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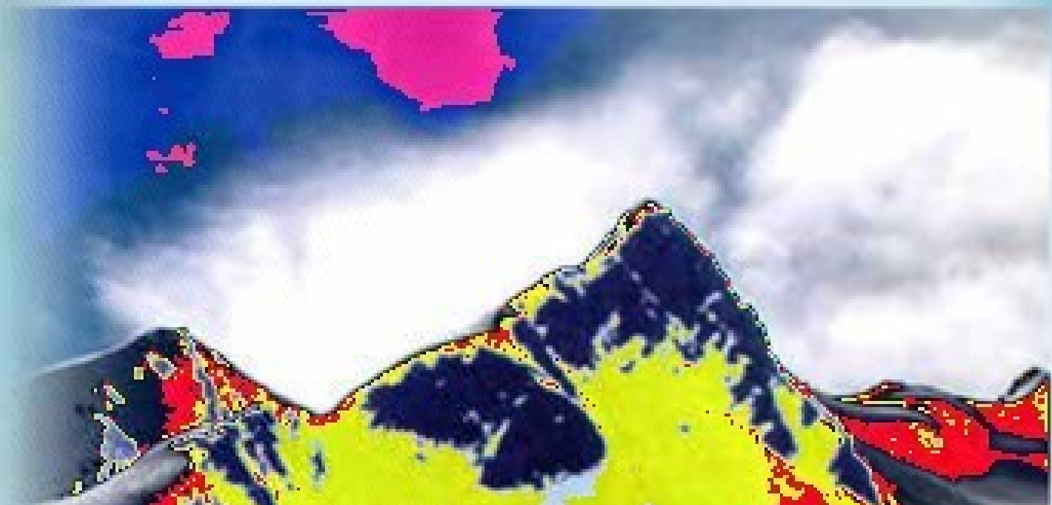

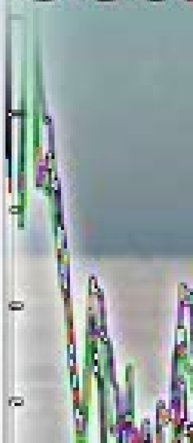

# Ice Ages and Interglacials

Measurements, Interpretation, and Models
(Second Edition)

Donald Rapp

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Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

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California
U.S.A.

SPRINGER–PRAXIS BOOKS IN ENVIRONMENTAL SCIENCES

ISBN 978-3-642-30028-8 ISBN 978-3-642-30029-5 (eBook)
DOI 10.1007/978-3-642-30029-5
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012937366

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First Edition published 2009
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Cover design: Jim Wilkie
Project management: OPS Ltd., Gt. Yarmouth, Norfolk, U.K.

Printed on acid-free paper

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# Preface

The typical description of the past million years would be that the Earth has experienced about 10 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 10 interruptions during which the climate resembled something like today's climate 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 thick. 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 tree line down by as much as 700 m (800 m in some cases). The temperature of Greenland dropped by as much as 20°C, but the climate was probably only a few degrees colder than normal in the tropics. Conditions were very harsh 20,000 years ago at the Last Glacial Maximum (LGM) when an ice sheet more than 2 miles thick pushed down from Canada into the northern U. S.

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 continents extended much farther out than today. 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- to mid-latitudes the climate was semi-Arctic and the flora shifted to tundra. Humidity was reduced and much of the land 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. This ice age began to wane around 15,000 years ago and dissipated through a series of gyrating climate oscillations, ending in the comparatively benign period that has lasted for the past ~10,000 years called the *Holocene*.

A few geologists in the 19th century were perceptive enough to notice signs of glaciation in rocks and geological formations and concluded that the Earth must have once (at least) 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 was not 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 the quasi-periodic variability of the Earth's orbital parameters that affect relative solar energy input to higher latitudes. As the theory goes, when summer solar energy input to higher northern latitudes drops below a critical threshold, ice and snow can better survive the summer. Data acquired in the 20th century suggest that ice sheets slowly begin to form over many millennia at latitudes roughly in the range 60°N to 70°N. As the ice cover spreads, the albedo (reflectivity) of the region increases, further adding to the cooling effect. Water increasingly leaves the oceans and gets deposited in the process of building ice sheets, lowering the oceans and extending shorelines. Since land has a higher albedo than the ocean, this provides further cooling. In regions adjacent to the ice sheets vegetation is inhibited, adding still further to increased Earth albedo. As northerly regions cool, the concentrations of key greenhouse gases such as water vapor, $CO_2$, and $CH_4$ decrease, creating a worldwide cooling effect that converts the budding ice age into a global phenomenon. Other effects such as widespread dust storms and the expansion of sea ice and mountain glaciers also contribute. Thus, the runaway expansion of ice sheets develops over many millennia. James Croll formulated the concept of the Sun acting as a trigger for ice ages based on variations of the Earth's orbit in 1875. In the first several decades of the 20th century, M. Milankovitch quantified this theory by carrying out extensive calculations by hand (no mean feat in the pre-computer age). Nevertheless, in the absence of long-term data over many ice ages, the astronomical theory remained an abstract concept. Furthermore, there were no credible mechanistic models to describe how changing solar energy input to higher latitudes could lead to alternating ice ages and deglaciations.

With the advent of marine sediment data in the 1970s, it became possible to compare the astronomical theory with data over many glacial cycles. John Imbrie was a pioneer in this regard. He built up a stack of ocean sediment data—which he dubbed the "SPECMAP" stack—from several sites with the objective of reducing noise and devised models to compare ice sheet volume ($V$) with solar variations. In doing this, he tuned the chronology of the SPECMAP stack using solar variability as a guide. He also used spectral analysis to show that some of the prominent frequency components in 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 as involving curve fitting in addition to physics. More importantly, when modeled ice sheet volume and solar intensity are dispassionately compared today, the results are not quite so overwhelming.

As ocean sediment data were extended backward in time, it became apparent that some features of the sediment record did not fit astronomical predictions. What stands out here 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 ~1 MYBP climate cycles have increased in period and amplitude. By contrast, the astronomical theory would not have predicted any such major shift in frequency and amplitude since there is no reason to believe that solar forcing at higher latitudes changed qualitatively during this time period. There were other problems with the theory as well; during some major 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 the astronomical theory. Some 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 the several parameters (obliquity, eccentricity, longitude of precession) acted separately over different eras to produce a changing data record. While there may indeed be strange and unusual nonlinear effects in the way that climate reacts to orbital parameters (e.g., Rial, 1999), as far as the conventional astronomical theory is concerned 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 the astronomical theory.

Yet, despite problems with the 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.

Roe (2006) looked at the astronomical theory in a way that is both novel and impressive. Instead of modeling ice sheet volume with a simplistic model, he took the slope of the SPECMAP curve as an indicator of $dV/dt$, the rate of change in ice volume. He then compared this with midsummer solar intensity at 65°N and found a very good correlation. This is perhaps the most convincing evidence in favor of the astronomical theory.

Solar intensity varies with a ~22,000-year period due to precession of the equinoxes. These oscillations vary in amplitude over long time periods due to the 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, periods with higher amplitude solar oscillations appear to be associated with increasing Earth temperatures and those 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 that 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 the 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, although the paper by Hansen and Sato (2011) provides some insights. The Imbrie model for comparing ocean sediment time series with the 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 further confuse matters. There is some evidence that the termination of ice ages may originate in the Southern Hemisphere—not the Northern hemisphere. In addition, there are alternativee theories that propose that ice age cycles are controlled by cosmic rays penetrating the Earth's atmosphere enhancing cloud formation and producing a cooling effect. However, such theories are very speculative.

The role of greenhouse gases, particularly $CO_2$, in transitions between ice ages and interglacials remains murky despite several attempts to unravel the processes involved. While measurements taken from ice cores clearly show that the $CO_2$ concentration rose and fell from interglacial to ice age in a repetitive pattern, the factors that caused these changes are still only partly understood. There is troubling evidence that past interglacials were warmer than the present one, yet they did not have higher $CO_2$ concentrations. How can that be?

Amidst 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 Great Ice Age* is a book that does a creditable job in many respects (Wilson, 2000). The closest that anyone has come to a thorough review is Richard A. Muller and Gordon J. MacDonald's *Ice Ages and Astronomical Causes*, published by Wiley/Praxis in 2000 (called "M&M" throughout the current book). M&M covers much of the data that were available at the time the book was written (late 1990s) and discusses the models in some depth. Spectral analysis was the dominant theme in M&M, almost to the neglect of other aspects. While it may be 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, ultimately, it is the time phasing of the two curves (temperature vs. time and solar intensity vs. time) that is of greatest importance in establishing a cause–effect relationship. I have relied upon 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. This topic is discussed briefly toward the end of this book. Some climatologists believe that global warming induced by $CO_2$ emissions will prevent ice ages from occurring.

Throughout this study of ice ages and climatology, what surprises me most is that climatologists seem determined to draw a dollar's worth of conclusions from a penny's worth of data. Even more amazing to this writer is the certainty and assurance that climatologists have in their conclusions, which are typically based on inadequate 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."

# Figures

# Tables

# Abbreviations and acronyms

| | |
|---|---|
| AABW | Antarctic Bottom Water |
| ACP | Age Control Point |
| AM | Amplitude Modulated |
| AMO | Atlantic Meridional Overturning |
| AMOC | Atlantic Meridional Overturning Circulation |
| AWS | Automated Weather Station |
| BCE | Before Christian Era |
| C&L | Chylek and Lohmann |
| CAS | Central America Seaway |
| CLIMAP | Climate: Long range Investigation, Mapping, And Prediction project |
| CNES | Centre National d'Etudes Spatiales |
| CRF | Cosmic Ray Flux |
| D-O | Dansgaard-Oeschger event |
| DEW | Distant Early Warning |
| EAIS | East Antarctic Ice Sheet |
| ECM | Electro-conductivity Measurements |
| EDC | Epica Dome C. |
| EDML | EPICA Dronning Maud Land |
| EEM | Previous interglacial period named after the Dutch river |
| ENSO | El Niño–Southern Oscillation |
| EOT | Eocene–Oligocene Transition |
| EPA | Environmental Protection Agency |
| EPICA | European Project for Ice Coring in Antarctica |
| ERBE | Earth Radiation Budget Experiment |
| GCM | Global Climate Model |
| GCR | Galactic Cosmic Ray |
| GICC | Glacial–Interglacial $CO_2$ Cycle |

| | |
|---|---|
| GIGO | Garbage In–Garbage Out |
| GISP | Greenland Ice Sheet Project |
| GISP2 | Greenland Ice Sheet Project 2 (see pp. 113, 137) |
| GRACE | Gravity Recovery and Climate Experiment |
| GRIP | Greenland Ice Core Project |
| GSLR | Global Sea Level Rise |
| GYBP | Billions of years before present |
| H&A | Hargreaves and Annan |
| H&W | Huybers and Wunsch (2004) |
| IPCC | Inter-government Panel on Climate Change |
| IR | InfraRed |
| IRD | Ice Rafted Debris |
| ISI | Information Sciences Institute |
| KYBP | Thousands of years before present |
| L&W | Landwehr and Winograd (2001) |
| LGM | Last Glacial Maximum |
| LIA | Little Ice Age |
| LLS | Laser Light Scattering |
| L&R | Lisiecki and Raymo |
| L&W | Landwehr and Winograd |
| M&M | The book by Richard A. Muller and Gordon J. MacDonald: *Ice Ages and Astronomical Causes*, Wiley/Praxis (2000) |
| M&W | McShane and Wyner |
| MBH | Mann, Bradley, and Hughes |
| MECO | Middle Eocene Climatic Optimum |
| MOC | Meridional Overturning Circulation |
| MPR | Mid-Pleistocene Revolution |
| MPT | Mid-Pleistocene Transition |
| MWP | Medieval Warm Period |
| MYBP | Millions of years before present |
| NADW | North Atlantic Deep Water |
| NASA | National Aeronautical and Space Administration (see p. 370) |
| NGRIP | North Greenland Ice Core Project |
| NH | Northern Hemisphere |
| NHG | Northern Hemisphere Glaciation |
| NOAA | National Oceanic and Atmospheric Administration |
| NSF | National Science Foundation |
| OCO | Orbiting Carbon Observatory |
| OLR | Outgoing Long-wavelength Radiation |
| PAL | Present Atmospheric Level |
| PCA | Principal Component Analysis |
| PDB | Crushed belemnite (*Belemnitella americana*) from the Peedee formation (Cretaceous) in South Carolina |
| PDO | Pacific Decadal Oscillation |
| PETM | Paleocene–Eocene Thermal Maximum |

| | |
|---|---|
| RSL | Relative Sea Level |
| SETI | Search for ExtraTerrestrial Intelligence |
| SH | Southern Hemisphere |
| SMB | Surface Mass Balance |
| SMOW | Standard Mean Ocean Water |
| SOI | Southern Oscillation Index |
| SST | Sea Surface Temperature |
| TIMS | Thermal-Ionization Mass-Spectrometric |
| TOA | Top Of Atmosphere |
| TSI | Total Solar Irradiance |
| UAH | University of Alabama in Huntsville |
| UWESS | University of Washington Earth and Space Sciences Department |
| VEI | Volcano Explosivity Index |
| W&L | Winograd and Landwehr (1993) |
| WAIS | West Antarctic ice sheet |
| WAIS Divide | West Antarctica Ice Sheet Divide |
| WB | Wally Broecker |
| YBP | Years before present |

# 1

# Life and climate in an ice age

What was the global impact of the growth of large ice sheets in the far north during past ice ages? What were the climates of the various continents 20,000 years ago at the height of the Last Glacial Maximum? Why was there a greater diversity of species, higher numbers of animals, more large animals, and larger animals? How did climate changes impact the evolution and migration of humans, animals, and vegetation? These are questions that have been pondered and studied by many researchers. Several scenarios have been put forth. However, it is difficult to draw firm conclusions. All we can do is provide a few fragmentary insights.

## 1.1 CONTINENTAL CLIMATES DURING THE ICE AGE

As we will show in subsequent chapters, based on geological evidence, and data from ice cores and ocean sediments, we know that the Earth was immersed in an ice age over the past ~100,000 years that peaked about 20,000 years ago, began to wane about 15,000 years ago, and ended roughly 10,000 years ago. The immensity of the ice sheets is difficult to comprehend. The maximum volume of the ice sheets—about 18,500 years before the present (YBP)—was about $57 \times 10^6$ km$^3$. This huge volume of ice resulted in a lowering of sea level of about 110 m (Zweck and Huybrechts, 2005).[1] Assuming that this ice sheet was built up over ~60,000 years, that would imply that ice was added to the ice sheets at the average rate of about $10^{12}$ m$^3$ per year. The lowering of sea level exposed large areas of continental shelves that were (at least initially) barren and susceptible to wind erosion.

Ice core data from Greenland and Antarctica indicate that the atmosphere was heavily laden with dust and salt during periods of high glaciation, suggesting

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[1] The removal of water from the oceans was actually about 50 m greater than this because the crust below the ocean rebounded about 50 m when water was removed at the LGM.

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books, DOI 10.1007/978-3-642-30029-5_1,

that the world was a stormy place with high winds that whipped up dust from land and salt from oceans. The dustiness would suggest that many areas of the Earth were arid. And indeed, the prevailing view seems to be that the Earth was predominantly arid during ice ages, although some areas, particularly the Southwestern U. S., were extremely wet. Yet, there had to be winds that carried moisture to northern climes in order to drop some $10^{12}$ $m^3$ of ice per year on the growing ice sheets. Since the temperature drop during ice ages at high latitudes was far greater than the temperature drop in the tropics, the temperature differential between the tropics and polar areas was greater during ice ages, creating a greater driving force for flow of atmosphere toward polar areas.

A comparison of the distribution of vegetation for all the continents of the world at the height of the last ice age with the distribution today was provided by Adams and Faure (1997). Their comparison for North and Central America is provided here in Figures 1.1 and 1.2. According to this model, the distribution of flora (and presumably fauna as well) migrated toward the equator during ice ages, and areas adjacent to the ice sheets were converted to tundra and semi-desert. Burroughs (2005) provides a similar flora map of Europe.

Barton *et al.* (2002) provide a window into life, flora, and fauna in North America as the last ice age began to wane:

> “Flying over the ice fields of Canada it is easy to imagine being back in the last Ice Age. There is ice as far as the eye can see. Glaciers roll down the valleys, towering ice sculptures rise out of the mountainsides, and exquisite turquoise pools glisten in the fissures below.”

Figure 1.3 shows the Wrangell–Saint Elias ice field on the Alaska–Yukon border. It is the largest non-polar ice field in the world and shows what much of the continent would have looked like at the height of the glaciation around 20,000 years ago. Barton *et al.* (2002) describe this scene as follows:

> “Sheets of ice stretch as far as the eye can see, with strange shell-like patterns scalloped into the surface. Snow clings to mountainsides in great crumbling chunks while in the glaciers below, ultramarine pools glint in the sunlight. Rivers run across this glacial landscape and suddenly disappear through the ice to the valleys below. The ice here is up to 900 m deep and the glaciers move up to 200 m a year as they grind and sculpt the landscape around them.”

During the last ice age, glaciers radically changed the north of the continent, leading to the human invasion of North America through the creation of the Bering land bridge. At the peak of the last ice age the land bridge was 1,600 km wide (see Figure 1.4). For the first time since the previous ice age (about 100,000 years prior), animals could travel across the land bridge from Siberia into the North American continent. According to Barton *et al.* (2002):

> “The land bridge was part of a larger ice-free area called Beringia, which

**Figure 1.1.** Distribution of vegetation in North and Central America at the height of the last ice age (Adams and Faure, 1997).

included Siberia, Alaska and parts of the Yukon. Beringia was bounded by the then permanently frozen Arctic Ocean and the continental ice sheets. Rain and snow tended to fall on the high southern ice fields of the Yukon and Alaska, thus reducing the amount that fell on the Beringian side. At the height of glaciation the retreat of the sea meant that most of the land was far from maritime influence and so had an arid, continental climate. The low winter snowfall prevented glaciers from forming and left grass and other vegetation accessible to grazers throughout the winter. This is what made Beringia habitable at a time when much of the land to the south was buried in ice.

As well as creating a dry climate, the ice sheets also made loess—a fine dust produced by the grinding action of the glaciers and deposited on the edge of streams emerging from the ice front. Loess blew across Beringia, establishing a well-draining soil. The result was a land of grassy steppes. An array of tiny plants