

Chapter 3

The Scientific Method and Its Use

Abstract The scientific method is not a linear one-dimensional sequence of events but a three-dimensional approach to solving problems and obtaining answers to questions. A description of the scientific method and examples are given in this chapter. An understanding of the scientific method (or methods) is necessary in order to gain an insight into, and to hopefully gain some appreciation for, what most scientists do and the way they do it, so this chapter deals with the scientific method and how some important scientists have used it to achieve their results. The emphasis is on climate science and climate scientists but other important scientists are mentioned and their results given. Newton's laws of motion are described and their relationship to climate change is given. Continental drift is introduced and related to climates of the past.

Keywords Theories • Hypotheses • Guyots • GISS • Newton • Hess • Tyndall • Wegener • Ussher • Plass • Flemming • Broecker • Callendar • Rahmstorf • DNA • Libby • Sea-floor spreading • Plate tectonics • Hansen • Keeling • Manabe • Franklin • GFDL • Peer review • Continental drift • Arrhenius • Serendipity • Hutton • Uniformitarianism • Darwin • Evolution • Creationism • Fourier • Scientific method • Data • Watson • Crick • Revelle

Things to Know

The following is a list of things to know from this chapter. It is intended, as in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the “Things

to Know” should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor. This is not intended to be a complete list concerning this subject.

Things to Know	
The scientific method	How are scientific data collected?
Theories	Hypotheses
Peer-review	Alfred Wegener
Alexander Flemming	Newton’s laws of motion
Rosalind Franklin	John Tyndall
DNA	Wallace Broecker
Plate Tectonics	Guyots
Arrhenius	Gilbert Plass
Callendar	Willard Libby
International geophysical year	Keeling Curve
Syukuro Manabe	GFDL
James Hansen	GISS
Sea-floor Spreading	Stefan Rahmstorf
Continental drift	<i>Staphylococcus</i>

3.1 The Scientific Method

The scientific method is difficult to define because it is more than one method. The best one can do is to illustrate the method used by most scientists by listing the steps taken along with some concrete examples from actual scientific papers.

The scientific method is that method or methods used by scientists to study a scientific problem or to answer a scientific question, draw conclusions, and publish results. What this methodology is, how it is used, and some examples from actual scientific work are given in the following sections. The scientific method actually consists of many methods, as varied as the scientists themselves, and is loosely defined as the way scientists do their work.

The scientific method is not a rigid method or set of methods but it needs to be discussed and understood. It is not possible to understand a science without some understanding of the ways scientists conduct their tasks. The scientific method can be thought of as a series of logical steps; but often it is simply trial and error. However, trial and error without a method takes longer and allows for more mistakes. Scientists try to cut down on mistakes and to make as few as possible.

Scientists are often part of a team that conducts research into an area of study for which they have received funding. Funding for research is often obtained by writing a proposal and receiving a research grant if the proposal is accepted. This is not always the case and was less so in the earlier days of scientific work. In earlier work, especially work done prior to the 1960s, scientists often labored alone on a project that they designed and that they carried out supported by the institution or company for which they worked. Often the institution was a university or government, or an institution supported by a government.

A preliminary look at the scientific method involves at least the following steps:

1. Consider or define a problem;
2. Try to state an explanation for the problem;
3. Determine or deduce a prediction based on the explanation;
4. Perform tests or experiments to see if the explanation is valid.

The four steps above form the basis of the scientific inquiry; they constitute a simple model for the scientific method. One possible sequence is 1, 2, 3, and 4. If 2 is true, what are the consequences? Testing (4) should include considering the opposite of each consequence in order to disprove 2. If 2 can be disproved, then start again with 1.

There must be a fifth step. What good are steps 1 through 4 if no one knows about the results? The fifth step is communication; publication or presentation. The results of scientific research are made known to colleagues by discussion, presentation, publication, or all three; and in the modern world, discussion is largely done by email or in the halls at conferences or the written word. Publication is usually done in peer-reviewed journals or by presentation at a professional conference.

Scientific research is the most important way to determine the causes, trends, and possible solutions to climate change if it is determined that climate change is heading in the wrong direction and will need proper action. Science is an important part of society and the advances made by scientists have been important to human beings' continuance and well-being on Planet Earth.

Scientific discoveries are made by following the logic of the scientific method, and sometimes discoveries are made because of accidents and even stupidity. Serendipity in science is a scientific discovery made by accident and this has played a role in scientific research in the past and will certainly play a role in the future. Hopefully, scientific research will lead to the advancement of human knowledge, which is the primary purpose of conducting scientific research.

Scientific research has already led to many advances beneficial to humans in the medical sciences, such as drug research, and innovations which continue to make life better for humankind; Velcro, solid state electronics, microwave ovens, the personal computer, laptops, ipads, smart phones, etc. are the result of scientific research.

Scientists do their work in many different ways. Some use data they collect themselves; others use data collected by someone else. Some work alone; others work in teams. Most publish their work as soon as possible; others keep their research secret, publishing rarely if at all. Some are brilliant; others are not so smart. Scientists are human; some are even more so than others.

One of the most unusual and enlightening essays about the methods and the way scientists work and think is entitled "*The importance of stupidity in scientific research.*" Scientists in general are not stupid. Actually, most of them are quite intelligent. But stupidity often plays a part in the way scientists work. Stupidity in scientific research, which is nothing to be ashamed of, is due to the fact that scientific research is most often into the unknown.

Scientists ask questions and then attempt to find answers to those questions. Some questions do not lead to answers but lead to other questions or to blind alleys, and the scientist has to start over again or change course. Eventually, the scientist will hopefully ask the right question, possibly in collaboration with others, and proceed in the right direction to arrive at the correct answer or answers. Scientists use logic, both inductive and deductive reasoning, and have a set of ethics by which they accomplish their work.

To quote Sherlock Holmes (actually Sir Arthur Conan Doyle, the author), “How many times must I tell you, Watson, when you eliminate all the impossible, what is left, no matter how improbable, must be the truth.” And most scientists are interested in obtaining the truth.

The scientific method is that which all reputable scientists follow. It is not a mystery and it is fairly simple but not rigid. It is as varied as the scientists who use it but there are basic parts to it which can be recognized. It is a methodology by which most scientists conduct research and alert fellow scientists (and sometimes the public) to new information.

The scientific method may begin with an idea before any information is collected. It may be the idea that something may exist which has not been thought of before; an original idea, like Albert Einstein’s formula for energy and matter, $E = MC^2$, relativity, or plate tectonics, sea-floor spreading, and continental drift; or the origin of species. It is often an idea based on observations; empiricism, such as the movement of stars in the sky or the Earth’s place in the Solar System (such as the celestial observations of Copernicus and Galileo, or the configuration of continents on a map).

After an idea is defined or formulated, the scientist begins to collect data, information, or to test, experiment, and make observations. Or the idea may come after the scientist begins to collect data. The collection of data may result in an original idea and this idea then becomes the hypothesis or theory.

An example of the collection of data coming first before the idea is Darwin’s theory on the origin of species by means of natural selection. Darwin spent a large part of his life collecting and studying living and fossil organisms. From his observations he formulated his theory on the origin of species.

Hypotheses and theories are usually presented at professional scientific meetings, published in peer-reviewed scientific journals, and discussed with colleagues. This is what is called the peer-review process. This process allows the scientist to receive feedback from peers and to refine their ideas or to change them.

Meetings, journals, and discussions provide feedback and possibly new ideas or information to the scientist. Then the theory is revised if necessary.

It is by this method of logical steps that scientists gain confidence that their theory is correct. Often, new ideas happen by serendipity (by accident or chance), such as in the discovery of a powerful antibiotic. One was discovered by accident and named by a Scottish scientist, Alexander Flemming, who left a Petri dish containing the bacterium *Staphylococcus* sitting uncovered overnight by mistake and discovered an odd-looking substance in the Petri dish the next morning. The substance

formed a ring around the *Staphylococcus* and appeared to be impeding the growth of the culture. The substance was named penicillin.

A scientist might be working on formulating a hypothesis or establishing a theory and discover a new line of inquiry by accident or pure luck. This new information may lead to the abandonment of the original hypothesis or may lead to the start of a new one.

Because the scientific process is not rigid, it is subject to abuse. To restrict abuse of the process a code of ethics has been developed among scientists. According to this code, a scientist must give full credit to all other scientists whose work they have used. Data must not be falsified, omitted, or embellished and they must accept responsibility for all their work.

Examples of well-known hypotheses and theories are as follows:

- Nebular hypothesis for Earth's origin and the origin of the Solar System;
- Hypotheses for extinction of life forms;
- Hypotheses of dinosaur origin;
- Theory of dinosaur extinction by means of meteorite impact;
- Theory of gravity;
- Theory of evolution;
- Theory of the Origin of the Universe (the Big Bang Theory);
- Theory of Plate Tectonics.

There are different ways of outlining the basic methods used for scientific research. Scientists and philosophers of science have generally agreed on certain steps that should be taken in all scientific research. These steps and organization of procedures tend to be more characteristic of natural sciences than social sciences, however, but the social scientist also uses them. The cycle of formulating hypotheses, testing, and analyzing the results, and formulating new hypotheses resembles the steps described below.

A more complete list of the essential elements of the scientific method is the following:

1. Characterizations (observations, definitions, and measurements of the subject of inquiry);
2. Hypotheses (theoretical, hypothetical explanations of observations and measurements of the subject);
3. Predictions (reasoning including logical deduction from the data, hypothesis, or theory);
4. Experiments (tests of all of the above);
5. Conclusions;
6. Peer review;
7. Publication.

Each element of a scientific method, if the work is shared, is subject to peer review for possible mistakes, oversights, and enhancements and many iterations of each may be necessary. These activities do not describe all that scientists do but apply

mostly to the experimental sciences (e.g., some physics, chemistry, some biology, and some Earth science including climate science). The elements of the scientific method are often taught in classrooms, as they should be for any science class.

Some may question whether climate science is conducted using the scientific method, but it surely is. Climate science only lacks the ability to be able to bring climate inside of the laboratory to conduct experiments, but many experiments related to climate science can, are being, and have been conducted in the laboratory. Examples are as follows:

- Experiments with weak acids which are found in nature and their effects on carbonate (calcite and aragonite, both consisting of CaCO_3) dissolution. Carbonates are important constituents of coral reefs, sea shells, sedimentary rocks, cave deposits, and ornamentals and weak acids are present in the environment. For example, every time it rains the CO_2 in the atmosphere combines with H_2O forming H_2CO_3 , or carbonic acid. Information gathered from laboratory experiments using carbonic acid and CaCO_3 may lead to the protection and preservation of corals in coral reefs and those other things made of calcium carbonate.
- Scientists conduct experiments in the laboratory on the effects of temperature on survival of different species to determine the species' range of tolerance to temperature. They also conduct laboratory experiments with other aspects of the environment to determine limits of tolerance such as atmospheric pressure, various contaminants, and soil conditions for plant species.

There are many experiments that can be done in the laboratory and in the field that relate to climate science. They are being conducted by scientists in laboratories and in fields all over the world.

The scientific method is not a recipe. It requires intelligence, imagination, perseverance and creativity, and some degree of stupidity and accidents from time to time during the scientific process. It is also an ongoing cycle, constantly developing more useful, accurate, and comprehensive models and methods. For example, when Albert Einstein developed the Special and General Theories of Relativity, he did not in any way refute or discount Isaac Newton's laws as set forth in Newton's *Principia* in the seventeenth century. It has been said that if the astronomically large, the infinitely small, and the extremely fast are omitted from Einstein's theories, all phenomena that Newton could not have observed, Newton's equations remain valid. Einstein's theories are expansions and refinements of Newton's theories and they increase our confidence in Newton's work. Ideally, this is the way science should and does work most of the time.

Most nonscientists view science as marching along from step to step and increasing knowledge of the natural world in a linear fashion. Mathematics may work in this way, for example, if a equals b , then c ; but science doesn't. A more likely example from science would be if a equals b , then c , d , e , and maybe f .

When advancement in science occurs, scientists try first to evaluate the new information to see if the new advancement is valid. Then they try and use the new information to make further advancements in knowledge by attacking new research problems and trying to find new answers. This is not a linear process as scientists go

about their work in different ways and may research a problem with different tools to hopefully arrive at the answer.

A recent (November 2011) example of the scientific method in action comes from work being done at the Large Hadron Collider (LHC) with neutrinos. During a recent test, neutrinos were measured to be traveling faster than the speed of light. The speed of light is thought to be a universal constant and forms the basis of modern physics and Einstein's theories of relativity; in the formula $E = MC^2$, C is the speed of light.

The Large Hadron Collider is a gigantic scientific instrument near Geneva, Switzerland where it spans the border between Switzerland and France about 100 meters underground. It is a particle accelerator used by physicists to study the smallest known particles, the fundamental building blocks of all things. It will revolutionize our understanding, from the minuscule world deep within atoms to the vastness of the Universe. It is in the LHC that neutrinos were said to exceed the speed of light. If this experiment can be duplicated and all the steps conducted adequately documented, Einstein's theory of relativity will collapse.

Scientists in Italy measured the time of passage of neutrinos in the LHC traveling from Switzerland to Italy at a rate faster than the speed of light. Two subsequent measurements have been done at this writing (January 2012), one substantiating the original experiment, the other refuting it. Other experiments are planned which will either refute or substantiate the original result. Neutrinos either travel faster than the speed of light or they do not. Most of the subsequent experiments have shown that neutrinos do not travel faster than the speed of light.

Results such as those with neutrinos at the LHC are often the case with experiments. If the experiment results in a new finding, the experiment must be repeated for confirmation. The results have to be confirmed by additional experiments. If additional experiments are not possible or are not done properly, questions about the results of the original experiment will always remain.

3.2 A Linearized Approach to the Scientific Method

It is a useful exercise to look at a linearized approach to doing scientific research, keeping in mind that this does not represent exactly how most scientific research is done.

A linearized, pragmatic scheme of some of the points above is sometimes offered as a guideline for proceeding with scientific research:

1. Define the question and determine the boundaries;
2. Gather information and resources (observe, count, document);
3. Form a hypothesis;
4. Perform experiments, collect data and document;
5. Analyze the data;
6. Interpret the data and draw conclusions that may serve as a starting point for a new hypothesis;

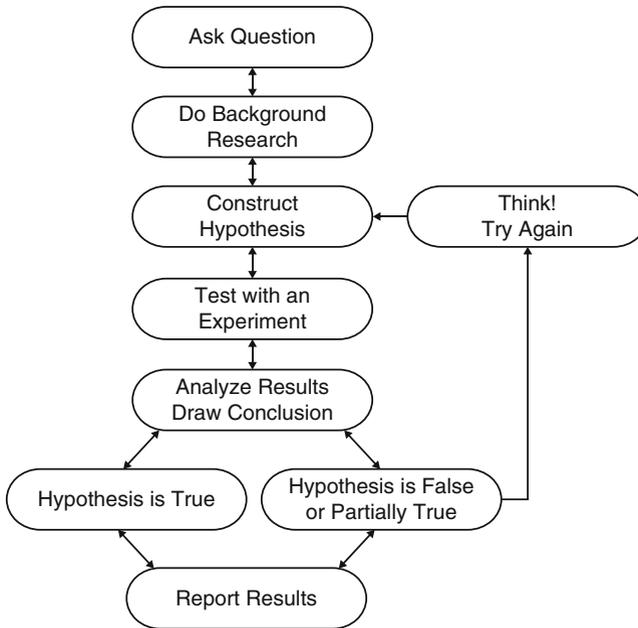


Fig. 3.1 The scientific method's flow of logic (Source: John Cook)

7. Discuss the procedures and results with colleagues;
8. Publish the results;
9. Re-test (frequently done by other scientists).

The iterative cycle inherent in this step-by-step methodology goes from point 3 to 7 back to 3 again. Of course, it is known that scientific thinking (as well as most thought processes) is not, nor should it necessarily be, linear.

While this scheme outlines a typical hypothesis/testing method, it should also be noted that a number of philosophers, historians, and sociologists of science, and scientists claim that such descriptions of the scientific method have little relation to the way science is actually practiced.

The illustration above (Fig. 3.1) is a flow diagram of the thought process often used when conducting a scientific study. A flow of logical thought is essential to a valid scientific study.

Science progresses by argument, skepticism, and debate but it advances through formulating hypotheses clearly and testing them objectively. Testing, experimentation, and objectivity are the keys to science.

In practice, contemporary scientists usually submit their research findings to the scrutiny of their peers, which includes disclosing the methods that they use (and a detailed documentation of those methods), so their results can be checked through replication by other scientists. The insights and research results of individual or teams of scientists are confirmed or rejected in the peer-reviewed literature by the combined efforts of many other scientists.

In conducting scientific research, it is not the belief of the scientists that is important, but rather the results of the testing. Indeed, when Albert Einstein was informed of the publication of a book entitled “100 Authors against Einstein,” he is said to have remarked, “If I were wrong, then one would have been enough!” However, that one opposing scientist would have needed proof in the form of reliable data and testable results. And this is also the case for global warming and climate change science. Those that cite 300 or 3,000 or so people signing petitions against global warming are just as important as those who signed the petition about Albert Einstein and relativity; not important at all, as a glance at the names of the dead and irrelevant reveal! Getting people to sign a petition has nothing to do with evidence for or against the science of Earth’s climate or anything else, except possibly in a political recall. The scientific evidence speaks for itself and it has spoken literally volumes over the past several decades and centuries. If climate scientists are wrong about global warming, than one proof that the Earth is not warming would be enough.

3.3 Data Collection – Experimentation, Measurement, Observation

Scientists collect information, but it is not collected haphazardly. Data, which are bits (parts) of information, are collected in a certain prescribed manner. Data (yes, the word data is plural; the singular is datum) must always be well documented as they are collected; and subjected to controls on accuracy, quality, and pertinence to the problem that is being considered. In mineral, rock, biota or any other item being collected, the label or documentation is as important as the specimen. Without adequate documentation, the specimen or measurement may be a curiosity but it will have no scientific value.

Climate change data collection involves land, ocean, and atmospheric temperature readings; precipitation changes in regions of the world, wind directions, glacial advances and retreats, sea level lowering or raising worldwide, changes in atmospheric and oceanic currents and their effects, and the long-range trends in these data.

Climate change data are collected according to strict rules of quality assurance (QA) and quality control (QC); often stated together as (QA/QC) so that they can be reproduced according to one part of the scientific method (i.e., reproducibility).

3.4 Ideas, Persistence, Documentation, Testing, Reproducibility, Publication

Scientific work usually begins with an idea, remains current due to scientific persistence and documentation, and ultimately survives due to experimentation, its being tested, and its reproducibility.

An example of a scientific idea is the following: “A map of the world shows that the east coast of South America looks like it could snugly fit into the west coast of



Fig. 3.2 The continents of South America and Africa and the fit of their coastlines (From <http://www.bvillage.co.uk/black-roots-village/106867-making-connections.html>; From NASA, Public Domain)

Africa like pieces of a jigsaw puzzle. Perhaps the two continents were together at one time.” This idea was first proposed soon after the first map of the world was made in the 1500s. Figure 3.2 shows the outline of the two Southern Hemisphere continents, South America and Africa, and their “fit” as if they were pieces of a jigsaw puzzle. The first test of this idea came when maps were made of the submerged areas off the coasts of the two continents and geologists saw an even better fit; then the age of the Atlantic Ocean was determined to be younger than originally thought and the theory of Plate Tectonics was born after it was realized that the oceanic crust was being subducted (pulled downward) in the ocean trenches. Of course, it is impossible to reproduce the movement of South America and Africa away from each other, but other evidence clearly shows that they had indeed moved away from each other as new crust was added along what is now the Mid-Atlantic Ridge.

The idea that the continents of Africa and South America were once together was formalized by a German meteorologist and amateur geologist by the name of Alfred Wegener (1880–1930), who in 1912 published a book on continental drift entitled (in English; it was originally published in German) “On the Origin on Continents and Oceans.” Wegener had first proposed the idea earlier, but he did not publish it formally until 1912.

Wegener failed to provide a convincing argument because there was no known mechanism for explaining how the continents had drifted apart. His proposed mechanism had to do with the Earth’s rotation about its axis and the centrifugal force thus generated, but this was known not to be strong enough to move continents.

Wegener postulated that the continents had drifted apart, from an original landmass he called “Pangaea,” due to the centrifugal force caused by the Earth’s rotation.

The major question became “How could these large continental masses (Africa and South America) plow through the ocean basins to move to their current locations?” However, the idea of continental drift took root early in the 1900s as some geologists began to see further evidence for the former existence of Pangaea. Soon Earth scientists (mainly geologists) were divided into two camps; “drifters” and “non-drifters”: the “drifters” citing abundant evidence from the Southern Hemisphere continents of continental drift and the “non-drifters” arguing that the continents could not have moved over the vast expanses of the ocean basins.

The concept of continental drift persisted throughout the first half of the twentieth century and geologists working in the Southern Hemisphere continents began to find evidence in the rocks and fossils that strongly supported the idea. They were documenting the rocks and fossils from areas that could support the reproducibility of their evidence, but they still could not provide any evidence for a mechanism even though the “drifters” knew that there must be one. Scientists were finding plants and animal fossils in the Southern Hemisphere continents that could not have been dispersed great distances by any known mechanism. There had to be proof that the southern continents were once together.

The hypothesis or theory of continental drift remained in the minds of scientists who were waiting for a mechanism to explain it. What was “continental drift?” Was it a hypothesis or a theory and what is the difference between the two? We need to first define each of them.

3.5 Hypotheses

A hypothesis is usually a precursor to a theory, but not always. In science a hypothesis is conceived either before or after data are collected. By definition, a hypothesis is a proposed possible explanation for a phenomenon or problem. It provides a tentative explanation for a scientific problem that can be tested.

Wegener’s idea of drifting continents was a hypothesis which became a theory only after additional information was acquired by geologists working in the Southern Hemisphere continents and it would remain a hypothesis until the theory of plate tectonics was formulated and accepted in the 1960s and early 1970s. But plate tectonics is still a theory although it is well on its way to becoming fact. It is supported by an abundance of facts, as all theories must be.

3.6 Theories

Theories are explanations of phenomena, as opposed to hypotheses which often preclude theories. An example of a theory is evidenced by Newton’s theory of gravity, or Darwin’s theory of evolution, Albert Einstein’s theory of relativity, Harry

Hess' theory of sea-floor spreading. Theories explain a cohesive set of facts. They are not "just a theory" as one former President of the U.S. stated when asked if he believed in evolution. He obviously didn't understand the scientific meaning of theory. Theories are as close to the truth as scientists can often come and are mostly on a par with scientific "laws." Scientific theories are usually more complex than scientific laws but they are essentially the same.

The laws of science are also called physical laws and are considered universal and invariable and are accepted by scientists and the educated public as facts. Many theories are also considered facts, such as the theories of gravity and organic evolution. Examples of scientific laws are Newton's laws of motion.

3.7 Newton's Laws of Motion

Newton's three Laws of Motion are well-known and were first published in 1687 and are stated below. The Newtonian laws of motion are seen in the moving parts of the atmosphere such as high and low pressure systems, wind which is simply moving air, and solid particles and liquids which are carried by wind and currents in the atmosphere.

Newton's First Law of Motion states that in order for the motion of an object to change, a force must act upon it. An object at rest tends to stay at rest until some force causes it to move. An object in motion will continue in motion in a straight line until a force acts upon it to change it from moving in a straight line or stops it from moving.

Newton's Second Law of Motion defines the relationship between acceleration, force, and mass. The acceleration (**a**) of a body is parallel and directly proportional to the net force **F** and inversely proportional to the mass *m*, i.e., $F = ma$.

Newton's Third Law of Motion states that any time a force acts from one object to another, there is equal force acting back on the original object.

There are other physical and chemical laws that govern the behavior of materials on Planet Earth and are treated further and in detail in courses in chemistry and physics.

3.8 The Peer-Review Process

The peer-review process is what is done prior to publication of a scientific paper or legitimate book published by a reputable scientific journal or publisher. It also continues after publication. It is this process that enables a scientist to receive opinions and constructive criticisms from colleagues prior to publication (or before the next edition). Journals and publishers have editors which review and usually send out for review papers and books that are submitted to them.

Reviewers send comments back to the editor who sends them on to the author of the paper or book. Corrections are then made to the written text if the author agrees

with the comments and the author then resubmits the material to the editor. If the editor agrees that the material has been improved and it is ready for publication, it is then published.

Editors have the prerogative to refuse to publish material that they think is mistaken, not appropriate, or is irrelevant to the topic at hand. For example, if there is a scientific consensus that CO₂ is a greenhouse gas that causes global warming and a paper is submitted to a professional journal that says the opposite (that CO₂ doesn't cause global warming) and cites no data to substantiate the author's claim, it is most likely that the editor will refuse to publish the paper.

In general, editors are fair-minded and are responsible for the integrity of their product. They do not routinely reject papers or materials that are pertinent and scientifically valid.

3.9 Use of the Scientific Method

The scientific method, and those that have applied it, has resulted in major advances in humankind's understanding of the world around him (or her) and laid the foundation for additional knowledge. Some examples of this use of the scientific method and the resulting understanding are given below.

3.9.1 *James Hutton and Uniformitarianism*

James Hutton (1726–1797) was a Scotsman farmer and naturalist who is known as the founder of modern geology. Geology forms a large part of Earth and climate change science.

Prior to Hutton's time, Earth history was thought to consist of one catastrophe after another, the most recent being the flood of Noah, or the Noachian Flood. Hutton, being a naturalist, was a keen observer of the world around him and he reasoned that there was not a need for a series of catastrophes to explain the natural world and the history of the Earth; one only had to look at modern processes of erosion and deposition to understand the past history of Earth. These processes could explain how much of Hutton's world could have been formed. All that was needed was a long time. In Hutton's day, the Earth was thought to have been created in a few days and nights and was only a few thousand years old, still old in the minds of most humans.

In the middle of the eighteenth century when Hutton was carefully observing nature, the Earth was believed to be only about 6,000 years old. It was thought that the world had been created on October 22, 4004 BC because that was the date arrived at by an Irish Archbishop by the name of Ussher, whose name still lives in infamy due to his scholarly research on what is often called the "Holy Bible." It seems that Archbishop Ussher had very carefully worked out the genealogies in

Genesis to come up with the absolute date for the Earth's "creation." Fossils were thought to have been placed in the rocks as a result of the "Flood." Others would later say that fossils were placed in rocks to "make atheists of geologists." It is true that many geologists are atheists but surely fossils in rocks are not the cause.

Hutton noted that many rocks were not flat and stacked one upon another as was called for in the "Flood" hypothesis, but at some places, such as at Siccar Point, near Edinburgh, Scotland, vertical layers of grey shale were directly overlain by nearly horizontal layers of red sandstone. Such juxtaposition could only be explained by great Earth movements tilting the shale vertically, then eroding the shale by wind, rain, and sea, and then depositing the red sandstones on top of the eroded surface of the shale.

Hutton, in 1788, presented a paper to the Royal Society of Edinburgh in which he stated that in his studies and observations of the natural world; "The result, therefore, of this physical inquiry is that we find no vestige of a beginning, no prospect of an end." Current Earth scientists and particularly geologists still hold Hutton's view of the Earth.

Hutton had been formally educated in the fields of medicine and chemistry but managed two small family farms while studying natural processes at work on the land. Hutton thought that sediments were deposited by water slowly, then compressed, and turned into rock and that the oldest rocks were made up of "materials furnished from the ruins of former continents." He recognized that this process could be a continuous cycle; when rock is exposed to the atmosphere it decays and erodes. He called this the "great geological cycle" and realized that it had been completed many times. Hutton's approach to the study of Earth and its materials and processes has been called uniformitarianism, which can be simply stated as "the present is the key to the past." The implication of uniformitarianism is that processes now operating on the Earth have been operating throughout Earth history, differing only in their location and intensity.

Hutton's development of uniformitarianism was based on empiricism, carefully observing how things worked in the real world. Geologists today use uniformitarianism to interpret Earth history and climate scientists use a reverse uniformitarianism, stated as "the past is the key to the present." In studying ice and sediment cores, detailed information of the atmospheric conditions of the past gathered from air bubbles in the ice may lead us to a better understanding of the present climate and projections into the future.

3.9.2 Charles Darwin and the Origin of Species

Charles Darwin (1809–1882) was an English naturalist, biologist, and geologist who developed a theory on the origin of species after much time spent observing, collecting, and cataloging fossils, rocks, and animal and plant specimens from around the world. He established that all species on Earth have descended from a common ancestor. He was the originator of the idea of natural selection, that nature gave rise to new species through competition. His theory of natural selection was

based on empiricism. In his own words, he attributed his success to “the love of science, unbounded patience in long reflecting over any subject, industry in observing and collecting facts, and a fair share of invention as well as of common sense.” This is a fair description of the scientific method as Darwin used it. He also said about himself, “I have steadily endeavoured to keep my mind free so as to give up any hypothesis, however much beloved (and I cannot resist forming one on every subject), as soon as facts are shown to be opposed to it.” And this is as it should be for any scientist or science student, or for any person, for that matter. But we see today, especially in politicians, that often they do not have an open mind, and some even debate the presence of mind in some.

Darwin’s theory on the origin of species was that a new species would arise by means of natural selection. He explained that the great variety of living and fossil things that he had observed was due to the fact that certain organisms were favored over others for survival; that new species would arise by acts of nature and not by divine creation. Darwin’s theory of evolution was put forth in his 1859 book *On the Origin of Species by Means of Natural Selection* which was published in London, England.

The publication of Darwin’s book caused a firestorm. The Church (the Roman Catholic Church and the Church of England) immediately condemned it and many religious fundamentalists today still speak out against the theory of evolution; but over 150 years of documentation in science support the theory and it forms the cornerstone of the sciences of biology, geology, and paleontology today.

Charles Darwin was not the first scientist to formulate a theory of evolution but it was the extensive documentation of the facts that the idea was based on that caused it to be accepted almost universally by the scientific community. Without the extensive documentation and the detailed formulation of the theory, Darwin’s idea of the origin of species by means of natural selection would not have been as readily accepted.

Darwin’s meaning was misrepresented by many after the 1859 publication of the “Origin” and only a careful reading of the book would allow complete understanding of his meaning. Perhaps the phrase, “survival of the fittest” best summarizes Darwin’s meaning, but it was not a phrase used by Darwin himself. The phrase was first used by another Englishman, Herbert Spencer.

Darwin’s theory of evolution is based on key facts and the inferences drawn from them, which biologist Ernst Mayr summarized as follows (based on facts and inferences):

- Every species is fertile enough that if all offspring survived to reproduce the population would grow (fact).
- Despite periodic fluctuations, populations remain roughly the same size (fact).
- Resources such as food are limited and are relatively stable over time (fact).
- A struggle for survival ensues (inference).
- Individuals in a population vary significantly from one another (fact).
- Much of this variation is inheritable, i.e., genetic (fact).
- Individuals less suited to the environment are less likely to survive and less likely to reproduce; individuals more suited to the environment are more likely

to survive and more likely to reproduce and leave their inheritable traits to future generations, which produces the process of natural selection (inference).

- This slowly effected process results in populations changing to adapt to their environments, and ultimately, these variations accumulate over time to form new species (inference).

Charles Darwin was the naturalist on the ship HMS Beagle, which left England in December of 1831 and returned in October of 1836. This voyage was most likely the most important experience in Darwin's life, as it visited the Cape Verde and other Atlantic islands, then surveyed the South American coasts and islands, including the Galapagos Islands. It then visited Tahiti, New Zealand, Australia, Tasmania and the Azores before returning to England in October of 1836. It is thought that Darwin did not leave England again after 1836. He used information gathered during the voyage of the Beagle to write and publish his books on coral reefs, sexual selection, variation under domestication, botany, geology, a diary of the voyage, and a book entitled *The Descent of Man*.

3.9.3 *James Watson and Francis Crick – The Structure of DNA*

In 1953 James D. Watson and Francis Crick, using x-ray diffraction data, proposed the spiral staircase structure of DNA (deoxyribonucleic acid). This became known as the double helix for the structure of the DNA molecule. For this work, they were awarded the Nobel Prize in Physiology and Medicine in 1962 which was shared with Maurice Wilkins, a researcher at King's College, London.

James D. Watson (1928–) is an American molecular biologist, geneticist, and zoologist.

Francis Harry Compton Crick (1916–2004) was an English molecular biologist, biophysicist, and neuroscientist and an honorary fellow at the University of Cambridge, U.K. He was a Distinguished Research Professor at the Salk Institute for Biological Studies in La Jolla, CA where he died in 2004.

Watson and Crick's work was founded on earlier work by Linus Pauling and others. As is often the case, major discoveries could not have been made without the work of others. Sir Isaac Newton said that his work was important because he had "stood on the shoulders of giants."

In the early 1950s, the race to discover the structure of DNA was on. At Cambridge University, graduate student Crick and research fellow Watson had become interested, impressed especially by Pauling's work. Meanwhile at King's College in London, Maurice Wilkins (1916–) and Rosalind Franklin were also studying DNA. The Cambridge team's approach was to make physical models to narrow down the possibilities and eventually create an accurate picture of the molecule. The King's team took an experimental approach, looking particularly at x-ray diffraction images of DNA.

In 1951, Watson attended a lecture by Franklin on her work to date. She had found that DNA can exist in two forms, depending on the relative humidity in the surrounding air. This had helped her deduce that the phosphate part of the molecule

was on the outside of the structure. Watson returned to Cambridge with a rather muddy recollection of the facts Franklin had presented, though clearly critical of her lecture style and personal appearance. Based on this information, Watson and Crick made a failed model. It caused the head of their unit at the laboratory to tell them to stop DNA research. But the subject kept coming up and they continued to experiment.

Franklin, working mostly alone, found that her x-ray diffractions showed that the “wet” form of DNA (in higher humidity) had all the characteristics of a helix. She suspected that all DNA was helical but did not want to announce this finding until she had sufficient evidence on the other form as well. Wilkins was frustrated. In January, 1953, he showed Franklin’s results to Watson, apparently without her knowledge or consent. The x-ray diffraction work showed Watson a distinct double helix.

Watson and Crick took a crucial conceptual step, suggesting the molecule was made of two chains of nucleotides, each in a helix as Franklin had found, but one going up and the other going down.

Watson and Crick showed that each strand of the DNA molecule was a template for the other. During cell division the two strands separate and on each strand a new “other half” is built, just like the one before. This way DNA can reproduce itself without changing its structure, except for occasional errors, or mutations.

The structure so perfectly fit the experimental data that it was almost immediately accepted. The discovery of DNA’s structure has been called the most important biological work of the last 100 years, and, some say the field it opened may be the scientific frontier for the next 100. By 1962, when Watson, Crick, and Wilkins won the Nobel Prize for physiology and medicine, Franklin had died. The Nobel Prize only goes to living recipients, and can only be shared among three winners. Crick said that she, if she had lived, would have been honored also for her work. It was actually Franklin’s work that led Watson and Crick to their DNA structure, as it was her x-ray crystallography that sealed the deal. Again, empiricism was used with careful observation and the physical building of models to solve the problem of DNA structure.

3.9.4 Harry Hess and Plate Tectonic Theory

The theory of plate tectonics represents a paradigm shift in the Earth sciences. It has caused geologists to view the world and the way it works in an entirely different light.

Harry Hess (1906–1969) was a Professor of Geology at Princeton University and his work set the stage for the later idea of Plate Tectonics. He served in the U.S. Navy in WWII and with the blessing of his crew was able to survey parts of the ocean floor of the Pacific Ocean basin with echo sounding equipment.

Hess formulated a hypothesis about a spreading sea floor in 1959 in an informal manuscript that was widely circulated. It was later published (1962) in a paper entitled “History of Ocean Basins” which was one of the most important and groundbreaking contributions in the development of the theory of Plate Tectonics. Hess built upon the work of an English geologist, Arthur Holmes (1890–1965), who worked in the early to middle parts of the twentieth century.

In Hess’ 1962 paper, he described how seafloor spreading worked; molten rock (magma) oozes from the Earth’s interior along the mid-oceanic ridges creating new

seafloor that spreads away from the active ridge and eventually sinks into the deep ocean trenches.

At the time of Hess' paper, there were certain questions about the seafloor that were still unanswered. It had been discovered that the ocean basins were not as old as they had been thought to be. Geologists had long thought that the ocean basins would yield sediments that would provide evidence for the beginning of time on Earth, the Earth's origin (about 4.54 billion years ago). This was not the case and Hess reasoned that sediment had been accumulating on the ocean floor for only about 300 million years. Hess estimated that it took that long for the ocean floor to move from the mid-ocean ridges to the oceanic trenches near the continents.

Hess' idea received the expected resistance from the scientific community because geologists were still skeptical about a mechanism, although Hess knew that the oldest fossils found at that time on the seafloor were only about 180 million years old. He proposed that the mechanism for sea-floor spreading was new crust formed at the mid-ocean ridges that forced, or pushed, the seafloor to move to the trenches. Many still clung to the belief that continents and ocean basins had been too brittle for them to move great distances as was called for by the sea-floor spreading concept. Earlier ideas on continental drift had the continents plowing through the oceanic crust to their present locations.

Hess was aware that there were limited ways to test his hypothesis, but later geophysical studies confirmed that oceanic crust was disappearing into the Earth's oceanic trenches. Hess, unlike Wegener, lived to see the confirmation of his hypothesis and it resulted in the concept of Plate Tectonics that caused a paradigm shift in the Earth sciences. It caused geologists around the world to look at rocks in an entirely different way than they had before and to analyze their story in an entirely new context.

Hess also discovered hills on the seafloor that had flat tops. These he called guyots, which are flat-topped volcanic hills that were built from the seafloor to the surface of the ocean when they were formed and had their tops cut off (eroded) by wave action. Others were just called seamounts. They then slowly sank below the surface of the sea under their own weight. The geology building at Princeton University is named Guyot Hall in honor of Harry Hess and his ground-breaking research. Hess was a long-time professor at Princeton University.

The relationship of sea-floor spreading to climate change science is further developed in Volume II of this textbook series.

3.9.5 Plate Tectonic Theory

In 1963 it was discovered that there were strips on each side of the mid-oceanic ridges, parallel to the ridges that showed repeated and alternating polarity. Magnetic minerals in the strips, which align themselves with Earth's magnetic field, showed alternating reversals of polarity in the rocks on each side of the mid-ocean ridges; that is, one strip would show the magnetic south end of the magnetic minerals

pointing to the North Pole and the adjacent strip showing the reverse (the magnetic north end pointing toward the North Pole), and this alternating sequence was repeated as one went away from the ridge on either side. Each side of the ridge had matching strips of alternating polarity.

Additional studies using age-dating techniques showed that the seafloor became older as one went away from the mid-ocean ridges in either direction, thereby lending further support to Hess' concept of seafloor spreading. If crust was being added at the ridges, it made sense that the younger crust would be near the ridges and therefore, older crust had to be further and further away from the ridges.

The concept that the continents and ocean basins had not always been as they are today was a revolutionary idea to geologists at the time. Geologists tend to be a conservative lot, and it took some time before they became convinced that the Earth's crust was actively engaged in movements that could result in moving whole continents (continental drift).

By the late 1960s enough information had been gathered to propose a theory based on the evidence, and the concept of continental drift would fit nicely into the new theory.

The Plate Tectonic Theory is that the outermost layer of the Earth, the crust, is made up of plates that move relative to each other and have moved relative to each other throughout much of the geologic past. They have probably moved at different rates and perhaps in different directions in the geologic past, but they have wandered or drifted over the face of the Earth to their present positions. Relative movement of these tectonic plates has greatly affected the climate history of Earth and is treated in greater detail in Volume II of this textbook series.

Climate change scientists are those scientists whose contributions are in the realm of climate change. Many of the following scientists have also contributed to other sciences and areas of science, but the emphasis here is on their contributions to climate science and its current implications.

3.9.6 Wallace Broecker and the First Use of the Term Global Warming

Wallace (Wally) Smith Broecker (1931–) is the Newberry Professor in the Department of Earth and Environmental Sciences at Columbia University and a research scientist at Columbia's Lamont-Doherty Earth Observatory. He is widely credited with coining the term "Global Warming." He is also credited with being the originator of the "conveyor belt" concept of oceanic circulation (see Fig. 12.6); a global concept of the oceans acting as a conveyor belt to distribute carbon throughout the World Ocean. He is credited with laying the foundation of carbon cycle science. He has authored over 450 publications in the peer-reviewed literature and is the author of ten (10) books, one of which is *Tracers in the Sea*, which established him as one of the leaders in chemical oceanography. His work with radiocarbon (^{14}C) and tying it to paleoceanography are described as landmarks in the field.

In 1975 in the weekly journal *Science*, Broecker published the first legitimate use of the term “Global Warming” in a peer-reviewed paper entitled “*Climate Change: Are we on the Brink of a Pronounced Global Warming?*” Broecker’s paper was written during a brief episode of global cooling in the 1970s, making it even more amazing and prescient.

3.10 Use of the Scientific Method in Climate Change Science

The Earth is warming globally; the temperature of our planet is getting hotter. Global warming is a fact, is unequivocal, and is due mainly to human’s burning of fossil fuels for the past few hundred and possibly a few thousand years. Fossil fuels are coal, natural gas, and petroleum. Humans have also been responsible for Earth’s warming without realizing it by cutting down trees (deforestation), the making of charcoal, and growing food, especially rice. But the main cause, by far, is the massive burning of fossil fuels since the Industrial Revolution and the mass production of the internal combustion engine that most use as a power source. These advances in the use of power have caused a steady and steadily increasing rise in the concentration of atmospheric carbon dioxide and the Earth continues to warm as a result.

Fossil fuels are composed of hydrocarbons that have been buried in the Earth for millions of years. They form slowly and are not being replaced, and it is getting harder and more expensive to find them and to economically bring them to market. For instance oil, new deposits of which used to be found by drilling on land, now is found by drilling in ocean waters (as in the Gulf of Mexico). The first oil well in the U.S. was in the State of Pennsylvania. The most recent new wells have been drilled off-shore and are being drilled in deeper and deeper waters as new deposits or reservoirs of oil continue to be discovered.

Humans will soon run out of cheap fossil fuels. Fossil fuels have provided humans with a relatively cheap source of power for a long time. At the rate of consumption, we may run out of cheap fossil fuels sooner than later and as we do, they will become more and more expensive to extract, transport, sell, and burn. Many scientists are calling for a policy of leaving the remainder of fossil fuels in the ground before mankind burns all of them. There are at least two reasons for this:

1. Humans may need them later; and
2. Burning them is causing the planet to warm.

It is impossible to know just when the first fire was built with coal, but scientists know early man in Europe was burning coal. It is known that coal was used during the Bronze Age, more than 4,000 years ago. Today (June 2012), coal burning is the greatest source of carbon dioxide (CO₂) in the atmosphere where it stays for a long time (perhaps for thousands of years) and continues to contribute to global warming.

3.10.1 Joseph Fourier and the Greenhouse Effect

Jean Baptiste Joseph Fourier (1768–1830) was a French mathematician and physicist who had studied for the priesthood but never took his vows. Beginning with his work in the 1820s, scientists had understood that gases in the atmosphere might trap heat received from the Sun. Fourier realized that energy in the form of visible light from the Sun easily penetrates the atmosphere to reach the surface and heat it, but heat cannot so easily escape back into space. The air absorbs invisible heat rays (infrared radiation) rising from the surface. The warmed air radiates some of the energy back down to the surface, helping it stay warm. This is the effect that would later be called the “greenhouse effect.” The equations and data available to nineteenth-century scientists were too poor to allow an accurate calculation of this effect but Fourier laid the foundation for later physics (e.g., blackbody radiation theory) that showed that a bare, airless Earth at its distance from the Sun should be far colder than it actually is (about 30°C colder).

3.10.2 John Tyndall and Thermal Radiation

John Tyndall (1820–1893) was an Irish physicist, mathematician, and mountaineer who began studying the radiative properties of various gases. He built the first spectrophotometer which he used to measure the absorptive power of gases such as water vapor, carbon dioxide, ozone, and hydrocarbons. He was the first to show the vast differences between gases to absorb and transmit radiant heat.

Tyndall showed that water vapor, carbon dioxide, and ozone were the best absorbers of thermal or heat radiation (not the radiation from atomic and hydrogen bombs, i.e., radioactivity) and they absorb much more strongly than the atmosphere itself. He concluded that water vapor was the strongest absorber of radiant heat and that it is the most important gas in controlling the temperature of the atmosphere. He even speculated on how fluctuations in water vapor and carbon dioxide were related to climate change. Thus, he was many years ahead of his time.

Tyndall became aware that the Earth’s climate had changed drastically in the past by observing glaciers in the Alps. He also noted that glaciers had been more extensive in the Earth’s past. He is the first scientist known who told his students why the sky is blue. Tyndall suggested that the sky is blue because molecules in the atmosphere preferentially scatter the Sun’s blue rays, so that what we see looking up at a cloudless sky is the color blue. This is also true looking at the Earth from outer space; Earth is the blue planet (see frontpiece).

The Sun, stars, Moon, and other planets radiate light which travels to Earth. This light is electromagnetic radiation which travels through space as either waves or photons. Electromagnetic waves are produced by the motion of electrically charged particles. These waves are called electromagnetic radiation because they radiate from electrically charged particles. They travel through outer space as well as through air and other substances.

Electromagnetic radiation, besides acting like waves, acts like a stream of particles that have no mass. The photons with the highest energy correspond to the shortest wavelengths. Electromagnetic radiation travels at the speed of light.

Visible-light waves range in size from 0.4 to 0.7 μm (4,000–7,000 \AA), whereas an atom is only a few angstroms in size.

Electromagnetic radiation is discussed in more detail later in this text.

3.10.3 *Svante Arrhenius and Carbon Dioxide*

Svante Arrhenius (1859–1927) was the first person to investigate what the effect of doubling atmospheric carbon dioxide would have on global climate. Arrhenius was a Swedish scientist and one of the founders of physical chemistry. He was apparently one of the first to discuss quantifying carbon dioxide in the atmosphere. He was the first to predict that emissions of carbon dioxide from the burning of fossil fuels and other combustion processes would cause global warming. Arrhenius stated the following:

That the atmospheric envelopes limit the heat losses from the planets had been suggested about 1800 by the great French physicist Fourier. His ideas were further developed afterwards by Pouillet and Tyndall. Their theory has been styled the hot-house theory, because they thought that the atmosphere acted after the manner of the glass panes of hot-houses.

If the quantity of carbonic acid in the air should sink to one-half its present percentage, the temperature would fall by about 4° ; a diminution to one-quarter would reduce the temperature by 8° . On the other hand, any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4° ; and if the carbon dioxide were increased fourfold, the temperature would rise by 8° .

Arrhenius was the first to predict that emissions of carbon dioxide from the burning of fossil fuels and other combustion processes would cause global warming.

In 1903 Arrhenius was awarded the Nobel Prize for Chemistry. His interest in climate science grew out of his interest in the cause or causes of the ice ages. His work laid the foundation for later work in climate change science.

Arrhenius was aware of the works of Fourier, Tyndall, and others before him and in 1895 presented a paper on the influence of carbon dioxide on climate. The article used an energy budget model that was ahead of its time in considering the radiative effects of carbon dioxide and water vapor on the surface temperature of Earth. He performed a series of calculations based on the data available to him on the temperature effects of increasing and decreasing amounts of carbon dioxide in the Earth's atmosphere. His work showed that the Arctic region would experience an increase in temperature of about 8 or 9°C if carbon dioxide increased 2.5–3 times its value (in 1895). Carbon dioxide prior to the Industrial Revolution stood at an estimated 270–280 parts per million (ppm). Today (June 2012), it stands at over 396 ppm.

Arrhenius calculated that in order to get the temperature of the last glacial advance between the 40th and 50th parallels of latitude, the carbon dioxide in the atmosphere would have to decrease between 0.62 and 0.55 of its value in 1895 to lower the temperature $4\text{--}5^\circ\text{C}$.

A few years after Arrhenius published his work, another Swedish scientist, Knut Angström, asked his assistant to measure the passage of infrared radiation through a tube filled with carbon dioxide. The assistant reported that the amount of radiation hardly changed when he reduced the gas by a third. This meant that it took only a trace of the carbon dioxide gas to absorb the radiation. Adding more carbon dioxide made little difference and only a trace of it in the tube was blocking infrared radiation from getting through.

3.10.4 T. C. Chamberlin and the Ice Ages

Thomas Chrowder Chamberlin (1843–1928) was an American geologist who is perhaps best known for his presentation of multiple working hypotheses. He was Head of the Glacial Division of the U.S. Geological Survey, president of the University of Wisconsin (at Madison), founder of the *Journal of Geology*, organizer of the department of geology at the University of Chicago, and with Forest Ray Moulton, developed a hypothesis of the formation of the Solar System known as the Chamberlin-Moulton planetesimal hypothesis. The planetesimal hypothesis had at its center the idea that smaller objects (planetesimals) collided with each other in the early stages of the Solar System and formed the planets by accretion (growing together and becoming larger).

In 1899, Chamberlin proposed that carbon dioxide in the atmosphere decreased during times of enhanced continental erosion, resulting in glaciation episodes during the last “ice age.” Enhanced erosion was due to higher standing mountains (due to mountain-building or orogenies; or plate tectonics) and increased chemical weathering. The oceanic record of strontium isotopes, preserved in marine sediment, supports his suggestion that glacial climates during the Phanerozoic are in part linked to increases in the rate of global chemical erosion relative to outgassing from Earth’s interior. Also, the close correlation of the major mountain building episodes of the Late Ordovician and Early Silurian, the Devonian, the Carboniferous and Permian Periods, and the late Cenozoic Era (see Appendix I for geologic Periods, Epochs, and Eras) to times of increased continental erosion and glaciation suggests that Chamberlin’s hypothesis of the cause of glacial episodes should be revisited, at least for the earlier glacial episodes prior to the Cenozoic.

Chamberlin formulated his ideas about the ice ages when he worked in the glacial deposits of his native Illinois and Wisconsin. He was responsible for naming the Illinoian (310,000–128,000 years ago) and Wisconsin (35,000–11,800 years ago) glaciations and others of Pleistocene age.

3.10.5 Guy Stewart Callendar and Rising Temperatures

Guy Stewart Callendar (1897–1964) was a British engineer who was the first scientist to study climate change in a systematic way. He was the first to connect rising carbon

dioxide concentrations in the atmosphere to the increase in Earth's temperature. He was aware of increasing carbon dioxide in the atmosphere as a result of burning fossil fuels and an increase in atmospheric temperature over the first 40 years of the twentieth century, which he linked empirically. He used the term "enhanced greenhouse effect" to describe what was happening to Earth's climate. The enhanced greenhouse effect is also called the Callendar effect.

Callendar formulated a coherent theory of infrared absorption and emission by trace gases, established the nineteenth-century background concentration of carbon dioxide (290 ppm), and stated that its atmospheric concentration was rising due to human activities, which was causing the Earth's climate to warm.

Callendar's research resulted in fundamental new insights into the spectra of water vapor, carbon dioxide, and ozone at low concentrations and low temperatures in the atmosphere, of critical importance to studies of the Earth's heat budget. He collaborated with a Cambridge physicist on delineating the absorption and emission characteristics of infrared spectra of hydrocarbons and atmospheric trace gases.

Callendar's main scientific contribution was specifically in anthropogenic climate change; the carbon dioxide theory of climate change.

Beginning in 1938, Callendar revived and reformulated the carbon dioxide theory by arguing that rising global temperatures and increased fossil fuel burning were closely linked. Callendar compiled weather data from stations around the world that clearly indicated a global warming trend of about 0.5°C in the early decades of the twentieth century. Callendar established what would become the standard number of 290 parts per million as the nineteenth-century background concentration of carbon dioxide in the atmosphere and documented an increase of 10% in this figure between 1900 and 1935, which closely matched the amount of fuel burned. Callendar pointed out that humans had long been able to intervene in and accelerate natural processes, and that humanity was now intervening heavily in the slow-moving carbon cycle by "throwing some 9,000 tons of carbon dioxide into the air each minute." In an era before computer climate modeling, Callendar compiled all the available information at that time on the detailed infrared absorption and emission spectra of atmospheric trace gases into a coherent picture of interest and relevance to climate scientists. He argued that the rising carbon dioxide content of the atmosphere and the rising temperature were due to human activities, thus establishing the carbon dioxide theory of climate change in its recognizably modern form. He was the first to establish the link between carbon dioxide and Earth's temperature and this is an amazing contribution to climate change science.

3.10.6 Gilbert Plass and Doubling of Carbon Dioxide

Gilbert Norman Plass (1920–2004) was a Canadian physicist who in the 1950s made predictions about the increase in atmospheric carbon dioxide levels in the twentieth century and its effect on the average Earth temperature that closely matches temperature measurements reported half a century later.

Plass worked mainly in the U.S. and worked as a physicist at the Metallurgical Laboratory of the University of Chicago and later at the Johns Hopkins University. He left academia in 1955 and worked for Lockheed Aircraft Corporation, then joined Ford Motor Company in their Aeronutronic division. In 1963 he accepted a position as the first professor of atmospheric and space science at the Southwest Center for Advanced Studies (now the University of Texas at Arlington). In 1968 he became a professor and head of the department of physics at Texas A & M University.

In 1953 as a result of his work on the effects of carbon dioxide from industrial sources as a greenhouse gas, he stated “At its present rate of increase, the carbon dioxide in the atmosphere will raise the Earth’s average temperature 1.5 °F every 100 years for centuries to come if man’s industrial growth continues, the Earth’s climate will continue to grow warmer.”

Plass made use of early electronic computers and predicted that a doubling of carbon dioxide would cause a warming of Earth’s temperature by 3.6°C. He also predicted that carbon dioxide levels in 2000 would be 30% higher than in 1900 and that the planet would be about 1°C warmer in 2000 than in 1900. Intergovernmental Panel on Climate Change (IPCC) 2007 Fourth Assessment Report estimated a climate sensitivity of 2–4.5°C for a doubling of carbon dioxide, a rise of 37% since pre-industrial times (from about 1750 AD) and a 1900–2000 warming of around 0.7°C.

3.10.7 Hans Suess and Carbon-14 in Carbon Dioxide

Hans Suess (1909–1993) was an Austrian physicist, physical chemist, and geochemist who grew up in Vienna and who had a major role in climate science using radiocarbon (carbon-14, or ^{14}C). In the 1950s, a group at the University of Chicago headed by Willard Libby was using carbon-14 to date ancient materials. These materials were mainly archeological and anthropological, such as pottery and mummies. The Chicago group was also working on the separation and enrichment of isotopes for use in the medical field.

New techniques for isotope separation and enrichment were developed by the Chicago researchers and were used by Suess, who had joined the staff of the U.S. Geological Survey as a geochemist. He later was a founding faculty member of the University of California, Davis. He was responsible for developing radiocarbon dating techniques and contributed to knowledge of the elements and the evolution of the Solar System.

Suess devised a plan to measure carbon isotopes in tree rings. He began to collect old trees with the assistance of staff from the National Park Service and the U.S. Department of Agriculture. Suess’ main concern was studying how carbon moved through the environment.

Carbon-14 originates in the upper atmosphere by bombardment of nitrogen by cosmic rays. Carbon-14 has a half-life of around 50,000 years, so the carbon-14 in fossil fuels has largely disappeared, as most fossil fuels are millions of years old.

Suess was the first one to notice that tree rings had less carbon-14 than would have been present in natural carbon tree rings. The carbon in tree rings had to come from the burning of fossil fuels; otherwise there would be more carbon-14 present.

Libby, in the early 1950s, had suggested that perhaps carbon-14 might be used to determine circulation in the deep oceans. The oceans were known to be a sink for carbon (taken up by the oceans) and were known to play a role as a major part of the carbon cycle. Just how carbon was distributed in the oceans was unknown. It was known that carbon dioxide was exchanged between the atmosphere and ocean water at the ocean's surface, but just how or even if this carbon dioxide was mixed in the deeper ocean waters was not known. It seemed certain that the tremendous mass of the oceans would absorb any excess carbon that might come from human activities like the burning of fossil fuels. Suess' measurements of the distribution of carbon ions in the oceans resulted in the prediction that it could take 1,000 years for them to circulate both horizontally and vertically.

There are three isotopes of carbon found in nature, carbon-12 (^{12}C), carbon-13 (^{13}C), and carbon-14 (^{14}C). ^{14}C is radioactive carbon or radiocarbon. ^{12}C and ^{13}C are stable isotopes of carbon and radiocarbon is not measureable after around 50,000 years, so ancient deposits (more than 50,000 years old) contain no measureable amounts of ^{14}C .

Hans Suess' main contribution to climate change science was to determine that oceanic circulation took too long to distribute carbon ions and as a result the oceans would not absorb the amounts of carbon dioxide that mankind was putting into the atmosphere.

3.10.8 Roger Revelle and Ocean Chemistry

Roger Revelle (1909–1991) was a U.S. scientist who made significant contributions to mankind's understanding of the oceans. He was an oceanographer and a major spokesman for science. He was one of the first scientists to recognize the effects of rising levels of atmospheric carbon dioxide on the Earth's surface temperature. He was a long-time member of Scripps Institute of Oceanography and served as its director from 1951 to 1964.

Revelle served on numerous national committees and was chairman of the Panel of Oceanography of the U.S. National Committee on the International Geophysical Year (IGY). During the planning for the IGY, Scripps was named as the principal center in the Atmospheric Carbon Dioxide Program.

Revelle hired Charles David Keeling who joined the Scripps staff to head the IGY program and began measurements of atmospheric carbon dioxide in 1956. Keeling started measurements of CO_2 in Antarctica and at the volcano Mauna Loa, Hawaii. Revelle became interested in the solubility of calcium carbonate and his interest in carbon dioxide in the atmosphere remained for the remainder of his life.

In 1965, Revelle served as a member of the President's Science Advisory Committee on Environmental Pollution. The committee published the first authoritative U.S.

governmental report in which carbon dioxide was officially recognized as a potential global problem.

3.10.9 *Charles David Keeling and CO₂*

Charles David Keeling (1928–2005) was a U.S. chemist who came to Scripps from California Institute of Technology (Cal Tech) where he had been a postdoctoral fellow in geochemistry. As was seen above, Roger Revelle hired Keeling at Scripps in 1956 to study the geochemistry of carbon and oxygen with an emphasis on the carbon cycle. He was the first scientist to confirm the increase of carbon dioxide in the atmosphere by very precise measurements that produced data which resulted in what is now called the Keeling Curve (Fig. 1.2). Prior to the work of Keeling, no one had quantified that carbon dioxide was steadily increasing in atmospheric concentration and his measurements became a milestone in historical climate change science.

Keeling discovered that the atmosphere breathes in an annual cycle that reflects the influences of photosynthesis, respiration, and atmospheric mixing. Keeling's discovery of the atmospheric background was of great importance, for it motivated his subsequent climatological studies of atmospheric carbon dioxide of the Earth as a whole. By way of example, the discovery of an atmospheric background also eventually motivated global studies by other scientists of additional greenhouse gases such as methane and nitrous oxide and of stratospheric ozone-destroying gases such as chlorofluorocarbons.

Keeling started the observatory on the flanks of Mauna Loa volcano in Hawaii and began his measurement of CO₂ in 1958. He located the observatory up-wind of the volcanic vent. One of the sources of carbon dioxide in the atmosphere is known to be volcanoes, so Keeling had to take care that his CO₂ measurements were not influenced by the gases escaping from the Mauna Loa vent.

Keeling's measurements on Mauna Loa have provided a true measure of the global carbon cycle, an effectively continuous record of the burning of fossil fuel. They also maintain an accuracy and precision that allow scientists to separate fossil fuel emissions from those due to the natural annual cycle of the biosphere, demonstrating a long-term change in the seasonal exchange of CO₂ between the atmosphere, biosphere and ocean.

Mauna Loa is indeed an active volcano and volcanoes release carbon dioxide to the atmosphere; it erupted in 1950, 1975, and 1984. Between eruptions, it emits variable amounts of carbon dioxide (CO₂) and sulfur dioxide (SO₂) from fissures at the summit. The observatory is located on the northern slope of the mountain, 4 miles away from and 2,600 ft lower than the summit, which is 13,675 ft above sea level.

Most of the time, the observatory experiences "baseline" conditions and measures clean air which has been over the Pacific Ocean for days or weeks. Observers know this because the CO₂ analyzer usually gives a very steady reading which varies by less than 3/10 of a part per million (ppm) from hour to hour. These are the conditions used to calculate the averages that go into the graph of atmospheric CO₂ concentrations.

Volcanic CO₂ from the Mauna Loa summit are only detected late at night at times when the regional winds are light and southerly. Under these conditions, a temperature inversion forms above the ground, and the volcanic emissions are trapped near the surface and travel down the side of the mountain slope toward the observatory. When the volcanic emissions arrive at the observatory, the CO₂ analyzer readings increase by several parts per million, and the measured amounts become highly variable for periods of several minutes to a few hours. In the last decade, this has occurred on about 15% of nights between midnight and 6 am.

The carbon dioxide data, measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO₂ in the atmosphere. They were started by Keeling in March of 1958 at a facility now run by the National Oceanic and Atmospheric Administration (NOAA). NOAA started its own CO₂ measurements in May of 1974, and they have run in parallel with those made by Scripps since then. The black curve in the Keeling Curve (Fig. 1.2) represents the seasonally corrected data.

Data are reported as a dry mole fraction defined as the number of molecules of carbon dioxide divided by the number of molecules of dry air multiplied by one million (ppm).

Keeling also noted a seasonal variation in his CO₂ measurements. In the summer months the CO₂ readings would decrease due to plants taking CO₂ out of the atmosphere and using CO₂ in photosynthesis. In winter the CO₂ readings would increase due to plants dying or going dormant and giving up their CO₂ to the atmosphere. This can be seen in the Keeling Curve illustrated in Fig. 1.2.

Keeling's work was motivated by the suggestion, originally made by Svante Arrhenius, that atmospheric carbon dioxide levels might be increasing due to the burning of fossil fuels with potential consequences for global climate. At that time, however, the suggestion was controversial; in part because it was unclear as to what extent the oceans might be buffering the atmospheric CO₂ increase. Within a few years of measurements, the Mauna Loa record had changed the notion of the atmospheric CO₂ increase from a matter of theory to a matter of fact. This was an achievement of tremendous scientific, social, and political importance, and within the scientific community stimulated the involvement of climate researchers such as Syukuro Manabe and others to quantify more precisely the impact of rising CO₂ on global climate. The Mauna Loa record, or Keeling Curve, has become a standard icon symbolizing the impact of humans on the planet.

3.10.10 Syukuro (“Suki”) Manabe and Climate Modeling

Syukuro (“Suki”) Manabe (1931–) is a meteorologist at the Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA located at Princeton University in the U.S. Shortly after receiving his Ph.D. in meteorology in Japan he emigrated to the

U.S. and began work on some of the earliest attempts to model the atmospheric-oceanic system to be able to solve some of the problems of climate science. In the 1960s, Manabe and his research team developed a radiative-convective model of the atmosphere and modeled greenhouse gases such as water vapor, carbon dioxide, and ozone. This was the beginning of long-term research on climate change and global warming. In the late 1960s he began to develop a general circulation model (GCM) of the atmosphere-ocean-land system.

Suki Manabe pioneered the use of computers to simulate global climate change and natural climate variations.

3.10.11 James Hansen and Temperature Analysis

James Hansen (1941–) is the director of the Goddard Institute of Space Studies (GISS) at Columbia University in New York City, New York and is an adjunct professor in the Department of Earth and Environmental Sciences at Columbia University. He began studying the atmosphere of Venus and later applied his work to the Earth's atmosphere. He developed radiative transfer models to better understand the effects of aerosols and trace gases on Earth's climate. Hansen's development and use of global climate models has contributed to the further understanding of the Earth's climate.

Hansen has become an activist for action to mitigate the effects of climate change, which on a few occasions has led to his arrest. He is particularly active in opposition to coal mining and coal-fired power plants and the contaminants they emit, including carbon dioxide, mercury, arsenic, and others.

In 1987, Hansen and one of his colleagues (S. Lebedeff) devised a method of obtaining a global average temperature. This method continues to be used by GISS and agencies in other countries to arrive at an annual average global temperature. Additional information can be obtained from the following website: <http://www.giss.nasa.gov/>.

3.10.12 William Ruddiman and Paleoclimate

William F. Ruddiman is a noted paleoclimatologist and a professor emeritus in the Environmental Sciences Department at the University of Virginia. He is perhaps best known for proposing that humans began to affect carbon dioxide and methane concentrations in the atmosphere as early as 10,000 years prior to the present (2012) by deforestation and the beginnings of agriculture. Ruddiman is the author of two books and over 150 scientific papers in peer-reviewed scientific journals. He is a strong proponent of the Anthropocene designation beginning 8,000 years BC when humans began to change the composition of the atmosphere with early agricultural practices.

3.10.13 *Gavin Schmidt and GISS*

Gavin Schmidt is a climate scientist at the Goddard Institute of Space Studies (GISS) in New York City, NY. He specializes in climate models and is interested in modeling past, present, and future climate. He works on developing and improving coupled climate models and, in particular, is interested in how their results can be compared to paleoclimate data. He has worked on assessing the climate response to multiple forcings, including solar irradiance, atmospheric chemistry, aerosols, and greenhouse gases.

A general outline of one of Gavin Schmidt's recent papers shows the following:

1. Abstract – a synopsis of what is contained in the paper;
2. Introduction – an introduction to the problems to be solved with the work done for the project;
3. Data and Methods – what materials are available for study and how the study was conducted;
4. Results and Conclusions;
5. Appendices;
6. References.

3.10.14 *Stefan Rahmstorf, Sea Level and Temperature Rise*

A physicist and oceanographer by training, Stefan Rahmstorf has moved from early work in general relativity theory to working on climate issues. He has done research at the New Zealand Oceanographic Institute, at the Institute of Marine Science in Kiel and since 1996 at the Potsdam Institute for Climate Impact Research in Germany (in Potsdam near Berlin, Germany). His work focuses on the role of ocean currents in climate change, past and present. He teaches physics of the oceans as a professor at Potsdam University.

Rahmstorf is a frequent publisher in the area of ocean effects on climate and rising sea level due to melting glaciers. He is a regular contributor to the website RealClimate.com which is highly recommended as a source of updated climate change information.

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