MYBP) to about 1 MYBP was characterized by relatively rapid, smaller amplitude climate cycles, whereas since about ~1 MYBP, climate cycles have increased in period and amplitude. By contrast, astronomical theory would not have predicted any such major shift in frequency and amplitude since there is no reason to believe that solar forcing to higher latitudes changed qualitatively during this time period. There were other problems with the theory as well; at some prominent occurrences of climate change there were no corresponding variations in solar input (e.g., 400,000 years ago). Since the 1990s, a number of studies have attempted to resolve the differences between the data and astronomical theory. A number of these studies had an obvious and pervasive bias in favor of the astronomical theory—in some cases seemingly an attempt to preserve the theory against all odds. Scientific objectivity seems to have been lost somewhere along the way. For example, a number of investigators suggested that each of several parameters (obliquity, eccentricity, longitude of precession) acts separately over different eras to produce a changing data record. While there may indeed be strange and unusual non-linear effects in the way that climate reacts to orbital parameters (e.g., Rial, 1999) nevertheless within the scope of conventional astronomical theory, these parameters do not act separately. They act in concert to change solar intensity, and it is solar intensity that determines the climate—at least according to astronomical theory.

Yet despite the problems with astronomical theory, there are several tantalizing similarities between climate data and the historical solar record. These include the correlation of several important frequencies in spectral analyses and certain undeniable rough similarities in the climate and solar records over some periods during the past several hundred thousand years.

Solar intensity varies with a $\sim$22,000-year period due to precession of the equinoxes. These oscillations vary in amplitude over long time periods due to variability of eccentricity and obliquity. The temperatures implied by ice core records do not oscillate with this frequency. However, there does seem to be some correlation between the amplitude of solar oscillations and ice core temperatures. In many (but not all) cases, the eras with higher amplitude solar oscillations appear to be associated with increasing Earth temperatures, and the eras during which solar oscillations are weak seem to be associated with decreasing temperatures. This would be the case if (1) there were a fundamental tendency toward glaciation, and (2) ice sheets grow slowly and disintegrate rapidly. In that case ice sheets would disintegrate and not recover when solar oscillations were large, but would grow when solar oscillations were small. As in AM radio, the oscillating precession signal is amplitude-modulated due to changes in eccentricity and obliquity. The precession cycle merely acts as a "carrier wave". All of this is very tenuous and represents a somewhat subjective interpretation of the data. However, the fact that the frequency spectrum shows frequencies for eccentricity and obliquity, but not precession, suggests that it is the amplitude of solar oscillations that matters, and the precession frequency does not directly contribute to climate change. Only eccentricity and obliquity determine the amplitude of precession oscillations.

Nevertheless, what seems to be most glaringly absent from astronomical theory is a clear quantitative mechanism by which variations in solar input to higher latitudes produce changes in climate, including various positive feedback effects due to changes in albedo, greenhouse gas concentrations, ocean currents, and north–south energy exchange. The Imbries' model for comparing ocean sediment time series with astronomical theory has the virtues of clarity and simplicity, but it is too simplistic to describe the variable climate of the Earth with all its intricate feedback mechanisms and complexities.

There are other aspects of long-term climate change that add confusion. There is some evidence that the termination of ice ages originates in the southern hemisphere, not the northern hemisphere. In addition, there are alternative theories that propose that ice age cycles are controlled by the penetration of cosmic rays into the Earth's atmosphere, which enhance cloud formation and produce a cooling effect.

Amid all this work, both experimental and theoretical, there does not seem to be a single reference work that provides an in-depth review of the data and models. The book *The Great Ice Age* does a creditable job in some respects (Wilson, 2000). The closest that anyone has come to a thorough review is the book by Richard A. Muller and Gordon J. MacDonald: *Ice Ages and Astronomical Causes*, Springer/Praxis (2000). This book (denoted here as M&M) provides coverage of a good portion of the data that were available at the time of writing (late 1990s), and it provides quite a bit of discussion of models. The topic of spectral analysis was a dominant theme in this book, almost to the neglect of other aspects. It is true that in seeking a relationship between two noisy time series, comparison of the important frequencies in the frequency domain has implications for a possible connection. Nevertheless, ultimately, it is the time phasing of the two curves that is of greatest importance in establishing a cause–effect relationship. I have relied on the book by M&M as a source of data, analysis, and discussion in a number of places. Their book is an obvious starting point for anyone interested in ice ages.

It is interesting to speculate when the next ice age might occur in the future. This topic is discussed toward the end of this book. Some climatologists believe that global warming induced by CO_2 emissions will prevent future ice ages from occurring. However, the connection between CO_2 emissions and global warming is far from firm. Because the CO_2-warming connection has been heavily politicized, much of the literature on this topic is biased.

Throughout this entire study of ice ages and climatology, climatologists seem determined to draw a dollar's worth of conclusions from a penny's worth of data. The most perceptive comment I have found is that of Wunsch (1999):

> "Sometimes there is no alternative to uncertainty except to await the arrival of more and better data."

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I would like to thank Clive Horwood and John Mason of Praxis Publishing for encouraging me to write this book. Their support was important to me throughout and I hope that I have produced a product worthy of this fine publishing house. I also want to thank Neil Shuttlewood of Originator Publishing Services for his usual exemplary job in setting this book into type.

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