Discovering the Causes of the Ice Ages and Human-Caused Climate Change: a History of the Late Nineteenth and Early Twentieth Century

Discovering the Causes of the Ice Ages and Human-Caused Climate Change:

A History of the Late Nineteenth and Early Twentieth Century

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Abstract

Human-caused climate change is a contentious issue today among some non-scientific communities who argue that scientists support climate change because of their political beliefs. In contrast, some historians today argue that the carbon dioxide hypothesis, which says that increased carbon dioxide in the air increases global temperatures and that much of the increase in carbon dioxide is due to human causes, was not taken seriously during the early twentieth century. These contradictory views led to my investigation of the history of human-caused climate change, which originally evolved out of the search in the late nineteenth and early twentieth century to find a cause(s) of the ice ages. This thesis investigates early research into the origin of the ice ages, which generated fourteen hypotheses, including the carbon dioxide hypothesis. Historically, climate change research included contributions from many scientific disciplines: astronomy, chemistry, geology, meteorology, and others.

The main challenge to finding the cause(s) of the ice age was the diversity and limitations of the evidence and the inadequate scientific instrumentation and theories in the early twentieth century, which explains why the plausibility of hypotheses by this problem-centered scientific community changed during this period, including the changing views on human-caused climate change. Still, progress was made and, 1950, only five hypotheses were still under consideration. Contrary to what some historians say today, the carbon dioxide hypothesis was treated like any other hypothesis, and

there is no evidence that the scientific communities were biased against it. In addition, the criticisms that the carbon dioxide hypothesis received in the early twentieth century demonstrate that it was not always unquestioned by the scientific community, contrary to assertions made by some non-scientists today. However, there was less controversy surrounding the origin of the ice ages during this period.

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Of course, any errors or omissions in the thesis are my responsibility.

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Chapter I

Introduction

Over the past few decades, the theory of human-caused climate change has been and continues to be a contentious political issue today, even though the majority of climate scientists find overwhelming evidence in support of the theory.[1] Nonetheless, there are many who do not believe human-caused climate change has been proven and claim that scientific consensus is not relevant to forming scientific knowledge.[2] Some even contend there is a conspiracy among today's scientists to push their views of climate change onto the public, and some suggest that perhaps the entire field of climate science has been contaminated from the beginning.[3]

One response to these charges has been to document the history of human-caused climate change research to demonstrate it has a long history, dating back to the middle of the nineteenth century, and the results are not a fabrication of today's scientists.[4] In addition, perhaps in response to these challenges to the validity of climate science, some historians and others have told the story of climate science in a "heroic" style, highlighting the role of the early scientists struggling against the conservative scientific

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[1] Naomi Oreskes, "Beyond the Ivory Tower: The Scientific Consensus on Climate Change," *Science* 306, no. 5702 (December 3, 2004): 1686.

[2] James Lawrence Powell, *The Inquisition of Climate Science* (New York: Columbia University Press, 2011), 26-7, 53.

[3] Powell, *Inquisition of Climate Science*, 10–11.

[4] See for example: Spencer Weart, *The Discovery of Global Warming*, 2nd ed. (Cambridge, MA: Harvard University Press, 2008); James Rodger Fleming, *Historical Perspectives on Climate Change* (New York: Oxford University Press, 1998).

establishment,[5] which demonstrates that the hypothesis of human-caused climate change has not always been accepted or taken seriously by the scientific community.[6]

In either case, neither the criticisms by deniers of human-caused climate change, nor the "heroic" histories of early climate scientists written by some of today's historians, "rings" true. The purpose of this thesis is to investigate the development of knowledge about climate change in the late nineteenth and early twentieth century. This thesis focuses on the causes of the ice ages because it is out of this research that the theory of human-caused climate change first emerged.

To begin, many current histories of the early twentieth century focus only on a small part of the whole story of climate change. For example, historians interested in human-caused climate change focus on the development of the carbon dioxide hypothesis, while those interested in the origin of the ice ages focus on the development of the astronomical hypothesis. For example, Spencer Weart, who is interested in human-caused climate change, allocates eight out of nine chapters to the history of human-caused climate change.[7] In contrast, John Imbrie, a paleoceanographer interested in the origin of the ice ages, allocates one chapter in his book on the ice ages to an overview of the discovery of the ice ages and eleven chapters out of sixteen to the astronomical theory of the origin of the ice ages.[8] There is nothing wrong with these approaches, but my

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[5] S. Daniels and G. H. Endfield, "Narratives of Climate Change: Introduction," *Journal of Historical Geography* 35, no. 2 (April 2009): 215–22.

[6] S. R. Weart, "Global Warming, Cold War, and the Evolution of Research Plans," *Historical Studies in the Physical and Biological Sciences* 27 (1997): 319–56.

[7] Weart, *Discovery*.

[8] John Imbrie, *Ice Ages: Solving the Mystery*, ed. Katherine Palmer Imbrie (Cambridge, MA: Harvard University Press, 1986).

interest lies in the interplay between all the hypotheses from the late nineteenth and early twentieth century on the origin of climate change, which included investigations into human-caused climate change and origin of the ice ages.

Though discussed in greater detail later, it is helpful to briefly set the stage of early twentieth century climate science research and to mention a few of the key scientists from this period. From the middle of the nineteenth century to the early twentieth century eleven categories of hypotheses for the origin of climate change were initially cataloged. By 1950, in a more comprehensive review, fourteen categories of hypotheses were identified as potential causes of the ice ages, including the carbon dioxide hypothesis.[9] There was much uncertainty during this period about the cause(s) of the ice ages and, though the number of hypotheses had been reduced to five by the 1950s, scientists still had not discovered the cause(s) of the ice ages.

A short snippet of the history of the carbon dioxide hypothesis highlights some of the changes in the viability of climate change hypotheses during this period, which is discussed in detail later.

Several scientists are always mentioned when describing the early history of climate change. Histories often start with John Tyndall (1820–1893), who measured the absorption of heat radiation (infrared radiation) by carbon dioxide and other gases, building upon the work of Joseph Fourier (1768–1830), who first recognized the role of carbon dioxide in controlling the temperature. Svante Arrhenius (1859–1927), who has been called the "father" of the theory of human-caused climate change, was the first to

[9] C. E. P. Brooks, *Climate through the Ages: A Study of the Climatic Factors and Their Variations* (London, UK: Ernest Benn Limited, 1926), 430-32. C. E. P. Brooks, "A Selective Annotated Bibliography on Climatic Changes," *Meteorological Abstracts and Bibliography* 1, no. 7 (July 1950): 446–75.

calculate the effect on the temperature of the earth's atmosphere from changes in carbon dioxide levels.[10] However, as further evidence accumulated against his hypothesis, it fell out of favor in the early twentieth century.

G. S. Callendar (1897–1964) is credited with bringing the carbon dioxide hypothesis back to the scientific community as new evidence became available. Initially, Callendar's work was "dismissed by the academicians as the dabbling of an amateur,"[11] and though "Callendar's publications attracted some attention … most meteorologists dismissed his figures with a few condescending remarks."[12] But it is Callendar who is treated as the modern "hero" in the history of climate change, not just for reinvigorating the hypothesis, but for standing up to the scientific establishment.[13] From Callendar's work the modern studies of human-caused climate change accelerated, finally resulting in the current understanding of how human sources of carbon dioxide, along with other human activities, such as forest clearing and raising of livestock, affect the temperature of the earth's atmosphere.

Scope and Study Questions of Thesis

The views of the challengers of human-caused climate change research and some of the responses by historians provided the inspiration to undertake this study. I initially

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[10] Fleming, *Historical Perspectives*, 79.

[11] Tim F. Flannery, *The Weather Makers: How Man Is Changing the Climate and What It Means for Life on Earth*, 1st American ed., (New York: Atlantic Monthly Press, 2005), 40–41.

[12] Weart, "Global Warming," 325.

[13] Weart, *Discovery*.

intended to focus on the development of the carbon dioxide hypotheses, but after starting my investigation, I discovered that climate change research in the late nineteenth and early twentieth century turned out to be more interesting and complex than just this one hypothesis. The carbon dioxide hypothesis was just one of fourteen hypotheses under investigation to explain the origin of the ice ages, which is the research program that the carbon dioxide hypothesis emerged from. But there did not appear to be studies that explored the carbon dioxide hypothesis within the context of all the proposed hypotheses to solve the origin of the ice ages. Rather, many histories focus on the carbon dioxide hypothesis, more or less, in isolation from the other hypotheses.[14] As a result, the goal of this thesis is to investigate scientific research on climate change as a whole, not just research on carbon dioxide, in the early twentieth century.

From a practical perspective, how much of the history of climate change should be investigated because of its long duration, starting in the late nineteenth century and continuing until today? The period around World War II (WWII) appears to be a natural break point for investigating the early phases of this research because after WWII there was a significant shift in the direction of research due to the new technologies that were developed or improved during the war effort that made their way into the scientific communities. As will be discussed later, some of these technologies include: improved mass spectrometry used in radiometric dating of rocks, digital computers which made modeling climate change much easier, and many others.[15] For the purposes of this thesis,

[14] See for example: Weart, *Discovery*; Fleming, *Historical Perspectives*.

[15] J. D. Macdougall, *Nature's Clocks: How Scientists Measure the Age of Almost Everything* (Berkeley: University of California Press, 2008), 107; Naomi Oreskes, "How Plate Tectonics Clicked," *Nature* 501, no. 7465 (2013): 27–29.

the focus is on research from the late nineteenth century up to and shortly after the end of WWII.

In addition, the early 1950s is a good place to end this study because research, particularly into human-caused climate change, began to ramp up with new technology, and there was significant growth in theoretical understanding. This resulted in an increasing number of publications, the beginning of large-scale international organizations, and the beginnings of the challenge to human-caused climate change research primarily from outside the scientific community. Readers interested in this period are referred to the work of Fleming, Hulme, and Weart, among others.[16]

Research at the turn of the century elaborated on, tested, and evaluated the many hypotheses offered to explain the origin of the ice ages. Because understanding the origin of the ice ages is not part of our current political discourse, it should be untainted by external political influences and should provide clearer insight into how science worked in the early twentieth century. Scientists were interested in solving the ice age problem; hence we would not expect them to be especially biased against the carbon dioxide hypothesis because it was just one of the many hypothesis tossed into the pot to explain the ice ages. My approach is placed backward in time as though one was living in the early twentieth century; I do not use the knowledge we have today about the role of human-caused climate change, nor do I bring modern day political concerns into my analysis.

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[16] Fleming, *Historical Perspectives*; M. Hulme, *Why We Disagree about Climate Change: Understanding Controversy, Inaction and Opportunity* (Cambridge: Cambridge University Press, 2009); Weart, *Discovery*.

Investigating how the scientific community developed and evaluated each of these hypotheses provided me an opportunity to explore four questions:

- What were the characteristics of the scientific communities investigating the problem, or what are the characteristics of the problem itself, that either aided or hindered solving it? One feature of this period, from the middle 1800s to the middle 1900s, is the question of climate change did not belong to a single scientific discipline; it was a synthetic question cross-cutting many traditional scientific domains and requiring the work of many scientific communities, similar to the discovery of plate tectonics.[17]
- How did the scientific communities evaluate and decide which were plausible hypotheses? The problem of the origin of the ice ages differed from many typical scientific problems, which typically had only a few hypotheses; for example, the structure of the solar system had just two hypotheses: the Ptolemaic hypothesis and the Copernican hypothesis. In this case, up to fourteen hypotheses were under consideration over this period.
- Is there any evidence of a biased response against any hypothesis, specifically, the carbon dioxide hypothesis, within these scientific communities? As previously mentioned, some of today's historians have argued that the scientific community was biased against the carbon dioxide hypothesis and have suggested that it was treated more critically than others.[18]

[17] Naomi Oreskes, *The Rejection of Continental Drift: Theory and Method in American Earth Science* (Oxford: Oxford University Press, 1999).

[18] Weart, "Global Warming," 319–56.

- Are models of scientific change adequate to explain and predict the observed historical evidence? I use historical data from this study to briefly compare these observations with philosophical models of scientific change. For purposes of comparison, I look at two typical models of scientific change: Thomas Kuhn's paradigmatic model of scientific change and Imre Lakatos' model of scientific progress.[19]

Methodology

The focus of this thesis is to explore the history of early-twentieth-century research into climate change and to use the findings to study scientific change both from a historical perspective and a philosophy of science perspective. Four sources were used to investigate this period of climate change research: texts, citation network analysis, scientific instrumentation, and the understanding gained from philosophy of science.

To understand the state of knowledge during this period, I started with the work of C. E. P. Brooks (1888–1957), a scientist within the community, who documented the hypotheses under consideration and the status of those hypotheses within the scientific community. As Fleming describes it:

> In 1950, Brooks who had spent much of his career attempting to sort out the "nine and sixty" theories of climate change, published a selective annotated bibliography on the subject in the first volume of the new journal Meteorological Abstracts and Bibliography.[20]

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[19] Thomas S. Kuhn, *The Structure of Scientific Revolutions*, Foundations of the Unity of Science, vol. 2 (Chicago: University of Chicago Press, 1970); Imre Lakatos, "Falsification and the Methodology of Scientific Research Programmes," in *Criticism and the Growth of Knowledge*, vol. 4 of Proceedings of the International Colloquium in the Philosophy of Science, London, 1965, ed. I. Lakatos and A. Musgrave (Cambridge University Press, 1970), 91–196.

[20] Fleming, *Historical Perspectives*, 108.

In his annotated bibliography, Brooks lists the major papers from each of fourteen categories of hypotheses on the cause(s) of the ice ages; this provided the starting point for my investigation.[21] In addition, not only did he summarize the papers in 1950, he also reviewed them in the two editions of his textbook, *Climate through the Ages* (1926, 1949) and provided his view on the state of the science in two summary papers in 1947 and 1955, as well in other publications.[22]

To keep the analysis manageable, rather than investigate all fourteen categories, I investigate the development of a subset of hypothesis, exemplars, which include the two categories that later become modern theories explaining the origin of the ice ages and the origin of human-caused global warming: hypotheses related to changes in the earth's orbit and tilt of its axis and hypotheses related to changes in the composition of the atmosphere, respectively. I also studied four other broad categories of hypotheses that span the range of all hypotheses: hypotheses related to changes in geography, hypotheses related to changes in atmospheric circulation, hypotheses related to continental drift, and hypotheses related to cosmic dust. In my analysis, the continental drift hypothesis is combined with the geographical hypothesis because it is a variant of the geographical hypothesis.

I began with the papers referenced by Brooks[23] and expanded the list as I identified additional relevant papers. However, because there were many papers in some

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[21] Brooks, "Selective Annotated Bibliography," 446–75.

[22] C. E. P. Brooks, "Unsolved Problem of Climate Change: Part II Theories," *Meteorological Magazine* 76, no. 901 (1947): 147-51; C. E. P. Brooks, "Present Position of Theories of Climatic Change," *Meteorological Magazine* 84, no. 997 (1955): 204–6.

[23] Brooks, "Selective Annotated Bibliography," 446–75.

categories, I have selected only a small subset for analysis. Also, this analysis is limited to published scientific literature, in English only, from scientists involved in proposing, testing, and evaluating the hypotheses. Limited use will be made of scientific reviews, except for reviews from scientists, such as C. E. P. Brooks, W. J. Humphreys, G. C. Simpson, and others, who were participants in the scientific debate at the time.

I investigated the published research to determine how it was preformed and how scientists evaluated the research, including trends over time of the plausibility of the hypotheses within the scientific communities. I analyzed texts to compare changes in publications, such as, changes in textbooks over multiple editions, which demonstrate changes in views of the author and implies changes in the views of the scientific community, as a whole.

Citation network analysis as used here is similar to, but different from, other citation network analyses because of its limited scope, focusing only on a subset of the published papers discussed in this thesis and the papers cited by them. There are many examples of literature citation analyses, and most are based on a large number of papers, thousands or more; for example, see Small.[24] Citation analysis used in this thesis focuses on exploring whether there were obvious differences in citations between different scientific communities or advocates of different hypotheses. For example, I investigate whether the astronomers and geologists use a different set of published research or, if there was overlap, I want to know how much overlap there was between these domains.

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[24] Henry Small, "Co-Citation in the Scientific Literature: A New Measure of the Relationship between Two Documents," *Journal of the American Society for Information Science* 24, no. 4 (1973): 265-69; S. Upham and Henry Small, "Emerging Research Fronts in Science and Technology: Patterns of New Knowledge Development," *Scientometrics* 83, no. 1 (2010): 15–38.

For this analysis, a subset of the papers, mainly from the carbon dioxide hypothesis and the astronomical hypothesis categories, called sources, and their references, called targets, were entered in the database. A cloud-based database, AirTable, stored the sources and targets in two linked tables.[25] The network analysis software was CytoScape, originally developed for biomedical research, but is sufficiently general to be used in other network analysis.[26]

There are several limitations to this analysis. First, only 30 source papers were analyzed from which their references were entered in the database, yielding 408 references, or targets. The analyzed papers came primarily from the astronomical and carbon dioxide hypotheses, though this was not a complete selection of the total possible papers. Papers from the other three categories of hypotheses, along with many review books, were not included. This limitation was due to a lack of time. Secondly, a full quality assurance of the database was not completed, and some of the references may be duplicates. Some target references were too ambiguous to clearly identify without significant additional research, and in these cases, a place holder target was created that could be updated later after further citation research. Because there are limited integrated databases that automatically collect the references from a paper published during the late nineteenth and early twentieth century in machine readable form, sources from this period were entered manually into the database.

[25] AirTable, San Francisco, CA, https://airtable.com.

[26] Cytoscape version 3.4.0, Cytoscape Consortium, San Diego, CA, http://www.cytoscape.org; Paul Shannon, Andrew Markiel, Owen Ozier, Nitin S. Baliga, Jonathan T. Wang, Daniel Ramage, Nada Amin, Benno Schwikowski, and Trey Ideker, "Cytoscape: A Software Environment for Integrated Models of Biomolecular Interaction Networks," *Genome Research* 13, no. 11 (2003): 2498.

To understand the role of changes in scientific instrumentation and field evidence and how that information was used by various scientists, an analysis was done on a subset of categories of hypotheses—the carbon dioxide hypothesis, the geographical hypothesis, and the astronomical hypothesis—to elucidate changes over time. The arguments, data, and critiques from the papers were used to summarize the change in views about the plausibility of the hypotheses based on changes in instrumentation and field evidence.

After discussing the history of climate change, I use the historical data to investigate models of scientific change. Although there are many philosophical theories of scientific change, I investigated only two theories, Thomas Kuhn's theory and Imre Lakatos' theory, because these cover a broad range of ideas. Kuhn's model of scientific change describes periods of quiet scientific progress and puzzle solving, interspersed with major changes in the scientific view, or paradigms. In contrast Lakatos found that science tends to be organized as an ongoing project focusing with progress defined as increasing success in explaining the evidence, experiments and theory. In this model, change is more continuous and not as episodic as in the Kuhn model. Both models are described in greater detail later.

A Final Aspiration for this Thesis

It is hoped this thesis provides a small contribution to understanding this historical period. I was motivated to conduct this research, in part, as a response to a comment by Fleming:

> With notable exceptions, however, the changing nature of global change—the historical dimension—has not yet received adequate attention. Most writing addresses current issues in either science or policy; much of it draws on a few authoritative scientific statements such as those by the Intergovernmental Panel

on Climate Change (IPCC); almost none of it is informed by historical sensibility.[27]

[27] J. R. Fleming, "Climate, History, Society, Culture: An Editorial Essay," *Wiley Interdisciplinary Reviews—Climate Change* 1, no. 4 (July–August 2010): 476.

Chapter II

Setting the Stage—Discovery of the Ice Ages

Investigations into the causes of the ice ages and human-caused climate change both have their beginnings in the scientific work of the nineteenth and early twentieth century following the discovery of the ice ages in the mid-eighteenth century. To better understand the context of the work in identifying the causes of the ice ages, it is helpful to have some background in the discovery of the ice ages themselves and, also, the development of geology as a science during this period.[28]

Though geology, as we think of it today, can be traced back to the seventeenth century,[29] it was the early nineteenth century when its foundations were laid.[30] I will only describe a few events in the early history of geology to highlight the rapid growth of the science.

One of the earliest geological texts, *The Theory of the Earth* (1795) by James Hutton (1726–1797), "often regarded as the father of geology," was not widely read.[31] Rather, it was John Playfair's book, *Illustrations of the Huttonian Theory of the Earth* (1802), based on Hutton's book, which was widely read and from which Hutton's ideas

[28] This section is expanded from: Thomas L. Norris, "Proposal for Thesis in the Field of History of Science in Partial Fulfillment of Requirements for the Master of Liberal Arts Degree," Harvard University, Extension School, May 5, 2016.

[29] John A. Henry, *A Short History of Scientific Thought* (New York: Palgrave Macmillan, 2012), 194.

[30] M. J. S. Rudwick, *Worlds before Adam: The Reconstruction of Geohistory in the Age of Reform* (Chicago: University of Chicago Press, 2008), 28.

[31] Diane H. Carlson, Lisa Hammersley, and Charles C. Plummer, *Physical Geology*, 14th ed. (New York: McGraw-Hill Education, 2012), 194.

were disseminated. Hutton's work was important because it focused on evidence and searched for geological causes, rather than grandly theorizing about the origin of the earth, a common approach in many earlier writings on geology.[32] For example, Hutton realized that to generate sedimentary formations would require, given current rates of deposition, a very long time and, hence, the earth was much older than commonly believed: "We find no vestige of a beginning—no prospect of an end."[33] He also laid out many of the foundational principles in geology, such as uniformitarianism, the idea that "the present is the key to the past."[34]

Hutton's ideas laid the groundwork of geology for the early decades of the nineteenth century resulting in a period of explosive growth in the quantity and variety of new geological information with ideas was coming fast and furious.[35]

One important example from this period was the first geological map of Britain produced by William Smith in 1815. Geological maps are the backbone of geology because they represent geological formations and their interrelationships. Though there were geological maps before Smith's, his was the first to include all of England in a single map and "Smith's map and ideas paved the way for a better understanding of geological time [using index fossils] and laid the founding for geological surveys world-wide."[36]

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[32] Henry, *Short History*, 199.

[33] Quoted in: Henry, *Short History*, 201.

[34] Carlson, Hammersley, and Plummer, *Physical Geology*, 194.

[35] Henry, *Short History*, 204.

[36] Natural History Museum, "Britain's First Geological Map," London, UK, accessed September 13, 2016, http://www.nhm.ac.uk/discover/first-geological-map-of-britain.html.

Charles Lyell (1797–1875), with his influential book, *Principles of Geology*, which went through twelve editions by 1875, took this newly acquired geological data along with the earlier ideas of Hutton and put them together into a coherent whole and created the beginning modern geology. He made one of the principle ideas of Hutton, uniformitarianism, the key idea in geology. Uniformitarianism says that change is slow and continuous and that only processes observed to be working today should be considered in explaining past geological history. Lyell further strengthened the idea of uniformitarianism by highlighting its similarity to Issac Newton's laws of physics; that is, there are fixed natural laws operating over time, and they continue to operate today.[37] Uniformitarianism would eventually become an underlying principle in geology and is referenced in modern geology texts, though today the framework is often called "actualism," which "comes closer to conveying Hutton's principle that the same processes and natural laws that operated in the past are those we can actually observe or infer from observations as operating at present."[38]

In addition to the development of the sciences at that time, there was another view which intersected with science and described the relationship between science and theology, that is, natural theology, which held that science, when properly investigated, would be consistent with the Bible.[39] One major proponent of intertwining geology and

[37] Henry, *Short History*, 208.

[38] Carlson, Hammersley, and Plummer, *Physical Geology*, 194.

[39] William Paley, *Natural Theology or, Evidences of the Existence and Attributes of the Deity, Collected from the Appearances of Nature* (London: Printed for R. Faulder, 1802).

natural theology was William Buckland (1784–1856), a preeminent British geologist.[40] He wrote one of the Bridgewater Treatises, which were prepared for the Royal Society of London, in support of natural theology, *Geology and Mineralogy Considered with Reference to Natural Theology* (1836).[41] He argued the results of geology matched the descriptions given in the Bible but with one major caveat: the geological evidence pointed to a very old earth while the Bible did not. However, Buckland did not think this was a conflict with the Bible.[42]

> *All* the geologists [of this time] were convinced that geohistory had been played out on a timescale humanly inconceivable magnitude…. The many who were also religious believers saw no conflict between their geology and their understanding of the Creation stories in Genesis; they had long since learned that it was a *religious* mistake to treat biblical texts as if they were scientific sources, because an inappropriate literalism deflected attention away from religious meaning.[43]

However, there was tension between some theologians and Buckland and others in the interpretation of the Bible, which resulted in some of Buckland's critics accusing

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[40] For one view on geology and natural theology, see: Charles Coulston Gillispie, *Genesis and Geology, a Study in the Relations of Scientific Thought, Natural Theology, and Social Opinion in Great Britain, 1790-1850* (Cambridge: Harvard University Press, 1951).

[41] "Francis Henry, Earl of Bridgewater, in his bequest, provided funds to the Royal Society of London to prepare treatises: "of a work On the Power, Wisdom, and Goodness of God, as manifested in the Creation; illustrating such work by all reasonable arguments, as for instance the variety and formation of God's creatures in the animal, vegetable, and mineral kingdoms…as also by discoveries, ancient and modern, in arts, sciences, and the whole extent of literature." The bequest resulted in eight treatises during the 1830s: "On the Power, Wisdom, and Goodness of God, as manifested in the Adaptation of External Nature to the Moral and Intellectual Constitution of Man; Adaptation of External Nature to the Physical Conditions of Man; Astronomy and General Physics Considered with Reference to Natural Theology; The Hand, its Mechanism and Vital Endowments, as evincing design; Animal and Vegetable Physiology considered with reference to Natural Theology; On Geology and Mineralogy; On the History, Habits, and Instincts of Animals; and, Chemistry, Meteorology and the Function of Digestion, considered with reference to Natural Theology." Wyhe, John van. The Bridgewater Treatises On the Power Wisdom and Goodness of God As Manifested in the Creation." The Victorian Web. Accessed September 14, 2016. http://www.victorianweb.org/science/bridgewater.html.

[42] William Buckland, *Geology and Mineralogy Considered with Reference to Natural Theology*, 3rd ed., vol. 1 (London: G. Routledge, 1836).

[43] Rudwick, *Worlds before Adam*, 30, italics in original.

him of atheism.[44] As an aside, one other well-known geologist, Charles Darwin (1809–1882), initially had a favorable view of natural theology, but later found that natural theology was not consistent with his theory of natural selection.[45]

I mention natural theology because one proposal to explain many geological phenomena, such as erratics, to be discussed next, was based on biblical events.

During this period of explosive growth in geological understanding, many geological phenomena were discovered that did not make sense, such as the various geological phenomena which would eventually lead to the discovery of the ice ages. Though the discovery of the ice ages is not part of this thesis, I briefly describe its history because it created the question: what were the cause(s) of the ice ages and, later, human-caused climate change, which is the focus of this thesis.

The discovery of the ice ages and the investigation into their cause(s) can be divided into four general phases: 1) identification of anomalous geological phenomena; 2) recognition of the existence of ice ages as an explanation for the anomalous phenomena; 3) further investigations into the geological details of the ice ages, including, geographical distribution of evidence on multiple continents, the number of the ice ages, one or many, and their timing; and, 4) the identification of the cause(s) of the ice ages,

[44] Henry, *Short History*, 201

[45] "Although I did not think much about the existence of a personal God until a considerably later period of my life, I will here give the vague conclusions to which I have been driven. The old argument of design in nature, as given by Paley, [Natural Theology or Evidences of the Existence and Attributes of the Deity, 1802.], which formerly seemed to me so conclusive, fails, now that the law of natural selection has been discovered. We can no longer argue that, for instance, the beautiful hinge of a bivalve shell must have been made by an intelligent being, like the hinge of a door by man. There seems to be no more design in the variability of organic beings and in the action of natural selection, than in the course which the wind blows. Everything in nature is the result of fixed laws." Charles Darwin, *The Autobiography of Charles Darwin 1809–1882*, quoted in Christopher Hitchens, ed., *The Portable Atheist: Essential Readings for the Nonbeliever*, 3rd ed. (Cambridge, MA: Da Capo, 2007), 94.

that whether the ice ages had one cause or multiple causes and whether it was the same cause for all the ice ages. These are general phases and should not be taken as entirely separate from each other, because they overlap with each other. In this section I briefly review the first two areas and provide an overview of the third, which is the core of this thesis. The fourth phase, the resolution of the cause(s) of the ice ages and human-caused climate change, is not a significant part of this thesis because it occurred after the period covered by the thesis.

This overview of the discovery of the ice ages is necessarily brief. For a detailed historical description, see Kruger,[46] or for a shorter overview, see Imbrie[47] or Woodward.[48]

During the early nineteenth century, as geology was developing into a scientific discipline, one major geologic anomaly that captured the attention of geologists was erratic blocks, also called findlinge, which are dispersed throughout Europe and are also found in North America.[49] Erratics are very large blocks of rock often found on flat fields where the presence of a large rock, sometimes as large as five to ten meters in height, clearly stands out and begs an answer as to how they got there (Figure 1). In addition, the composition of erratics does not match local geology, rather, they match the composition of geological formations far away from their current location. One well-known example

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[46] Tobias Kruger, *Discovering the Ice Ages: International Reception and Consequences for a Historical Understanding of Climate* (Leiden, The Netherlands: Brill, 2013).

[47] Imbrie, *Ice Ages*.

[48] Jamie C. Woodward, *The Ice Age: A Very Short Introduction*,1st ed. (Oxford University Press, 2014).

[49] Kruger, *Discovering the Ice Ages*, 23.

of an erratic was found in North America: "A lump of Dedham Granodiorite, better known as Plymouth Rock, the iconic symbol marking the arrival of the Pilgrim Fathers in New England in 1620, is also a glacial erratic."[50]

In addition to erratic blocks, other geological phenomena puzzled geologists, including surface deposits, which later would be recognized as various types of moraines: terminal, lateral and medial; gouge marks (Figure 2) on rocks on the bottom and sides of many valleys; and the shape of some valleys which are U-shaped and differ in appearance from valleys caused by erosion.[51]

Figure 1. Typical Erratic Block, from Mont Blanc Range.
Note the human figures in the foreground showing the size of this erratic.
Source: Archibald Geikie, *Textbook of Geology* (London: Macmillan, 1882), 412.

[50] Woodward, *Ice Age*, 24.

[51] Carlson, Hammersley, and Plummer, *Physical Geology*, 322.

Figure 2. Striated Rock.
Note the gouge marks on the surface. Source: James Geikie, *The Great Ice Age, and Its Relation to the Antiquity of Man*, 1st ed. (New York: D. Appleton, 1874), 12.

It is not surprising that one of the early hypothesis to explain erratic blocks was based on the Bible and proposed that erratics were transported to their current location by the diluvial flood, that is, the Noahatic flood. However, problems were quickly identified with this hypothesis. First, erratics have sharp edges, which are not found on rocks that have been tumbled by flowing water, as is obvious when inspecting rocks in a river bed where all of them have smooth edges. In addition, it was difficult to envision that flowing water provides a sufficient force to move these large sized blocks, some of which are the size of small houses. A related hypothesis, transport by mud, was also proposed based on the observation that mud flows often contain rocks, but again, very large blocks are not observed in modern mud flows. In both cases, one might propose there were types of floods or mud flows in the past, not observed today, that could move very large blocks, but this hypothesis was inconsistent with the commonly held view of the time, uniformitarianism, wherein only processes observed operating today are considered in geology.

Another hypothesis proposed that erratics had been trapped inside icebergs and were released when the icebergs melted. This hypothesis is based on the observation that icebergs often contain rocks, but because many erratics are found on the land, this hypothesis requires that there were times in the past when sea levels were much higher than today. Lyell was one of the main proponents of this hypothesis, partly because this process could be observed operating today.[52] Lyell based his hypothesis on the presence of rock and debris seen in current icebergs, even if the amount of debris contained in modern icebergs is low and it would take many icebergs to account for the observed geological features.

Geologists, during their study of glacial domains, had noticed many similarities between phenomena created by modern glaciers and the unexplained erratics, gouge marks, and debris on valley floors that were found far from current glacier activity. An early proposal that glaciers were the cause of erratics and other phenomena, dates to the eighteenth century, when one of the first scientific studies on the glacial transport of rocks was published by Bernhard Friedrich Kuhn (1752–1821) in 1786.[53] However, large glaciers extending far beyond their current distribution was not favored by the majority of scientists who thought either giant floods or mud flows caused the distribution of the erratics. One major critique of the glacial model was if glaciers transported erratics to

[52] Woodward, *Ice Age*, 37–38.

[53] Kruger, *Discovering the Ice Ages*, 48.

locations far from their source rock, it would require glaciers much larger than geologists thought could have existed, and it required colder temperatures.[54]

At the time, none of the explanations for the existence of erratics was satisfactory, but geological investigations continued, resulting in additional evidence on the distribution of erratics, the mapping of gouge marks on the rocks on the sides and floor of valleys and distribution of moraine materials. Additional evidence along with additional study of existing glaciers helped build support for large-scale glaciations.

Louis Agassiz (1807–1873), who would become recognized as the primary champion of the existence of ice ages, was fortunate, in that, he was born in Switzerland, a region in which it was easy to study the characteristics of modern glaciers. However, he started his scientific career based on his fascination with paleontology, not glaciology, and it did not take long for him to be recognized as one of the premier leaders in the field. Eventually, around 1835, he joined the hunt for an explanation of erratics and, working with other geologists, investigated erratics and other anomalous evidence. It did not take long for Agassiz and his primary colleague, Karl Schimper (1803–1867), to become "obsessed" with solving the puzzle.[55]

Agassiz and Schimper brought together the evidence in a "grand synthesis" in support of the existence of ice ages.[56] Agassiz first presented this theory at a meeting of the Society des Sciences Naturelles in 1837 at Neuchhatel, while he was president of the society. However, the hypothesis was not well received, and some scientists laughed at

[54] Kruger, *Discovering the Ice Ages*, 84.

[55] Woodward, *Ice Age*, 51.

[56] Kruger, *Discovering the Ice Ages,* 187.

his proposal. Nonetheless, because of this presentation, Agassiz was later credited with the discovery of the ice ages, even though many others were involved in the studying and publishing on the ice age hypothesis.[57] Agassiz "was determined to ensure that *his* glacial epoch would not become just another footnote in the history of geology."[58] As an aside, as early as 1887, it was recognized that Karl Schimper, who collaborated with Agassiz in preparing the talk, deserved credit as a co-discover of the ice ages.[59]

Acceptance of Agassiz' hypothesis was not immediate, not only because the evidence was not convincing, but also because the idea of ice ages did not fit the general understanding of the history of the earth. It took many decades for evidence to accumulate from around the world, making the path to acceptance of the ice age theory long and convoluted.[60]

By 1887, Archibald Geikie, could summarize the status of the ice ages:

> It is now well ascertained that during a comparatively recent geological period, the climate of the northern hemisphere was much colder than at present, and that in the British Islands, as well as in other countries where glaciers are now unknown, the land was enveloped in snow and ice. This part of the geological record is known as the Ice Age or Glacial Period.[61]

Even before the full recognition of the existence of ice ages, focus shifted to identifying their additional characteristics, such as the number of ice ages, when and how

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[57] Kruger, *Discovering the Ice Ages*, 178.

[58] Woodward, *Ice Age*, 55, emphasis in original.

[59] E. P. Evans, "The Authorship of the Glacial Theory," *North American Review* 145, no. 368 (1887): 94-97. For further discussion of the role of K. Schimper, see: Kruger, *Discovering the Ice Ages*, 158–60, 166–88.

[60] Imbrie, *Ice Ages*, 47; Kruger, *Discovering the Ice Age*s.

[61] Quoted in: Woodward, *Ice Age*, xix.

widespread they were, and what caused them. These activities were intertwined with each other; for example, very soon after Agassiz' talk, the astronomical hypothesis was proposed by J. Adhemar in 1842 (to be discussed later), even though most scientists had not yet accepted the existence of ice ages.

Before delving into the history of the identification of the cause(s) of the ice ages, I want to review the major steps in the development of geology, including the discovery of the ice ages, all of which came during a short period.

1795 - Hutton's *Theory of the Earth*

1815 - Smith's geologic map of Britain

1830 - Lyell's *Principles of Geology*

1837 - Agassiz' presentation on the existence of the ice ages

With this rapid growth in knowledge, we now turn to a history of the attempts to solve the origin of the ice ages.

Chapter III

Climate Change Hypotheses—Their Histories

Almost as soon as the existence of ice ages began to receive serious consideration, scientists began to speculate on what caused them. However, investigations did not take off until the late nineteenth century, once the acceptance of the existence of ice ages was widespread. Many hypotheses were offered. C. E. P. Brooks recorded in 1926 that eleven categories of hypotheses had been proposed; though later, in a more comprehensive review,[62] he listed fourteen categories. Table 1 lists the hypotheses Brooks and others considered plausible causes of the ice ages, and this list has changed over time. The last list, from Brooks in 1955, describes seven hypotheses, but only one of these, "change in solar radiation," was considered the primary hypotheses. One thing to note, in 1955 the carbon dioxide hypotheses was no longer considered a plausible cause for the ice ages, but this does not say anything about its possible role in human-caused climate change. Not all hypotheses were considered equally plausible; for example, one hypothesis mentioned in 1926, earth heat, that is, heat from the interior of the earth, quickly dropped from consideration.

Brooks was not the only scientist to provide a summary of hypotheses. W. J. Humphreys (1862-1949), another scientist and textbook author of this period, listed and evaluated the hypotheses in two editions of his textbook on atmospheric physics

[62] Brooks, *Climate through the Ages*, 1926, 431–32; Brooks, "A Selective Annotated Bibliography," 446–75.

published in 1920 and 1940.[63] Humphreys included most, but not all hypotheses that Brooks identified (see Table 1), but he grouped them slightly differently. I've reorganized his list into the categories provided by Brooks so they may be compared. Humphreys included one new category, surface covering, that is, what type of material is covering various parts of earth's surface, such as soil, vegetation, snow, etc., called albedo, the reflectivity of a surface, but other scientists treat this as a secondary effect, not a primary cause of the ice ages. Changes in albedo result in positive feedback, either increasing or decreasing the atmospheric temperature. For example, increasing the albedo via increased snow or glaciers, such as during the beginning of an ice age, will reflect additional sunlight, reducing the energy input to the atmosphere and lowering the temperature even further.

I also include a small review paper by G. C. Simpson (1878–1965), as an exemplar of the hypotheses that were included in published papers. His review included fewer hypotheses than the more comprehensive reviews by Brooks and Humphreys. In addition, Simpson does not cover many of the proposed fundamental causes of climate change and focuses instead on meteorology; for example, his section on changes in solar radiation refers to changes on the earth that can cause a change in solar insolation, not necessarily changes in the radiation from the sun as caused by earth's orbit or solar emittance.

The short review of various lists of hypotheses under consideration in the early twentieth century shows that Brooks' list of 1926 was one of the most comprehensive,

[63] William Jackson Humphreys, *Physics of the Air*, 1st ed. (Philadelphia: Franklin Institute by J. P. Lippincott, 1920).

and I use it as the starting point for describing the scientific history of this period. It should be mentioned that in a review of Brooks' 1949 revised version of *Climate Through the Ages*, the reviewer noted that the 1926 version was considered a classic text on which "has been part of the intellectual equipment of a whole generation of Earth scientists and paleoecologists," although the reviewer did not think the revised version, in 1949, had been updated sufficiently.[64] The review highlights the role this text had in the scientific community at the time and using Brooks' text as a starting point for my analysis is a good choice.

The categories I have selected as exemplars, except for continental drift, are included in the lists of all the reviewers, though the reviewers might label the categories differently. There were a few hypotheses proposed in the late twentieth century, such as changes in the Antarctic ice sheet, and uncommon meteorological conditions in the Arctic.[65] These are not included in this study, which focuses on scientific work in the early twentieth century. Before exploring possible reasons for this abundance of hypotheses, I provide a brief historical summary of six exemplar hypotheses, although I group two of the hypotheses, geography and continental drift, into one category because continental drift is a variant of geographical changes. These five categories of hypotheses cover a wide range of the total collection of hypotheses. Reducing the number of hypotheses investigated from fourteen to five will keep the focus on the "forest" and not get lost in the "trees."

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[64] Edward S. Deevey, "The Evolution of *Climate through the Ages*—Review of *Climate through the Ages: A Study of the Climatic Factors and their Variations*, C. E. P. Brooks," *Ecology* 31, no. 4 (1950): 662–3.

[65] Imbrie, *Ice Ages*, 65–6.

Table 1. Categories of the Hypotheses on the Origin(s) of the Ice Ages.

Causes	Scientist	C. E. P. Brooks				W. J. Humphreys		G. C. Simpson
	Date of Publication	1950	1926	1949	1955	1920	1940	1929
Fundamental Causes	Changes earth's orbit	X	X	X	X	X	X	
	Changes solar radiation	X	X	X	X (First favorite)	X	X	X
	Lunar influences					X	X	
	Elevation land masses, mountain building	X	X	X		X	X	
	Changes atmospheric circulation	X	X	X		X	X	
	Changes oceanic circulation	X	X	X		X	X	
	Changes continent-ocean distribtuion	X	X	X	X	X	X	X
	Changes atmospheric composition, usually refers to CO2	X	X	X		X	X	X
	Volcanic dust in atmosphere	X	X	X	X	X	X	X
	Cosmic dust theory	X	X	X	X			
	Sunspot theory					X	X	
	Continental drift theory	X	X	X	X		X	
	Polar migration theory	X	X	X	X			
	Glacial anticyclone theory							
	Earth Heat	X	X	X				
	Surface covering					X	X	
	Variations of mean annual temperature within a zone							X
Secondary Effects	Effect of changes in solar radiation: changes in temperature surface earth, water vapor in atmosphere, and upper surface of clouds.							X
	Sources:	Brooks, "Selected Annotated Bibliography."	Brooks, *Climate*, 1926.	Brooks, *Climate*, 1949.	Brooks, "Present Position."	Humphreys, *Physics*, 1920.	Humphreys, *Physics*, 1940.	Simpson, "Past Climates."

To provide the historical data used in the next chapter, used in identifying general patterns of research in late nineteenth and early twentieth century, I first provide a summary description of the history of the development of these six hypotheses grouped into five categories based on published literature.

The titles for the categories are taken from Brooks.[66]

- "Variations in elements of the earth's orbit." One of the proposed astronomical hypotheses will eventually turn out to be the main cause of the ice ages.
- "Variations in the composition of the earth's atmosphere." This is primarily concerned with changes in carbon dioxide concentration, which will eventually be found to describe human-caused climate change, but play little role in the causation of the ice ages.

[66] Brooks, "Selective Annotated Bibliography," 446–75.

- “Changes in atmospheric circulation.” This represents an intermediate cause, not a primary cause of the ice ages, even though Brooks includes it in the same list when discussing primary causes
- “Geographical Hypothesis.” This hypothesis is interesting because it is the one favored by C. E. P. Brooks and Charles Lyell. And the “Continental Drift Theory.” Continental drift will be briefly discussed for two reasons: 1) it is a variation of the geographical hypothesis but Brooks categorizes as a separate class of hypotheses, and 2) it played a major role in the history of what would become known as plate tectonic theory in geology. The continental drift hypothesis is included with the geography hypothesis.
- “Cosmic Dust Theory.” I include this minor hypothesis, one not developed very extensively. It did not get much traction within the scientific community and was not significantly developed over time. It is an example of a “one off” hypothesis tossed into the pot of hypotheses but never considered to be a serious contender for explaining the origin of the ice ages.

I provide longer histories of the astronomical and the carbon dioxide hypotheses because they will develop into modern theories to explain the ice ages and human-caused climate change, respectively.

Astronomical Hypothesis

Proposals linking astronomical cycles to the origin of the ice ages was one of the earliest hypotheses proposed. It is an obvious cause to consider because we all experience the seasonal change in weather due to fluctuations in solar insolation throughout the year.

This hypothesis was actively investigated during the late nineteenth and early twentieth century and was one of the more popular hypotheses, as evidenced by Brooks[67] listing sixteen key papers in his annotated review, the category with the greatest number of citations.

In my summary, I discuss the work four scientists: Joseph Adhemar, James Croll, Alfred Wilkes Drayson, and Mulitin Milankovitch, three of which—Adhemar, Croll, and Milankovitch—are considered critical to the development of this hypothesis, while Drayson, also mentioned by Brooks, a practical astronomer and not an academic, had a different approach. There were others involved in the development of this hypotheses; for a more detailed history, I suggest either the book by Kruger[68] or Imbrie.[69]

Joseph Adhemar (1797–1862) was the first person recognized by Brooks to propose an astronomical cause of the ice ages in 1842.[70] Adhemar's proposal came rapidly after the presentation by Agassiz on the existence of ice ages to the scientific community in 1837. His hypothesis was probably encouraged by the discussion of the ice ages long before the Agassiz lecture, and his solution to the ice ages was the idea of polar wandering about the axis of rotation, along with the precession of the equinoxes; that is, the earth's axis had significantly shifted during different geological periods resulting in changes in insolation.[71] Adhemar predicted the shifts of the poles would result in changes

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[67] Brooks, "Selective Annotated Bibliography," 446–75.

[68] Kruger, *Discovering the Ice Ages*.

[69] Imbrie, *Ice Ages*.

[70] Brooks, "Selective Annotated Bibliography," 446-75; J. Adhémar, *Révolutions De La Mer*, *Déluges Périodiques* (Paris, 1842).

[71] Fleming, *Historical Perspectives*, 110.

in solar insolation in different parts of the world during different times and result in the ice age occurring in different hemispheres at different times.[72] The problem was that his hypothesis (discussed later) did not match the evidence as interpreted by geologists, who found that glaciations happened simultaneously in both the Northern and Southern Hemispheres.

The astronomical hypothesis was taken up by James Croll (1821–1890), a self-taught geologist, who published evidence for regular patterns of warmer and colder periods in the geologic record and proposed: "The true cosmical cause must be sought for in the relations of our earth to the sun."[73] From the evidence, he proposed this regular pattern is caused by the characteristics of the earth's orbit resulting in changes in climate. He studied several of the patterns of the earth in relation to the sun and found that "the precession of the equinoxes and the change in the eccentricity of the earth's orbit were the two key causes of changes in solar insolation and hence the climate of the earth."[74]

One challenge to proving his hypothesis was whether the geological evidence pointed to regular patterns of climate change. This would require precise geological dating, but what he had available to him was based on relative geological dating, that is, whether a sedimentary deposit came before or after another deposit, along with estimates of its rate of formation. Geological dating during this time was based on the thickness of the sedimentary layers and estimating the rate of deposition from which you can estimate time duration, but there was no absolute dating. Related to this, was the assumption, not

[72] Imbrie, *Ice Ages*, 75

[73] James Croll, "On the Physical Cause of the Change of Climate During Geological Epochs," *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 28 no. 187 (1864): 121.

[74] Croll, "Physical Cause," 129.

unreasonable at the time, that geological formations with similar characteristics spread over a wide geographical region were deposited at the same time. There was no way to prove the evidence for multiple ice ages, particularly in the Pleistocene, exhibits a regular mathematical pattern. It would take radiometric data to prove that this was the case; nonetheless many thought the astronomical hypothesis was a strong candidate to explain the ice ages.

We come next to a proposal by Lt. Col. Alfred Wilkes Drayson (1827–1901), who was a military man, astronomer, author, friend of Arthur Conan Doyle, and professor of practical astronomy.[75] He proposed that the cause of the ice ages was a change in the obliquity of the earth's orbit, that is, the angle of the rotational axis of the earth, which he calculated had changed significantly throughout time, reaching a minimum of 12 degrees.[76] However, Drayson's proposal did not meet acceptance in the astronomical community because calculations at the time showed a variation of only a few degrees, from about 22.5 to 24.5 degrees, not 12° as he proposed.[77] Thus, his argument for a significant change in the obliquity was challenged as impossible based on known astronomical physics.

[75] Anonymous, "Alfred William Drayson Obituary," *Monthly Notices of the Royal Astronomical Society* 62, no. 4 (February 14, 1902): 241–42. The article got his middle name wrong, it is Wilkes.

[76] Alfred Wilks Drayson, *On the Cause, Date, and Duration of the Last Glacial Epoch of Geology, and the Probable Antiquity of Man, With an Investigation and Description of a New Movement of the Earth* (London: Chapman & Hall, 1873), 143.

[77] Holli Riebeek, "Paleoclimatology: Explaining the Evidence," *Earth Observatory*, NASA Goddard Space Flight Center, accessed January 29, 2017, http://earthobservatory.nasa.gov/Features/Paleoclimatology_Evidence/.

One of Drayson's critics was James Croll, a contemporary of his. Although he did not mention Drayson by name, Croll appears to describe his hypothesis and the scientific opinion of it:

> A change in the obliquity of the ecliptic has frequently been, and still is, appealed to as an explanation of geological climate. This theory appears, however, to be beset by a twofold objection: (1) it can be shown from celestial mechanics, that the variations in the obliquity of the ecliptic must always have been so small that they could not materially affect the climatic condition of the globe; and (2) even admitting that the obliquity could change to an indefinite extent, it can be shown that no increase or decrease, however great, could possibly account for either the glacial epoch or a warm temperature condition in polar regions.[78]

From these challenges, Drayson's work was not considered further by his contemporaries. I include his ideas to show the varieties of hypotheses proposed, even within the astronomical domain, and that though they might be considered extreme, they appear to have been considered without bias, even if later they were rejected. As Brooks remarks: "Drayson believes that the pole traces a circle around a center 6° from its present position. This is considered to explain glacial and interglacial periods and to provide an absolute chronology. Not accepted by astronomers."[79]

Croll revisited his hypothesis in 1875, in his book *Climate and Time* in which he more fully lays out his proposal. Brooks calls it "a classical … work on the theory of geological climates putting forward a complete description of the geological description of the ice ages, how changes in solar insolation would change the climate and arguing that it is changes in the ecliptic…that results in the fundamental changes in solar

[78] James Croll, *Climate and Time in Their Geological Relations: A Theory of Secular Changes of the Earth's Climate* (New York: D. Appleton, 1875), 8.

[79] Brooks, "Selective Annotated Bibliography," 449.

insolation" and thus describing one of the versions of astronomical causation.[80] As an aside, even without a formal university education, Croll was made a Fellow of the Royal Society of London in 1876, which is quite an accomplishment.[81]

Finally, we come to Mulitin Milankovitch (1879-1958), who takes up the astronomical hypothesis after it had fallen into neglect because of challenges to its plausibility.[82] Milankovitch would later be recognized as providing the fully developed the astronomical hypothesis on the origin of the ice ages, now called Milankovitch cycles.[83] Brooks describes Milankovitch's work as "the basis of a great deal of later work on astronomical causes of climatic variation."[84]

Milankovitch picked up the trail of the astronomical hypothesis: "It was true that Adhemar and Croll … had discussed the climatic effects of orbital variations … [but] neither had had sufficient mathematic training to calculate the magnitude of such effects accurately."[85] Even though Milankovitch excelled in mathematics, it still took many years for him to calculate the effects of the various components of the earth's orbit, including ecliptic, axis of rotation, etc. and the amount of solar insolation reaching the earth's surface at various locations, from which he could estimate the effect on

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[80] Brooks, "Selective Annotated Bibliography," 449.

[81] Imbrie, *Ice Ages*, 87.

[82] Imbrie, *Ice Ages*, 97

[83] NASA Earth Observatory, "Milutin Milankovitch (1879-1958)," NASA Goddard Space Flight Center, accessed January 28, 2017, http://earthobservatory.nasa.gov/Features/Milankovitch/.

[84] Brooks, "Selective Annotated Bibliography," 451-52.

[85] Imbrie, *Ice Ages,* 99

atmospheric temperature. His first results were published in 1920,[86] but this addressed the present climate of the earth, which was part of the puzzle but not yet a calculation of past climates. Wladimir Koppen (1846-1940), after having read the book, contacted Milankovitch and helped him understand how the distribution of insolation could result in ice ages and from which Milankovitch would now calculate the effects of radiation on the earth over time. These calculations were reasonably consistent with geological data from Alpine glaciers, and Milankovitch's results were published in *Climates of the Geological Past* by Koppen and Alfred Wegener (1880–1930) in 1924[87], which "assured a wide circulation for the radiation curves so laboriously computed by Milankovitch, [while] some geologists agreed with Koppen and Wegener that the curves fitted neatly with the geological records; others disagreed."[88]

The astronomical hypothesis had variable acceptance within the scientific community, but the response depended on which version of the hypothesis was considered and whether the evidence for the ice ages indicated a periodicity or not. There are two versions of the hypothesis, that of Croll and that of Milankovitch.[89]

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[86] Milutin Milanković, *Théorie Mathématique Des Phénomènes Thermiques Produits Par La Radiation Solaire,* ed. Jugoslavenska Akademija Znanosti i Umjetnosti (Paris: Gauthier-Villars et Cie, 1920).

[87] Wladimir Koppen and Alfred Wegener, *The Climates of the Geological Past* [*Die Klimate der geologischen Vorzeit*], trans. Bernard Oelkers (Stuttgart: Gebr. Borntraeger Verlagsbuchhandlung, 2015, 1924).

[88] Imbrie, *Ice Ages*, 106.

[89] Nils Ekholm, "On the Variations of the Climate of the Geological and Historical Past and their Causes," *Quarterly Journal of the Royal Meteorological Society* 27 (1901): 1-61.

There are two major parts to this hypothesis: 1) the need for evidence of a regular periodicity of the ice ages, and 2) quantifying the effect of orbital variations on solar insolation; both parts were challenged.

In 1901, Nils Ekholm (1848–1923) critiqued the astronomical hypotheses, and he did not consider the Croll proposal viable:

> Adhemar, Croll, Schmick, and others have tried to explain the Ice Age, though in a somewhat different way, by the difference in length of the summer and the winter halves of the year during the periods of great eccentricity of the earth's orbit, when the difference may amount to somewhat more than a month (35 to 36 days). But this explanation is untenable, for the simple reason that the total amount of heat which the short summer of the one hemisphere receives from the sun is equal to that which the long summer of the other hemisphere receives.[90]

It should be noted that Ekholm's critique came before the detailed calculations made later by Milankovitch. Ekholm thought the primary cause of climate change was changes in carbon dioxide and that astronomical effects were minor.[91] His role in developing the carbon dioxide hypothesis is discussed later.

Milankovitch's detailed calculations were critiqued in the middle of the twentieth century. As late as 1950, there were still controversy about the plausibility of the astronomical hypothesis. Brooks wrote, "Variations of solar radiation, either alone or combined with some other cause, are now first favorite,"[92] but this does not specifically refer to the astronomical hypothesis. Rather it refers to internal changes in the sun, not changes in the earth's orbit. Brooks' view on the orbital theory was less positive: "Changes in the elements of the earth's orbit and the inclination of the axis are rather out

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[90] Ekholm, "On the Variations of the Climate," 2.

[91] Ekholm, "On the Variations of the Climate," 1-61.

[92] Brooks, "Present Position," 204.

of favor. They are still maintained by F. E. Zeuner and G. Bacsak, while D. Brouwer has produced a new solution, but they are rejected as insufficient by A. J. J. van Woerkom."[93] In addition, Richard Foster Flint (1902–1976), "Yale University's eminent authority on the glacial ages,"[94] argued that there was no evidence for periodicity in the ice ages and argued the astronomical hypothesis was not plausible.[95]

Flint noted that glaciers were currently retreating in both hemispheres, but the understanding of the astronomical hypothesis at that time would suggest changes should not be simultaneous in both hemispheres: "As Matthes … pointed out, the fact that glacier shrinkage has been occurring simultaneously in both polar hemispheres bears on the existing hypotheses of the cause of climatic change. This fact disfavors those astronomic hypotheses: which demand, at least to some degree offsets of climatic effects between the polar hemispheres."[96]

Again, he pointed to geological evidence of the retreat and advance of glaciers. Flint wrote, "No periodicity is apparent in the sequence," although he admitted that dating of the glacial periods was but a "controlled guess," which highlights one of the major challenges to glacial studies, the lack of good dating techniques.[97]

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[93] Brooks, "Present Position," 204.

[94] S. C. Porter, "Memorial to Richard Foster Flint, 1902-1976," *Memorials—Geological Society of America* 8 (1978): 1.

[95] Richard Foster Flint, "Climatic Implications of Glacier Research," in *Compendium of Meteorology*, ed. Thomas F. Malone (Boston: American Meteorological Society, 1951), 1019–23

[96] Flint, "Climatic Implications," 1021.

[97] Flint, "Climatic Implications," 1021.

He summarized his analysis of the evidence in 1951: "Neither the facts of glaciology, evidencing recent climate changes, nor the facts of glacial geology, evidencing more ancient ones, afford a basis for inferring a periodic recurrence of any particular climatic condition."[98] Keep in mind this was after Milankovitch's work. Both the original 1924 paper, published in French, and the Koppen and Wegener book, which contained the complete theory, appears to be unknown to Flint. The evidence that Flint did not know of this work is that it is not mentioned in his bibliography to this paper, published in 1951. This suggests Flint and maybe others were not familiar with Milankovitch's work.

There is one advantage to the astronomical hypothesis: it makes very precise predictions about the timing of the ice ages, which could easily be tested. The role of radiometric dating of the ice ages in sufficient resolution so that they could be compared to the predictions by Milankovitch is discussed in the section on geochronology (page 122).

As we see, the astronomical hypothesis came into and out of favor. We first had Adhemar's proposal, which was challenged by Croll, who offered his own version, but Croll's hypothesis also ran into challenges by Ekholm and others. Milankovitch's theory, currently accepted as one of the causal factors of the ice ages, was not universally accepted when it was first put forth but was challenged by Flint and others.[99] These changes in the viability of this hypothesis is discussed later in the context of the viability of other hypotheses.

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[98] Flint, "Climatic Implications," 1021.

[99] NASA Earth Observatory," Milutin Milankovitch.

Carbon Dioxide Hypothesis

This hypothesis proposes that changes in concentration of carbon dioxide in the atmosphere should result in changes in atmospheric temperature and earth's climate. This hypothesis has had a long and contentious history, as did many other hypotheses, coming into and out of favor depending on the state of scientific knowledge, particularly the state of infrared spectroscopy, as described below. This short history will focus on a few key scientists of this period. If the reader wishes a more in-depth history, there are many publications to consult.[100]

The history of the carbon dioxide hypothesis often starts with John Tyndall (1820-1893), although some historians begin with Joseph Fourier (1768–1830). But the role Fourier played in this history is contentious, and Fleming suggests many writers may have misinterpreted Fourier's writings.[101] For the purposes of this thesis, I begin with Tyndall's work.

In 1861, John Tyndall published measurements on the absorption of heat radiation, what we now call infrared radiation, by several gases. Tyndall used the "first ratio spectrophotometer" to compare infrared radiation absorption using a galvanometer connected to a "differential themorpile."[102] The method compares infrared radiation absorption: "If the intensity of the reference source of radiation was known, the intensity of the other source (and thus the absorptive power of the gas in the tube) could be

[100] See for example: Fleming, *Historical Perspectives*; Hulme, *Why We Disagree about Climate Change*; Weart, *Discovery*.

[101] Fleming, *Historical Perspectives*, 58.

[102] Fleming, *Historical Perspectives*, 68.

calculated."[103] He found that the major components of the atmosphere—nitrogen and oxygen—do not absorb infrared radiation, but that other gases, such as water vapor and carbon dioxide, which are smaller components in the atmosphere, absorb infrared radiation.[104] He discovered that water vapor was the highest absorber of infrared radiation and was important in maintaining the atmospheric temperature because infrared radiation, radiated from the earth's surface, is absorbed by these gases maintaining the temperature of the earth's atmosphere. He predicted that changes in the concentration of these gases would change the temperature of the atmosphere. Tyndall described the effect: "The aqueous vapor constitutes a local dam, by which the temperature at the earth's surface is deepened; the dam, however, finally overflows, and we give to space all that we receive from the sun."[105] From this, the astronomer, John Hersche, F. R.S. (1792–1871) commented, "You [Tyndall] have made a grand step in meteorology in showing that the dry air is perfectly transparent and that the invisible moisture is what stops the sun's heat."[106] From these and other results, Tyndall pointed out the role of water vapor, which "must form one of the chief foundation-stones of the science of meteorology."[107]

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[103] Fleming, *Historical Perspectives*, 69.

[104] John Tyndall, "The Bakerian Lecture: On the Absorption and Radiation of Heat by Gases and Vapors, and on the Physical Connection of Radiation, Absorption, and Conduction," *Philosophical Transactions of the Royal Society of London* 151 (1861): 1–36; Fleming, *Historical Perspectives*, 67; Weart, *Discovery*.

[105] Quoted in: Fleming, *Historical Perspectives*, 71.

[106] Quotes in: Fleming, *Historical Perspectives*, 72.

[107] Fleming, *Historical Perspectives*, 73.

We come next to Svante Arrhenius (1859–1927) whose paper in 1896,[108] was the first to calculate the effect of increasing or decreasing carbon dioxide to the earth's atmosphere resulted in increases or decreases, respectively, of the temperature.[109] He based his calculations on the observations of Samuel Pierpont Langley (1834–1906), who measured the "transmission of heat radiation through the atmosphere."[110] Langley estimated the infrared radiation absorption through the atmosphere by measuring the absorption of reflected solar light from the moon through various angles as the moon rises in the sky. To reduce the effect of absorption by water vapor, the measurements were made on Mount Whitney, in California, where the concentration of water vapor is small and moderately stable. Arrhenius used these observations to model the absorption of heat through the earth's atmosphere and to calculate the effect of the addition or reduction of carbon dioxide.

In the 1896 paper, Arrhenius investigated the cause of the ice ages, not human-caused climate change. Arrhenius included a paper by Arvid Hogbom, which proposed how geological phenomena could change the amount of carbon dioxide in the earth's atmosphere. He also included an estimate of the quantity of carbon dioxide added to the atmosphere by human actions, but at that time it raised no concern.[111] Even with a

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[108] Svante Arrhenius, "XXXI. On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground," *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 41, no. 251 (1896): 237–76.

[109] See for example: Fleming, *Historical Perspectives*; and Weart *Discovery*.

[110] S. P. Langley, *Researches on Solar Heat and Its Absorption by the Earth's Atmosphere: A Report on the Mount Whitney Expedition* (Washington, DC: Government Printing Office, 1884); Fleming, *Historical Perspectives*, 76.

[111] Fleming, *Historical Perspectives*, 77.

proposed mechanism, his theory was not well received by the geological community because it did not fit current geological understanding. Some of today's historians, note that "although the theory was based on thorough calculations, it won no recognition from geologists."[112] However, not all geologists disagreed with the hypothesis. T. C. Chamberlin wrote a three-part scientific paper suggesting geological means by which carbon dioxide could be increased or decreased.

It wasn't until Arrhenius published his popular book, *Worlds in the Making* (1908), that he emphasized human-caused climate change by using the analogy of the glass in a greenhouse. He thought increasing the amount of carbon dioxide would be a good thing because the Scandinavian countries would warm up.[113] With the 1896 paper and the 1906 book, he is often recognized as the "founder of human-caused" climate change, a hero to many. As an aside, Brooks in his annotated bibliography[114] does not mention Arrhenius under the category "Changes in atmospheric composition," whereas most historians today focus on Arrhenius. Why Brooks did not include him this category is unknown.

An early supporter of Arrhenius' proposal was Nils Ekholm (1848–1923), a Swedish meteorologist, who argued that the evidence indicated that the "transparency of the atmosphere for heat radiations of different kinds, and with it also the radiation from earth into space, have no doubt varied considerably, and thus produced the great climatic

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[112] Complete Dictionary of Scientific Biography, "Arrhenius, Svante August," Charles Scribner's Sons, accessed January 28, 2017, http://www.encyclopedia.com/people/science-and-technology/ chemistry-biographies/svante-august-arrhenius.

[113]Svante Arrhenius, *Worlds in the Making: The Evolution of the Universe*, trans. H. Borns (New York: Harper & Brothers, 1908); Fleming, *Historical Perspectives*, 80.

[114] Brooks, "Selective Annotated Bibliography," 446–75.

changes evidenced by geology."[115] Ekholm, in reviewing many of the other proposed hypotheses, such as astronomical causes, wrote that most were secondary causes and could not explain the ice ages.

Ekholm summed up his analysis:

> Among all the numerous hypotheses imagined to explain the great climatic changes of the geological ages, that worked out by S. Arrhenius on the ground gradually laid by Fourier, Pouillet, Tyndall, Langley, Knut Angstrom, Paschen, and others is the only one which has stood the test of a scientific examination. It is founded on the fact that carbonic acid, though as transparent as pure air to the solar rays, is partly opaque to the heat radiating from the ground and the lower and warmer strata of the atmosphere.[116]

Fleming notes that Ekholm was a lifelong friend of Arrhenius. Whether this influenced his interpretation of the carbon dioxide hypothesis is unexplored, but Ekholm was "an early and eager spokesman for anthropogenic climate control … by controlling the production and consumption of carbonic acid."[117]

Returning to the views of the geological community, one of the premier geologists of the early twentieth century, T. C. Chamberlin (1843-1928), published three papers expanding on the carbon dioxide hypothesis by proposing geological mechanisms that could cause changes in carbon dioxide concentration.[118] Chamberlin had mixed opinions about the work but believed that "Dr. Arrhenius has taken a great step in advance of his predecessors in reducing his conclusions to definite quantitative terms,

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[115] Ekholm, "On the Variations," 17–18.

[116] Ekholm, "On the Variations," 20.

[117] Fleming, *Historical Perspectives*, 111.

[118] T. C. Chamberlin, "An Attempt to Frame a Working Hypothesis of the Cause of Glacial Periods on an Atmospheric Basis," *Journal of Geology* 7, nos. 6–8 (1899): 545–84, 667–85, 751–87.

deduced from observational data."[119] Nonetheless, Chamberlin did not accept all of the ideas. "Chamberlin, however, found the assumption of Hogbom and Arrhenius, that volcanic eruptions were the chief source of carbonic acid for the atmosphere, overly simplistic and not clearly and inevitably connected with the known current of geologic events."[120]

In response to these flaws, Chamberlin's three-part paper (1899) sets out in detail a working hypothesis on how changes in carbon dioxide could come about over geologic time, which would turn the carbon dioxide hypothesis into a working hypothesis, one from which future scientific work could be derived.[121] Chamberlin discussed, in detail, multiple proposed sources and sinks for carbon dioxide. For example, long-term sources of carbon dioxide were primarily volcanoes, while long-term sinks are processes such as carbonate deposition in the oceans. He discussed short-term sources and sinks, changes in vegetation and other organisms, and discussed the rates of change in each of these sources and sinks. From this analysis, Chamberlin thought he had provided a solid geological foundation to explain changes in the concentration of carbon dioxide in the atmosphere.

However, in 1900 soon after Arrhenius' publication, "Knut Angstrom concluded that carbon dioxide and water vapor absorb infrared radiation in the same regions … and experiments done in 1905 demonstrated that a column of carbon dioxide fifty centimeters long was ample for maximum absorption" whereas the amount of carbon dioxide in the

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[119] Fleming, *Historical Perspectives*, 79.

[120] Fleming, *Historical Perspectives*, 79.

[121] T. C. Chamberlin, "Attempt to Frame a Working Hypothesis," 545–84, 667–85, 751–87.

atmosphere was estimated to be 250 cm.[122] There is disagreement among today's historians as to the evidence Arrhenius had at his disposal for his model calculations.

> Arrhenius has been lauded as the father of the theory of the greenhouse effect, even of global warming. One author [Spencer Weart] claimed that 'Arrhenius had enough spectroscopic information to estimate that doubling the amount of carbon dioxide in the air could warm the world by four to six degrees,' that 'the industrial output of carbon dioxide had already reached a level comparable to the amount that circulated naturally,' and that Arrhenius had 'discovered' the greenhouse effect in 1896. All three statements are misleading and incorrect.[123]

Angstrom's experimental results raised serious challenges to Arrhenius' proposal, and changes in the experimental evidence eventually convinced Chamberlin that the hypothesis was no longer a plausible working hypothesis. Fleming quotes Chamberlin from a letter (1913):

> It seemed to be founded on mathematical deductions from Langley's observations and to have come with a high authority, it drew a large following. Unfortunately … Arrhenius' deductions from Langley's observations appear to have been unwarranted and when this was discovered a reaction was inevitable.… I greatly regret that I was among the early victims of Arrhenius' error.[124]

As additional evidence accumulated, "Chamberlin later regretted his overeager acceptance of Arrhenius' results."[125]

Arrhenius' proposal received an immediate, positive response, with Chamberlin in 1899 and Ekholm in 1901 publishing papers in support of it. But there were also critiques from early geologists, and even Chamberlin changed his view on the viability of the hypothesis by 1913. The mixed views of the carbon dioxide hypothesis may have resulted

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[122] Fleming, *Historical Perspectives*, 111.

[123] Fleming, *Historical Perspectives*, 79.

[124] Quoted in Fleming, *Historical Perspectives*, 90.

[125] Fleming, *Historical Perspectives*, 79

in a gap in publications for many decades in the early twentieth century, which resulted in limited work on it.

Nonetheless, the carbon dioxide hypothesis was not ignored, as some of today's historians have suggested. It was discussed in the scientific literature, particularly in textbooks; that is, the hypothesis was carried along with other hypotheses during this period.[126] For example, in his 1926 textbook, Brooks, after allocating an entire chapter to discussing the carbon dioxide hypothesis and the evidence for and against it, summarized its status: "Carbon dioxide can never have been an important factor in climatic variations."[127] This conclusion was based on a review of the evidence, which suggests the hypothesis did receive a fair hearing. But this was not Brooks' final view on the hypothesis because his view went through many cycles in the early twentieth century, possibly reflecting the views of the scientific community. In his 1926 book, *Climate through the Ages*,[128] he argues it is not a plausible hypothesis; yet in the second edition in 1949,[129] he says the work of Callendar has revived the hypothesis, but he still thinks it can only play a minor role. See the section, Scientists and Their Views, starting on page 95, for a more complete description of the changes in the two editions of the text.

Like Brooks, W. J. Humphreys (1862-1949), reviewed the hypothesis in two editions of his text, *Physics of the Air*, the first edition published in 1920 and the third edition published in 1940. During this time, Humphreys' view of the hypothesis did not

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[126] Weart, "Global Warming," 319–56.

[127] Brooks, *Climate through the Ages*, 1926, 132–33.

[128] Brooks, *Climate through the Ages*, 1926.

[129] C. E. P. Brooks, *Climate through the Ages: A Study in the Climatic Factors and Their Variations* (New York: McGraw-Hill, 1949).

show any changes, in contrast to that of Brooks. In the 1940 edition of his text, after reviewing all the hypotheses on the origin of the ice ages, he states of the carbon dioxide hypothesis: "It seems that changes in the amount of carbon dioxide in the atmosphere might have been a factor in the production of certain climatic changes of the past, but that it could not, by itself, have produced the great changes of temperature that actually occurred."[130] The second edition was published in 1938 just after Callendar's publication; and therefore Humphreys could not have read the papers of 1939, 1940, and 1941 in time to incorporate Callendar's evidence into his new edition, if in fact, Humphreys did believe that Callendar's evidence was persuasive.

Earlier, in 1929, George Clark Simpson (1878-1965), director of the United Kingdom's Meteorological Office from 1920 to 1938, reviewed the carbon dioxide hypotheses:

> There are three reasons why carbon-dioxide can play little part in altering the temperature of the atmosphere. In the first place, the absorption band of carbon-dioxide is very narrow and therefore despite its intensity it can have very little effect on the terrestrial radiation. Secondly, there is so much carbon-dioxide in the atmosphere now that it exerts its full effect and any further addition would have little or no influence. Thirdly, the carbon-dioxide band occurs where water vapor exerts much absorption and in most parts of the atmosphere there is so much water vapor that it alone would absorb all the radiation of the wave lengths under consideration, hence the presence or absence of carbon-dioxide can have very little effect. It is now generally accepted that variations in carbon-dioxide in the atmosphere even if they do occur, can have no appreciable effect on the climate.[131]

Simpson's succinct statement of the problems with the hypothesis, challenged researchers to overcome them, if possible, before the hypothesis could be reconsidered.

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[130] William Jackson Humphreys, *Physics of the Air*, 3rd ed. (Philadelphia: Franklin Institute by J. P. Lippincott, 1940), 662.

[131] G. C. Simpson, "Past Climates," *Memoirs and Proceedings of the Manchester Literary and Philosophical Society* 74, no. 1 (1929): 9–10.

The next major step in the development of the carbon dioxide story came in 1938[132] with a paper by Guy Stewart Callendar (1897-1964) where "anthropogenic carbon dioxide in climate change was reevaluated, [and] G. S. Callendar … acknowledged the 'checkered history' of the carbon dioxide theory."[133] One advantage Callendar had, which previous scientists did not, was evidence showing that the amount of carbon dioxide in the atmosphere was increasing, along with new infrared spectroscopic data.[134]

Callendar published in rapid succession four papers that laid out the evidence for the effect of carbon dioxide on the temperature of the atmosphere: the production and influence of carbon dioxide (1938)[135]; the composition of the earth's atmosphere through time (1939)[136]; the history of concentrations of carbon dioxide in the atmosphere (1940)[137]; and infrared spectroscopy of carbon dioxide and the effect of atmospheric pressure on the spectra (1941).[138] He was very interested in human-caused climate change and continued working on it for many years.

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[132] G. S. Callendar, "The Artificial Production of Carbon Dioxide and Its Influence on Temperature," *Quarterly Journal of the Royal Meteorological Society* 64 (1938): 223–40.

[133] Fleming, *Historical Perspectives*, 113.

[134] Fleming, *Historical Perspectives*, 114.

[135] Callendar, "Artificial Production," 223–40.

[136] G. S. Callendar, "The Composition of the Atmosphere through the Ages," *Meteorological Magazine* 74, no. 878 (1939): 33–9.

[137] G. S. Callendar, "Variations of the Amount of Carbon Dioxide in Different Air Currents." *Quarterly Journal of the Royal Meteorological Society* 66, no. 287 (1940): 395–400.

[138] G. S. Callendar, "Infra-Red Absorption by Carbon Dioxide, with Special Reference to Atmospheric Radiation," *Quarterly Journal of the Royal Meteorological Societ*y 67, no. 291 (1941): 263–75.

In the 1938 paper, Callendar notes that "much new knowledge has been accumulated which has a direct bearing on this problem[:] … the temperature-pressure-alkalinity-CO_2 relation for sea water … the vapor pressure-atmospheric radiation relation … the absorption spectrum of atmospheric water vapor … and a full knowledge of the thermal structure of the atmosphere."[139] With this new knowledge, Callendar revisited the carbon dioxide hypothesis, because it addressed earlier limitations of infrared spectroscopy, which indicated water vapor and carbon dioxide absorption lines overlapped with each other.[140] Improved resolution in infrared spectroscopy was critical to re-evaluating the carbon dioxide hypothesis because, from early studies, water vapor and carbon dioxide bands were thought to overlap in the 13 to 16 micron band. Callendar, with improved spectroscopy, calculated the absorption of water vapor, which had a variable concentration, and carbon dioxide, a fixed concentration, to obtain the overall absorption from which he "calculate[s] [for temperate regions] that 95 percent of the radiation comes from the water vapor; for arctic conditions the carbon dioxide may supply as much as 15 percent of the total," not an insignificant effect from CO_2.[141] He goes onto calculate the effect of changes in carbon dioxide and changes in the infrared absorption as a function of height. As part of his presentation he provided evidence showing a small continuous temperature rise of the earth's atmosphere.

The response to Callendar's 1938 presentation was mixed, as seen from the published questions to his presentation he made to the Royal Meteorological Society.

[139] Callendar, "Artificial Production," 223.

[140] Callendar, "Artificial Production," 223–40.

[141] Callendar, "Artificial Production," 229.

There was general recognition of the excellent work of Callendar, but most criticisms came from meteorologists pointing out that he used a very simple model of the atmosphere and ignored the effects of meteorology. Others, such as Brooks, agreed there had been a temperature rise in the atmosphere but attributed it to other changes in meteorological conditions. But the response was not entirely negative or challenging; for example, Brooks did not think carbon dioxide could have this effect, but Brooks said, "the possibility certainly merited discussion…and he welcomed the paper as a valuable contribution to the problem of climatic change."[142]

Even with Callendar's new work, the generally negative view of carbon dioxide as a causal agent of the ice ages continued. Thomas A. Blair (1879–1963?) summarized the status of the carbon dioxide hypothesis in 1942 by reiterating the previously mentioned problems with it:

> It has been shown, however, that with a moderate amount of it [carbon dioxide], as at present, doubling the amount would not materially increase the absorption of earth radiation, and it has been further shown that water vapor in the air acts in the same way as carbon dioxide and on the same wavelengths. Apparently, the only way in which changes in carbon dioxide could materially affect the climate of the world would be by affecting the upper air above the water vapor; it is doubtful whether this was an important factor in glaciation.[143]

Note that Blair is concerned with the ice ages, not with human-caused climate change.

Blair did not cite Callendar's work, and it is unclear whether Blair was aware of the 1938 work of Callendar and whether this might have changed his opinion. This

[142] Callendar, "Artificial Production," 223–40.

[143] Thomas A. Blair, *Climatology: General and Regional* (New York: Prentice Hall, 1942), 97.

example raises the question as to whether the role of carbon dioxide in the origin of the ice ages or human-caused climate change may occasionally have been conflated.

In a review from 1955, Brooks stated indirectly the status of the carbon dioxide hypothesis as no longer plausible, at least regarding the origin of the ice ages. He said: "Changes in the constitution of the earth's atmosphere now reduce almost entirely to the effects of volcanic dust."[144] He did not mention the carbon dioxide hypothesis at all. But this does not mean the idea was not being carried along within the scientific community as a hypothesis that could be relevant to human-caused climate change when evidence for its existence became clear.

In fact, starting in the 1950s, extensive new research on the role of carbon dioxide in human-caused climate change expanded rapidly. I refer readers to other historians, for example, Fleming, Weart, and many others, for detailed histories of work in late twentieth century on human-caused climate change.

From this short review, we can see that the carbon dioxide hypothesis did indeed have a "checkered history," although scientists' view of the viability of the hypothesis decreased as new evidence became available after an initial limited acceptance of the hypothesis. During this period, the hypothesis was not ignored; it was continually discussed in the early twentieth century, even if research into the hypothesis during the early twentieth century was limited.

[144] Brooks, "Present Position," 205.

Changes in Atmospheric Circulation Hypothesis

The changes in atmospheric circulation hypothesis stands in a different relationship to the question of the origin of the ice ages than do other hypotheses because it is a proposed mechanism by which glaciers form and expand, not a fundamental cause of temperature change. Though Brooks does not differentiate this category from the other categories, many scientists recognize a difference. Frederick William Harmer (1835–1923) points out that many geologists and others studying the origin of the ice ages of the Pleistocene rarely studied meteorology in sufficient depth to understand how the glaciers formed and spread.[145]

Although many scientists in this category were educated as geologists, they studied the meteorological conditions by which glaciers expanded or shrank during the Pleistocene. They used current meteorological knowledge and applied it to previous geological periods on the assumption that the fundamentals affecting weather had not changed with time.[146]

The research described in this category is not often concerned with the fundamental cause(s) of the ice ages, but rather, given a change in temperature, what would be the effect on meteorology and how does this affect glacial conditions, Harmer

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[145] Frederic William Harmer, "The Influence of the Winds Upon Climate During the Pleistocene Epoch: A Palæometeorological Explanation of Some Geological Problems," *Quarterly Journal of the Geological Society of London* 57, no. 1-4 (1901): 405–78.

[146] Harmer, "Influence of the Winds," 405–78.

expressed the view of many scientists in this program when he wrote: “I do not venture to express any opinion as to the cause of the Glacial cold.”[147]

Frederick W. Harmer, in 1901, presented results which described how changes in large-scale climate resulted in the expansion of glaciers into lower latitudes, that is, how meteorological conditions could result in expansion or contraction of glaciers.[148] He also presented evidence that indicated the glacial periods alternated between the hemispheres. His last paper, published posthumously in 1925, was edited by Brooks. In the preface, Brooks notes that there were few changes from Harmer’s original 1901 paper, but some of Harmer’s assertions were no longer credible, in particular, Brooks noted, “The hypothesis of alternating glaciations in Europe and North America, which was contained in the first paper, has been shown by the researches of G. de Geer and other geologists to be untenable; the latest glacial stage at least was certainly contemporaneous on both sides of the Atlantic.”[149] Brooks removed Harmer’s comments from the paper, noting Harmer would also have made these corrections if he could: “The author would no doubt have accepted this view.”[150] Brooks’ actions on this paper, along with other evidence, is discussed in this historical analysis section because it bears on the relationships between scientists during the early twentieth century.

[147] Harmer, “Influence of the Winds,” 431.

[148] Harmer, “Influence of the Winds,” 405–78.

[149] F. W. Harmer, “Further Remarks on the Meteorological Conditions of the Pleistocene Epoch,” *Quarterly Journal of the Royal Meteorological Society* 51, no. 215 (1925): 247–60.

[150] Harmer, “Further Remarks,” 247.

In summing up Harmer's work, Brooks describes it as of "historical interest only," which I assume is because Harmer's interpretation of evidence of the alternating glacial periods between the hemispheres was no longer accepted.[151]

H. N. Dickson (1866–1922), though not mentioned by Brooks (1950), writing at the same time as Harmer, says: "My object is rather to point out some consequences which must follow if we adopt certain theories still on trial." He is included in this section because his emphasis is the study of atmospheric conditions during glacial periods and, secondarily, because of his interest in the fundamental causes of ice ages. He critiques some of the meteorological models of the climate belts because they contradict geology and physics. From his analysis, there are two possible causes of the glacial periods: "1. Tectonic changes … 2. General lowering of the mean temperature of the atmosphere."[152] Dickson investigated the role of lowering of the mean temperature of the atmosphere to identify the predicted meteorological effects. From analyzing the evidence, he finds changes in temperature can produce the observed effects, including expansion of glaciers, but he questions the causes of the change in temperature. He reviews several hypotheses, such as the astronomical and carbon dioxide hypotheses and whether they account for the change in temperature, and finds that the carbon dioxide hypothesis is most promising, though there are difficulties with it.

Another approach was based on local meteorological effects rather than large-scale global changes. In 1908, John Walter Gregory (1864-1932) argued the growth of

[151] Brooks, "Selective Annotated Bibliography," 450.

[152] H. N. Dickson, "The Mean Temperature of the Atmosphere and the Causes of Glacial Periods," *Geographical Journal* 18, no. 5 (1901): 517.

glaciers was not simultaneous, and therefore there was probably no widespread glacial period. From this evidence, he argued glacial expansion was a local phenomenon, e.g. due only to changes in local weather and climate, not widespread climate change. "The range of climatic variations in the past has been often greatly exaggerated.… But the climatic changes we have to explain appear to have been either local in area or moderate in degree."[153]

From the above-mentioned research, there were differences in how the evidence was interpreted. Possibly in response to this, in 1926, William Herbert Hobbs (1884–1953) summarized the meteorological and glacial data from many, if not all, of the various research expeditions exploring the Arctic and Antarctic regions, along with data from northern Europe and other locations.[154] Hobbs focused on the understanding of the role of anti-cyclones in the development and expansion of the glaciers, using meteorological studies and noting deficiencies in global climate research.[155]

> Quite otherwise has it been with the school of meteorologists. Ignoring the vital difference between the north and the south polar regions proper—the northern polar area a level expanse of sea covered by floating ice-floes, the southern a continent deeply buried beneath a flat dome of ice and snow—they have in their discussions treated both as though these polar areas were identical.[156]

Emphasis on the use of extensive expedition reports highlights Hobbs' view of the importance of observations over mathematical models. He complains that there is "a wide

[153] John Walter Gregory, "Climatic Variations, Their Extent and Causes," *Smithsonian Institution, Annual Report*, Part 1 (1908): 339–54.

[154] William Herbert Hobbs, *The Glacial Anticyclones: The Poles of the Atmospheric Circulation* (New York: Macmillan, 1926).

[155] William Herbert Hobbs, *Characteristics of Existing Glaciers* (New York: Macmillan, 1911).

[156] Hobbs, *Characteristics of Existing Glaciers*, 172.

misapprehension among those meteorologists and climatologists who treat their subjects largely from the standpoint of mathematics."[157] He adds,

> It has seemed necessary to furnish extracts in some fullness from the more recent meteorological treatises in order to show how generally their authors have ignored the existence of the great Greenland continental glacier with its powerful anticyclone; and, further, how they have likewise ignored the evidence from observation of generally normal air pressures over the north polar region. Humphreys the one noteworthy exception to this rule.[158]

Though he does not explicitly say so, Hobbs could have been addressing his comments to scientists, such as Arrhenius, who made limited use of meteorological data in their models.[159]

The last paper cited by Brooks (1950) is one by Richard Foster Flint (1902–1976) and Herbert Grove Dorsey (1876-1961). Although they discuss the ice ages in their paper, they do not focus on large-scale glacial development or causation, rather their paper describes glacial evidence from North America and is not focused on changes in atmospheric circulation.[160] There is a more interesting paper by Flint (1951), which expands on the role glaciers played in climate while critiquing other hypotheses. The focus of the paper is on recent changes in the glaciers, which helps us to understand the phenomena from past glacial periods rather than the fundamental cause(s) of the ice ages.[161]

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[157] Hobbs, *Characteristics of Existing Glaciers*, 5.

[158] Hobbs, *Characteristics of Existing Glaciers*, 183.

[159] Fleming, *Historical Perspectives*, 76.

[160] Richard Foster Flint and Herbert Grove Dorsey, Jr., "Iowan and Tazewell Drifts and the North American Ice Sheet," *American Journal of Science* 243, no. 11 (1945): 627–36.

[161] Flint, "Climatic Implications," 1019–23.

Flint found two problems with current hypotheses: they were missing critical information upon which to develop or critique the hypotheses, and many hypotheses were stated without sufficient rigor to make testable claims. He notes that at that time, 1951, dating of the glacial periods is but a "controlled guess," highlighting one of the major challenges to glacial studies: the lack of good dating techniques.[162] Other missing data are good estimates of the actual temperatures present during glacial and interglacial periods.

Both Harmer and Hobbs each published two papers on the topic, we might expect to see changes in their views as evidence changed. However, because they focused on the meteorology of the glacial periods and not the fundamental cause(s), though their analysis became more sophisticated, there were no significant changes in their views.

This category of research covered a wide variety of topics though all relate to the ice ages. Hobbs was interested in the formation and expansion of glaciers using his anti-cyclone model. Gregory thought the evidence of widespread glaciation was nonexistent and focused instead on local glaciation, which is consistent with Harmer (1926) who also thought the existence of widespread glaciation was overstated. Finally, we have Flint and Dorsey who focused on the development of a set of glaciers on the North American continent. The disjointedness of research in this category may have arisen because the research was not primarily focused on a fundamental cause of climate change but rather on the effects on meteorology.

[162] Flint, "Climatic Implications," 1019–23.

Geographical Hypothesis

This hypothesis describes how changes in geography—such as, height and location of mountains, and locations of deserts and bodies of water—effect the weather and large-scale climate patterns. The effect of changes in geography are easily recognized today: for example, dry regions of the intermountain west, Nevada and New Mexico, all have low annual precipitation because the mountains in California, such as the Sierra Nevada, intercept weather systems from the Pacific Ocean and reduce the water content of them, leaving very little moisture for the eastern flanks of the mountains.

There are three variants of the geographical hypothesis: 1) local geographical effects with no major change in global geography,[163] 2) major changes in global geography,[164] and 3) major changes in geography caused by continental drift, with variants (2) and (3) resulting in global ice ages. I've added the continental drift hypothesis to this section, rather than keep it as a separate category as Brooks (1950) did because it is just a different mechanism for changing the geography. The hypotheses in all their variants were developed over a period of about 70-80 years.

Before describing this hypothesis, there are a couple of interesting characteristics to keep in mind. First, one of the major proponents was Brooks; and though there is no evidence he slanted his reviews of other hypotheses, it is well to keep in mind that the geography hypothesis was his preferred solution to the origin of the ice ages. One reason that I do not think he slanted his reviews or was not sufficiently protective of this

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[163] Gregory, "Climatic Variations," 339–54.

[164] Bailey Willis, "Isthmian Links," *Geological Society of America Bulletin* 43, no. 4 (December 30, 1932): 917–52.

hypothesis was that over time he came to regard the geographical hypothesis as no longer plausible. His change in acceptance of this hypothesis will be described later in this section.

In addition, most of the authors in this section, for example, Harmer (1901, 1926) and Gregory (1908), are also listed in the ATM section because they were considered by Brooks (1950), which is appropriate, because changes in geography result in changes in atmospheric circulation. It is geography, along with ocean circulation, that affects atmospheric circulation and, thus, their papers are discussed in both sections.

James Geikie (1839–1915), a Scottish geologist, describes only two hypotheses in his 1874 book on the ice ages: the geographical hypothesis and the astronomical hypothesis. This is early in the investigation into the causes of the ice ages, and there were not many hypotheses to consider; for example, the CRD hypothesis was not fully proposed till 1896.[165] Geikie provides a good summary of the geographical hypothesis as it stood at the time, which was proposed by Charles Lyell, whose theory "has taken firmest hold of the geological mind."[166] Lyell's theory claims that the changes in climate were caused by changes in the distribution between the land and the oceans, which he derived from the geological evidence. For example, it was well-known that rocks containing certain fossils had clearly been formed in the oceans, and these rocks could now be found at the top of mountains, far from the ocean; hence there had been major changes in geography. Other evidence pointed to changes in coastlines that had been

[165] Geikie, *Great Ice Age,* 1874, 103–49.

[166] Geikie, *Great Ice Age*, 1874, 109.

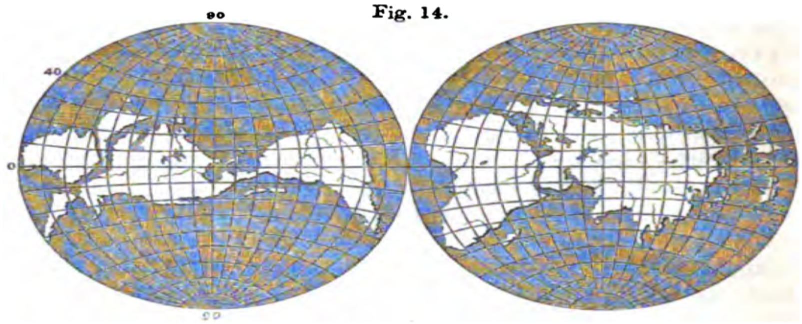
higher in the past but were now sinking, and to the existence of tropical fossils found in arctic regions.

Lyell's proposal did not provide a good mechanism for the movement of land masses. Geikie writes, "Lyell conceives, that, if land were massed chiefly in the region of the equator and the tropics, the climate of the globe would be such that tree-ferns might grow luxuriantly on any islands that might happen to lie within the Arctic or Antarctic Circle."[167] A secondary mechanism for the change in climate would be changes in ocean and wind currents caused by changes in geography.

Lyell proposed a radical shift in the location of the continents, and his theory is best understood by the two layouts of the continents, one for cold climate and one for warm climates, from the 1867 edition of his *Principles of Geology*, see Figure 3.

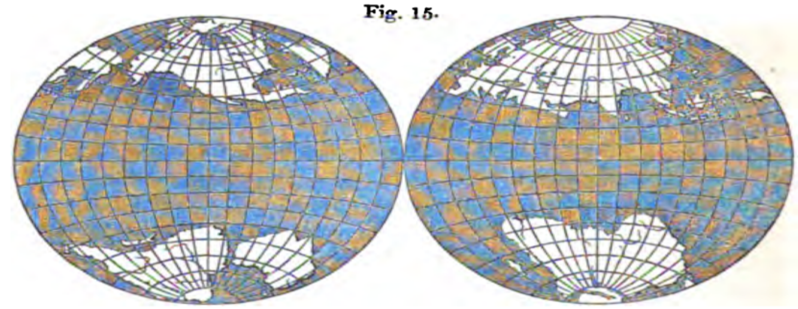
[167] Geikie, *Great Ice Age*, 1874, 110.

Fig. 14.



Extreme of Heat.

Fig. 15.



Extreme of Cold.

Figure 3. Lyell's Proposed Distribution of the Continents During the Ice Ages and Warm Interglacial Periods.
The light regions are the continents and the dark regions are the oceans. Source: Charles Lyell, *Principles of Geology or, the Modern Changes of the Earth and Its Inhabitants Considered as Illustrative of Geology*, 10th ed., vol. 2 (London: John Murray, 1867), 266.

After reviewing Lyell's hypothesis, Geikie raised several objections to it, questioning whether Lyell's proposed distribution of the continents could have the proposed effect on climate. Geikie, using Lyell's proposal, calculated the effect on the climate of the continents grouped in the tropics and found the changed geography could not have the desired effect; he admits that if the continents were located at the poles, perhaps a cold climate could result.[168] His main challenge to Lyell is that he sees no mechanism by which the continents would be grouped together, and even if they were,

[168] Geikie, *Great Ice Age*, 1874, 116

there would be other consequences to current and atmospheric flow that were not taken into effect.

Geikie concludes: "During these great oscillations of climate there were not infrequent shifting in the distribution of land and sea; but such vicissitudes, although doubtless producing local effects, certainly do not seem to have been the causes of the chief climatal changes."[169]

Instead, Geikie believes the evidence supports the astronomical hypothesis, proposed by Croll in 1875: "Upwards of 200,000 years ago the earth … was placed in regard to the sun [so] that a series of physical changes was induced, which eventually resulted in conferring upon our hemisphere a most intensely severe climate"[170]; and "It is much more likely that the mild inter-glacial periods were induced by eccentricity of the earth's orbit, combined with precession of the equinoxes."[171] I discussed the astronomical hypothesis above.

Geikie revised his monograph in 1895 to include a review of additional hypotheses that had been proposed since his previous edition, but in his new monograph he still focuses on the two primary hypotheses: AST and GEG. However, he gives short shrift to many additional hypotheses that had been proposed, a few of which were briefly mentioned in his first edition, such as the solar system passing through hot or cold regions of space, the sliding of the crust around the globe, the sun as a variable star, etc.

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[169] Geikie, *Great Ice Age*, 1874, 506

[170] Geikie, *Great Ice Age*, 1874, 504.

[171] Geikie, *Great Ice Age*, 1874, 506–7.

Geikie quickly dismisses these hypotheses as not being consistent with the geological evidence or consistent with known physics.[172]

As in the first edition, Geikie reviews the geological evidence, the evidence which any hypothesis must account for, and again finds the geographical hypothesis of Lyell, as modified by later scientists, to be untenable in explaining the ice ages. Geikie still finds the AST hypothesis, mainly that of Croll with modifications from Robert Ball, to best explain the geological evidence: "So far, then, as we have gone, the Astronomical theory would appear to offer the best solution of the glacial puzzle."[173] Geikie does recognize that AST does not account for "minor climatic oscillations of the so-called postglacial times … and thus it must be confessed that a complete solution of the problem has not yet been found."[174]

As previously discussed, Harmer's research focused on the mechanism of glaciation, its expansion and contraction, which is caused by changes in atmospheric circulation.[175] These changes come about via temperature changes and changes in ocean currents caused by changes in geography, which he thinks is probably the best explanation. He does suggest there may be other minor influences, such as the carbon dioxide hypothesis as suggested by Chamberlin.[176]

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[172] James Geikie, *The Great Ice Age and Its Relation to the Antiquity of Man*, 3rd ed. (New York: D. Appleton, 1895), 789–91.

[173] Geikie, *Great Ice Age*, 1895, 808.

[174] Geikie, *Great Ice Age*, 1895, 815–6

[175] Harmer, "Further Remarks," 247–60.

[176] Harmer, "Influence of the Winds," 405–78.

From the geological estimates of the changes in geography, Harmer calculates the effect on the climatic systems, which were discussed in the earlier section on ATM, but recognizes that his calculations are of "a highly speculative character.… [T]he views here stated are offered in a suggestive, and not a dogmatic spirit, and the most that I can hope for is to have shown a *prima-facie* case for further investigation."[177] Harmer notes in an appendix that he had recently received papers written by Chamberlin and by Ekholm, both of who argue for CRD, but he has some doubts about whether the changes could be rapid enough to have initiated ice ages. In the end, Harmer is "still inclined to think that the minor variations of the Pleistocene, the prehistoric and the historic periods, may have belonged to one great series of events, and been alike due to the cause which gives Great Britain its variable seasons, at the present day, namely, to alterations in the direction of the primary winds," but the question is then what caused the changes in the winds. [178] Harmer believed that the evidence supported geographical changes as the cause, but since his main concern was meteorology, he did not concern himself with primary causes.

In contrast, John Walter Gregory (1864–1932) challenges many of the interpretations of the geological evidence and argues that the growth of glaciers were not simultaneous and that there was probably no widespread glacial period; because the timing was not simultaneous, glaciers were caused by local phenomena—changes in local weather and climate.[179] His view is an extreme version of changes in geography, in that,

[177] Harmer, "Influence of the Winds," 469.

[178] Harmer, "Influence of the Winds," 474.

[179] Gregory, "Climatic Variations," 339–54.

glaciers form dependent of local geography and not because of worldwide changes in climate.

Willis J. Bailey (1854–1932) had a different approach to geographical change.[180] He argued there were land bridges between the continents, which is how he explains the similarity of paleontological and other evidence across the Atlantic while dismissing the view put forward by Wegener and others for continental drift. Instead, he proposes land bridges, which do not exist now except in some situations like the land bridge between North and South America, to explain changes in atmospheric and oceanic circulation and hence the origin of glaciers.

To validate his proposal, Bailey submitted his maps for his paper to Brooks, Humphreys, and Simpson to evaluate the proposed climatological effect on the assumption that if there were land bridges, they would cause local changes in climate leading to the formation of glaciers.[181] The reviewers generally agreed that if these land belts had existed, such changes in climate would occur, but the reviewers did not necessarily accept his hypothesis. He said their comments helped him to further refine his hypothesis about the existence of land bridges and the resultant formation of continental glaciers.

Bailey did not explore the possible challenges his hypothesis might face; rather, he merely wanted to "test … the hypothesis of isthmian links [if] it will suffice to show that under the geographic development the oceanic and atmospheric conditions would change distinctly in favor of glaciation in the southern areas where Permian ice-sheets

[180] Willis, "Isthmian Links," 917–52.

[181] Willis, "Isthmian Links," 917–52.

accumulated, while temperate airs and waters would prevail in the Arctic."[182] However, his hypothesis was challenged by Henry Newton Dickson (1866–1922), who, in reviewing the geographical hypotheses, found the evidence did not support it.[183] Bailey notes that there is a competing explanation for the similarity of geology from South America and Africa, the continental drift hypothesis by Wegener, though he indicates there is very little evidence to support this view.

One of the difficulties with the geographical hypotheses is to identify a mechanism for significant changes in geography. Brooks[184] argues that though there have been some difficulties with a "lack of precision," nonetheless, "the geographical theory, which states that the Ice Age was brought about by elevation in high latitudes, and by changes in the land and sea distribution, [was] never seriously challenged." He takes up the argument again in his textbook *Climate Through the Ages* (1926) where he does recognize there are problems with this hypothesis, specifically with coming up with a mechanism for changes in geography during the Pleistocene, which was only 2.6 million years ago, too short a time for major geographical changes to have altered the Pleistocene's ice ages to today's warmer climate.

Later, in 1947, Brooks wrote:

> Finally, we come to a large and diverse group of theories which depend only on the effect of the ordinary geological processes of elevation, erosion and depression of continents on the configuration of the earth, the height of mountain ranges and the course of ocean currents.… The climate of the Permo-

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[182] Willis, "Isthmian Links," 945.

[183] Dickson, "Mean Temperature," 516–23.

[184] C. E. P. Brooks, *The Evolution of Climate* (London: Benn Brothers, 1925), 22–23.

> Carboniferous was unique, but so also was the distribution of land and sea, and the geographical explanation may not be entirely ruled out.[185]

He thought this was one of the best hypotheses for explaining the origin of at least one of the ice ages. However, in 1955 Brooks' view of the hypothesis had changed: "Orogenesis and changes of land and sea distribution do not now appear to be accepted as the major cause of climatic changes, but several authors express the view that both solar and geographical changes are required for ice ages."[186] In his view, the geographical hypothesis is, at most, a secondary cause of the ice ages.

In contrast to the proposals of geographical change by Bailey and others, we come to the continental drift hypothesis, which never gained much traction. The continental drift hypothesis was proposed as a cause of the ice ages; in this case continents moved into geographically colder regions rather than the ice ages resulting from a change in climate.

Interestingly, Brooks in the two editions of his text *Climate Through the Ages* (1926, 1949) allocates an entire chapter to discussing Wegener's hypothesis and the effect changes in the location of the continents would have on climate. He basis his discussion on the work of Koppen and Wegener, *The Climates of the Geological Past*, originally published in 1924.[187] Koppen and Wegener discuss not just past climates and the evidence for them, but they propose continental drift as the cause for major changes in geography, which result in the ice ages. Wegener had only recently published his book

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[185] Brooks, "Unsolved Problem Part II Theories," 150.

[186] Brooks, "Present Position," 205.

[187] Koppen, *Climates of the Geological Past*.

on continental drift in the same year. The joint work with Koppen took the continental drift hypothesis and explored its effect on climate.[188]

Again, one of the challenges to the continental drift hypothesis is that it could not account for the Pleistocene ice ages, which occurred from 2.6 million years ago until 10,000 years ago, with four different phases. The Pleistocene ice age is too recent for there to have been significant movement in the continents, though continental drift might account for much earlier ice ages.

In the end, Brooks concludes: "These considerations show that the theory of 'continental drift' is not so complete and irresistible an explanation of the peculiar distribution of climate in the Carboniferous and Permian periods as Koppen and Wegener seem to think."[189]

Cosmic Dust Hypothesis

The cosmic dust theory, as Brooks (1950) calls it, is probably not what you think it is. It is not about the solar system passing through a cloud of interstellar particles blocking sunlight from reaching the earth. Rather, it describes the effect of the sun's gravitational pull, which drags particles from an interstellar cloud onto the sun increasing the sun's overall luminosity, that is, increasing the solar constant. As Max Krook (1913–1985) pointed out in 1953, "any obscuring or blanketing effect by interstellar matter on

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[188] A. Wegener, *The Origin of Continents and Oceans*, 3rd ed., trans. J. G. A. Skerl (London: Metheun, 1924).

[189] Brooks, *Climate through the Ages*, 1949, 237-38.

the sunlight reaching the earth can be neglected" because particulate density in interstellar matter is far too small.[190]

This hypothesis was first proposed by astrophysicists Fred Hoyle (1915–2001) and Raymond Arthur Lyttleton (1911–1995) in 1939[191] and possibly arose from their research on the accretion of matter by stars, one of their joint research interests.[192] They did not do much research beyond the first paper; the only other publication was very short, a three-page scientific note in 1950.[193]

Ice ages can result from an increase, not a decrease, in solar radiation because the increase in solar radiation causes increased evaporation from the oceans and thus increased snow precipitation. Based on calculations, Hoyle and Lyttleton show that when the sun passes through a typical interstellar cloud, the kinetic energy released from the quantity of material accreted by the sun would be sufficient to temporarily increase the sun's luminosity and result in heating the earth, with the increased evaporation triggering an ice age.[194]

Hoyle and Lyttleton argue that their hypothesis has advantages over other hypotheses because their hypothesis requires no periodicity in the timing of the ice ages.

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[190] Max Krook, "Interstellar Matter and the Solar Constant," in *Climatic Change: Evidence, Causes, and Effects*, ed. Harlow Shapley (Cambridge, MA: Harvard University Press, 1953), 143-46.

[191] F. Hoyle and R. A. Lyttleton, "The Effect of Interstellar Matter on Climatic Variation," *Mathematical Proceedings of the Cambridge Philosophical Society* 35, no. 3 (1939): 405–15.

[192] Out of a list of sixteen joint papers, at least eight papers discussed stellar matter accretion, of which two papers dealt with the topic of climate change due to interstellar matter accreting onto the sun. The search was performed on October 24, 2016, using the Hollis library database at Harvard. The search terms were for papers jointly written by Holye and Lyttleton.

[193] F. Hoyle and R. A. Lyttleton, "Variations in Solar Radiation and the Cause of Ice Ages," *Journal of Glaciology*, no. 8 (1950): 453–55.

[194] Hoyle and Lyttleton, "Effect of Interstellar Matter," 405–15.

This differs from the other astronomical hypothesis, for example the one by Croll and Milankovitch, which is based on the periodicity of the ice ages. Hoyle and Lyttleton argue:

> The theories … based on extra-terrestrial causes … have mainly invoked dynamical effects such as precession and changes in the solar eccentricity. But even if these suggestions were otherwise satisfactory, there is a fixed period associated with such dynamical motions, and this would be reflected in the effects of the climatic changes. The periods are not at all comparable with the irregular intervals at which exceptional climatic conditions have occurred as indicated by geographical and geological evidence.[195]

Their hypothesis "does not give rise to the defect of periodicity"[196] because interstellar clouds are spread irregularly throughout the galaxy, and thus there is variation in the timing of the ice ages. Unfortunately, they did not provide a reference to support their claim that the ice ages were not periodic.

In their paper, Hoyle and Lyttleton briefly review other categories of hypotheses, dividing them into terrestrial or astronomical. They mention only one terrestrial hypothesis, changes in sea-level, that could produce the ice ages; but they find it inadequate because they do not think that changes could occur rapidly enough and repeatedly to account for the multiple phases of glacial advance during the Pleistocene. As mentioned, their main critique of the other astronomical hypotheses is their view that there is no periodicity in the timing of the ice ages.

They are modest in their claims for their hypothesis:

> The present hypothesis is not advocated with a view to contradicting the opinions and results of those investigators who have confined their researches to terrestrial sources of climatic variation. The claim made is simply that an important process

[195] Hoyle and Lyttleton, "Effect of Interstellar Matter," 407.

[196] Hoyle and Lyttleton, "Effect of Interstellar Matter," 407.

is brought to light and must be accorded some place in discussions of terrestrial climate.[197]

They reprised the interstellar dust hypothesis in 1950 in a short scientific note, published in a glaciological journal. The structure of the argument and the evidence they present is like the 1939 paper, though in the 1950 paper they added critiques of the CRD and the volcanic dust hypotheses, in addition to AST. They conclude there is now "incontrovertible evidence of the solar system passing through interstellar clouds, the only problem is what were the effects."[198] They leave the study of the climatic effects to others, but add that "the probability is strong that an adequate first cause of the major climatic variations lies here."[199]

Krook in 1953, reviewed the interstellar dust hypothesis, and cited only the 1939 paper by Hoyle and Lyttleton, which suggests this hypothesis was not further developed during the intervening fourteen years.[200] He does not mention the short 1950 paper by Hoyle and Lyttleton,[201] which is a summary of the hypothesis and does not significantly develop the hypothesis. Krook, in his calculations, corrected some of the work of Hoyle and Lyttleton; for example, he used a significantly lower particle density in the clouds, 10^{-21} compared to the higher value of 10^{-18} gm/cm^3, used by Hoyle and Lyttleton and highlighted their neglect of the effect of shock waves as the sun passes through the cloud. He points out that "there is considerable divergence of opinion on the order of magnitude

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[197] Hoyle and Lyttleton, "Effect of Interstellar Matter," 415.

[198] Hoyle and Lyttleton, "Variations in Solar Radiation," 455.

[199] Hoyle and Lyttleton, "Variations in Solar Radiation," 455.

[200] Krook, "Interstellar Matter," 143–46.

[201] Hoyle and Lyttleton, "Variations in Solar Radiation," 453–55.

and the importance of accretion,"[202] the key mechanism proposed by Hoyle and Lyttleton.

He concluded in 1953 that "neither the arguments for nor the arguments against the accretion hypothesis are completely conclusive."[203]

There was one other paper cited by Brooks in support of this hypothesis, but it is not in English so I am unable to review it.[204] Thus, given the two papers by Hoyle and Lyttleton, and the one from Krook, this hypothesis did not appear plausible and was not developed.

The cosmic dust hypothesis did not completely disappear from consideration; rather it resurfaced in the early twenty-first century. Studies today on the effect of interstellar dust are not related to increasing solar luminosity but rather investigate the effect of interstellar particles as they enter the earth's atmosphere.[205] The research investigates the role of these particles in providing nucleation sites in forming clouds and hence reflecting solar radiation. A recent news article reports research on whether this mechanism could have resulted in a "snowball" earth during the early history of the earth.

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[202] Krook, "Interstellar Matter,"146.

[203] Krook, "Interstellar Matter,"146.

[204] Kurt Himpel, *Ein Beitrag zum Eiszeitproblem* [*A Contribution to the Ice Age Problem*], ^ternwarte des physikalischen Vereins, Frankfurt, no. 1 (reprinted from Zeitschrift fiir Nalurfor- schung, 2a. 1947), 419–27.

[205] University of Leeds, *CODITA—Cosmic Dust in the Terrestrial Atmosphere*, School of Chemistry, University of Leeds, UK, 2011, accessed October 24, 2016, http://www.chem.leeds.ac.uk/ john-plane/laboratory/mesosphere/current-research/codita.html.

But this hypothesis has been challenged as inconsistent with the geological evidence, and the role of cosmic dust, even in its modern variation, is still speculative.[206]

I included this hypothesis to highlight the diversity of proposals from scientists from a variety of scientific disciplines. As previously discussed, there were a small number of hypotheses, such as AST, CRD, etc. that received the most attention from scientists, perhaps because there was sufficient evidence and means to test them. For example, the AST hypothesis, which predicts periodicity of the ice ages, generates a testable hypothesis: once one can determine the ice ages via radiometric dating, periodicity will or will not be found. In contrast, the cosmic dust hypothesis did not seem to generate any testable predictions.

[206] Philip Ball, "Did Stardust Trigger Snowball Earth?," *Springer Nature,* February 9, 20015, accessed October 24, 2016, http://www.nature.com/news/2005/050207/full/news050207-12.html.

Chapter IV

Solving the Cause of Climate Change—What Were the Challenges?

In Chapter III, we saw from the history of research into the causes of ice ages that this was not an easy problem to solve; and after about 100 years of research, the problem was still unsolved, and five hypotheses remained. What made solving this problem so hard? There are two general areas that can affect the ability to solve scientific problems: issues within the scientific community and challenges to obtaining and evaluating evidence.

In this chapter I first investigate scientific communities engaged in research, particularly consider comments from a few modern historians about potential bias within the community against the carbon dioxide hypothesis (CRD). Next, I investigate the challenges to obtaining and interpreting the core data needed to solve the problem. Even though there were many different communities, all to some extent had to understand the core data they were trying to explain, including the distribution and timing of the ice ages, along with the related geological, astronomical, chemical, and meteorological evidence. As part of this last section, I describe two examples of changes in scientific instrumentation that enabled studies to move forward.

Scientific Communities—Who Was Interested in this Problem?

Following the recognition of the existence of the ice ages, fourteen hypotheses, along with many variants, had been proposed from a wide range of scientific domains: astronomy, chemistry, meteorology, geology, and physics. By reviewing the published literature, we gain an understanding of who was part of this scientific community and how they interacted with each other.

Before continuing, we need to understand what is meant by scientific community within the context of this thesis; who were the members and what are the characteristics of the scientific community(ies)? There are many ways to subdivide scientists into various communities; three common categories include scientific discipline, nationality, and social structures.

Dividing scientists by discipline is a common criterion for categorizing; scientists do it themselves; they call themselves geologists, chemists, physicists, and so on. These high-level categories can be further subdivided by sub-discipline or by use of scientific instruments. An example from geology divides geologists into paleontologists, structural geologists, submarine geologists, along with cross-discipline categories such as geochemists or geophysicists. By way of instrumentation, chemists can be divided into Raman, ultra-violet, and infrared spectroscopists, or mass spectroscopists, radiochemists, and so on. These subdivisions are discussed later in this chapter, but these categories are not the main classification of scientists in this analysis because this problem was not investigated by a single scientific discipline.

Another categorization is by nationality, though this is not as common as categorizing by discipline. Nonetheless, there are studies that highlight differences between national scientific traditions or communities. For example, Naomi Oreskes,[207] in her studies of the history of continental drift, found that though scientific communities

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[207] Naomi Oreskes, *The Rejection of Continental Drift: Theory and Method in American Earth Science* (Oxford: Oxford University Press, 1999), 4, 278, 281, 291, 292.

had basically the same evidence, there were national differences in the interpretation of the evidence. For the South African geological community, the paleontological evidence, along with other evidence, was sufficient to make continental drift a plausible hypothesis. In contrast, the U. S. geological community did not find the evidence persuasive; rather, for them, geophysics provides the best evidence in geological questions, and it wasn't until the use of magnetometers and other instruments, repurposed from work during World War II, that persuasive evidence in the form of magnetic striping on the oceanic floor, began to convince them of the plausibility of continental drift, renamed plate tectonics. Changes in instrumentation will aid in solving the problems of the origins of the ice age and human-caused climate change and is discussed below.

Another categorization is based on the social structure of scientific communities, such as was described by M. Rudwick in his study *The Great Devonian Controversy*.[208] He studied geologists in the 1820s and 1830s as they worked to understand structural geology and the stratigraphic record and what it could tell us about the geologic past. He identified various social groups, such as elite, accomplished, amateur, in terms of technical competence or by social interests and power, such as, rhetorical skills, financial resources, and so on. For example, geologists in the cities, particularly London, were part of a group of elite geologists who evaluated and theorized about the meaning of the evidence. In contrast, geologists from the country and smaller cities provided high quality geological evidence, but the elite geologists did not often take seriously their theoretical proposals. The role of social structures in solving the cause of the ice ages is beyond the

[208] M. J. S. Rudwick, *The Great Devonian Controversy: The Shaping of Scientific Knowledge among Gentlemanly Specialists* (Chicago: University of Chicago Press, 1985), 418–26.

scope of this thesis, partly because the historical evidence in this study consisted entirely of publications, not unpublished letters and journals that would have thrown light onto social structures.

Instead, it appears the scientific community(ies) investigated in this thesis might best be described as problem-centered; that is, it was the problem, the cause of the ice ages, that intrigued a variety of scientists, and from many disciplines their work on this question formed the problem-centered scientific community studied in this thesis. Evidence discussed later supports this designation.

There is another category by which this scientific community could be categorized: the core set, as defined by Rudwick. The core set:

> can be defined as the small set of individuals through whose changing opinions a focal problem is ultimately treated by the rest of the "scientific community" as having been settled. Once those few individuals have concluded that the problem has been solved satisfactorily, then it *has* been solved, not in any prescriptive sense.… [T]hus as soon as conflict and controversy within the core set for any focal problem are replaced by a virtual consensus, the focal problem is at an end and the core set dissolves.[209]

The core set is a small group of scientists, who, because of their reputation, status, and track record in solving scientific problems, is the group that evaluates the evidence and determines if the problem has been satisfactorily solved. This is a smaller and more specialized group than the problem-centered category used in this thesis. The problem-centered community includes all scientists who have chosen to work on the problem; though some of their work is more plausible than others, the evaluation comes from not only the problem-centered community itself, but also the elite scientists, such as Chamberlin, Brooks, and Humphreys, among others. Because this thesis focuses on

[209] Rudwick, *Great Devonian*, 427.

published documents and because my analysis only goes until about 1950 when the ice age problem had not yet been solved, I did not identify a core set. Given that the problem of the origin of the ice ages was investigated over a period of about 100 years, the core set in this case study would have changed over time, adding to the complexity of the analysis. Identification of the core set and the roles they played is an opportunity for future research.

There are four parts to this section.

1. In a problem-centered community, did all members use the same methodologies to investigate the problems or were there obvious differences? To limit the length of this discussion, I focus on one exemplar, T. C. Chamberlin's working hypothesis methodology. He was a well-respected geologist, as evidenced from the comments in his obituaries.
2. As part of understanding how the science was done, I investigated the linkages between published papers, via citations, in a network diagram to understand how aware scientists were of each other's work.
3. Next, I investigated whether the evidence points to scientists getting "stuck" in their views; that is, once they accepted a hypothesis did they remain committed to it even as evidence and analyses changed? If their views changed, can we identify what caused the change? Was it caused by new evidence?
4. Finally, because this community was composed of several disciplines, I investigated how scientists responded to views they did not consider correct. Did they summarily dismiss others' views or was it a collegial environment?

This analysis was important because of comments by a few modern historians who suggested that some communities were overly biased against CRD.

How They Did Science: An Example and Comments on Others' Methods

In this exploratory study of a problem-centered scientific community, it is helpful to understand how they "did" science and what they considered "good" science. It is beyond the scope of this thesis to do an in-depth analysis, yet it is useful to look at at least one exemplar. To that end, I describe the approach taught by Chamberlin, one of the preeminent geologists of the time and professor of geology at the University of Chicago,[210] and because geology was the core discipline, it supplied the evidence of the ice ages. This is not to say there may have been variations to his approach, but his methodology and research results were referenced by others.

Chamberlin describes his method explicitly in a paper written for his students titled, "Studies for Students, the Method of Multiple Working Hypotheses," which he published for the larger geologic community.[211] He also used this method throughout his textbook on geology to demonstrate how the technique can be used in geological studies.

> Throughout the work the central purpose has been not merely to set forth the present status of knowledge, but to present it in such a way that the student will be introduced to the methods and spirit of the science.... To this end the working methods of the practical geologist have been implied as frequently as practicable.[212]

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[210] See for example: Robert H. Dott, "Thomas Chrowder Chamberlin (1843–1928)," *GSA Today* (2006): 30-31; Rollin Thomas Chamberlin, *Biographical Memoir of Thomas Chrowder Chamberlin 1843-1928* (Biographical Memoirs, National Academy of Sciences, 1932); William C. Alden, "Thomas Chrowder Chamberlin's Contributions to Glacial Geology," *Journal of Geology* 37, no. 4 (1929): 293-319.

[211] T. C. Chamberlin, "Studies for Students: The Method of Multiple Working Hypotheses," *Geology* 5, no. 8 (1897): 837; reprinted as "Multiple Hypotheses: A Method for Research, Teaching, and Creative Thinking," Institute for Humane Studies, *Journal of Geology* 5, no. 8 (1897): 837-48.

[212] Chamberlin, "Studies for Students," 837–48.

Chamberlin recognized the many problems, which come from latching onto a theory too early in the process of a scientific investigation; this mistake he calls the "method of the ruling theory."[213] Latching onto a theory leads to many problems, such as the growth of general theories, without sufficient evidence, and looking only for evidence to support the theory. In addition, it becomes difficult to dislodge a ruling theory even if evidence begins to mount against it. He considered the "method of working hypothesis," which had been "affirmed as the scientific method, as a counter to the method of the ruling theory," and which is like the inductive approach: first find the facts then induce a hypothesis to explain them.[214] Though this method is an improvement, Chamberlin was concerned that it was too like the method of ruling theories and that the hypothesis could easily morph into the ruling theory.

The approach he recommends is an expansion on the method of working hypothesis: the method of working *hypotheses*; that is, the method of keeping many hypotheses open for consideration when solving scientific problems. Here, "the investigator thus becomes the parent of a family of hypotheses; and by his parental relations to all is morally forbidden to fasten his affections unduly on any one."[215] He finds this approach to be particularly fruitful in the study of geology, which deals with a "class of complicated phenomena," and thus he expects the explanation will be "therefore necessarily complex."[216]

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[213] Chamberlin, "Studies for Students," 843.

[214] Chamberlin, "Studies for Students," 842.

[215] Chamberlin, "Studies for Students," 843.

[216] Chamberlin, "Studies for Students," 844.

Chamberlin used an example from geology to demonstrate the approach. In studying the origin of the Great Lakes, several hypotheses had been put forward, such as, were the lakes caused by the ice sheets of North America or were there valleys already in existence prior to the ice ages. For Chamberlin, the evidence pointed to multiple causes for the Great Lakes, not one single cause. The method he suggests, particularly when used in geology, has the "special merit of the use of a full staff of hypotheses … [and] invites thoroughness."[217] Yet, at the same time he does recognize a disadvantage of this method because it is often difficult to fully explain a hypothesis such that it can be compared to other hypotheses, sometimes it is difficult to "put into words more than a single line of thought," and thus the complexity of the hypothesis may be left not fully stated.[218] He notes that in a teaching environment it is difficult for students, new to the subject, to be able to keep multiple hypotheses in mind. It is easier to focus on a single hypothesis at this stage of the development of the future geologist, and later, when they have more understanding, they will be more readily interested in the complexity of the problem.

Another factor of Chamberlin's method of working hypotheses is that the working hypotheses must contain within them a series of questions that can lead to investigation, that is, they are testable claims. One example Chamberlin described that does not meet this criterion is a variation of the cosmic hypothesis, where "the passage of the solar system through a cold region of space may be styled a hypothesis, but scarcely a working

[217] Chamberlin, "Studies for Students," 845.

[218] Chamberlin, "Studies for Students," 846.

hypothesis in the geological sense because it does not form a groundwork or incentive for geological inquiry."[219]

One final example from Chamberlin will highlight how he himself used the method of working hypotheses. Shortly following Arrhenius' 1896 publication on the CRD, Chamberlin thought it a good working hypothesis because "Arrhenius … has taken a great step in advance of his predecessors in reducing his conclusions to definite quantitative terms deduced from observational data."[220] Yet, that did not stop him from criticizing it, particularly because he thought "they fall short of furnishing an ample working hypothesis from the geologist's point of view" to explain the geological processes that would lead to these changes in carbon dioxide levels.[221] This was part of the impetus for him to explore possible causes and publish a three-part paper on the topic, proposing sources and sinks of carbon dioxide. This was discussed in the history section on CRD.

The criticisms scientists made about the work of other scientists did not challenge the basic methods by which they did science, rather the criticisms focused on gaps in the evidence or areas that were ignored. Two examples have been described above, the lack of the use of meteorological understanding in many of the hypotheses and issues with the quality of infrared spectroscopy and how that limited what could be asserted about CRD.

We can see where this approach may have been used by other geologists in investigating the cause of the ice ages, at least implicitly. For example, Brooks argues the

[219] Chamberlin, "Attempt to Frame," 545.

[220] Chamberlin, "Attempt to Frame," 547.

[221] Chamberlin, "Attempt to Frame," 548.

problem is complex and perhaps there is no simple cause of the ice ages; this is an example of trying not to focus on a single cause for such a complex phenomenon.[222]

Challenges When There Are Many Scientific Communities—Network Analysis

If, as suggested, this was a problem-centered scientific community, composed of members from many scientific disciplines, investigating linkages within the published record should highlight any difficulties they experienced in their research. In this case, we would expect there to be a disconnect between papers published by scientists from different disciplines; that is, because of the breadth of scientific research, even in the early twentieth century, scientists would not be expected to be familiar with research in other disciplines. Scientists may be familiar in general with research in other disciplines but are not expected to have in-depth knowledge, and because of this they may rely on review papers.

One approach to testing this hypothesis is to construct a network diagram showing the links between papers and the works they cite. This section describes the citation network analysis, a prototype study, to determine if this type of analysis provides useful information. The analysis helps us to understand links and flows of scientific information via the citations used in publications for two of the hypotheses, AST and CRD.

This approach expands on the work of Kruger who used it to describe the major scientists involved in the discovery of the ice ages (see Figure 4), though his analysis showed only the major links between scientists not between their publications.[223] In

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[222] Brooks, "Present Position," 204–6.

[223] Kruger, *Discovering the Ice Ages*.

addition, a previous analysis investigated how two philosophies of scientific change described the discovery of plate tectonics; in this case, the focus, though limited, was on the publications (see Figure 5).[224] However, as with Kruger's work, the plate tectonics diagram was constructed from a limited set of papers showing the links between the analysis and the philosophical approach they were evaluating. In this prototypical analysis, I expand the investigation by a more formal and quantitative citation analysis.[225] I described the methodology in detail on page 8.

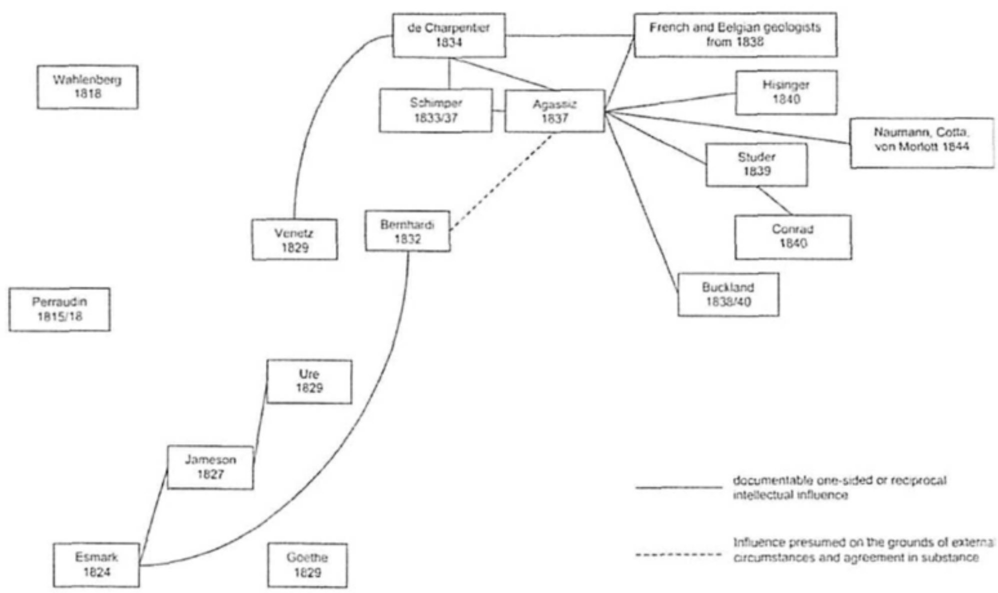

Figure 4. Major Scientists in Discovery of the Ice Ages.
The diagram shows which scientists depended on the work of other scientists during the early nineteenth century. Source: Kruger, *Discovering the Ice Ages*, 450.

[224] Norris, "Proposal for Thesis."

[225] This work was expanded from initial network analysis into a more formal approach at the suggestion of Prof. Galison.

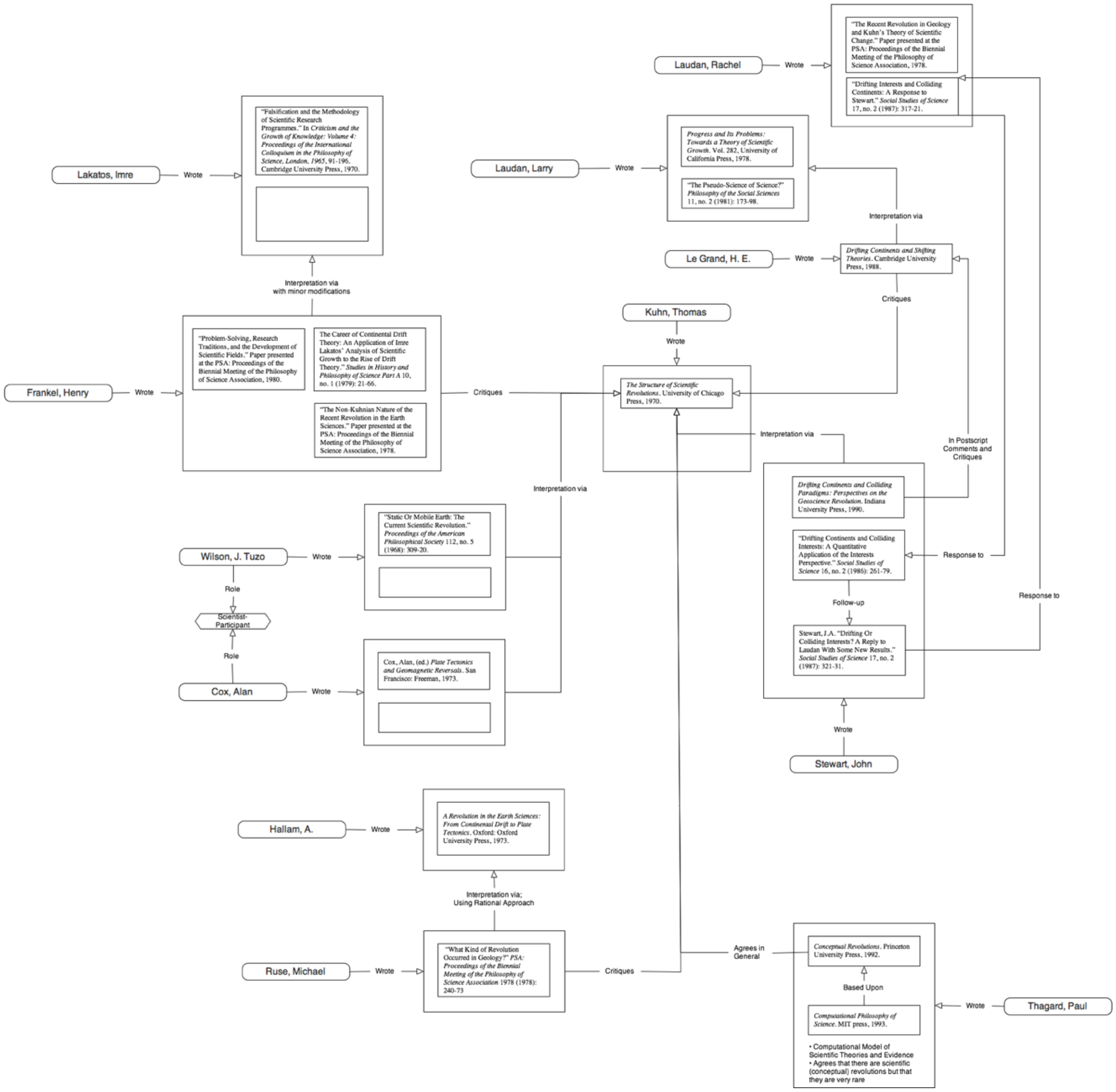

Figure 5. Models of Scientific Change Applied to Development of Plate Tectonics Theory.
High-level Relationships between the Histories Describing Arguments for Plate Tectonics Viewed through Theories of Scientific Change. Source: Thomas Norris, "Plate Tectonics–One New Theory, but Dueling Historical Interpretations of Scientific Change" (Unpublished Term Paper, Harvard University, Division of Continuing Education, 2012), 8.

A preliminary analysis used a subset of 30 published papers, called sources, along with 408 citations, called targets, and found that there was minimal overlap in the target papers. Figure 6 is a network plot of all the source and target papers, using the prefuse force directed layout, with lines drawn between the source and targets when a source cites the target.[226] It is obvious from inspection that most sources do not cite the same targets because there are “bubbles” of target papers emanating from source papers, which are not cited, not connected to, other source papers. Because there are very few links between sources, papers at the center of the “bubbles,” it suggests that authors may not have relied on the same evidence as other authors because of the lack of overlap of target papers. At the bottom of the figure are five isolated clusters, indicating they do not connect via a citation to other papers in the dataset, which may be due to the small size of the sample set.

[226] “The force-directed layout is based on the ‘force-directed’ paradigm, the default layout, and is based on the algorithm implemented as part of the prefuse toolkit (http://www.prefuse.org/) provided by Jeff Heer. The algorithm is very fast and with the right parameters can provide a very visually pleasing layout.” Cytoscape User Manual, 84.

Figure 6. Full Network of Papers and Citations.
The citation network of source references (at the center of “bubble”) and the papers they cited (targets), which emanate from the source. The network only extends one level from the sources, that is, degree = 1.

Removing the papers with degree equal to 1, that is, where there is only a single in or out link, greatly simplifies the network (see Figure 7). To clarify the links in this network, the direction of the links is included, with the arrow pointing to the target. With this simplified network, it is easier to recognize three features: two clusters and one sparsely connected section.

One cluster, located at the bottom of the figure and expanded in Figure 8, is connected via a single paper, TC Chamberlin's 1898 paper, to the rest of the network. This paper describes the role of limestone formation in the composition of the atmosphere.[227] This is not unexpected because his analysis focused on CRD and AST, and the isolated cluster is focused mainly on CRD. This being an earlier paper is citied because it describes the effect of changes to the atmosphere.

In the second cluster, expanded in Figure 9, there are two types of papers: those with many in and out links, for example, Chamberlin, 1899, and Arrhenius ,1896. The other group includes papers such as Dickson, 1901, and Gregory, 1908, written many years after the papers by Chamberlin and Arrhenius. These later papers only have outward pointing links, suggesting these are primarily review papers. The 1899 Chamberlin paper and the 1896 Arrhenius paper are cited many times because they are core papers in the development of the CRD hypothesis because scientists thought were important for the development of their work.

The second cluster, Figure 9, is more varied, representing several hypotheses, with most papers by Brooks and Simpson. The papers by Brooks represent either his textbook or other review papers; hence they are primarily out links. In contrast, several of Simpson's papers, who was not an advocate of either CRD or AST, were included in the

[227] T. C. Chamberlin, "The Influence of Great Epochs of Limestone Formation Upon the Constitution of the Atmosphere," *Journal of Geology* 6, no. 6 (1898): 609–21.

sources because they were review papers and provided links to additional target references.

The two clusters of this prototypical analysis highlight what may be observed in a more complete analysis of all five exemplar hypotheses or the complete set of fourteen hypotheses. Of the results discussed above, the lack of interconnection between the target papers is moderately robust and probably will not change with increasing the number of papers because a problem-centered scientific community. Though other classifications, based on nationality, could also show this pattern coming may also have been at least partially responsible for the lack of connection between target papers. In addition, language difficulties and difficulties in obtaining papers from other countries could play a role. Further analysis with a complete set of papers identified by scientific discipline and nationality may disentangle the cause of the lack of interconnection between source and target papers. The identification of the other clusters, while suggestive, would require a complete network analysis to be verified or not, and a complete analysis might find additional interesting clusters.

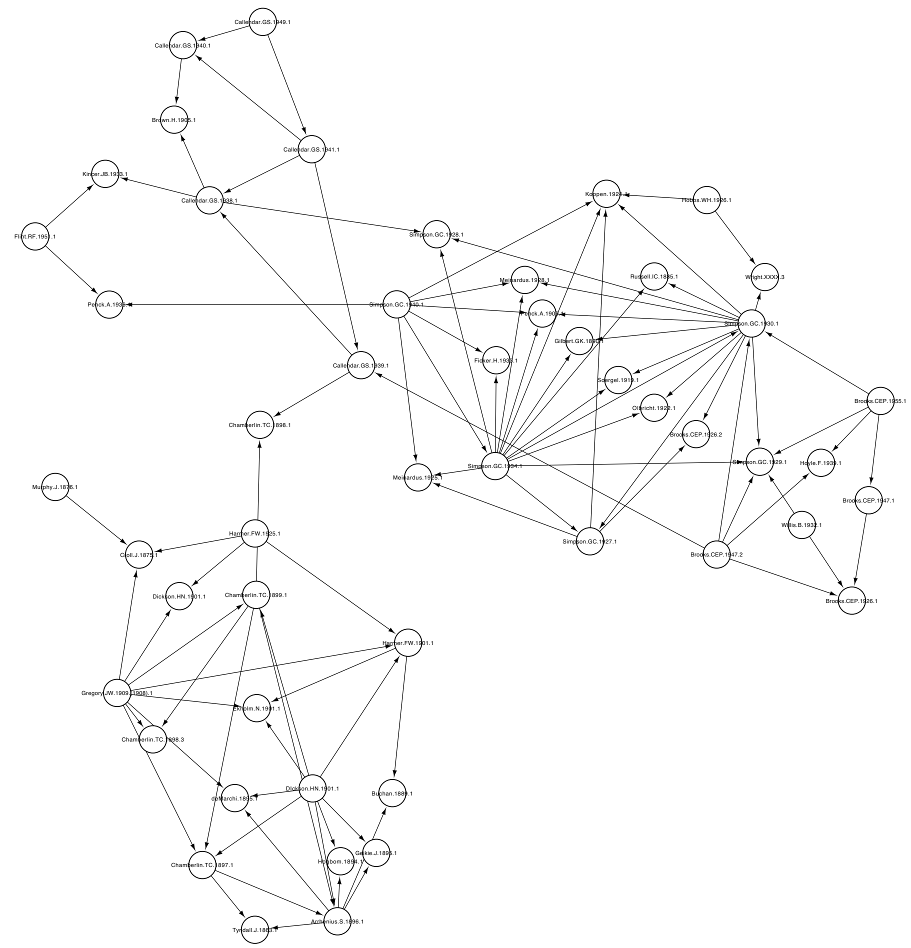

Figure 7. Simplified Network.
The same network as in Figure 6, except targets, and some sources, that have only one in or out connection have been removed, that is, degree > 1. This shows references which have multiple citations.

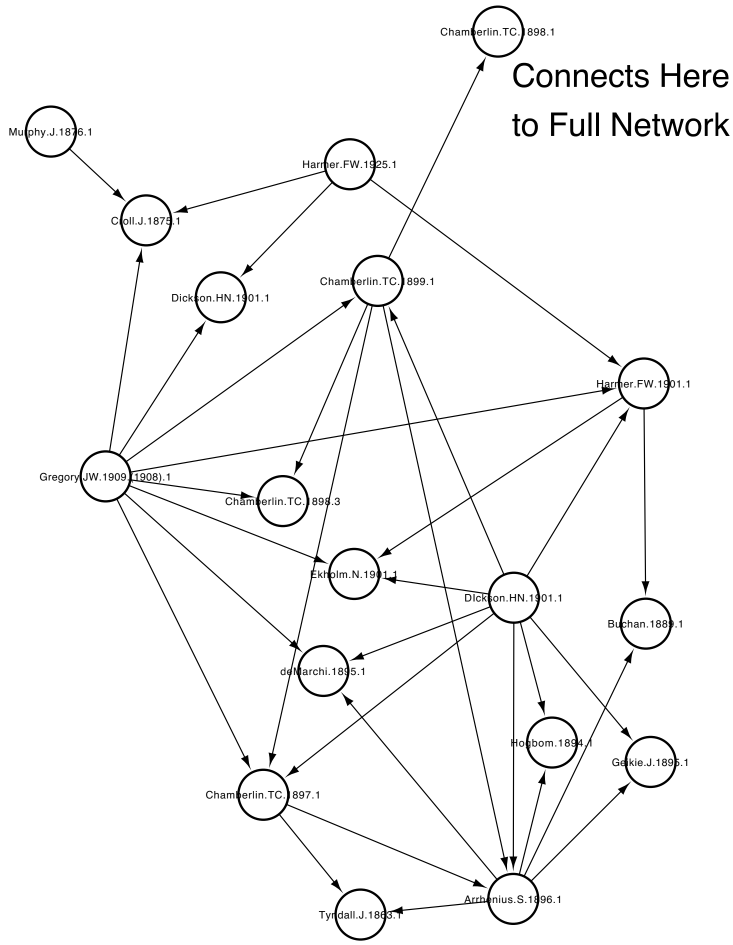

Figure 8. First Cluster – Focused Primarily on the Carbon Dioxide Hypothesis. This subnetwork extracted from the network shown in Figure 7. This subnetwork is connected to the main network by only one link.

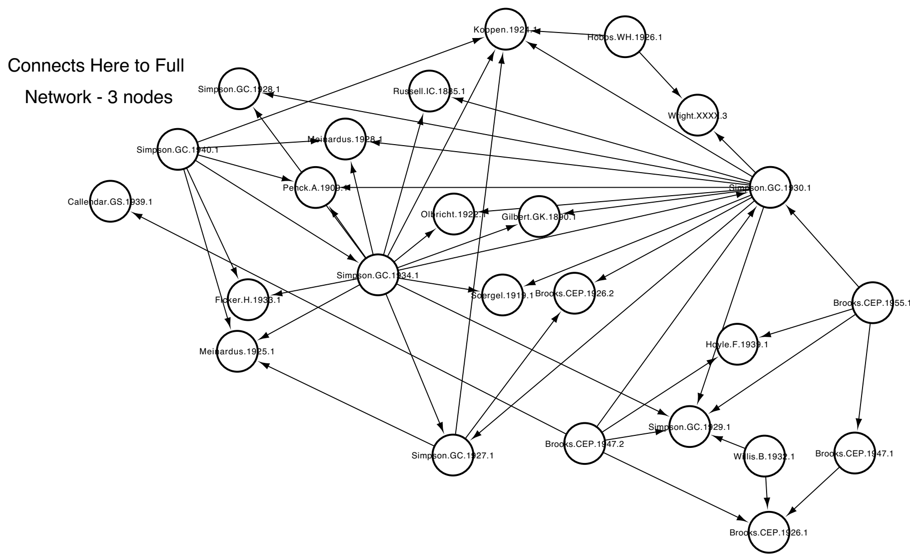

Figure 9. Second Cluster – Related to work by Simpson and Brooks
This subnetwork contains several papers by Simpson or papers, which cite Simpson. It connects to the rest of the network by the three nodes in the upper left section.

Scientists and Their Views

Next we look at how scientists responded to each other's views. Was this a collegiate environment? Was it hostile and biased? Or is there any evidence that shows scientists giving deference to scientists in other disciplines recognizing they are not familiar with the full body of work in the other disciplines? This question of bias was raised by some of today's historians, either explicitly or implicitly. For example, Weart[228] says that Callendar's work was "dismissed ... with a few condescending remarks"[229] by the meteorological community and suggests there was a

> mental environment that included confidence in the balance of nature was inhospitable to any research plan centered on the idea that human activity was overwhelming an entire geophysical system. There were also more specific toxic

[228] Weart, "Global Warming," 319–56.

[229] Weart, "Global Warming," 325.

> elements in the environment of scientific opinion. Within a decade after Arrhenius published his hypothesis it had been discredited by laboratory measurements.[230]

Although this describes the time during the reception of Callendar's work, Weart also mentions that Arrhenius was eventually "discredited" and, within the context of this paragraph, Weart implies that the critique of Arrhenius was "biased."

Weart is not the only one who raised questions about the scientific environment. R. Hamblyn describes the "image of the lone voice who has come to occupy a central position at the heart of the global warming story. Historical accounts of the subject tend to hinge on moments of individual conviction or testimony, the 'lone voice in the greenhouse', as a headline in Nature [2007] dubbed the early twentieth-century climate scientist Guy Stewart Callendar."[231] Hamblyn says that Weart's description of Callendar: "makes direct appeal to the image of the doughty British engineer as a man whose professional successes derive from defying 'the consensus of the experts', conformists whose only role in the story is to claim that something can't be said or done."[232]

One final comment from a modern historian, S. Sorlin: "This evangelical narrative of scientific spirit is sometimes repeated in the popular history of the climate issue, which tends to reiterate an old-style history of science, presenting 'forerunners', 'early warners', and 'forgotten' but 'rediscovered' papers, all lined up along the path of enlightenment ending with current common knowledge."[233]

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[230] Weart, "Global Warming," 328.

[231] R. Hamblyn, "The Whistleblower and the Canary: Rhetorical Constructions of Climate Change," *Journal of Historical Geography* 35, no. 2 (April 2009): 227.

[232] Hamblyn, "Whistleblower," 228.

[233] S. Sorlin, "Narratives and Counter-Narratives of Climate Change: North Atlantic Glaciology and Meteorology, 1930-1955," *Journal of Historical Geography* 35, no. 2 (April 2009): 238.

Given some of these interpretations of early climate science, particularly regarding CRD, can we use the published literature to fill in some of the details about how the scientific community viewed other scientists, particularly when they criticized their own preferred hypothesis? This brief analysis will only provide some hints to the social scientific environment; without delving deeply into personal records, unpublished notebooks, and letters, I will not be able to do more than give hints about what the environment was like.

There are various factors that can result in bias; the obvious one is the inability to reevaluate your views on a hypothesis given new evidence. A second one is being overly critical of hypotheses you do not agree with.

An approach to determine if scientific communities were biased against a hypothesis is to look for evidence of openness, the ability to change one's interpretation of a hypothesis based on new evidence. If this is a problem-centered community, openness to evidence and theories from other disciplines is necessary to progress toward a solution to the problem.

Recall, Harmer had two publications in this field, one which was published during his life[234] and the other published posthumously.[235] The relevant comments are in the second paper, which was edited by Brooks. As previously discussed in the preface, Brooks notes that there were few changes from the first paper to the draft of the second. However, when Brooks edited the second paper, he removed those sections that included views that were no longer consistent with the current evidence, while leaving most of the

[234] Harmer, "Influence of the Winds," 405–78.

[235] Harmer, "Further Remarks," 247–60.

rest unchanged. Brooks claimed Harmer would have made these changes himself given the new evidence.

> While most of the author's deductions are still valid in the light of present day knowledge, in one respect they have proved erroneous. The hypothesis of alternating glaciations in Europe and North America, which was contained in the first paper, has been shown by the researches … to be untenable.… The author would no doubt have accepted this view, and I have accordingly thought it best to delete the passages which depend on this supposed alternation of glaciations.[236]

It would be presumptuous of Brooks to make these modifications if he did not know Harmer well enough to know that Harmer would agree with Brooks' changes.

Another example comes from the critiques of some modern historians, who focus on Callendar's research on human-caused climate change and claimed his ideas were not treated equitably. Let's look at how Brooks describes Callendar's presentation:

> The rise in temperature … presumably had a cause. One possible cause was put forward at the February meeting of the Royal Meteorological Society by G. S. Callendar, namely, the addition of carbon dioxide to the air by consumption of fuel but the effects of this addition seem to require further examination.[237]

This comment, early in the discussion of the reinvestigation of the role of carbon dioxide in human-caused climate change, does not appear biased. Brooks merely mentions that the hypothesis needs further investigation, but he does not dismiss it out of hand.

Brooks produced several editions of *Climate through the Ages*, in which, he changes his view on the plausibility of the carbon dioxide hypothesis. In the 1926 edition, he says at most, it is a minor contribution.[238] In the 1949 edition, after reviewing the new

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[236] Harmer, "Further Remarks," 247.

[237] C. E. P. Brooks, "The Warming Arctic," *Meteorological Magazine* 73, no. 866 (1938): 32.

[238] Brooks, *Climate through the Ages*, 1926.

research by Callendar, Brooks modifies the text. The sentence describing the status of the carbon dioxide hypothesis in the 1926 edition of *Climate Through the Ages* was: "Carbon dioxide can *never* have been an important factor in climatic variations."[239] In the 1949 edition Brooks removed this sentence and replaced with a new paragraph:

> In 1939, however, the question was taken up again by G.S. Callendar who relates the cold of the Permian to the exhaustion of carbon dioxide by the Carboniferous forests. During the Mesozoic, the relative small development of plant life allowed the amount of CO_2, steadily replenished by the animal life of the seas, to increase again, but a great deal was locked up in the Tertiary lignite formation, especially in western North America, and this may have brought about a progressive cooling which ended in the Quaternary Ice-Age. This theory cannot account for the oscillations of the individual glaciations, the time-scale of which is too short. Callendar ends up pointing out that the great coal consumption in the twentieth century has raised the amount of CO_2 in the atmosphere from .028 per cent about 1900 to .030 per cent in the 1930's, and that this increase has been accompanied by a small but steady rise in the mean temperature of the colder regions of the earth. This argument has rather broken down in the last few years, however, for the rise of temperature seems to have reached its crest and to have given place to a fall. The possibility that changes in the amount of CO_2 have been responsible for some small part of the climatic changes of geological time seems to remain open however.[240]

Although this is not a resounding endorsement of the carbon dioxide hypothesis, it does indicate a change in Brooks' evaluation of its role in causing the ice ages; the evidence has changed and so has his opinion on the plausibility of the hypothesis. This is a scientist, in this case a geologist, who took seriously the evidence from other disciplines: Callendar was a steam engineer and amateur meteorologist. This is a necessary characteristic if a problem-centered community is to work together in solving a problem.

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[239] Brooks, *Climate through the Ages*, 1926, 116–117, emphasis added.

[240] Brooks, *Climate through the Ages*, 1949, 117.

This analysis suggests scientists were not as “stuck” in their views as some modern historians or philosophers might claim. They did change their views of the plausibility of a hypothesis as evidence changed, and at least some scientists were not recalcitrant in revisiting their views. Though these are only two examples of published evidence of shifts in interpretation, further study, particularly of unpublished works, might bring to light other examples. I do not argue that all scientists were open to reinterpretation, but rather I argue that not all scientists were beholden to their earlier ideas, even when evidence comes from another scientific discipline.

Response to the Views of Others, Evidence from Obituaries

Another source of information about possible bias comes from descriptions provided by biographers, particularly in obituaries. Generally, one might expect an obituary to be routine, not extremely critical of the deceased, yet that was not always the case. For example, “Although Gregory, as Fellow of the Royal Society, was undeniably a great geologist, explorer, geographer and writer, this account is not an adulation exercise; several of his conclusions were totally wrong.”[241]

In contrast, sometimes there was delayed credit for previous work. Ekholm wrote, “Also the remarks of Croll as to the influence of this variation on the temperature in other latitudes are essentially correct.… I wish now to acknowledge Croll’s indisputable priority as to the theory in question.”[242]

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[241] Bernard Leake, “The Life and Work of Professor J. W. Gregory F. R. S. (1864-1932); Geologist, Writer and Explorer,” *Memoirs of the Geological Society of London* 34, 2011.

[242] Ekholm, “Variations of the Climate,” 61.

Though the examples I have of the interactions within the scientific communities are limited in number, and one may think the scientists are being overly polite, nonetheless, it suggests that the community had respect for other scientists, even when they disagreed, and does not suggest a "toxic" environment for some hypotheses. But it does not prove it.

Summary Scientific Communities

The scientists involved in solving the puzzle of the ice ages can best be described as a problem-centered community. There was no organized structure to which they belonged; rather it was the problem that attracted their interest, they were self-selected. There are many characteristics we might expect if this community were to function successfully. First, as we found, though there might be discipline specific variations in scientific methodologies, they recognized and accepted the research results from other disciplines, implying they accepted the scientific methodologies they used. T. C. Chamberlin's approach was not unique to geology and some from other disciplines recommended more expansive studies, such as including more work from meteorology, to enhance finding solution(s) to the problem.

One characteristic of a multi-discipline problem-centered community would be a lack of deep familiarity to the core research common to a discipline by scientists in other disciplines. But because there were many review books and articles upon which scientists could draw when evaluating research from other disciplines, scientists were not hampered in their cross-disciplinary work. They did winnow the number of hypotheses from fourteen to five by the 1950s.

The evidence suggests they had a cordial relationship with scientists from other disciplines and within their own discipline. And because of this when evidence came from another discipline that challenged a hypothesis outside their domain, they gave it honest consideration, for example, Brooks' evaluation of Callendar's work.

The evidence does not point to any explicit bias in the scientific community to any hypothesis, rather, given the complexity of the problem we observed what might be called typical scientific behavior. There were disagreements between advocates of hypotheses but that did not appear to result in excessive bias against other scientists or their hypotheses.

As is described next, one challenge to solving this problem was the complexity of the evidence needed. It came from many disciplines, but primarily from geology.

Generating the Core Data Set

A key challenge to finding the cause(s) of the ice ages lay in collecting and evaluating the evidence against which all proposed hypotheses would be evaluated. One of my hypotheses was that the availability of evidence, along with its interpretation, is key to understanding how this problem was solved and why it was so difficult to make progress.

One possible problem to scientists was that the evidence was insufficient to solve the problem of the cause of the ice ages, that is, the hypotheses were underdetermined from the evidence. To explore this possibility, I first need to define how I use term "underdetermination." There are a wide range of philosophical approaches to underdetermination, which I do not go into because it is beyond the scope of this thesis to investigate the philosophical appropriateness of various definitions of underdetermination in regards to this case study.[243]

For the purposes of this analysis, I use a simple definition of underdetermination, which I call Insufficient or Ambiguous Evidence (IAE) to keep it separate from the philosophical discourse on underdetermination. IAE describes the conditions where there is a lack of evidence or where the evidence is too ambiguous to clearly support or challenge a hypothesis, as used within the common daily practice of science, that is, the evidence is insufficient or ambiguous to convince scientists of the plausibility of a hypothesis.

To investigate IAE, I looked at the arguments in the published papers to determine statements about what evidence was used to support various hypotheses whether it was clearly accepted by all members of the community or whether some scientists challenged the evidence or the interpretation of the evidence. I describe several categories in which scientists were not able to reach clear conclusions from the available evidence, which changed over time from new discoveries or interpretations. The core data set was composed primarily of geological evidence of the ice ages, and much of it was collected in the first half of the nineteenth century as part of making the case for the existence of ices ages. I examine high-end interpretation of three categories of evidence: local versus global, synchronicity between the occurrence of ice ages between different hemispheres, and time-based patterns of the ice ages.

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[243] "Scientific Underdetermination," *Stanford Encyclopedia of Philosophy*, Stanford University, accessed January 28, 2017, http://plato.stanford.edu/entries/scientific-underdetermination.

Local versus Global Ice Ages?

One of the first questions posed was whether the ice ages were a global or local phenomenon. Answering this question could select between many hypotheses because some hypotheses predict global effects not local effects, as Gregory summarized the case for CRD:

> Such an alteration in the atmospheric constitution must have been, however (as Prof. Chamberlin points out), of general and not of local operation, and the hypothesis that the latter group of events was so caused is inconsistent with that suggested by me that the maximum glaciation of one region may have been contemporaneous with the existence of genial conditions in another, situated in a similar latitude.[244]

Gregory, an advocate for the local distribution of glaciers, argued there was no evidence to suggest the ice ages were widespread simultaneous global phenomena. "The range of climatic variations in the past has been often greatly exaggerated … But the climatic changes we have to explain appear to have been either local in area or moderate in degree," and "the evidence so far adduced appears to be quite insufficient to justify this view" of global effects. He is one of the few who argued the evidence supported only local climatic variations.[245]

Another advocate for local glaciations was Harmer (1901), whose main interest was the meteorological conditions that would explain glacial conditions, which resulted in ice sheets. He argues it was not necessary for there to be simultaneous ice sheets in North American and Europe because the cause of the ice sheets, the effect of anti-cyclone

[244] Harmer, "Influence of the Winds," 473.

[245] Gregory, "Climatic Variations," 342.

meteorological conditions could affect one region differently than another.[246] In addition, he argues the glaciation on Great Britain "could only have taken place at a time when the Iceland-British channel was closed either by an elevation of the submarine ridge connecting those countries, or by its being blocked with ice," suggesting that a partial answer to the ice ages may include a geographical component, in addition, to meteorological effects.[247] Like Gregory, Harmer suggests local glaciation provides a simpler explanation of the geological evidence.

But many geologists and other scientists thought the geological evidence supported the existence of widespread glaciation, not only across Europe and North America, but also between the Southern and Northern hemispheres. Chamberlin, in his series of papers from which he forms a working hypothesis for the cause of the ice ages, states, ""If the atmospheric line is followed [CRD], it seems necessary to postulate a reduction of carbon dioxide near the close of the Paleozoic era … so effectual as to produce glaciation between 20° and 35° on both sides of the equator"; that is, glaciations are widespread occurring simultaneously in the Northern and Southern Hemispheres.[248]

One of the most explicit catalogs of the geological evidence that must be explained comes from Humphreys in his textbook, *Physics of the Air* (1920), where he lists several facts that the hypotheses of the origin of the ice ages must account for, including: "The greater changes and doubtless many of the smaller also were

[246] Harmer, "Influence of the Winds," 405–78.

[247] Harmer, "Influence of the Winds," 472.

[248] Chamberlin, "Attempt to Frame," 549.

simultaneous over the entire earth."[249] This fact includes two components: glaciation was widespread across the globe and it was simultaneous, which is discussed next. He notes there were local variations in the intensity of glaciation, "There are numerous local changes, suggestive of local causes" and that there were centers of maximum intensity of glaciation.[250] Perhaps these local variations resulted in some scientists focusing on them rather than recognizing ice ages were a global phenomenon? Humphreys' list, because it comes from a textbook, may reflect the consensus of the scientific community regarding the general characteristics of the ice ages. In his 1940 revised text, he notes that the observations of widespread glaciation and simultaneity was strengthened by additional evidence: "The greater changes, and, doubtless, many of the smaller also, were simultaneous over the entire earth (there is accumulating evidence in favor of this conclusion), and in the same sense; that is, the world became colder everywhere at the same time (climatically speaking) or warmer everywhere."[251] Again, Humphreys identifies two characteristics: a global distribution and simultaneity across the globe.

As previously discussed, Lyell, in a roundabout manner, claimed the ice ages and the intervening warmer periods were global in nature, not because the earth, as currently configured, was either primarily entirely glacial or warm, but because the location of the continents were in different positions. As Geikie describes it: "Lyell conceives, that, if land were massed chiefly in the region of the equator and tropics, the climate would be such that tree-ferns might grow luxuriantly on any islands that might happen to lie within

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[249] Humphreys, *Physics of the Air*, 1920, 558.

[250] Humphreys, *Physics of the Air*, 1920, 558.

[251] Humphreys, *Physics of the Air*, 1940, 579.

the Arctic or Antarctic."[252] The reverse is also claimed, that if the continents were located at the poles, the winds would carry the cold to the temperate and equatorial regions of the earth. Lyell's proposal can be seen in Figure 1, which shows his proposed locations of the continents which would result in either the ice ages or the warmer interglacial periods.[253]

However, interesting though Lyell's proposal is, Geikie does not think "that the massing of the land in the tropics, and under the equator, would have the effect which is supposed."[254] Geikie notes that it is not the winds that transfer heat from one location of the earth to another, rather it is ocean currents, for example: "Were it not for the genial influence of the Gulf-stream, Scotland would experience a climate as severe at least as that of Labrador," and it is "the air in contact with this broad ocean-stream [which] is everywhere warmed."[255]

Something as seemingly simple to determine, whether the ice ages were local or global, was contested throughout the early part of the investigation.

Synchronicity

Once one knows the extent of the ice ages, whether local or global, a follow-up question is whether they occurred at the same time; that is, if they were global in nature, did they occur at the same time? Or did different parts of the world experienced ice ages while other regions did not? For example, one hemisphere could be cold and the other

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[252] Geikie, *Great Ice Age*, 110.

[253] See figures 14 and 15 in: Lyell, *Principles of Geology*, 266.

[254] Geikie, *Great Ice Age*, 111.

[255] Geikie, *Great Ice*, 113.

warm and vice versa. These would be different effects but they would still be synchronous. The synchronicity of ice ages, particularly between Northern and Southern Hemispheres, was discussed in the literature, but scientists quickly reached the conclusion, based on geological evidence, that the ice ages were synchronous; nonetheless, for a while it was a matter of dispute. Humphreys (1940) summarized the consensus:

> The greater changes, and, doubtless, many of the smaller also, were simultaneous over the entire earth (there is accumulating evidence in favor of this conclusion), and in the same sense; that is, the world became colder everywhere at the same time (climatically speaking) or warmer everywhere.[256]

As noted previously, Humphreys identifies two characteristics: a global distribution and simultaneity across the globe. He also claimed the evidence supported this interpretation in the first edition of his 1920 text.[257]

The evidence against synchronicity was a topic of discussion as late as 1951: "A generally comparable sequence exists in northern Europe, however, definite time correlations between events in Europe and those in North America have not yet been made."[258] In contrast, "Paschinger … assembled data on regional snowiness, from which he concluded that climatic cycles occur in opposite phase in the north and south polar regions. This conclusion is refuted by Matthes."[259] H. Paschinger thought the evidence did not support synchronicity of the ice ages in different hemispheres (published in

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[256] Humphreys, *Physics of the Air*, 1940, 579.

[257] Humphreys, *Physics of the Air*, 1920.

[258] Flint, "Climatic Implications," 1021.

[259] Flint, "Climatic Implications," 1022.

1912), but his results were refuted in 1939, the topic of synchronicity was still discussed well into the twentieth century.

Part of the challenge to determine synchronicity was estimating whether geological formations across the globe occurred during the same period. Geochronology during this period was limited in effectiveness because dating was relative between nearby regions and was commonly done by comparing geologic formations, particularly the sequence of fossils, which over short to moderate distances could be reliably used. Using this technique across global dimensions was more problematic. The issues with geological dating will be discussed later. Referring again to Humphreys, 1949, and Brooks' preface to Harmer, synchronicity between the Northern and Southern Hemispheres was eventually conclusively established.

Patterns in the Timing of the Ice Ages

Patterns in the timing of the ice ages was one area where there was significant and continuing disagreement; again, this was a problem related to the relative dating of geological evidence. Some hypotheses, such as the cosmic dust hypothesis or the geographical hypothesis are not periodic, whereas hypotheses derived from elements of the earth's orbit predict that evidence should demonstrate regular patterns in the timing of the ice ages.

Strong arguments, based on the interpretation of the evidence, claimed there was no periodicity:

> The climatic implication of this sequence of events is, by analogy, a general increase of temperature punctuated by temporary, diminishing reversals of this trend.… No periodicity is apparent in the sequence [because] neither the facts of glaciology, evidencing recent climate changes, nor the facts of glacial geology,

evidencing more ancient ones, afford a basis for inferring a periodic recurrence of any particular climatic condition.[260]

Lyell, in the tenth edition of *Principles of Geology*, also claimed the evidence did not support periodicity: "It will at once be seen that glacial periods have not been perpetually recurring in the northern temperate zones, as they ought to have done were a large eccentricity alone sufficient."[261] This text is ambiguous, but the index of the book leaves no doubt that Lyell did not think the ice ages exhibited periodicity: the phrase "periods have not recurred periodically" is listed in the index under "glacial period."[262]

In the early twentieth century, Hoyle and Lyttleton, both in their 1939 and 1950 papers, argue against periodicity, although they do not give evidence or citations. Their cosmic dust hypothesis is consistent in their interpretation of the evidence that the timing of the ice ages is irregular.[263]

On the other hand, there were many who thought the geological evidence supported the periodic timing of the ice ages and that it demonstrated the astronomical cause of the ice ages.

Croll in 1864, after reviewing the evidence for several hypotheses, including those of Lyell and others, concluded: "The true cosmical cause must be sought for in the relations of our earth to the sun." Croll said that the "recurrence of cold and warmer periods evidently points to some great, fixed, and continuously operating cosmical

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[260] Flint, "Climatic Implications," 1021.

[261] Lyell, *Principles of Geology*, 299.

[262] Lyell, *Principles of Geology*, 627.

[263] Hoyle and Lyttleton, "The Effect of Interstellar Matter," 405-15; Hoyle and Lyttleton, "Variations in Solar Radiation," 453–55.

law."[264] This points to regular periodicity in the timing of the glaciers, but unfortunately, he does not provide evidence for this conclusion. Croll does think the evidence based on alternative warm interglacial and cold periods is "sufficient to establish the truth of that theory"; that is, variations in eccentricity act as a trigger to the ice ages.[265]

Milankovitch most clearly argues that the geological evidence matches a detailed mathematical astronomical model of variations in solar radiation, demonstrating a periodic relationship. The best evidence Milankovitch cites for the "secular march of insolation" are the "clear traces and marked … deflection and rhythm [of] the terminal moraines formed by individual glacier thrusts … and a chronology of the Alpine Glacial Period."[266] He used the work of Wolfgang Soergel, who provided a detailed analysis of glacial periods from the Alps, which resulted in a "division of the Ice Age into 11 cold and 11 moderate periods."[267] Soergel's work provided higher resolution timing of glacial advances and retreats than previously existed and could be compared to the predictions of the astronomical hypothesis. Soergel's work covered a period of about one million years from the Gung glaciation (600-800 thousand years ago) to the Wurm glaciation (ending about 11 million years ago).

Even with the detailed work by Milankovitch, published in English in 1941, others, for example Flint in 1951, did not agree that the evidence pointed to a periodic

[264] James Croll, "The Physical Cause of the Change of Climate During Geological Epochs," *London, Edinburgh and Dublin Philosophical Magazine and Journal of Science* 28, no. 187 (1864): 121.

[265] Croll, *Climate and Time*, 19.

[266] Milutin Milanković, *Canon of Insolation and the Ice-Age Problem* [*Kanon Der Erdbestrahlung Und Seine Anwendung Auf Das Eiszeitenproblem*] (Belgrade, 1941; Jerusalem: Israel Program for Scientific Translations, available from U.S. Dept. of Commerce), 421.

[267] Milanković, *Canon of Insolation*, 422.

pattern of glaciations. Perhaps one of the causes of the different interpretations was the lack of absolute dating of the timing of the ice ages; that is, they needed good radiometric dating, which is discussed later. Milankovitch's work is further discussed below in the section on geochronology.

Changes in the Understanding of the Core Data Set

We can summarize the result of changes in the evidence by listing the changes in the acceptance of different interpretations over time. Table 2 lists the broad interpretations of the data discussed above, for example, global versus local glaciation, about hundred years, up to about 1950, in decade units. The table was generated by reviewing the papers discussed above and noting whether the scientist interpreted the evidence in one direction or another and ordered by the publication date. The data is not as straightforward as is suggested in this table because I have forced interpretations that were more nuanced into one of the two categories for each class of evidence.

Table 2. Core Data Set.
Changes in the Interpretation of Major Characteristics of the Ice Ages by Early Climate Scientists.

Author(s)	Year	Can CO2 in atm Affect		Simultaneity of ice ages in		Periodicity of ice ages, was		Major widespread glaciation	
		Can influence climate	Not able to influence climate, or only minor influence	Simultaneous	Not Simultaneous	Periodic	Not Periodic	Widespread, Continental	Local
Geikei, James	1874					X			
Geikie, J.	1894			X					
Arrhenius, S.	1896	X		X				X	
Chamberlin, TC	1897	X							
Chamberlin, TC	1899	X		X				X	
Ekholm, Nils	1901	X				X			
Dickson, H. N.	1901	X							
Harmer, F. W.	1901				X			X	
Gregory	1908						X		X
Humphres, W. J.	1920		X	X			X	X	X
Callendar, G. S.	1938	X							
Brooks, C. E. P.	1926		X	X				X	
Hoyle, Fred	1939						X		
Milankovitch, M.	1941			X		X			
Blair, Thomas A.	1942			X			X		
Brooks, C. E. P.	1947			X				X	
Flint, R. F.	1951			X			X		
Wolbach, J.	1953					X		X	

Though there is variation between interpretations of the evidence, most of the time a consensus developed in some categories. In this table, I have limited the data to those instances where the author explicitly mentions the evidence, for example, local versus global, rather than impose an interpretation upon them. In some instances, such as global versus local, scientists found the evidence persuasive for a global distribution with only a few outlier scientists, such as Gregory. In other cases, such as periodicity, there is greater disagreement among scientists as to whether the interpretation was plausible.

The lack of definitive evidence resulted in several hypotheses being considered plausible by several scientists while at the same time being critiqued by other scientists. Table 3 shows a series of papers, sorted by publication date, from various scientists and noting, which hypothesis they thought was best supported by the evidence (P) and which hypotheses they critiqued (C) either positively or negatively from the available evidence.

Looking first at the two primary hypotheses, there are times when neither hypothesis had significant support. In the case of AST, it was challenged around 1900 and later in the early 1900s until the work of Milankovitch, yet his model was not immediately accepted. CRD had a similar pattern: early support around 1900 until evidence surfaced that challenged the hypothesis. It would take additional evidence and new scientific technology, infrared, before it could be considered viable again.

Table 3. Summary of Preferred (P) and Challenged (C) Hypotheses from Papers by Climate Scientists.
Preferred Hypotheses are Those Proposed as Plausible and Critiqued Papers are Those Hypotheses They Challenged as Implausible.

Author	Date	Changes earth's orbit	Changes atmospheric composition, usually refers to CO2	Changes atmospheric circulation	Elevation land masses, mountain building	Cosmic dust theory	Changes continent-ocean distribtuion	Volcanic dust in atmosphere	Changes solar radiation	Polar migration theory
Geikei, James	1874	P			C					
Murphy , J.J.	1876	P								
Geikie, J.	1894	P			C					
Arrhenius, S.	1896	C	P							
Chamberlin, TC	1897	C	P							
Chamberlin, TC	1899	C	P		C			C		
Ekholm, Nils	1901	C	P							
Dickson, H. N.	1901	P	P	C	C					
Harmer, F. W.	1901	C		P						
Gregory	1908	C	C	P	C					C
Humprheys, W. J.	1920	C	C		C		C	C	C	
Callendar, G. S.	1938		P							
Hoyle, Fred	1939	C			C	P				
Milankovitch, M.	1940	P								
Simpson, G. C.	1940	C			C				P	
Flint, R. F.	1951	C		P(?)	C					
Wolbach, J.	1953	P			C		C	C		
Brooks, CEP	1955	C	C		C				P	

Another interesting example is the cosmical hypothesis (COS) of Hoyle and Lyttleton, which had only limited support for a short time because there was limited evidence to argue for its viability and because there was no obvious way to test it. Even after it was proposed, it was rarely mentioned in the literature, not even as a hypothesis to be critiqued.

A different view of the status of hypotheses is to collect the number of times they were mentioned as the preferred hypothesis in each decade and plot this as a function of time, see Figure 10. From this subset of papers there appear to be two bursts of interest in the ice age problem, 1890–1900 and 1930–1950. If the graph were extended, it would show increased progress in solving the problem because of new technology and new evidence.

This effect is more apparent when plotting the number of times a hypothesis was critiqued because the data comes not just from papers asserting a hypothesis, but also from review papers, Figure 11, with two larger clusters (1890–1900 and 1950) and a smaller cluster around 1930.

Progress on the problem continued throughout this period, but there were gaps, apparently due to WWI and WWII, when work slowed. It appears that no hypotheses were worked on continuously throughout the 80 years.

The lack of unambiguous evidence also led many to consider that there may be more than one cause to the origin of the ice ages especially after much research had achieved no clear resolution to the problem. Brooks commented: "The conclusion forced upon us is that no single cause can explain all the phenomena of geological changes of climate and we must look to a combination of causes."[268]

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[268] Brooks, "Unsolved Problem," 150.

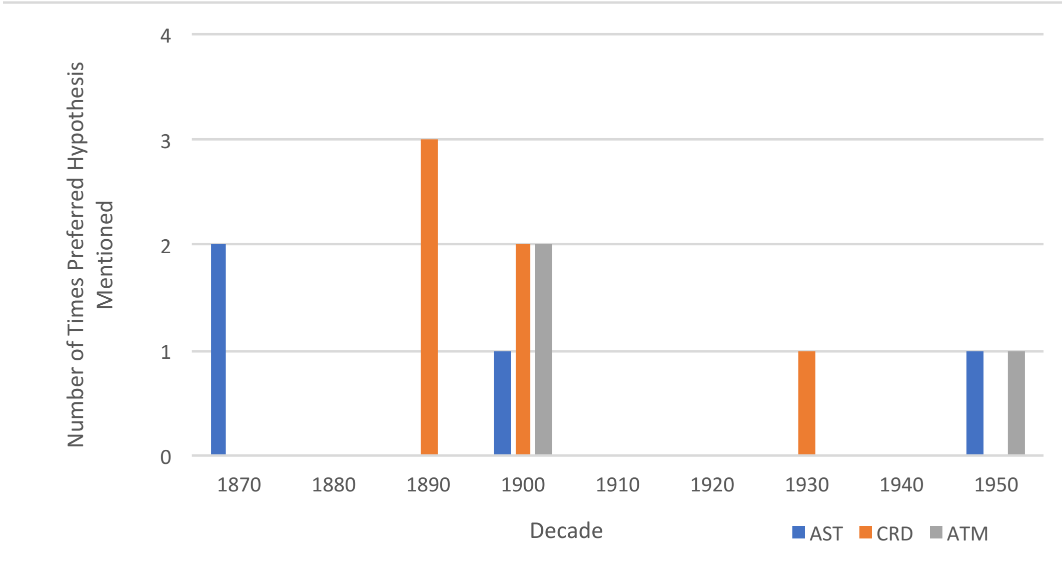

Figure 10. Number of Times Preferred Hypotheses Mentioned by Decade.
Histogram of the number of times, in a decade, a hypothesis was argued it was the preferred hypothesis. Key: AST: Changes earth's orbit; CRD: Changes atmospheric composition, usually refers to CO_2; ATM: Changes atmospheric circulation.

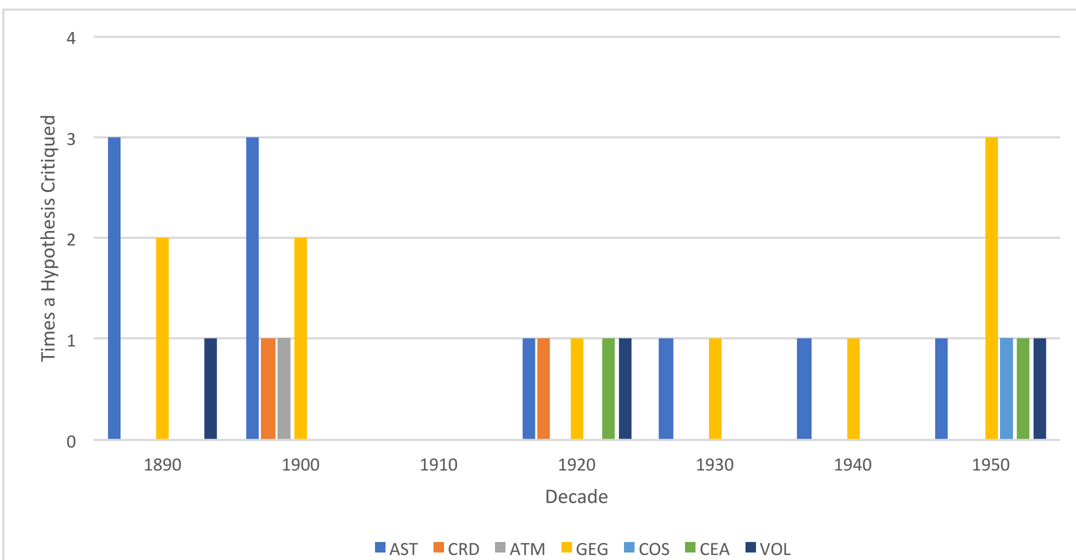

Figure 11. Number of Times Hypotheses Critiqued by Decade.
Histogram of the number of times a non-preferred thesis was critiqued, either positively or negatively. Key: AST: Changes earth's orbit; CRD: Changes atmospheric composition, usually refers to CO_2; ATM: Changes atmospheric circulation, GEG: Changes in geography, COS: Cosmic Dust, CEA: Changes in distribution of continents and oceans and VOL: Volcanic Dust.

Making Progress

During the late nineteenth and early twentieth century, fourteen hypotheses were proposed. This may not be unusual for the early stages of solving a scientific problem, but it is many more than is often seen for typical problems in physics or chemistry. And yet, more than fifty years later, five hypotheses were still under consideration. From the previous section, I identified two areas where insufficient evidence may be responsible for difficulties in solving this problem: infrared and geochronology. In the case of infrared, there was controversy over how much the carbon dioxide infrared absorption bands overlapped those of water vapor. In the case of geochronology, the lack of good absolute dating, that is, radiometric dating, limited the ability to understand the time of the cycles, if any, of the ice ages. The solution to these two challenges led to the development of the modern understanding of the causes of the ice ages and the origin of human-caused climate change.

In this section, I briefly look at the technological history of infrared and radiometric dating, which were developed to answer a variety of scientific problems, not just the ice age question.

Infrared Spectroscopy

I have previously described the role infrared spectroscopy played as part of the CRD and how varying interpretations of the results of infrared spectroscopy challenged the CRD. In this section, I briefly review the status of infrared spectroscopy as described by Fleming and then discuss infrared spectroscopy during the early twentieth century, particularly as reviewed by Callendar in his 1941 paper.[269]

Infrared absorption of carbon dioxide has been studied since the work of Tyndall (1861), but the results were limited because of low spectral resolution. It appeared the absorption spectra of carbon dioxide overlapped and was overwhelmed by that of water vapor, which is more prevalent in the atmosphere. The measurements by Knut Angstrom, 1900, were sufficient to raise doubts about the role of carbon dioxide in absorbing infrared in the atmosphere.[270] Angstrom's work was probably considered decisive given his reputation as a spectroscopist and, possibly, because his father, Anders Angstrom, was recognized as one of the founders of modern spectroscopy.[271] Knut Angstrom's specialty was spectroscopic measurement of solar radiation, and "his Pyrheliometer for direct measuring of the incoming solar radiation was accepted as official standard in 1905. The instrument has later been modified and is still used as reference."[272]

Fleming, commenting on K. Angstrom's work, along with other measurements on the optical path length of carbon dioxide, said that "any additional CO_2 … would have

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[269] Fleming, *Historical Perspectives*, 111–13.

[270] Fleming, *Historical Perspectives*, 111; Knut Ångström, "Uber Die Bedeutung Des Wasserdampfes Und Der Kohlensäure Bei Der Absorption Der Erdatmosphäre," *Annalen der Physik* 308, no. 12 (1900): 720–32.

[271] Simón Reif-Acherman, "Anders Jonas Ångström and the Foundation of Spectroscopy—Commemorative Article on the Second Centenary of His Birth," *Spectrochimica Acta Part B: Atomic Spectroscopy* 102 (2014): 12–23.

[272] Uppsala Universitet, "The Ångström Family," Upsala University, Uppsala, Sweden, accessed January 28, 2017, http://www.polacksbacken.uu.se/Welcome+to+Polacksbacken/history_Polacksbacken/Angstromlaboratoriet/Familjen_Angstrom/.

little or no effect."[273] These results were used by others to challenge the hypothesis previously put forward by Arrhenius, which said that changes in carbon dioxide would affect the earth's atmospheric temperature.[274]

The state of understanding in the early twentieth century resulted in little further studies on CRD until Callendar took it up in the late 1930s. Weart writes, "In 1941 Callendar had complained that he had to rely on papers of 1905 and 1911 for the best available figures on the intensities of some types of infrared absorption."[275] When Callendar took up his interest in the role of carbon dioxide in the atmosphere, he wrote a series of four papers describing his hypothesis, one of which concerned infrared spectroscopy. [276]

Callendar begins the infrared paper by reviewing the state of measurements of infrared absorption by carbon dioxide and water vapor, both measurements being necessary to his work. He briefly describes work done in the early twentieth century and said that "recent additions ... of the structure of the water spectrum ... and the atmospheric transmission of infra-red radiation, have tended to emphasize the importance of atmospheric radiation as a fundamental factor in meteorological processes."[277] The recent

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[273] The amount of carbon dioxide in the atmosphere was thought to be equivalent to a column of the pure case 250 centimeters in length at standard temperature and pressure. Experiments done in 1905 demonstrated that a column of carbon dioxide fifty centimeters long was ample for maximum absorption." Fleming, *Historical Perspectives*, 111. See also: Humphreys, *Physics of the Air*, 1940, 585 Fleming, *Historical Perspectives*, 111.

[274] Fleming, *Historical Perspectives*, 111.

[275] Weart, "Global Warming," 319-–6.

[276] Callendar, "Infra-Red Absorption," 263–75.

[277] Callendar, "Infra-Red Absorption," 263.

studies he refers to were published in 1939 and 1941, and with the increased quality of the spectra, Callendar could present stronger evidence for human-caused CRD.

The scientific community's response to Callendar's proposals was mixed, Humphreys, in the third edition of *Physics of the Air*, 1940, reviews CRD along with many other hypotheses concerning the origin of the ice ages, concluding, "the carbon dioxide theory ... has been sadly impaired" because of evidence which challenges its plausibility.[278] This was written at the time Callendar was publishing his results, so Callendar's work was not considered in Humphrey's evaluation. Brooks, writing a little later in 1949, does mention Callendar and, citing his work, concludes, "The possibility that changes in the amount of CO_2 have been responsible for some small part of the climatic changes of geological time seems to remain open however."[279] This comment is in a section on the general factors affecting climate. Later Brooks, in reviewing historical climate in regard to human-caused climate change, concluded, "In the past hundred years the burning of coal [resulting in an increase of carbon dioxide in the atmosphere] ... Callendar [saw] in this an explanation of the recent rise in world temperatures. But in the past 7000 years there have greater fluctuations in temperature without the intervention of man.... This theory is not considered further."[280] Returning to CRD as a cause of the ice ages, Brooks concluded, ""The theory was never widely accepted, and was abandoned when it was found that all the long-wave radiation absorbed by CO_2 is also absorbed by water vapor."

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[278] Humphreys, *Physics of the Air*, 1940, 586.

[279] Brooks, *Climate through the Ages*, 1949, 117.

[280] C. E. P. Brooks, "Geological and Historical Aspects of Climate Change," in *Compendium of Meteorology*, ed. Thomas F. Malone (Boston: American Meteorological Society, 1951): 1016.

We see in these examples that there was uncertainty and perhaps some confusion about the role of carbon dioxide in the atmosphere because it was discussed within two different research programs: the origin of the ice ages and the possibility of human-caused climate change. From the brief history on infrared spectroscopy and the newness of recent technological improvements, it seems to be an overstatement to treat Callendar as a hero, "one who challenged the consensus of the experts ... had the audacity."[281] This was a period of technological change, and it would not be expected that there would be immediate acceptance of Callendar's hypothesis because it relied not only on recent technological improvements but also on limited amounts of evidence, such as increasing temperature in some parts of the world and changes in measured carbon dioxide in the atmosphere.

When Callendar restarted the CRD, it was no longer as an answer to the origin of the ice ages, rather it was regarding human-caused climate change, although the previous work was fundamentally about the ice ages. Callendar's work represents a split from the lineage of ice age research and the start of a new lineage focused on human-caused climate change. It is beyond the scope of this thesis to follow this new research project because it slows in the 1940s and 1950s, and then develops very rapidly thereafter. If the reader is interested in the history of this research project, I recommend the works by Fleming[282] and Weart.[283]

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[281] Weart, Discovery, 2.

[282] Fleming, *Historical Perspectives*.

[283] Weart, *Discovery*.

Geochronology

Another key question was the timing of the ice ages. Scientists wanted to know not only when the ice ages started, but whether there were fluctuations of temperature within a single ice age. Geochronology of the ice ages can help to separate out various hypotheses because some hypotheses, such as AST, predict a periodic pattern, while others, such as COS, argue for a non-periodic pattern. What was needed was an "accurate chronology of the glacial cycles [because it] was one of the key pieces of information necessary for understanding the ice age[;] but before radiocarbon dating, such a chronology was elusive."[284]

To understand the challenges geologists faced in dating these geological deposits, I briefly survey the various methods, how successful they were, along with their limitations. Most of the following history is from Frederick Zeuner (1946), rather than a contemporary historian, because it is informative to base the history on what scientists at the time thought about the problem.[285] Zeuner was a geochronologist, and his book was often cited in papers written at the time. Reviews of his monograph were generally positive.[286] Though the text was published in 1947, late in the time-period of interest, the book summarizes much previous work in geochronology.

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[284] Macdougall, *Nature's Clocks*, 68.

[285] Frederick Everard Zeuner, *Dating the Past* (London: Methuen, 1946).

[286] For example: John Wolbach, "The Insufficiency of Geographical Causes of Climatic Change," in *Climatic Change: Evidence, Causes, and Effects*, ed. Harlow Shapley (Cambridge: Harvard University Press, 1953), 107-16; Brooks, "Present Position," 204-6; Ernst Antevs, "Review of Dating the Past: An Introduction to Geochronology, Frederick E. Zeuner," *Journal of Geology* 55, no. 6 (1947): 527-30. An example of a review that is not as positive is: Edward S. Deevey, "Review of *Dating the Past: An Introduction to Geochronology*, 2nd ed., by Frederick E. Zeuner," *Science* 113, no. 2944 (1951): 633–34.

Zeuner describes the state of geochronology prior to the transformation, which occurred following further development during WWII, that is, with the development of isotope mass spectrometry. For the reader who is interested in an overall modern history of geochronology, see MacDougall.[287]

Although early estimates of the age of the earth did not address the timing of the glaciers, it sets the stage for the scientific determination of the age of geological phenomena. The most well-known early estimate of the age of the earth was published by W. Thomson (Lord Kelvin, 1824–1907) in 1862,[288] with a later revision in 1883,[289] in which he calculated the age of the earth using the amount of time it would take for the earth to cool from a molten state and for the oceans to condense. There were many assumptions in the calculation, resulting in an estimate of from 20 to 100 million years as the age of the earth. However, "these figures were considered too small by geologists, and a long controversy arose." Unfortunately, because the arguments were based on physics and given the reputation of Lord Kelvin, it "greatly hampered the advance of geological studies in absolute chronology."[290] It will be the discovery of radioactivity and the energy released from decay that provides the "missing" heat from the earth that made Kelvin's calculation incorrect, as Rutherford noted.[291]

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[287] Macdougall, *Nature's Clocks*.

[288] William Thomson Kelvin, "On the Secular Cooling of the Earth," Trans. Royal Society of Edinburgh XXIII (1862): 157–70.

[289] Sir W. [Lord Kelvin] Thomson and P. G. Tait, "On the Secular Cooling of the Earth," *Treatise on Natural Philosophy*, 2nd ed. (Cambridge, 1883): 468–85.

[290] Zeuner, *Dating the Past*, 316.

[291] Macdougall, *Nature's Clocks*, 41.

Geology was not without a dating method, but it used geological methods to estimate not only the age of the earth but to identify the time when geological phenomena occurred based on a variety of techniques such as estimating the time it took to deposit layers of sedimentary rock. There were several approaches, one based on estimating the time needed for evolution of a species found in the sedimentation, one based on the observed rates of deposition of sedimentary rock and another based on repetitive sequences, that is, where a depositional sequence is repeated many times.

The method based on evolution, favored by Lyell, was based on the well-known method of identifying stratigraphic layers and their relative age by the fossils contained within them. Assuming a constant rate of evolution, the age of various strata could be estimated, but the results from this methodology were questionable because of the assumed constant rate of evolution. One approach to reduce uncertainty was too average the rate of evolution over several species with variations in the rate averaging out.[292]

The dating technique based on rates of deposition, like the evolution method, calculates the rate of a geologic phenomenon, such as the rate of deposition of sediments and, given the thickness of a sedimentary layer, estimates the amount of time required for it to be laid down. Ignoring issues of unconformities and other secondary effects to the sedimentary layer, this technique suffers because it, too, is based on average rates.[293]

The third type of geological dating is based on counting layers within strata, such as counting the varves in lakes near glaciers. Varves are laid down on a yearly basis, usually two per year, one from summer, the other in winter, and by counting the layers,

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[292] Zeuner, *Dating the Past*, 308–10.

[293] Zeuner, *Dating the Past*, 310.

one can obtain the age of the larger sedimentary layer.[294] The difficulty with this method is finding locations in which the layers are preserved and not significantly altered. The varve method had been used to estimate the age of parts of the Pleistocene ice age, the last ice age, but cannot be used for early ice ages.

Given some of the difficulties with these geological methods, some geologists, such as Zeuner, used astronomical predictions based on the AST hypothesis to date the ice ages. This assumes that the cause of the ice ages, at least in the Pleistocene, was solar cycles: "The astronomical chronology of the Pleistocene is not based on geological considerations, but on a theory which explains the fluctuations of the climate."[295] In this approach, scientists used the calculations of Milankovitch, the most complete calculation of the effects of the earth's orbit, including all factors, on solar insolation. This showed a series of decreases in solar insolation during the Pleistocene and even earlier. Geologists already had a relative timeline of the Pleistocene ice ages showing patterns of glacial advance and retreat. For example, Zeuner referenced the pattern from Milankovitch, see Figure 12.

[294] Zeuner, *Dating the Past*, 310.

[295] Zeuner, *Dating the Past*, 135.

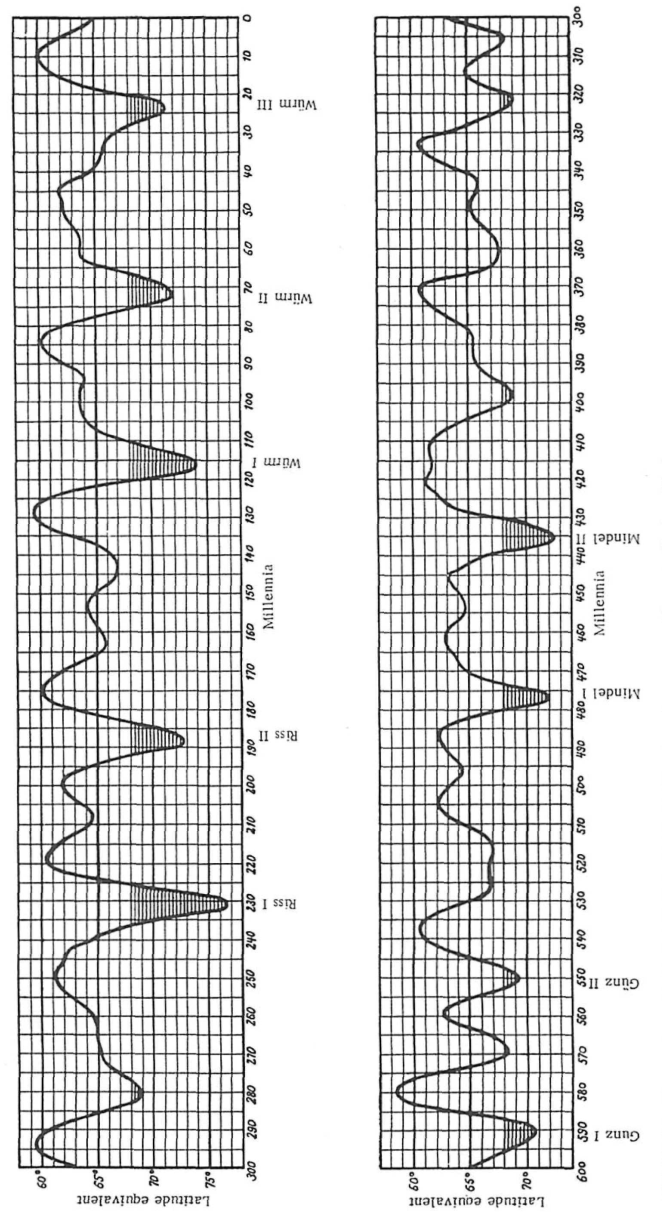

Figure 12. Plot of the Milankovitch cycles.
Plot of the level of solar insolation reaching the earth during the past 600 million years matched against known ice ages (the hatched markings). Source: Zeuner, *Dating the Past*, 474.

Zeuner’s approach was to match the pattern of the relative time of the ice ages with the cycles from astronomical calculations, assuming the AST hypothesis is correct. From a modern perspective, all one can say is that the pattern does or does not correlate.

A better approach would be to not assume AST, but independently determine the ages of the ice ages, and interglacial periods, and see if they match the AST model.

With the discovery of radioactivity near the end of the nineteenth century, there is now an independent method that is not dependent on any of the hypotheses on the causes of the ice ages for determining the age of geological phenomena.[296]

The discovery of uranium and the elucidation of its decay chain provided a method to determine the age of certain classes of rocks. It was noticed early in the development of the method that good samples for analysis were primarily igneous rocks that kept both the uranium and lead, the final decay product, locked up in the rock. The procedure, in theory, was simple. In a sample, extract both uranium and lead and determine their quantities. Using the decay rate of uranium, the amount of lead present gives the age of the rock from the lead/uranium ratio.[297] Unfortunately, it was not quite that simple. First, at that time there was more than one uranium isotope, called actino-uranium (U-235). Both action-uranium and thorium result in lead as the decay product. Corrections, if possible, had to be made for these other isotopes.

> In short, the application of the lead method has to be accompanied by a careful scrutiny of the chances of possible errors, and samples have to be selected accordingly. It is not surprising, therefore, that the number of really trustworthy age estimates is not very large, though it is continually increasing.[298]

A different approach measured the amount of helium. Based on the generation of helium from the decay process, the calculation of the age is, like the lead method, easily determined. However, this method had even more difficulties than the lead method

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[296] Macdougall, *Nature's Clocks*, 17.

[297] Zeuner, *Dating the Past*, 324–25

[298] Zeuner, *Dating the Past*, 328.

because helium could more readily escape from the matrix; hence, the ages were taken to be the minimum ages.

There were problems with both techniques, but “for the time being, the lead method will provide the more reliable age-estimates.”[299]

After WWII, with the significant development of mass spectrometry, and with further understanding of radioactive decay chains and decay products in geological materials, there was a shift in the general approach to radiometric dating. The move was to base dating on isotope ratios, where possible, rather than measuring two different elements, for example, uranium and lead, and then combining them to obtain the age of the sample.

Isotopes had been discovered in the early twentieth century, and their existence complicated radioactive dating because there are "two major isotopes of uranium and four of lead."[300] That is where mass spectrometry comes in. It had been developed in the early twentieth century, but there were major improvements during WWII as part of the Manhattan project to separate uranium isotopes. After the war, this technology could be widely used for geochronological studies, including studies of the ice ages.

In addition, radiocarbon dating, developed in the late 1940s and early 1950s by William Libby (1908–1980) and his team, could be used to date some Pleistocene ice ages.[301] Though early radiocarbon dating could only date back to 15,000–20,000 years, it can be extended given certain samples and conditions. This means it can reach back to

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[299]Zeuner, *Dating the Past*, 332.

[300] Macdougall, *Nature’s Clocks*, 107.

[301] James Richard Arnold and Willard Frank Libby, “Radiocarbon Dates,” *Science* 113, no. 2927 (1951): 111–20.

the end of the Pleistocene, about 11,700 years ago, and provide quality dating or organic materials. Unfortunately, radiocarbon dating does not go far enough back in time to date the earlier phases of the Pleistocene ice age. With geochronological dates from radioactive measurements, the ages of the ice ages and the intervening advances and retreats could be independently determined and hypotheses, such as AST, tested.

Progress Was Made, Nonetheless

Though there was limited progress during this period in coming determining the cause(s) of the ice ages, questions that needed to be answered were identified and, to some extent, the evidence they were lacking was identified so that scientists were primed to move forward when technology, experiments, and new evidence became available. But this new technology did not arrive until the middle of the twentieth century, which explains why progress was slow until then because previous tools were not sophisticated enough to provide unambiguous evidence. With these new tools, and many others, progress rapidly increased in solving the causes of the ice ages and human-caused climate change.

Chapter V

Concluding Remarks—No Simple History

When scientists started investigating the causes of the ice ages, they probably did not expect that finding a solution would be so challenging. Scientific communities had limited experience dealing with a question that required multiple scientific disciplines working together. Typically, scientific problems reside within a single scientific domain, such as identifying the chemical elements, determining the role of energy or heat, or developing the theory of the heliocentric solar system. But the ice age problem was different. It required the input of many different scientific domains: geology, chemistry, physics, astronomy, meteorology, and oceanography. The discovery of the ice ages, though it was discussed during most of the nineteenth century, reached a pinnacle in a seminar by Agassiz in 1837, which marked a critical turning point in the acceptance of the theory and, but it still took until 1887, when Geikie could claim that the existence of the of the ice ages was recognized by the geological community.[302] As early as 1842, scientists had begun searching for the cause(s) of the ice ages and by 1926, the search had resulted in fourteen categories of hypotheses, with many variants in each category, under discussion within the scientific community. One hypothesis proposed that changes in the carbon dioxide levels in the atmosphere could result in the ice ages. Arrhenius in 1896, and later in 1906, proposed, in addition, that human activities were resulting in a significant increase in the carbon dioxide levels in the atmosphere and that this could

[302] Quoted in: Woodward, *Ice Age*, xix.

change the temperature of the atmosphere. What started out as a search to explain the ice ages, generated another question: Are humans responsible for climate change today?

This thesis started out in response to two different challenges to the history of human-caused climate change. The first question came from current critics of human-caused climate change: Is work in the field, from the 1960s on, contaminated by a political agenda, making the science tainted and not believable? From this arose another question: If contemporary climate science is tainted with a political agenda, was previous work also tainted? The second question arose during my initial phases of investigating this history. I became puzzled when I found that some of today's historians claimed that the carbon dioxide hypothesis, at least in regards to human-caused climate change, had been unfairly criticized during its early development, for example, see Weart, but also, Hamblyn, Sorlin and Flannery.[303] Some historians claim that research in the early twentieth century was neglected until G. S. Callendar, a "hero," came along in the late 1930s and reinvigorated research into human-caused climate change, which had laid dormant. This modern historical interpretation is counter to the assertions made by today's climate change deniers, who claim that human-caused climate change has been unduly privileged and has never been challenged by scientists.

Neither of these two conflicting views rang true: the deniers claim of uncritical acceptance of human-caused climate change by the scientific community, nor the heroic picture of early climate scientists. These questions triggered my interest to better understand research into climate change in the late nineteenth and early twentieth

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[303] Weart, "Global Warming," 325, Hamblyn, 228, "Whistleblower," Sorlin, "Narratives and Counter-Narratives of Climate Change," 238, and Flannery, *The Weather Makers*, 40-1.

century, looking not just at the carbon dioxide hypothesis, but at all the hypotheses proposed to account for the ice ages.

Thesis Questions and Summary of Results

I chose four questions to guide my historical research into climate science at the turn of the twentieth century, the period during which climate research into the causes of the ice ages was in full swing and from which the possibility of human-caused climate change was first elaborated in detail. Briefly, the questions were: 1) What were the characteristics of the scientific communities engaged in this research? 2) How did they evaluate and decide which were plausible hypotheses? 3) Is there evidence of bias against the carbon dioxide hypothesis? and, 4) Are philosophical models of scientific change adequate to explain and predict the observed historical evidence? The results for the first three questions are reviewed in this section, while the fourth question, philosophy of science, is discussed in the next section.

The first question, the characteristics of the scientific communities, is important because investigating the origin of the ice ages required a multidisciplinary approach and was one of the early examples of diverse scientific communities working on the same problem. Given the variety of disciplines involved, what is a good approach to characterizing the scientists involved in the work? There are many ways of classifying scientific communities, such as by scientific discipline, nationality, social structure, and so on. None of these adequately characterized the scientists who studied the origin of the ice ages. They were self-selected; those who found the problem fascinating joined in the ongoing research program. Although this community was self-selected, it still had characteristics of a scientific community: they knew of each other's work and critiqued it, but did so in a collegial style—they gave credit to previous work, respected the approaches of other disciplines, even if they did not agree with the results, and so on. This ad hoc scientific community is best described as a temporary, problem-centered scientific community—temporary because once the problem was solved, the community would dissolve, and problem-centered because its membership crossed many institutions and countries and the focus was on a specific problem.

The second question provoked me to wonder how this problem-centered scientific community evaluated the scientific evidence and decided which of the many hypotheses was the most plausible explanation for the origin of the ice ages, and, in addition, if there was human-caused climate change, what was its cause.

The first part to answering this question, given that the scientists interested in solving the problem crossed many disciplines and countries, was how well versed the nineteenth and early twentieth century scientists were in the knowledge from other scientific disciplines. Through a review of the published literature, I followed how scientists evaluated the plausibility of the exemplar hypotheses from the mid-nineteenth until the mid-twentieth century. Though many of these papers reviewed competing hypotheses, they did not, in general, directly critique the evidence used for alternative explanations in-depth. I selected two of the fourteen original hypotheses, astronomical and carbon dioxide, and conducted a preliminary network analysis of the references cited by key published papers for these five hypotheses. Each of the source papers had its own "bubble" of references, which rarely overlapped with references cited by other authors, though there was overlap in the cited review papers. This is probably a result of the diversity in a problem-centered scientific community and the concomitant lack of knowledge about the research domains of other disciplines, but this may not be the main factor in the problem in finding a solution(s).

Instead, the main factor was probably insufficient and ambiguous evidence, that is, the hypotheses were underdetermined by evidence or theoretical understanding, hence it was hard to determine which was the most plausible hypothesis. During this period where there was inconclusive evidence, the plausibility of hypotheses changed as new evidence was obtained or theoretical interpretations improved.

One of the causes of insufficient and ambiguous evidence was the limitations of scientific instrumentation, specifically, infrared spectroscopy and geological dating. Infrared spectroscopy, first used by Tyndall in the 1860s, did not have sufficient resolution to disambiguate water and carbon dioxide spectra. The absorption bands were thought to overlap, and thus the addition of carbon dioxide to the atmosphere would have little or no effect on absorption of infrared radiation from the earth's surface when compared to the much larger quantity of water vapor in the atmosphere. This raised a question about the plausibility of changes of the quantity of carbon dioxide in the atmosphere as a mechanism to change atmospheric temperature. It was not until 1938, when Callendar, making use of improved infrared spectroscopy, along with better models of the atmosphere, restarted the discussion of human-caused climate change; however, his work did not address all the problems with the carbon dioxide hypothesis. But as infrared technology improved along with theoretical understanding and carbon dioxide measurements, human-caused climate change was identified as a plausible theory, though the carbon dioxide hypothesis was not a primary contender as the cause of the ice ages.

Another technology change, coming after World War II, was significant improvement in radiometric dating of geological samples using isotope mass spectrometry. Prior to this time, dating was based on the sequence of geological strata and using estimates of the rates of deposition, provided fairly-good relative dates but not accurate absolute dates. In the early twentieth century with the discovery of radioactivity, radiometric dating of geological samples became a possibility, which could give good absolute dates for geological samples. However, as discussed above, there were problems with this technique. First, it relied on measuring both the parent radioactive element and the daughter decay product element by two different techniques and then combining the results to get an age, for example, measuring the quantity of uranium and lead. This increased the uncertainty of the calculated age because of the need to use different samples for each analysis leading to concerns with sample variability or contamination. In addition, there were very few geological samples that had the right characteristics to retain both the parent and daughter elements over long geological times. With the significant improvement of isotope mass spectrometry, a single sample could be analyzed and, because the results are based on the measurements of the isotopic ratios of a single element, there was significant improvement in the accuracy of the technique, and, in addition, it was applicable to many more types of geological samples. It should be mentioned, there was another radiometric technique, carbon-14, developed in the early 1940s, but because of the short half-life of carbon-14, and because it needed carbon-based samples, it could only be used to date geological events over the past tens of thousands of years. In the case of isotope mass spectrometry, geological samples could be dated over billions of years.

Dating of the ice ages was needed to determine whether variations in the earth's orbit and, its effect on solar insolation, was a cause of the ice ages. The role of geological dating highlighted a difference between geologists and astronomers. Geologists used the observed dates to test the astronomical hypothesis since it predicted a regular pattern of ice ages. However, some astronomers, confident in their theory, wanted to use the dates predicted from celestial mechanics, to date geological strata, not the other way around.

Both spectroscopic and radiometric dating technology highlight one of the characteristics of this case study. All the basic techniques were present, but were insufficient to answer the questions until the technology improved. This was not a case where new scientific instrumentation was needed to investigate new phenomena. In comparison, the confirmation of plate tectonics did not occur until geophysical data from magnetometers and technological improvements in instrumentation became available.[304]

In addition, as we saw previously, the work by Milankovitch was crucial to building a strong case for the astronomical cause of the ice ages because he provided a complete calculation of the effects of all the earth's orbital parameters on the quantity of solar insolation the earth received from the sun. His work was not completely new; Croll and others had previously calculated some of the effects of celestial mechanics on solar insolation. What was new from Milankovitch was not the approach, but rather his use of a complete model of celestial mechanics and its effect of changes in solar insolation. Milankovitch's work was critical to improving the theoretical understanding of the astronomical cause of the ice ages.

[304] Oreskes, *Rejection*, 275.

In summary, even given some of the above-mentioned constraints, scientists reduced the number of hypotheses from fourteen categories to five by the middle of the twentieth century. Some categories were quickly dismissed, such as the lunar hypothesis, as contrary to well-known science and others had insufficient evidence or theoretical support. But frankly, I did not fully answer my second question, how the scientific communities reduced the number of hypotheses from fourteen to five by the early 1950s. This was difficult to answer from the published scientific review papers and research papers because not all hypotheses were discussed and because only a small number of hypotheses, such as the astronomical hypothesis and the carbon dioxide hypothesis, along with a few others, were continually discussed. It was not obvious from the literature that I investigated how scientists made decisions and evaluated evidence or how much weight was applied to each factor if there was contradictory evidence. Some hypotheses, such as the lunar influence hypothesis, may have been considered problematic from the beginning, while others may have been problematic because there was limited evidence available to reach solid conclusions. Other hypotheses, for example, the cosmic dust hypothesis, did not provide any testable claims. To fully answer this question would require a more exhaustive search of the published record, along with unpublished journals, letters, and notes. This is an area for future research.

In answer to the third question, whether they were biases in the late nineteenth or early twentieth centuries about either the ice age question or the question of human-caused climate change, I made progress. As previously described, some of today's historians suggest that the carbon dioxide hypothesis was unfairly criticized in the early twentieth century and that the role of carbon dioxide from human activities was downplayed, resulting in delaying the recognition of human-caused climate change. I had the advantage of investigating a time in which many hypotheses were under consideration and compared the response of the problem-centered scientific community to these hypotheses.

Although there were limitations to my study, the reception of carbon dioxide hypothesis did not appear to be different from that of other major hypotheses within an environment of insufficient or ambiguous evidence. During the early twentieth century, scientists did not know carbon dioxide hypothesis would become a controversial theory in the late twentieth century. For the early scientists, carbon dioxide hypothesis was one of several hypotheses proposed in response to the origins of the ice ages, although it was also proposed that it could possibly play a role in human-caused climate change.

During the early twentieth century, many hypotheses, such as astronomical, geographical, and others, were all critiqued at some point due to lack of supporting evidence or changing interpretations of the evidence. Many hypotheses had periods where development on them slowed or ceased due to lack of new evidence. Most of these hypotheses were not forgotten and were routinely included in review papers and books though a few hypotheses, such as the lunar thesis, were rarely mentioned. It appears that those hypotheses, which had fallen out of favor due to lack of evidence, were in stasis, waiting for new evidence, instrumentation, or advancements in theory because no hypothesis unambiguously solved the problem of the cause of the ice ages. It did not seem unusual for there to be significant scientific criticism of working hypotheses when there was insufficient evidence to clearly prove the that one out or many hypotheses was "true." The continental drift hypotheses proposed by Wegener, which was also a hypothesis proposed to answer the origin of the ice ages, was in a similar historical situation—with some scientific communities supporting the hypothesis and others criticizing it—because the evidence to support it was insufficient.[305] After WWII the continental drift hypothesis, renamed plate tectonics, received new evidence from new technologies, such as magnetometers, that conclusively proved the existence of plate tectonics and demonstrated sea floor spreading. In both cases, origin of the ice ages and plate tectonics, there had been insufficient evidence or theoretical understanding to convince the various scientific communities of the truth of the theories.

The carbon dioxide hypothesis as applied to human actions, like the astronomical hypothesis or the continental drift hypothesis, lacked sufficient evidence to unambiguously demonstrate its plausibility. The carbon dioxide hypotheses, when proposed as a cause of the ice ages, was found wanting primarily based on the lack of adequate mechanisms to supply and remove carbon dioxide from the atmosphere at an appropriate rate. In addition, once a regular pattern of the timing of the ice ages was established, the carbon dioxide hypotheses could not account for the regularity, only the astronomical hypothesis could match the timing data, and the carbon dioxide hypothesis was dismissed as a possible cause for the ice ages. However, regarding the carbon-dioxide hypothesis as applied to climate change from human activities, was problematic during the early twentieth century because the evidence from the limited resolution of infrared spectroscopy of water vapor and carbon dioxide, along with other theoretical concerns, led scientists to question whether this was a plausible hypothesis. When Callendar presented new evidence in a series of papers published from 1938 to 1941,

[305] Naomi, *Rejection*.291–296, 311–12.

interest in the possibility of human-caused climate change was restarted, as Weart and Fleming pointed out.[306] No evidence was found indicating bias against the human-caused climate change hypotheses, rather, given the insufficient or ambiguous evidence, there were different interpretations of its plausibility. To reiterate, the claim that carbon dioxide hypothesis was unduly challenged is not supported by the historical evidence.

Finally, after investigating this historical period because of its uncommon characteristics of multiple scientific domains and many hypotheses, I wondered how well this historical period fits, or doesn't, with theories of scientific change derived from the philosophy of science. This historical period provided a rich ground for investigating scientific change from a variety of perspectives, and we turn to this now.

Philosophical Models of Scientific Change

This case study is different than many other historical case studies, which typically have only a couple of competing hypotheses. This problem had fourteen categories of hypotheses. The ice age problem also had a wide variety of scientific disciplines involved in studying it, including geology, meteorology, astronomy, and others. Because the characteristics of the study of the ice age are quite different from those in other historical cases, it is fruitful to investigate it briefly from a philosophical viewpoint. Although there are many different philosophies of science regarding scientific change, I consider the work of Thomas Kuhn (1922–1996) and Imre Lakatos (1922–1974), two well-known historicist approaches to the philosophy of science, and I investigate whether either of these approaches describes the historical evidence or

[306] See Weart, *Discovery*, 2008, and Fleming, *Historical Perspectives*, 1998.

provides interesting predictions about where additional historical research would be productive.[307] This short investigation will not investigate whether any of these theories of philosophy of science is superior to the others; the analysis is limited to whether they are applicable to the historical evidence from studies on climate change.

Kuhn's Theory and Climate Change

Kuhn, in his 1962 book, *The Structure of Scientific Revolutions*, challenged a commonly held view that science progresses cumulatively towards the truth. He divided scientific change into three periods: normal science, crisis period, and revolution.[308]

During normal periods, sciences operate within an accepted paradigm, also called a disciplinary matrix, where scientists engage in puzzle solving with the paradigm providing guidance as to the types of scientific questions that are acceptable to investigate. A paradigm, or disciplinary matrix, comprises the "key theories, instruments, values and metaphysical assumptions" that are held fixed during a period of normal science, that is, the paradigm, or disciplinary matrix, is not questioned during this period.[309] Kuhn labels scientific questions that arise during this period "puzzles" because, like common puzzles, there is a given set of rules that are in operation and control what kind of puzzles are available and, also, in general, there will be a solution to the puzzle.

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[307] Carl Matheson and Justin Dallmann, "Historicist Theories of Scientific Rationality," *Stanford Encyclopedia of Philosophy*, Summer 2015, 42, https://plato.stanford.edu/entries/rationality-historicist/#Aca.

[308] Kuhn, *Structure*.

[309] Alexander Bird, "Thomas Kuhn," *Stanford Encyclopedia of Philosophy*, 2013, URL = <https://plato.stanford.edu/archives/fall2013/entries/thomas-kuhn/>.

If evidence accumulates that does not fit within the current paradigm, a crisis may occur, at which time scientists begin questioning the paradigm. At some point the number of anomalies is too great, and a crisis occurs, resulting in the investigation of the paradigm itself. Eventually a revolution occurs, overthrowing the current paradigm and replacing it with a new paradigm, which, in general, resolves the anomalies. With a new paradigm, the cycle of normal science begins again. A common example of scientific revolutions is the transition from Ptolemaic to Copernican astronomy. Scientific revolutions are rare, with normal science being the predominant mode of scientific research.

The normal-crisis-revolution cycle refers to a mature science, one that has developed techniques, ideas, and communities that are used in the normal science but challenged during a revolution. The period before this cycle begins, when there has not yet been a paradigm, is the pre-paradigm period where the fundamentals of the science are in question and there are many proposals on how to do science. Once the community settles on its first paradigm, the normal-crisis-revolution cycle begins.

Investigating climate change from Kuhn’s model, we must identify whether the work in the early twentieth century fits the definition of a pre-paradigm period, a normal science period, a crisis period, or a revolutionary period. Some of the evidence used by Kuhn to identify a period of normal science include the existence of textbooks, which lay out the “way” science is to be done in a scientific discipline, and the existence of exemplars, against which the new puzzle can be compared and which researchers use to guide their investigation. Kuhn did not think that the paradigm could be explicitly expressed but rather was understood via the use of exemplars.[310]

Scientists treated the study of the origin of the ice ages as a single problem and not a separate discipline, at least not yet; hence, if climate change is a puzzle to solve, it is part of normal science fitting within a scientific paradigm. But what is the paradigm? This problem appears to be attacked by using many paradigms, at least as paradigms are commonly defined by Kuhn, for example, chemistry, physics, or meteorology, with each of these fundamental sciences having their own paradigm.[311] In the case of climate change, textbooks, such as Brooks' 1926 text, *Climate Through the Ages*,[312] and Humphreys' 1920 text, *Physics of The Air*,[313] describe the state of knowledge of climate change at the beginning of the twentieth century and include discussions of the many hypotheses on the causes of the ice ages then under consideration. This was still the case in the second editions of these books, published in 1949 and 1940, respectively.

Another marker of normal science, exemplars, was also present during this time. Geologists used existing glaciers, such as those in the Alps, as models for ancient ice ages by comparing key characteristics, such as moraines—scratch marks on valley floors and walls found far from existing glaciers—to argue that these regions were at one time covered by glaciers. Comparing existing geological processes, from one region or time to

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[310] Bird, "Thomas Kuhn."

[311] Kuhn has many definitions of paradigm, see for example, Margaret Masterman, "The Nature of a Paradigm," in *Criticism and the Growth of Knowledge*, vol. 4 of *Proceedings of the International Colloquium in the Philosophy of Science*, London, 1965, ed. I. Lakatos and A. Musgrave (Cambridge: Cambridge University Press, 1970), 59–89.

[312] Brooks, *Climate through the Ages*, 1926.

[313] Humphreys, *Physics of the Air*, 1920.

another, was a normal part of the geological sciences, based on the assumption of uniformitarianism where fundamental geological processes have not changed over time.

But is there any evidence that during this period of investigation, from the mid-nineteenth to mid-twentieth century that a crisis occurred in the science, potentially leading to a revolution and change in paradigm? There is no evidence of this occurring. This problem was addressed by several scientific disciplines, and perhaps one of these disciplines reached a crisis while trying to solve the problem. The history of several the hypotheses, such as astronomy and carbon dioxide, were slowly developed over many decades with no evidence of a fundamental crisis. In the case of the astronomical hypothesis, many of the characteristics of the earth's orbit thought to influence climate were known throughout this period; the major development was the increasing sophistication of the calculations. As time progressed, additional orbital parameters were included, resulting in the work of Milankovitch, who included all of them in his calculations. If there had been a crisis, the crisis would have occurred in astronomy itself because it was one of the scientific disciplines used to solve the problem; there is no evidence that the ice age problem caused any crisis in astronomy.

One marker of a revolution is that the understanding before and after is, to some extent, incommensurable. The ideas after a revolution are very different from those before, so much so that scientists who come later are unable to understand the previous theories. This characteristic of Kuhn's model is not present during the period; for example, scientists had no problem understanding and building upon the work of previous scientists. Callendar understood the work of Tyndall on the measurement of infrared absorption from almost a century before his own work. Similarly, geologists, though they might disagree on interpretation, had no difficulty understanding the earlier work of Lyell, and Milankovitch had no difficulty understanding the work of Croll from the previous century.

The evidence points to this being a period of normal science. But does Kuhn's model predict anything new? Most, if not all, of Kuhn's examples describe a problem within a single conventional scientific discipline, such as chemistry, physics, or astronomy; each discipline operating within its own paradigm. But he does not predict, to my knowledge, what might occur if multiple paradigms converge on solving a problem, such as in the case of the cause of the ice ages. Related to the ice age problem, probably due to the large number of disciplines involved, there were many hypotheses under consideration, though not all were considered working hypotheses, as Chamberlin would describe them. These many hypotheses, over the century of time discussed in this thesis, were competing to explain the ice ages. Taking this into account, this period could be described as a "synthetic-normal" period; that is, the disciplines were operating within an integrated normal period, and were not operating in isolation, to solve a synthetic scientific question. But if this is the case, what would Kuhn have predicted to occur during a "synthetic-normal" period? Unfortunately, this appears to be left unanswered. It would have been interesting if his model of scientific change made testable predictions for this unusual case study. Rather, his model is descriptive, and can be applied after the facts to describe a historical period.

If this historical period is normative, within Kuhn's definition, then perhaps Kuhn's model of scientific change has little to say about it. Kuhn's focus is on major changes in science, revolutions, and paradigm shifts, not the inner workings of normal science. Normal science is of interest for Kuhn primarily because it sets the stage for crisis and revolution, and Kuhn places emphasis on revolutions in science in his seminal work. To gain insight into this normal period of science, perhaps a different model of scientific change would be more productive.

Lakatos' Model and Climate Change

Imre Lakatos' model of scientific change emphasizes continuous development of scientific research, in which a research program, consisting of a sequence of theories, progresses with each theory, building on or modifying previous theories as theories are found deficient in explaining the observations. In his approach, the focus of science is not on the theory, as is often the case in other models of scientific change, but rather the research program.

A research program consists of two major components: theories and heuristics, with two types of theories, core and auxiliary, and two types of heuristics, positive and negative.[314] A research program is composed of a series of theories that "share a hard core of central theses that are deemed irrefutable—or, at least, refutation-resistant—by methodological fiat."[315] For Lakatos, the hard core is not subject to being falsified not only because scientists are hesitant to give it up except under unusual challenges, but core theories are often very general in nature and do not provide any testable predictions. What is testable for Lakatos are the auxiliary hypotheses that surround the hard core.

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[314] Matheson and Dallmann, "Historicist Theories of Scientific Rationality."

[315] Alan Musgrave and Charles Pigden, "Imre Lakatos," *Stanford Encyclopedia of Philosophy*, Metaphysics Research Lab, Stanford University, Winter 2016, https://plato.stanford.edu/archives/win2016/entries/lakatos/.

Auxiliary theories take the ideas from the hard-core theories and convert them into testable hypotheses.

His ideas are best explained by an example: "Newtonian mechanics *by itself*—the three laws of mechanics and the law of gravitation—won't tell you what you will see in the night sky. To derive empirical predictions … you need a whole host of *auxiliary hypotheses* about positions, masses, and relative velocities of the heavenly bodies."[316] It is the auxiliary hypotheses that are tested and, if they fail, are replaced; rarely is the hard core modified. As Lakatos puts it, "It is this *protective belt* of auxiliary hypotheses which must bear the brunt of tests and gets adjusted and re-adjusted, or even completely replaced, to defend the thus-hardened core."[317]

There are two types of heuristics associated with a research program, positive and negative, associated with auxiliary and core hypotheses, respectively. Negative heuristics protects the core while positive heuristics improve the auxiliary hypotheses. Key to Lakatos' theory, as seen from his statement on the auxiliary hypotheses, is that a research program consists of constructing a series of theories in response to challenges to the auxiliary hypotheses, while the hard core remains at the center of the research program. It is the core that continues throughout the research program. From his perspective, "the unit of scientific evaluation is no longer the individual theory (as with Popper), but the *sequence* of theories, the *research program.*"[318] The ability of new theories in the

[316] Musgrave and Pigden, "Imre Lakatos," emphasis in original.

[317] Lakatos, "Falsification and the Methodology," 50.

[318] Musgrave, "Imre Lakatos."

sequence to explain new evidence or to make testable predictions means that the program is progressing; if not, it is declining.

From Lakatos' perspective research into the origin of the ice ages would corresponds to a research program, but in my case, there are multiple scientific domains involved. When applied to this problem, Lakatos might map the core theories to a variety of disciplines, e.g. celestial mechanics, chemistry including infrared spectroscopy, geology, etc., and the auxiliary hypotheses are the propositions that link the core to the current problem, in this case, applying core ideas to identifying the causes of the ice ages. For example, AST makes predictions about the timing of the ice ages, and using geological, or better still, radiometric dating, the time of the ice ages can be compared to AST predictions of changes in solar insolation.

In the history of this period, when testable propositions from many domains were found wanting, this did not affect core theories. Even if there was not correspondence with the timing of the ice ages, the core—celestial mechanics—would not have been challenged because it provided many successfully tested predictions in astronomy. In another case, CRD was often challenged, but the challenges did not attack whether carbon dioxide absorbed infrared radiation, rather it was whether carbon dioxide played a key role in controlling the temperature of the atmosphere. What changed over time was the improvement of infrared spectroscopy and modeling of the atmosphere, which eventually lead to the recognition of carbon dioxide as a component in controlling the atmospheric temperature, not for the ice ages, but its role in human-caused climate change. In these two examples, AST and CRD, there is a separation between core and auxiliary theories, consistent with Lakatos' model.

A second characteristic of Lakatos' model describes the process of science as it develops, with auxiliary hypotheses, which, when they fail, are replaced by new hypotheses that increase the explanatory content of the combined theories. The historical record demonstrates explicit progress in at least some hypotheses, for example, CRD, AST, GEO, in solving the problem. The clearest example of an evolving research program is AST, where the early hypotheses included only part of the orbital parameters of the earth. It wasn't until Milankovitch that the complete set of orbital parameters were calculated, along with their impact on solar insolation. AST slowly improved over time, with each modification adding more explanatory content and testable hypotheses. This is consistent with Lakatos' model.

Philosophy of Science Concluding Remarks

From this short review, Kuhn's model, though not at odds with the historical description, does not appear to be the best model for this period because of Kuhn's focus on the structure of scientific revolution, which did not occur during this period. This was a period of normal science from Kuhn's perspective. In contrast, Lakatos' model appears to describe historical observations better because his model is based around a research program with changes in the auxiliary hypotheses when new evidence is discovered or there are improved predictions to test, such as improvements in the astronomical model of the time of the ice ages. Lakatos' model is a better description of my case study, but it is not obvious that his model makes any novel predictions about characteristics of this period which could guide research into new areas of historical research.

However, neither Kuhn nor Lakatos focus significantly on competition between hypotheses, a major characteristic of this problem. There were fourteen hypotheses competing to supply the answer to the cause of the ice ages. From Kuhn's perspective, this is a characteristic of normal science, just another part of puzzle solving and not particularly interesting. Lakatos more directly brings in the idea of competition within a research program, but this is not explicitly investigated. He describes this as a sequence of theories, a theory that has not succeeded is replaced by one with more content and the capability to address new data. However, this is not quite the same as simultaneous competition. Further investigation of these two models within the context of climate change would be fruitful.

Final Remarks from the Research

This case study, because of the complexity of finding a solution to the origin of the ice ages and because it involved many different scientific disciplines, was an opportunity to explore the process of scientific change beyond the typical history of a couple of hypotheses in a single scientific discipline. Though the analysis was focused on two major hypotheses, the astronomical cause of the ice ages and human-caused climate change, a complete analysis of all fourteen hypotheses would probably provide further insight into problem-centered scientific communities of the late nineteenth and early twentieth century. My investigation raised many more questions than were answered, although a few questions have at least tentative answers. Yet much is left unresolved. Without the personal, unpublished papers as part of this study, I was not able to dig deeply into the interactions between scientists and what they may have thought about the various hypotheses compared to what they were willing to put into print.

Though I've not addressed all the issues associated with early research into the causes of the ice ages, we have seen that the environment was moderately complex, not only because there were many scientific disciplines involved, an early example of interdisciplinary science, for example geologists, chemists, physicists, meteorologists and other disciplines all joined in the search for a cause of the ice ages, but also there were problems with the lack or ambiguity of the available evidence, such as whether the ice ages exhibits periodicity or whether they were a global or local phenomena.

Given the interdisciplinary nature of the ice age problem, it was challenging to apply or determine the adequacy of many prominent theories of scientific change, such as developed by Kuhn or Lakatos, because theories of scientific change look at intra- rather than inter-disciplinary domains. In this case with many scientific disciplines, each discipline had its own background knowledge and approaches to solving problems, which were not known in depth by those in other disciplines. For example, because of the complexity of geological evidence, it was common, as Chamberlin[319] argued, to keep many hypotheses in play at the same time, while physicists tend to solve problems by mathematical models, which would focus on a single solution, such as that by Croll or Milankovitch, who did not investigate whether their predictions of changes in solar insolation could affect meteorology to produce ice ages. One partial solution to this challenge of the lack of expertise in other disciplines, is the existence of review papers and textbooks, of which there many during this period, particularly those from Brooks and Humphreys. Review papers and books bridged the knowledge gap. But this type of problem, interdisciplinary in nature, needs further investigation to better understand the

[319] Chamberlin, "Studies for Students."

social structure of the scientific communities and how they operate under these conditions. Given most models of scientific change study intra-disciplinary problem domains, additional studies of multi-disciplinary scientific problems would help us better understand scientific change, how they evaluate evidence from other disciplines, the credence they give to evidence from various techniques, how they share knowledge, how ontologies from multiple disciplines can be integrated, and so on.

This period was more complicated than often is presented by histories that only focus on one part of the story, such as the development of the carbon dioxide hypothesis or the astronomical hypothesis as a cause for the ice ages. When focusing only on tracing a modern theory back in time and not paying sufficient attention to all the hypotheses under consideration, we can get an incomplete history even of the hypothesis we are interested in. Investigating this type of historical problem may require the use of more quantitative, tools, such as network analysis, which, given time constraints, I was not able to fully explore. Applying new tools to historical analysis looks promising and an area I would like to investigate further.

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