Chapter 7

Scientists' Tools for Seeking Answers: Scientific Method and Verification

Underneath it all, the most important tool climatologists have for resolving unanswered climate questions is the scientific method, along with a wide range of approximations to it. This is important because science adopts the same basic principle that journalists use: verification.

We are all more or less familiar with the scientific method, but it tends to get lost in the razzle-dazzle and obscurity of high-tech science today. Scientists often (although by no means always) proceed in their investigations by forming hypotheses (informed guesses) about how the natural world works, devising experiments to test a hypothesis, gathering data, and then evaluating how closely the results fit their predictions. This cycle is repeated over and over, as losing hypotheses are rejected and winning hypotheses are ever more finely tuned and elaborated. Science seeks truths that can be demonstrated repeatedly, proven logically, and measured quantitatively.

Strengths and Limitations of Models

The real world is large, complex, and mysterious; this makes science interesting. Understanding the climate system is one of the biggest challenges scientists face because of the many physical, chemical, and biological systems it links in causal chains and cycles. Almost every earth science is involved in climate study — making it as much an organizational problem as an intellectual one.

Even greater challenges arise from the fact that Earth is too big and too precious to be put in a test tube. Some Earth systems are simply too big to be measured directly. For example, carbon flows between the seas, atmosphere, soil, and living things. Very sophisticated sampling and inference are needed to come up with good estimates of these things. Moreover, ethical constraints prevent scientists from testing Earth the way they would a laboratory rat, testing toxicity by seeing whether a given dose will kill the subject. We could "experiment" with climate by continuing to pump greenhouse gases into the atmosphere — but we might not want to accept the possible real-life consequences.

Computer Modeling

Computer models make a very good tool for investigating climatic complexity and variability. But no computer can simulate the behavior of every wisp of cloud or every gallon of sea water, even though today's gargantuan supercomputers can make calculations well beyond the power of the unaided human brain. Even more importantly, computer simulations give us the opportunity to ask "What if?" — to examine the possible consequences of our actions before they cause irreconcilable harm.

Nowhere is the power of computers more seductive than in their implied promise to tell us more than we know. Programmers know computers are capable of multiplying and replicating human errors as well as human knowledge. It is worth remembering that a computer "model" is merely a simplified mathematical description of how we think the climate system works. A model is nothing more than a set of working hypotheses or theories and is designed to encapsulate an understanding of the system in a quantitative way. Indeed, one who listens to scientists talk notices that they use the terms "theory" and "model" somewhat interchangeably. Computer models can only tell us the implications of what we think we already know about how natural climate processes work. Like any plausible rumor or tip, they too must be verified. A model can not "prove" a theory.

Simple Model

In the simplest sense, a model is a rule attempting to describe how something in the real world works. For example, an equation in physics states that for a given confined mass of gas held at a constant temperature, its pressure is inversely proportional to its volume. Squeeze the gas into half the space and its pressure doubles. This is known as Boyle's law. In other words, if P is pressure, V is volume, and K is a constant, then $PV=K$. This equation provides a way of predicting how a confined gas will behave. As long as Boyle's law holds true, and as long as the temperature does not change, it is a good model. We could program a pocket calculator to tell us what P is when we punch in V, and vice versa.

We could devise a model attempting to describe what happens to the solar energy arriving at Earth. Such a model might be built on the assumption (right or wrong) that because Earth seems to stay the same average temperature from year to year, incoming radiation must be balanced by outgoing radiation. This could be expressed as an equation, too. Or it could just as easily be expressed as a picture. Figure 4, on page 20, shows outgoing radiation balancing incoming. It also shows some further refinements: how much incoming radiation is reflected by clouds and by Earth's surface, and how much is absorbed and turned into heat. Each of these phenomena could be put into the equation as a numerical value, say a percentage. We could say that of the solar energy arriving at Earth, 25% is reflected by clouds, 5% is reflected by Earth, 25% is absorbed by the clouds, and 45% is absorbed by Earth. Hypothetically, we could make similar statements about the radiant heat energy leaving Earth. The whole thing could be stated as a single equation. The equation or picture would work as a system. If we raised the amount of energy reflected by Earth's surface, we would have to reduce the amount absorbed accordingly. This is a simple numerical model.

Such a model could be called zero-dimensional. It treats all solar energy as if it were a single ray, or arrow, impinging on Earth at various altitudes, and describes only a single thing: energy. A more complicated model might try to take into account the fact that Earth has a curved surface and is spinning, and that solar rays striking the equator might act differently than rays striking the poles. Such a model would add the spatial dimensions of latitude and longitude to the dimension of altitude.

Three-Dimensional Climate Model

Models used for weather and climate studies treat space three-dimensionally. They divide Earth's atmosphere into many grid boxes and many layers, then describe numerically what happens in each cell. They actually have many more variables than just three since they describe many more things than just energy flow and how processes occur in time as well.

Most climate study models are derived from a kind of model developed for weather forecasting, called general circulation models (GCMs). They attempt to describe flows of energy, air mass, movement, and moisture over the entire globe.

Much is understood about global circulation. Consequently, it is possible to construct a numerical model that describes it quite realistically. Climatologists know, for example, that the sun heats Earth's surface at the Equator more than it does at the poles. And they know, too, that the redistribution of heat from the Equator to the poles, together with Earth's spin, is what drives the major prevailing air currents, such as the jet stream and the trade winds. All this can be expressed in the form of five major equations that describe the laws of conservation of momentum, heat, and mass. This system of equations is solved repeatedly for each grid square over successive time steps in a GCM. The models work well enough to be quite useful for weather prediction.

GCMs are really just a foundation on which researchers build more complex models for studying possible climate change. For example, some models try to account for soil moisture, sea ice, or any number of other variables. Because the oceans serve as a giant reservoir, absorbing heat and delaying atmospheric warming, the coupling of atmospheric models to ocean circulation models is an important research frontier.

How Do Climate Models and Weather Forecast Models Differ?

Strengths, Weaknesses of Numerical Models

Meteorologists have developed such skill with computer models that they can use them to forecast weather quite successfully much of the time. These models are called numerical models, because they quantify heat, moisture, and wind momentum, using the same set of equations as GCMs. In fact, numerical weather models were developed first, and the principles expanded to make GCMs.

There are good reasons that numerical weather models work so well. They are based on the laws of physics. They are quantitative, which means they can sometimes be quite precise. They start with a known set of weather conditions. And they generally look only a few days into the future. They (actually their operators) are so skilled they can even assign probabilities to their predictions.

There are limits, however, to what traditional numerical weather or atmospheric circulation models can do for the prediction of climate.

For one thing, climate is influenced by many conditions and forces which aren't much taken into account in weather models: ocean currents, land cover, ice, and myriad chemical and biological processes. Climate models often have coarser resolution and are run forward much further into the future.

The further weather models look into the future, the worse they are at predicting. Models make a chain of predictions based on earlier conditions — "If it rains in Chicago Tuesday afternoon it will cool off that evening." If A then B; if B then C; and so on. But if it doesn't rain in Chicago until late Tuesday night, then all bets are off. The longer this chain of conditional predictions, the greater the uncertainty about the final outcome. Uncertainty, like compound interest, tends to grow geometrically over time.

So if long-term weather forecasts, on the order of a month ahead, have less than a 60 percent chance of accuracy, then how can a climate forecast 50 years into the future be reliable?

In answering some questions, far-future modeling will be no help at all. Will it rain or shine on a given April day in the year 2050? Models will not give a reliable answer. In answering other questions, however, the model may be quite reliable. How much will the average annual temperature at the Equator change? The model may be right on target in answering that question.

The key lies in asking the right questions. Climate is about those major aspects of the weather system that influence the atmosphere and vary only slowly over time even though weather varies. On any time scale we can imagine, the sun will always heat the poles less than it does the Equator because it strikes the poles at oblique angles. Earth will always spin in the same direction. The continents and oceans will "always" (for purposes of useful current perspectives) be in the same position. These underlying forces do not vary randomly over time but will continue to influence climate the same way 50 years into the future.

Roles of Satellites and of Ground-Truthing

It is easy for scientists — and even easier for journalists — to succumb to the temptation of confusing models with the reality they are supposed to represent. Models are theories, not facts. In the end, models cannot "prove" theories; only observable facts can do that. Models are only as good as the "reality checks" they are based on.

Fortunately, the reality checks available to climatologists are getting better all the time. Systematic measurements were institutionalized by many governments during the 20th century. In the United States, agencies like the National Oceanic and Atmospheric Administration (NOAA), parent agency of the National Weather Service, perform these jobs. In recent decades, coordination among nations has grown through organizations like the World Meteorological Organization (WMO). Even more recently, observations have been focused more specifically on climate through forums like the Intergovernmental Panel on Climate Change (IPCC).

Since the late 1950s, the U.S. and other countries' satellites have offered unprecedented observation platforms for instruments studying weather and climate on the global scale. We take for granted now the satellite pictures of swirling cloud formations we see on the evening TV news, but the density and detail of weather data they brought was revolutionary. Since national defense priorities changed with the end of the Cold War, the current generation of satellites (such as NASA's Earth Observing System) will focus unprecedented instrumental resources on Earth.

Still, satellite instruments are only as good as their calibration. The vast amounts of data they can supply are valuable only if they are repeatedly validated and adjusted by comparing them with "ground truth" — measurements from ground stations and instruments in the lower atmosphere and at sea — which will continue to be vital.

Historic Climate Information

One of the first ways to validate a climate model (or any theory) is to ask it a question you already know the answer to. Knowing the historic surface temperatures and concentrations of greenhouse gases, scientists can see how well their models "predict" what they know actually has happened.

Past climate, or what scientists call paleoclimate, offers a wealth of information that does more than just validate models. It supplies basic insight into climate processes and what we can expect from them. Unfortunately, the record of Earth's climate history, as measured consistently by instruments in many places, does not go back much more than a century. Consistent instrument measurements of CO_2 concentrations are not even five decades old.

Fortunately, however, paleoclimatologists have collected a vast amount of indirect data about past climate through hard work, ingenuity, and inference. For example, written shipping records noting ice conditions in the canals of the Netherlands, or wine-makers' records of grape harvests, can be used to infer long series of year-to-year variations. Tree-rings can tell much about patterns of wet and dry (or cold and warm) years going back in history. Other methods yield data about even older climates: examination of sea-bottom sediments, fossil pollen grains, oxygen isotopes in fossil water, air bubbles in deep glacial ice, and so forth. Still older geological clues, carved in the topography of the rocks themselves, record the changing sea levels associated with the coming and going of ice ages over millions of years.

Improvements in Weather and Climate Data and in Atmospheric and Oceanic Observations

The far-flung network of weather stations across the United States and around the globe have long provided fairly precise data with broad spatial coverage. They have measured basics like surface air temperature, humidity, precipitation, wind speed and direction, and barometric pressure. When such data are collected systematically by agencies like the National Weather Service, they provide a wealth of information for testing climate change theories.

The quality and quantity of this basic instrument data will need to be further improved to be more useful for studies of climate change. Longer and longer continuous time series are needed to evaluate climate changes which can occur not just over decades, but over centuries. A true measurement of "global mean" temperatures will require both satellite instruments and an array of ground stations that give a truly representative sample of ground temperatures. The current network is not all a statistician could ask for, since it is skewed toward land and toward the northern hemisphere, among other biases.

Although surface temperature is often seen as the “bottom line” in climate change as far as impacts on humans are concerned, climatologists need to know much more. They need to know more about temperatures, air movements, energy fluxes, moisture, trace gas concentrations, and many other variables through the whole vertical column, from the oceans depths to the stratosphere. Such data will help them build more realistic models and detect the “fingerprints” that might identify any greenhouse warming brought about by humans’ activities.

Even while we have yet to deploy enough of the old-fashioned basic instruments like thermometers, new and sophisticated instruments are being refined and coming into use. Many of these will help answer the more complex questions raised in climate studies. Such instruments on satellites, for example, already are helping scientists get a more exact fix on Earth’s radiation budget. Various spectrometers can do more than quantify incoming short-wave solar radiation and outgoing infrared radiation. They can help analyze trace gas concentrations at various atmospheric levels and assess how these gases respond to radiation.

Meteorologists have long used radiosondes — balloon-borne instrument pods reporting back via radio — to take a vertical cross-section of the atmosphere. Today, their information is supplemented with lidar (“light radar”), which uses laser beams to take indirect temperature and humidity readings at many distances through a column of air. Other high-tech methods, such as Doppler radar, which can map wind and storm movements in detail, are in use already. Satellite observations of water vapor content may dramatically improve the prediction of rainfall on time scales of weeks. This, for example, could make predictions of flooding in the Midwest possible with more lead time. Still more exotic developments are coming.

Inherent Predictability Limits

When statisticians talk about making a “prediction,” they mean something quite specific. A statement is not a prediction unless it has two parts: a statement about what might happen in the future, and a quantitative statement about the probability of that event’s happening.

When meteorologists tell us there is a “65 percent chance of snow,” they usually are making predictions, properly named, that are well-grounded statistically. In fact, computer models of weather systems — combined with lots of real-life data about how accurate those models have been in the past — allow them to come up with a number for their chances of being right.

Climate models, as they exist today, are not making “predictions” in this strict sense at all. You may hear politicians and journalists using this term about climate models, but you will rarely hear a rigorous or careful scientist using it. They use fuzzier terms like “scenario” because they still have a fairly weak theoretical basis for assigning probabilities to the outcomes their models simulate.

Even if the models had been available for centuries, and if they could be measured against centuries of real-life data, they might run into various possible limits on the predictability of climate change. Mentioned above are ways that uncertainty can grow, like interest being compounded, as predictions are pushed forward into the future. It is possible that the climate system, instead of changing smoothly as the models envision, might be unstable and change more abruptly, flipping into a new temporarily “stable” state, what scientists term “chaos.”

In terms of earth science, scenarios of climate change are guesses based on guesses based on other guesses ... many times over. There is some uncertainty about how most parts of the climate system behave. While this reality may undercut those who see only absolute certainty, it is not a circumstance from which “don’t worry-be happy” greenhouse skeptics can take much consolation. If we can’t say for certain that global warming is upon us, neither can we say for certain that it is not.

Economics of Data Collection, Observation

It will take large amounts of human effort — and money — in coming decades to gather the huge streams of worldwide data needed to assess climate change. This is not the sort of job a few scientists and a computer can do. Instead, it will be one of the largest-ever cooperative scientific enterprises. Organizational and economic problems will be some of the biggest problems in solving the puzzles of climate change.

Climate change research requires cooperation not only among many individual scientists, but among many scientific disciplines, federal agencies, and nations. Without joint efforts, there will not be enough resources to do the job. It is truly a global research problem.

Although they had started long before, coordinated U.S. national efforts to address climate change gained momentum in the mid-1980s, as did international efforts. By 1989, the White House had pulled together the U.S. Global Change Research Program (USGCRP) to link several agencies in the fiscal 1990 budget. By fiscal 1990, the proposed budget for the program rose above $1 billion. By fiscal 1999, the actual budget had grown to over $1.6 billion, and the White House was proposing almost $1.8 billion for fiscal 2000. Some of this money, of course, was for geoscience programs already long established. But much of the money was new or added to budgets of programs which had been in budget decline for a decade.

One way to get an idea of the enormity of this effort, is simply to count up all the U.S. agencies involved in global change research:

- National Oceanic and Atmospheric Administration (NOAA)
- National Aeronautics and Space Administration (NASA)
- Environmental Protection Agency (EPA)
- Department of Energy
- Department of Agriculture
- Department of Defense
- National Institute for Environmental Health Sciences
- Department of the Interior
- National Science Foundation
- Smithsonian Institution
- Tennessee Valley Authority
- Agency for International Development
- Various intelligence agencies

These are organized under White House and executive branch entities, such as the Office of Science and Technology Policy, the Council of Economic Advisors, the Office of Environmental Policy, and the Office of Management and Budget. Federal science activities are overseen by the president's National Science and Technology Council (NSTC). Below NSTC is the Committee on Environmental and Natural Resources Research (CENR), and below that, the Subcommittee on Global Change Research (SGCR), which puts together the U.S. Global Change Research Program.

That is not the whole list. The agencies with the biggest programs, such as NOAA or the Department of Energy, may each be doing this research in more than a dozen labs scattered across the country. And these are in addition to the dozens of programs at U.S. universities and other entities such as the National Academy of Sciences/National Research Council.

Just managing all the data will be a major challenge. NASA's forthcoming Earth Observing System (EOS) satellites will generate huge new flows of data. NASA and other federal agencies are building bigger mechanisms for archiving and storing such data under the interagency Global Change Data and Information System.

Impact Assessments and R&D Implications *vis a vis* Policy

There are other important research programs under way on climate change, apart from the basic research that will help us know whether, how fast, and how much climate may change. Many address its potential impacts, for example, on the human food supply.

Food crops depend on climate, and crop failure in some parts of the globe may mean that millions of people will starve. If warming continues, sea level will continue to rise, and the oceans will eventually inundate some coastal cities, industries, and ecosystems. Eventually climate change also would force many other changes in land and sea ecosystems. Not all of the changes will be bad for humanity: some could be good if humans know how to adapt to or take advantage of them. For example, global warming could mean increased agricultural production, although not necessarily in the same places that are the breadbaskets of today's world.

Agronomists, ecologists, foresters, and marine biologists are hard at work looking at the implications of a possible warmer world. Plant scientists, for example, are studying how to make crops more productive under colder, warmer, wetter, or drier conditions. They are even studying which plants grow better (as some do) with higher levels of carbon dioxide in the air.

Such research is built on assumptions that human activity that can change climate will continue or accelerate. U.S. and international research also is focused on developing technologies that will allow the human species to have a "sustainable future" on Earth by controlling greenhouse emissions. Research and development in energy efficiency, especially in the burning of fossil fuels, will be one key area. Studies on controlling agricultural methane releases, or efficient use of nitrogen fertilizers, also will be important. Even ways to put methane from landfills and sewage plants to better use are being studied. In fact, many major landfills already harvest methane for power needs.

A Longer View

If we take a step back from the global warming issue, we can see that it is merely a special case of a larger question: how is the growth of human population, technology, and economic activity changing the planet? And the important question behind that one is: how long and how well can Earth's resources sustain the human population?

With skill and luck, we may be able to adapt to a potential global warming for two or three hundred years. But soon after that we will be asking ourselves how long our centuries-long spree of fossil fuel burning can continue before the fuel is used up and gone. That larger question — scientists call it "global change" to be inclusive — is also coming under more scrutiny.