This is the text of an essay in the Web site *“The Discovery of Global Warming”* by Spencer Weart, http://www.aip.org/history/climate. **May 2009**. Hyperlinks within that site are not included in this file. For an overview see the book of the same title (Harvard Univ. Press, rev. ed. 2008).

Simple Models of Climate

What determines the climate? Explanations proliferated—models for climate built out of little more than basic physics, a few equations aided by hand-waving. All began with a traditional picture of a stable system, self-regulated by natural feedbacks. A few nineteenth-century scientists suggested that a change in the level of carbon dioxide gas might cause an ice age or global warming, but most scientists thought the gas could not possibly have such effects. Yet climate did change, as proven by past ice ages. Some pointed out that feedbacks did not necessarily bring stability: in particular, changes in snow cover might amplify rather than dampen a climate shift. In the 1950s, an ingenious (although faulty) model involving changes in the Arctic Ocean suggested a disturbing possibility of arbitrary shifts. Experiments with fluids made that more plausible. Apparently the interlinked system of atmosphere, ice sheets, and oceans could swing in regular cycles or even in random jerks. Worse, around 1970 highly simplified computer models raised the specter of a catastrophic climate runaway. In the 1980s, the center of research shifted to large and complex computer models. These did not show a runaway, but reinforced what many simpler models had been suggesting: the next century would probably see significant greenhouse warming. Meanwhile the simple models remained useful for exploring questions that the large models could not handle.

Basic general greenhouse effect ideas and observations are covered in the core essay on The Carbon Dioxide Greenhouse Effect. Technical calculations on how radiation and heat move through levels of the atmosphere are described in a supplementary essay on Basic Radiation Calculations and for the large-scale computer work, see the essay on General Circulation Models of the Atmosphere.

“This is a difficult subject: by long tradition the happy hunting ground for robust speculation, it suffers much because so few can separate fact from fancy.”
— *G.S. Callendar*[1]

“Meteorology is a branch of physics,” a weather expert remarked in 1939, “and physics makes use of two powerful tools: experiment and mathematics. The first of these tools is denied to the meteorologist and the second does not prove of much use to him in climatological problems.” So many interrelated factors affected climate, simplifying assumptions that the result would never match reality. It wasn’t even possible to calculate from first principles the average temperature of a place, let alone how the temperature might change in future years. And “without numerical values our deductions are only opinions.”[2]

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[1] Callendar (1961), p. 2.

[2] Simpson (1939-40), p. 191.

That didn’t stop people from putting forth explanations of climate change. A scientist would come up with an idea about how certain factors worked and explain it all in a page or two, helped along by some waving of hands. Some scientists went on to build a few equations and calculate a few numbers. At best they could show only that the factors they invoked could have effects of roughly the right magnitude. There was no way to prove that some other explanation, perhaps not yet thought of, would not work better. These mostly qualitative “theories” (in fact, merely plausible stories) were all anyone had to offer until digital computers came into their own, late in the 20th century. Until then, the climate community had good reason to keep theory at arms’ length. Even those who tried to think in general physical terms hesitated to call themselves “theorists,” an almost pejorative term in meteorology.

The science did have a foundation, at least potentially, in simple ideas based on undeniable physical principles. The structures that scientists tried to build on these principles were often called “models” rather than “theories.” Sometimes that was just an attempt to hide uncertainty (a paleontologist complained that “‘model’... is just a word for people who cannot spell ‘hypothesis’”).[1] But calling a structure of ideas a “model” did emphasize the scientist’s desire to deal with a simplified system that one could almost physically construct on a workbench—something that embodied a hands-on feeling for processes. The great trick of science is that you don’t have to understand everything at once. Scientists are not like the people who have to make decisions in, say, business or politics. Scientists can pare down a system into something so simple that they have a chance to understand it.

The first job of a model was to explain, however crudely, the world’s climates as presently seen in all their variety. After all, the main business of climatologists until the mid-20th century was the simple drudgery of compiling statistics. Knowledge of average and extreme temperatures and rainfall and the like was important to farmers, civil engineers, and others in their practical affairs—never mind guessing at explanations. But people could not resist trying to explain the numbers. A textbook would start off with the main factor, the way sunlight and thus warmth varies with latitude (perhaps with some calculations and charts). There would follow sections on the prevailing winds that brought rain, and how mountain ranges and ocean currents could affect the winds, and so forth. It was all soundly based on elementary physics. It was a dry exercise, however, not so much a theory of climate as a static regional description.[2]

Asked about changes in climate, most climatologists at mid-century would think of the extremes that people should plan for—the worst heat wave to be expected or the “hundred-year flood.” If there was any pattern to such changes, experts believed it would be cyclical. Rather than try to build a physical theory, those who took any interest in the question mostly looked to numerical studies. Perhaps eventually someone would find correlations that pointed to a simple physical

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[1] Ager (1993), p. xvi.

[2] A mid-century example of a technical text is Haurwitz and Austin (1944); and a more popular work, Hare (1953).

explanation. The varying number of sunspots, for example, might signal changes in the Sun that correlated with climate cycles.

The simplest and most widely accepted model of climate change was *self-regulation*, which meant that changes were only temporary excursions from some natural equilibrium. Through the first half of the 20th century, textbooks of climatology treated climate in a basically static fashion. The word “climate” itself was *defined* as the long-term average weather conditions, the stable point around which annual temperature and rainfall fluctuated.[1] After all, in their records of reliable observations the meteorologists found only minor fluctuations from decade to decade. These records went back less than a century, but they supposed that one century was much like the next (aside from changes that took place over many thousands of years, like the ice ages, which were themselves seen as excursions from the very long-term average). Climatologists expanded this idea into a “doctrine,” as one critic called it, “that the present causes of climatic instability are not competent to produce anything more than temporary variations, which disappear within a few years.”[2] A leading climatologist put it straightforwardly in 1946: “We can safely accept the past performance as an adequate guide for the future.”[3]

Almost everyone believed in the natural world’s propensity to automatically compensate for change in a self-sustaining “balance.” If climate ever diverged toward an extreme, before long it would restore itself to its “normal” state. As evidence, the atmosphere had not changed—or at least not *extremely* radically—over the past half-billion years.[4] And scientists came up with plausible regulating mechanisms (some of them are described below). The approach expressed a generally sound intuition about the nature of climate as a process governed by a complex set of interactions, all feeding back on one another. But romantic views that stability was guaranteed by the supra human, benevolent power of Nature gave a false confidence that every feature of our environment would stay within limits suitable for human civilization. *Issues of complexity and stability in the social structure of climate science are explored in a supplementary essay on Climatology as a Profession.*

Certainly people knew that climate did change. There was abundant historical evidence of variations lasting a few decades or centuries, random swings or (as some thought) regular cycles. Perhaps periods of drought like the American Dust Bowl of the 1930s recurred on some

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[1] E.g., “By 'climate' we mean the sum total of the meteorological phenomena that characterise the average condition of the atmosphere at any one place on the Earth’s surface.” Hann (1903), p. 1; I surveyed a sample of climate literature and textbooks, including, e.g., Blair (1942), pp. 90-94, 100-101; George C. Simpson, preface to Brooks (1922a), pp. 7-8.

[2] Huntington (1914), p. 479.

[3] Landsberg (1946), pp. 297-98; for the history in general see Lamb (1995), pp. 1-3.

[4] For example, Chamberlin (1906), pp. 364-65.

schedule, or perhaps not. Most of these changes were poorly measured, but some climatologists sought to understand them, more or less as a sideline. Far more impressive were the ice ages of the past few million years, undeniable proof that climate could change enormously. Looking farther back, geologists found evidence of much earlier ice ages, as well as periods when most of the Earth had basked in tropical warmth. Understanding these great alterations of the far past posed a fascinating scientific puzzle, with no apparent practical value whatsoever.

Basic Physics (19th century)

“As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth’s surface.” Thus in 1862 John Tyndall described the key to climate change. He had discovered in his laboratory that certain gases, including water vapor and carbon dioxide (CO_2), are opaque to heat rays. He understood that such gases high in the air help keep our planet warm by interfering with escaping radiation.[1]

This kind of intuitive physical reasoning had already appeared in the earliest speculations on how atmospheric composition could affect climate. It was in the 1820s that Joseph Fourier first explained that the Earth’s atmosphere retains heat radiation. He had asked himself a deceptively simple question, of a sort that physics theory was just then beginning to learn how to attack: what determines the average temperature of a planet like the Earth? When light from the Sun strikes the Earth’s surface and warms it up, why doesn’t the planet keep heating up until it is as hot as the Sun itself? Fourier’s answer was that the heated surface emits invisible infrared radiation, which carries the heat energy away into space. But when he calculated the effect with his new theoretical tools, he got a temperature well below freezing, much colder than the actual Earth.

The difference, Fourier recognized, was due to the Earth’s atmosphere. Somehow it kept part of the heat radiation in. He tried to explain this by comparing the Earth with its covering of air to a box with a glass cover. That was a well-known experiment—the box’s interior warms up when sunlight enters while the heat cannot escape.[2] This was an over simple explanation, for it is quite different physics that keeps heat inside an actual glass box, or similarly in a greenhouse. (The main effect of the glass is to keep the air, heated by contact with sun-warmed surfaces, from wafting away, although the glass does also keep heat radiation from escaping.) Nevertheless, trapping of heat by the atmosphere eventually came to be called “the greenhouse effect.”[3]

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[1] Tyndall (1873b), p. 117.

[2] “The effect of solar heat on air contained in transparent containers [*enveloppes*] has long since been observed.” Fourier (1824); Fourier (1827); reprinted in Fourier (1890), quote p. 110; for discussion, see Fleming (1998), ch. 5.

[3] The term was first widely popularized in the 1960s, although already in 1896 Arrhenius somewhat inaccurately wrote, “Fourier maintained that the atmosphere acts like the glass of a

Not until the mid-20th century would scientists fully grasp, and calculate with some precision, just how the effect works. A rough explanation goes like this. Visible sunlight penetrates easily through the air and warms the Earth's surface. When the surface emits invisible infrared heat radiation, this radiation too easily penetrates the main gases of the air. But as Tyndall found, even a trace of CO_2, no more than it took to fill a bottle in his laboratory, is almost opaque to heat radiation. Thus a good part of the radiation that rises from the surface is absorbed by CO_2 in the middle levels of the atmosphere. Its energy transfers into the air itself rather than escaping directly into space. Not only is the air thus warmed, but also some of the energy trapped there is radiated back to the surface, warming it further.

That's a shorthand way of explaining the greenhouse effect—seeing it from below, from "inside" the atmosphere. Unfortunately, shorthand arguments can be misleading if you push them too far. Fourier, Tyndall and most other scientists for nearly a century used this approach, looking at warming from ground level, so to speak, asking about the radiation that reaches and leaves the surface of the Earth. So they tended to think of the atmosphere overhead as a unit, as if it were a single sheet of glass. (Thus the "greenhouse" analogy.) But this is not how global warming actually works, if you look at the process in detail.

What happens to infrared radiation emitted by the Earth's surface? As it moves up layer by layer through the atmosphere, some is stopped in each layer. (To be specific: a molecule of carbon dioxide, water vapor or some other greenhouse gas absorbs a bit of energy from the radiation. The molecule may radiate the energy back out again in a random direction. Or it may transfer the energy into velocity in collisions with other air molecules, so that the layer of air where it sits gets warmer.) The layer of air radiates some of the energy it has absorbed back toward the ground, and some upwards to higher layers. As you go higher, the atmosphere gets thinner and colder. Eventually the energy reaches a layer so thin that radiation can escape into space.

What happens if we add more carbon dioxide? In the layers so high and thin that much of the heat radiation from lower down slips through, adding more greenhouse gas means the layer will absorb more of the rays. So the place from which most of the heat energy finally leaves the Earth will shift to higher layers. Those are colder layers, so they do not radiate heat as well. The planet as a whole is now taking in more energy than it radiates (which is in fact our current situation). As the higher levels radiate some of the excess downwards, all the lower levels down to the surface warm up. The imbalance must continue until the high levels get warmer and radiate out

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hothouse," Arrhenius (1896), p. 237; the word "greenhouse" perhaps first appeared in this context in a study which explained how greenhouses keep the warmed air from rising and blowing away, and that this matters more than the fact that infrared radiation from within does not escape through the glass (which is more like what happens in the atmosphere), Wood (1909); for the science, see also Lee (1973); Lee (1974); possibly the first widely seen use of the phrase "greenhouse effect" was in a 1937 textbook (repeated in later editions), wrongly describing "the so-called 'greenhouse effect' of the Earth's atmosphere" as an effect "analogous to that of a pane of glass." Trewartha (1943), p. 29.

more energy. As in Tyndall's analogy of a dam on a river, the barrier thrown across the outgoing radiation forces the level of temperature everywhere beneath it to rise until there is enough radiation pushing out to balance what the Sun sends in.

While that may sound fairly simple once it is explained, the process is not obvious if you have started by thinking of the atmosphere from below as a single slab. The correct way of thinking eluded neary all scientists for more than a century after Fourier. Physicists learned only gradually how to describe the greenhouse effect. To do so, they had to make detailed calculations of a variety of processes in each layer of the atmosphere. *(For more on absorption of infrared by gas molecules, see the essay on Basic Radiation Calculations.)*

Despite Fourier's exceptional prowess in mathematics and physics, he lacked the knowledge to make even the simplest numerical calculation of how radiation is absorbed in the atmosphere.[1] A few other 19th-century scientists attempted crude calculations and confirmed that at the Earth's distance from the Sun, our planet would be frozen and lifeless without its blanket of air .[2] Tyndall followed with rich Victorian prose, arguing that water vapor "is a blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapour from the air... and the sun would rise upon an island held fast in the iron grip of frost."[3] Tyndall needed no equations, but only simple logic, to see what many since him overlooked: it is at night that the gases are most important in blocking heat radiation from escape, so it is night-time temperatures that the greenhouse effect raises the most.

These elementary ideas were developed much further by the Swedish physical chemist Svante Arrhenius, in his pioneering 1896 study of how changes in the amount of CO_2 may affect climate. Following the same line of reasoning as Tyndall, Arrhenius pointed out that an increase in the blocking of heat radiation would make for a smaller temperature difference between summer and winter and between the tropics and the poles.

Arrhenius's model used an "energy budget," getting temperatures by adding up how much solar energy was received, absorbed, and reflected. This resembled what his predecessors had done with less precise physics.[4] But Arrhenius's equations went well beyond that by taking into account another physical concept, elementary but subtle, and essential for modeling real climate

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[1] Fourier admitted that "we are no longer guided in this study [of the temperature effects of the atmosphere] by a regular mathematical theory" Fourier (1827) (also in his 1824 paper); reprinted in Fourier (1890), p. 110.

[2] Pouillet (1838).

[3] Tyndall (1863a), pp. 204-05.

[4] For energy budget models, see Kutzbach (1996).

change. This was what one turn-of-the-century textbook called “the mutual reaction of the physical conditions”—today we would call it “feedback.”

An early example had been worked out by James Croll. This self-taught British scientist who worked as a janitor and clerk in institutions where he could be near the books he needed to develop his influential theory of the ice ages. Croll noted how the ice sheets themselves would influence climate. When snow and ice had covered a region, they would reflect most of the sunlight back into space. The Sun would warm bare, dark soil and trees, but a snowy region would tend to remain cool. If India were somehow covered with ice, its summers would be colder than England’s. Croll further argued that when a region became cooler, the pattern of winds would change, which would in turn change ocean currents, perhaps removing more heat from the region. Once something started an ice age, the pattern could become self-sustaining.[1]

Arrhenius stripped this down to the simple idea that a drop of temperature in an Arctic region could mean that some of the ground that had been bare in summer would become covered with snow year-round. With less of the dark tundra exposed, the region would have a higher “albedo” or reflectivity, that is, the ground would reflect more sunlight away from the Earth. That would lower the temperature still more, leaving more snow on the ground, which would reflect more sunlight, and so on. This kind of self-reinforcing cycle would today be called “positive feedback” (in contrast to “negative feedback,” a reaction that acts to hold back a change). Such a cycle, Arrhenius suggested, could turn minor cooling into an ice age. Such gradual processes were far beyond his power to calculate, however, and it would be a big enough job to find the immediate effect of a change in CO_2.

Arrhenius showed his physical insight at its best when he realized that he could not set aside another simple feedback, one that would immediately and crucially exaggerate the influence of any change. Warmer air would hold more moisture. Since water vapor is itself a greenhouse gas, the increase of water vapor in the atmosphere would augment the temperature rise. Arrhenius therefore built into his model an assumption that the amount of water vapor contained in the air would rise or fall with temperature. He supposed this would happen in such a way that relative humidity would remain constant. That oversimplified the actual changes in water vapor, but made it possible for Arrhenius to roughly incorporate the feedback into his calculations. The basic idea was sound. The consequences of adding CO_2 and warming the planet a bit would indeed be amplified because warmer air held more water vapor. In a sense, raising or lowering CO_2 acted mainly as a throttle to raise or lower the really important greenhouse gas, H_2O.

The numerical computations cost Arrhenius month after month of laborious pencil work as he estimated the energy balance for each zone of latitude. It seems he undertook the massive task partly as an escape from melancholy: he had just been through a divorce, losing not only his wife but custody of their little boy. The countless computations could hardly be justified scientifically, given the large uncertainties in the available data—for example, the details of how the

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[1] Croll (1875); “mutual reaction” Hann (1903), p. 389.

atmosphere absorbs radiation in different regions of the infrared spectrum were largely unknown. Moreover his model was crude, neglecting crucial effects such as possible changes in cloudiness as the moisture in the air changed with warming or cooling. Nevertheless he came up with numbers that he published with some confidence.[1]

"I should certainly not have undertaken these tedious calculations," Arrhenius wrote, "if an extraordinary interest had not been connected with them."[2] The prize sought by Arrhenius was the solution to the riddle of the ice ages. He focused on a *decrease* in CO_2 as a possible cause of cooling. But he also took the trouble to estimate what might happen if the amount of gas in the atmosphere, at some distant time in the past or future, was double its present value. He computed that would bring roughly 5 or 6 °C of global warming.

This result is not far from the range that scientists would compute a century later using vastly better models—the current estimate is that a doubling of CO_2 will bring some 3 degrees of warming, give or take a degree or two. Did Arrhenius end up in the same range by sheer luck? Partly, but not entirely. In the sort of simple physics and chemistry calculations where Arrhenius had made his name, you can expect to come out roughly right if you address a powerful physical effect in a straightforward way, starting with decent data. The data Arrhenius fed into his calculations (based on Samuel P. Langley's measurements of solar radiation reaching the Earth's surface) were mostly in the right range. And Arrhenius included all the obvious physics theory.

But climate is not a simple physical system. A true calculation of greenhouse effect warming requires measurements far more accurate and far more complete than Langley's. The details of exactly what bands of radiation are absorbed by CO_2 and water molecules might have happened to be arranged so as to produce a markedly higher or lower amount of warming. As for theory, Arrhenius's model planet was mostly static. He deliberately left aside factors he could not calculate, such as the way cloudiness might change over the real Earth when the temperature rose. He left aside the huge quantities of heat carried from the tropics to the poles by atmospheric movements and ocean currents, which also might well change when the climate changed. Most important, he left aside the way updrafts would carry heat from a warmer surface into the upper atmosphere. In 1963, when a scientist made a calculation using roughly comparable assumptions, but with the aid of improved data on the absorption of radiation and an electronic computer, he found a far greater greenhouse warming—indeed impossibly greater. Arrhenius's assumptions left out too much that was necessary to get a valid answer.[3]

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[1] Arrhenius (1896); see Crawford (1996), chap. 10; Crawford (1997); reprinted with further articles in Rodhe and Charlson (1998).

[2] Arrhenius (1896), p 267.

[3] If Langley's measurements had been entirely accurate, Arrhenius would have come even closer to the warming given by current estimates, according to Ramanathan and Vogelman (1997). But S. Manabe (personal communication) points out that Arrhenius got reasonable results

Yet Arrhenius could have felt some confidence that he had not overlooked any terribly potent effect. Calculations aside, since the atmosphere keeps the surface of the Earth warm—in fact, roughly 40°C warmer than a bare rock at the same distance from the Sun—a few degrees sounds like about the right effect for a change in the atmosphere that modestly altered the balance of radiation. Arrhenius also knew that in past geological ages the Earth's climate had in fact undergone changes of a few degrees up or down, not many tens of degrees nor mere tenths of a degree. While neither Arrhenius nor anyone for the next half-century had the tools to show what an increase of CO_2 would really do to climate, he had given a strong hint of what it *could possibly* do.

A crude idea of how the amount of CO_2 could affect radiation was only the first half of a calculation of global warming. The other half would be a model for figuring how the amount of CO_2 itself might change. A colleague of Arrhenius, Arvid Högbom, had already published some preliminary ideas. That stimulated an American geologist and bold thinker, Thomas C. Chamberlin, to ponder the role of the gas in climate change. Arrhenius's 1896 paper spurred Chamberlin to publish "a paper which, I am painfully aware, is very speculative..." The speculations revolved around the great puzzle of the ice ages. Chamberlin later remarked how ice ages were "intimately associated with a long chain of other phenomena to which at first they appeared to have no relationship." He was the first to demonstrate that the only way to understand climate was to understand almost everything about the planet together—not just the air but the oceans, the volcanoes bringing gases from the deep interior, the chemistry of weathered minerals, and more.

Chamberlin's novel hypothesis was that ice ages might follow a self-oscillating cycle driven by feedbacks involving CO_2. The gas was originally injected into the atmosphere in spates of volcanic activity. It was steadily withdrawn as it combined with minerals during the weathering of rocks and soil. If the volcanic activity faltered, then as minerals leached the gas out of the atmosphere, the planet would cool. Feedbacks could make a temporary dip spiral into a self-reinforcing decline. For one thing, as the land cooled, bogs and the like would decompose more slowly, which meant they would lock up carbon in frozen peat, further lowering the amount of CO_2 in the air. Moreover, as the oceans cooled, they too would take up the gas—warm water evaporates a gas out, cold water absorbs it. The process would stop by itself once ice sheets spread across the land, for there would then be less exposed rock and bogs taking up CO_2. Reversing the process could bring a warming cycle.[1]

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in large part because he underestimated the absorptivity of water vapor, and thus underestimated the crucial influence of water vapor feedback on the heat balance, a feedback kept within bounds in the real world by the upward convection of heat.

[1] Chamberlin (1897), "speculative" p. 653; see also Chamberlin (1898); Chamberlin (1899), "long chain" pp. 546-47; Tolman (1899); Fleming (1998), p. 90; Chamberlin (1923); for Chamberlin's work more generally, Fleming (2000); for Högbom's contribution, Berner (1995).

Chamberlin seemed only to be adding to the tall pile of speculations about ice ages, but along the way he had pioneered the modeling of global movements of carbon. He made rough calculations of how much carbon was stored up in rocks, oceans, and organic reservoirs such as forests. He went on to point out that compared with these stockpiles, the atmosphere contained only a minor fraction—and most of that CO_2 cycled in and out of the atmosphere every few thousand years. It was a delicate balance, he warned. Climate conditions "congenial to life" might be short-lived on geological time scales.[1]

Chamberlin quickly added that "This threat of disaster is not, however, a scientific argument..." He was offering the idea more for its value "in awakening interest and neutralizing inherited prejudice," namely, the assumption that the atmosphere is stable. Other scientists were not awakened. While some admitted that geological processes could alter the CO_2 concentration, on any time scale less than millions of years the atmosphere seemed to be unchanging and unchangeable.

The CO_2 model, "recommended to us by the brilliant advocacy and high authority of Prof. T.C. Chamberlin," briefly became a popular theory to explain the very slow climate changes of the past. Within a few years, however, scientists dismissed the theory for what seemed insuperable problems.[2] It appeared that there was already enough CO_2 in the air so that its effect on infrared radiation was "saturated"— meaning that all the radiation that the gas could block was already being absorbed, so that adding more gas could make little difference. Moreover, water vapor also absorbed heat rays, and water was enormously more abundant in the atmosphere than CO_2. How could adding CO_2 affect radiation in parts of the spectrum that H_2O (not to mention the CO_2 itself) already entirely blocked? These studies with the crude techniques of the early 20th century were inaccurate. Modern data show that even in the parts of the infrared spectrum where water vapor and CO_2 are effective, only a fraction of the heat radiation emitted from the surface of the Earth is blocked before it escapes into space. And that is beside the point anyway. The greenhouse process works regardless of whether the passage of radiation is saturated in lower layers. As explained above, the energy received at the Earth's surface must eventually work its way back up to the higher layers where radiation does slip out easily. Adding some greenhouse gas to those high, thin layers must warm the planet no matter what happens lower down.

Through the first half of the 20th century, however, hardly any of the few scientists who took an interest in the topic thought in this fashion. They were convinced by the subtly flawed viewpoint that looked at the atmosphere as a single slab. Even Chamberlin concluded that Arrhenius had failed to get his physics right. After all, was it reasonable to imagine that humans could alter something as grand as the world's climate by changing a tiny fraction of the atmosphere's

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[1] Chamberlin (1897), quote p. 655.

[2] Gregory (1908), quote p. 347; similarly, "one can scarcely study it [the Chamberlin model] without profound admiration... Nevertheless, we are unable to accept it in full...," Huntington and Visher (1922), p. 42; for further background, Mudge (1997).

content? The notion clashed with common ideas that everyone found reasonable. Scientists were confident they could dismiss changes like the global warming foreseen by Arrhenius, because the climate was known to be self-regulating.

Many Sorts of Models (1900-1960)

While most people thought it was obvious from everyday observation that the climate was self-regulating, scientists had not identified the mechanisms of regulation. They had several to choose from.

Through the first half of the 20th century, one common objection to the idea of a future global warming was that only a little of the CO_2 on the planet's surface was in the air. Vastly more was locked up in sea water, in equilibrium with the gas in the atmosphere. The oceans would absorb any excess from the atmosphere, or evaporate gas to fill out any deficiency. "The sea acts as a vast equalizer," as one scientist wrote, making sure all fluctuations "are ironed out and moderated."[1]

If the oceans somehow failed to stabilize the system, there was another large reservoir of carbon stored up in organic matter such as forests and peat bogs. That too seemed likely to provide what one scientist called "homeostatic regulation."[2] For if more CO_2 entered the atmosphere, it would act as fertilizer to help plants grow more lushly, and this would lock up the excess carbon in soil and other organic reservoirs.

Beginning in the 1950s, a few scientists attempted to work out real numbers to check the idea. They constructed primitive models representing the total carbon contained in an ocean layer, in the air, in vegetation, and so forth, with elementary equations for the fluxes of carbon between these reservoirs. These were only one of a number of "bookkeeping" studies, begun early in the century and increasingly common by the 1950s, that added up the entire atmosphere's stock of heat, energy, and various chemicals. The implicit aim was to balance each budget in an assumed equilibrium.[3] There was little solid data for any of these things, least of all the biological effects. Scientists could easily adjust numbers until their models showed self-stabilization by way of CO_2 fertilization, as expected.

Regardless of the CO_2 budget, scientists expected other feedbacks would regulate the world's temperature. In particular, any increase of temperature would allow the air to hold more moisture, where it would create more clouds, which would reflect sunlight away, moderating the heat and

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[1] Lotka (1924), pp. 222-24.

[2] Redfield (1958), 221, referring to atmospheric oxygen and other elements but not carbon.

[3] Nebeker (1995), pp. 123-24.

doubtless restoring the equilibrium. Such was the view of no less an authority than the President of the Royal Meteorological Society, Sir George Simpson, K.C.B., F.R.S. In 1939 he explained that "the change in the cloud amount is the predominating factor in the regulation of the temperature of the atmosphere. The atmosphere appears to act as a great thermostat, keeping the temperature nearly constant by changing the amount of cloud."[1] That was about as simple as a physical model could get.

Climate changes had undoubtedly happened in the past, and slightly more complicated models were needed to explain these. The most widely accepted style of explanation invoked altered "weather patterns." The atmosphere could shift to a different arrangement of winds, lasting decades or perhaps centuries, with different storm tracks and precipitation. Such changes could plausibly be caused by slow geological movements. The raising or lowering of a mountain range would obviously alter winds and temperatures, and opening or closing a strait would of course redirect ocean currents.[2] Perhaps changes of geography were all that geologists needed to explain the major climate changes in the Earth's history.

These changes would be mostly regional, not global, but many experts thought of climate changes as mostly local affairs in any case. This view was in line with the traditional climatology that explained the current distribution of deserts, rain forests, and ice caps in terms of the location of mountain ranges and warm or cold ocean currents. It was only necessary to take the reasoning about prevailing winds, the tracks followed by storms, and so forth, and apply it to a different geography. The result was what one expert described as "a large amount of literature which is both geological and meteorological."[3]

Through the first half of the 20th century, scientific theories on climate change continued to revolve mainly around attempts to explain the ice ages. The explanations by geological rearrangements remained the favorite type of theory, "never seriously challenged," as one authority said in 1922.[4] On the other hand, nobody ever made these explanations precise, and they remained more a kind of story-telling than useful science.

An important example of work on the topic was an idea developed by the meteorologist Alfred Wegener in the 1920s. It happened that Wegener loved geology as much as meteorology (he was also dedicated to studies in Greenland, where he disappeared on an expedition in his fiftieth

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[1] Simpson (1939-40), p. 213; the "rather surprising" conclusion that even a change in solar output could be thus compensated was still accepted in 1956 by Rossby (1959), p. 11.

[2] E.g., deflection of the Gulf Stream by a continent in the Antilles, Hull (1897); glaciation from the raising of mountains, Gregory (1908).

[3] Harmer (1925), quote in discussion by Napier Shaw, p. 258.

[4] Brooks (1922a), p. 23.

year). In collaboration with another meteorologist, Wladimir Köppen, Wegener worked through the geological evidence of radical climate change. Traces of ancient ice caps were found in rock beds near the equator, and fossils of tropical plants in rocks near the poles. Wegener hoped to resolve the puzzle with his controversial claim that continents drifted about from tropics to Arctic and back. Along the way the two meteorologists worked out a climate change theory.

They started off from Arrhenius's idea that the key variable, albedo, depended on whether snow melted or persisted through the summer. The great sheets of ice that reflected away sunlight could persist only if they rested on land, not ocean. So the authors figured that the recent epoch of ice ages had begun when the North Pole wandered over Greenland, and ice ages had ceased once it moved on into the Arctic Ocean.

Wegener and Köppen went into further detail using a theory that had been hanging around since the 19th century. Croll had suggested that ice ages could be linked with regular cycles in the Earth's orbit, the kind of thing astronomers computed. Over many centuries these shifts caused minor variations in the amount of sunlight that reached a given latitude on the Earth. The variations gave rise to ice ages, Croll argued, whenever enfeebled sunlight allowed excess snow accumulation. In the 1920s, Milutin Milankovitch began to develop these astronomical calculations and plug them into equations that simulated the global climate. His energy budget model was like Arrhenius's, but paid closer attention to how much sunlight was received at each latitude in each season, and what that would mean for ice and snow. Milankovitch found that it was summers with weaker sunlight, in other words colder summers, that counted for keeping the reflective snow in place—not cold winters, as Croll had supposed. Wegener and Köppen took up these ideas, insisting that they were "nearly self-evident, and yet contested by some authors!"[1]

From then on, everyone who worked on climate change took into account possible changes in albedo due to ice and snow. For example, when G.S. Callendar took up the question of greenhouse warming in 1938, in a discussion at a meeting of the Royal Meteorological Society he noted that in recent decades temperatures had been rising noticeably in the Arctic. That led him to suggest cryptically that an increase of CO_2 might be acting "as a promoter to start a series of imminent changes in the northern ice conditions."[2]

Some experts offered more specific elaboration, backed up by a few primitive calculations. The most striking came from a respected British scientist, C.E.P. Brooks. He argued that once an Arctic ice cap formed it would chill the overlying air, which would flow down upon the surrounding regions. Behind these frigid winds the snows would swiftly advance to lower

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[1] Köppen and Wegener (1924), "fast selbstverständliche und dennoch von einigen Autoren angefochtene," p. 3; Milankovitch published some of his in a work to which Köppen and Wegener referred, Milankovitch (1920); for the full theory, see Milankovitch (1930); on energy-budget models 1920s-1960s, see Kutzbach (1996), p. 357-60.

[2] Callendar (1938), p. 239.

latitudes. Wind patterns would thus redouble the impact of the familiar cooling feedback caused by increasing reflection of sunlight. Only two stable states of the polar climate were possible, Brooks asserted—one with little ice, the other with a vast white cap on the planet. A shift from one state to the other might be caused by a comparatively slight perturbation, say, a change of ocean currents that put a little extra heat into the Arctic Ocean. Such a shift, he warned, might be shockingly abrupt.[1]

Scientists were beginning to recognize that feedback might grossly magnify the smallest change. The meteorologist W. J. Humphreys, for one, wrote in *Atlantic* magazine in 1932 that the current situation was close to the conditions where ice sheets had ruled. Thus "we must be just teetering on an ice age which some relatively mild geologic action would be sufficient to start going." As an example, he suggested that if a very wide sea-level canal were built across Panama, currents flowing through it might shut off the Gulf Stream, bringing "utterly destructive glaciation" to Northern Europe. Or dust thrown into the air by a series of volcanic eruptions like the famous Krakatau explosion might block enough sunlight to allow the formation of ice sheets. This ice, scientists now understood, might reflect enough sunlight to sustain the cold.

Humphreys also mentioned (following Chamberlin and others) that additional feedbacks could reduce the main greenhouse gases: colder oceans would evaporate less water vapor into the air, and the colder water would also tend to take up more of the "Earth's blanket" of CO_2. However, like nearly all the scientists of his time, Humphreys did not consider changes in CO_2 particularly important. Believing that adding or subtracting the gas could have little effect on radiation, when they thought about climate change they concentrated on volcanic dust, reflective ice sheets and the like.[2]

These models evidently left much room for chance. Some pointed out that ice sheets should be self-sustaining only in certain geological periods, when gross geographical changes such as uplifting of mountain ranges had created a suitable configuration. Even then, Brooks pointed out, "if the Arctic ice could once be swept away, it might find some difficulty in re-establishing itself."[3] He told a *Life* magazine reporter in 1950 that the Arctic ice had declined to a "critical size" and might no longer be able to chill the air enough to maintain itself. Melting might increase, and over centuries the seas might rise by tens of meters.[4]

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[1] Brooks (1925); Brooks (1949), chaps. 1, 8.

[2] Humphreys (1932); in his well-known textbook, Humphreys flatly denied the greenhouse activity of CO_2, Humphreys (1940), p. 585.

[3] Brooks (1949), quote. p. 41, see chap. 12; Brooks (1951), p. 1013.

[4] Coughlan (1950). The cause would be melting of ice on Greenland and other land masses, since the melting of floating ice would not change sea level.

Even when experts worked these ideas up in a few equations, the results were scarcely quantitative, but only qualitative and indeed speculative. Overall, theory remained in much the same state that Simpson, as Director of the British Meteorological Office, had criticized back in 1922. Writers on climate, he had said, each pushed their own individual theory, and biased the evidence in their own favor. "There are so many theories and radically different points of view," he complained, "And new theories are always being propounded."[1]

Simpson himself did not resist the temptation to propound a personal theory, which can serve as an example of the general style of argument of the times. In 1937, he pointed out that, paradoxically, an increase of solar radiation might bring on an ice age. The logic was straightforward. A rise in the Sun's radiation would warm the equator more than the poles. More water would evaporate from the tropics and the rate of the general circulation of the atmosphere would increase. This would bring more snowfall in the higher latitudes, snow that would accumulate into ice sheets. The albedo of the ice sheets would cool the poles. Furthermore, "the ice which enters the sea from these regions will have a large effect on remote regions," cooling the entire hemisphere. Of course, if the Sun grew brighter still, the ice sheets would melt. Simpson worked out a complicated model of double-peaked glacial cycles, driven by a supposed long-term cycling in the level of solar radiation.[2] It was no more convincing than anyone else's ideas. At a time when scientists were unable to explain the observed general circulation of the atmosphere, not even the trade winds, theories about climate change could be little more than an amusement.

To wrestle with complex systems, for centuries scientists had imagined mechanical models, and some had physically constructed actual models. If you put a fluid in a rotating pan, you might learn something about the circulation of fluids in any rotating system—like the ocean currents or trade winds of the rotating Earth. You might even heat the edge of the pan to mimic the temperature gradient from equator to pole. Various scientists had tried their hand at this from time to time since the turn of the century.[3] The results seemed encouraging to the leading meteorologist Carl-Gustav Rossby, who invited young Athelstan Spilhaus to join him in such an experiment at the Woods Hole Oceanographic Institution. In their pan they produced a miniature current with eddies. If this represented an ocean, the current would have looked like the Gulf

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[1] Simpson, preface to Brooks (1922a), pp. 8-9.

[2] Simpson (1934); Simpson (1937); "ice which enters:" Simpson (1939-40), p. 215; Willett (1949) elaborated Simpson's theory: each solar maximum would produce a single ice age, not two.

[3] References to work by Aitken, Exner, Taylor, Spilhaus, etc. are in Fultz (1949); for a historical treatment, see Fultz et al. (1959), pp. 3-5.

Stream, if an atmosphere, like a jet stream (a phenomenon not understood at that time). But they could not make a significant connection with the real world.[1]

Rossby persevered after he moved to the University of Chicago in 1942 and built up an important school of meteorologists. His group was the pioneer in developing simple mathematical fluid-dynamics models for climate, taking climate as an average of the weather seen in the daily circulation of the atmosphere. They averaged weather charts over periods of 5 to 30 days to extract the general features, and sought to analyze these using basic hydrodynamic principles. The group had to make radical simplifying assumptions, ignoring essential but transient weather effects like the movements of water vapor and the dissipation of wind energy. Still, they began to get a feeling for how large-scale features of the general circulation might arise from simple dynamical principles.[2] In the 1950s, Rossby's students and others moved this work onto computers.

Meanwhile, to get another peephole into the physics, Rossby encouraged Dave Fultz and others to experiment with rotating mechanical systems. Funding came from the Geophysics Research Directorate of the U.S. Air Force, always keen to get a handle on weather patterns. The Chicago group started with a layer of water trapped between hemispheres (made by sawing down two glass flasks). They were delighted to see flow patterns that strongly resembled the Earth's pattern of trade winds, and even, what was wholly unexpected, miniature cyclonic storms. The group moved on to rotate a simple aluminum dishpan. They heated the dishpan at the outer rim (and later also cooled it in the middle), injecting dye to reveal the flow patterns. The results, as another meteorologist recalled, were "exciting and often mystifying."[3] The crude, physical model showed something rather like the wavering polar fronts that dominate much of the real world's weather.[4]

Meanwhile a group at Cambridge University carried out experiments with water held between two concentric cylinders, one of which they heated, rotating on a turntable. Their original idea had been to mimic the dynamics of the Earth's fluid core in hopes of learning about terrestrial magnetism. But the features that turned up looked more like meteorology. "The similarity between these motions and some of the main features of the general atmospheric circulation is striking," reported the experimenter. The water had something like a little jet stream and a pattern of circulation that vacillated among different states, sometimes interrupted by "intense

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[1] A. Spilhaus, interview by Ron Doel, Nov. 1989.

[2] Stringer (1972), p. 10.

[3] Exciting: Smagorinsky (1972), p. 27.

[4] Fultz (1949); Fultz (1952); see also Faller (1956); for background Lorenz (1967), p. 118; Lorenz (1993), pp. 86-94.

cyclones."[1] It seemed reminiscent of certain changing wind patterns at middle latitudes that Rossby had earlier observed in the atmosphere (the "Rossby waves" seen in the meanderings of the jet stream and elsewhere). He had explained these patterns theoretically with a simple two-dimensional mathematical model.

Following up with his own apparatus, Fultz reported in 1959 the most interesting result of all. His rotating fluid sometimes showed a symmetric circulation regime, resembling the real world's "Hadley" cells that bring the regular mid-latitude westerly winds. But at other times the pattern looked more like a "Rossby" regime with a regular set of wiggles. This pattern was somewhat like the standing waves that form in swift water downstream from a rock (in the real Earth, the Rocky Mountains act as the rock). Perturb the rotating fluid by stirring it with a pencil, and when it settled down again it might have flipped from one regime to the other. It could also flip between a Rossby system with four standing waves and one with five. In short, different configurations were equally stable under the given external conditions.[2] This was realistic, for the circulation of the actual atmosphere shifts among quite different states (the great trade winds in particular come and go with the seasons). Larger shifts in the circulation pattern might represent long-term climate changes.

Fultz hoped that this kind of work would lead meteorologists to "the type of close and fruitful interaction between theory and experiment, mostly lacking in the past, that is characteristic of the older sciences."[3] But in fact, fluid theory was wretchedly incapable of calculating the behavior of even this extremely simplified model system. Anyway the model was only a crude cartoon of the atmosphere—interesting to be sure, but unable to lead to anything definite about our actual planet. The real contribution of the "dishpan" experiments was to show plainly the tricky instability of any such system.

The physical models reinforced a growing suspicion that it was futile to attempt to model a pattern of global winds on a page of equations, in the way a physicist might represent the orbits of planets. This mathematical research plan, pursued ever since the 19th century, aimed to deduce from first principles the general pattern of atmospheric circulation. But nobody managed to derive a set of mathematical functions whose behavior approximated that of the real atmosphere.[4] The huge ignorance of scientists was nakedly visible to the public, which looked

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[1] Hide (1953).

[2] Fultz et al. (1959); Fultz et al. (1964); some of the results are shown in Lorenz (1967), see pp. 120-126.

[3] Fultz et al. (1959), p. 102.

[4] Eliassen and Kleinschmidt (1957) reviews mathematical approaches and their frustrations.

with bemusement on the farrago of simplistic theories that science reporters dug out and displayed in magazines and newspapers.

Maurice Ewing and William Donn had been interested for some time in natural catastrophes such as hurricanes and tsunamis.[1] Provoked by recent observations of a surprisingly abrupt end to the last ice age, they sought a mechanism that could produce rapid change. Also influencing them was recent work in geology—indications that over millions of years the Earth's poles had wandered, just as Wegener had claimed. Probably Ewing and Donn had also heard about speculations by Russian scientists on how diverting rivers that flowed into the Arctic Ocean might change the climate of Siberia. In 1956, all these strands came together in a radically new idea.[2]

Our current epoch of ice ages, Ewing and Donn argued, had begun when the North Pole wandered into the Arctic Ocean basin. The ocean, cooling but still free of ice, had evaporated moisture and promoted a pattern of severe weather. Heavy snows fell all around the Arctic, building continental ice sheets. That withdrew water from the world's oceans, and the sea level dropped. This blocked the shallow channels through which warm currents flowed into the Arctic Ocean, so the ocean froze over. That meant the continental ice sheets were deprived of storms bringing moisture evaporated from the Arctic Ocean, so the sheets began to dwindle. The seas rose, warm currents spilled back into the Arctic Ocean, and its ice cover melted. And so, in a great tangle of feedbacks, a new cycle began.[3]

The theory was especially interesting in view of reports that northern regions had been noticeably warming and ice was retreating. Ewing and Donn suggested that the polar ocean might become ice-free, and launch us into a new ice age, within the next few thousand years—or even the next few hundred years.

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[1] In 1954, they sent foundations a proposal to study geophysical catastrophes, which could be "more deadly than wars." Folder "Donn, William," Individual Files Series, prelim. box 242, Maurice Ewing Collection, Center for American History, University of Texas at Austin.

[2] Ewing and Donn cited in particular 1955 papers on continental drift by S.K. Runcorn. According to Lamb (1977), p. 661, the first to recognize that an ice-free Arctic Ocean would lead to more snow near the ocean (based on observations of 20th century warm years) and that this could lead to onset of glaciation was O.A. Drozdov; the work was not published at once, and Lamb cites a later publication, Drozdov (1966).

[3] The process was accelerated because dark, open water absorbed more sunlight. Ewing and Donn (1956a); Ewing and Donn (1956b). Besides this albedo effect, which Ewing and Donn did not stress, it was later noted that sea ice is an excellent insulator, so that the air over the ice is tens of degrees colder in winter than if the air were exposed to the water.

This theory was provocative, to say the least. “You will probably enjoy some criticism,” a colleague wrote Ewing, and indeed scientists promptly contested what struck many as a far-fetched scheme. “The ingenuity of this argument cannot be denied,” as one textbook author wrote, “but it involves such a bewildering array of assumptions that one scarcely knows where to begin.”[1] Talk about a swift onset of glaciation seemed only too likely to reinforce popular misconceptions about apocalyptic catastrophes, and contradicted everything known about the pace of climate change. Critics pointed out specific scientific problems (for example, the straits are in fact deep enough so that the Arctic and Atlantic Oceans would exchange water even in the midst of an ice age). Ewing and Donn worked to patch up the holes in their theory by invoking additional phenomena, and for a while many scientists found the idea intriguing, even partly plausible. But ultimately the scheme won no more credence than most other theories of the ice ages.[2] “Your initial idea was truly a great one,” a colleague wrote Ewing years later, “...a beautiful idea which just didn’t stand the test of time.”[3]

Ewing and Donn’s theory was nevertheless important. Published in 1956, and picked up by journalists who warned that ice sheets might advance within the next few hundred years, the theory gave the public for the first time a respectable scientific backing for images of disastrous climate change.[4] The discussions also pushed scientists to inspect data for new kinds of information. For example, the theory stimulated studies to find out whether, as Ewing and Donn claimed, the Arctic Ocean had ever been ice-free during the past hundred thousand years (evidently not). These studies included work on ancient ice that would eventually provide crucial clues about climate change. Above all, the daring Ewing-Donn theory rejuvenated speculation about the ice ages, provoking scientists to think broadly about possible mechanisms for climate change in general. As another oceanographer recalled, Donn would “go around and give lectures that made everybody mad. But in making them angry, they really started getting into it.”[5]

Feedbacks Causing Cycles or Catastrophe (1960s-1970s)

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[1] “enjoy”: C. Emiliani to Ewing, 10 Oct. 1956, folder “Ice ages Paper,” prelim. box 52, Ewing Papers, University of Texas. Contested: e.g., Schell (1957); “ingenuity” Crowe (1971), p. 493.

[2] Typical critiques: Sellers (1965), p. 213; and Crowe (1971), p. 493; Ewing and Donn (1958); see also Donn and Shaw (1966).

[3] Wallace Broecker to Ewing, 20 Jan. 1969, “Ewing” file, Office Files of Wallace Broecker, Lamont Doherty Geophysical Observatory, Palisades, NY.

[4] e.g., Science Newsletter (1956).

[5] W. Broecker, interview by Weart, Nov. 1997, AIP; data: e.g., a biologist reported pollen evidence that there was no open polar sea in the Wisconsin glacial period. Colinvaux (1964).

Norbert Wiener, a mathematical prodigy, had interests ranging from electronic computers to the organization of animals' nervous systems. It was while working on automatic control systems for antiaircraft guns during the Second World War that he had his most famous insights. The result was a theory, and a popular book published in 1948, on something he called "cybernetics."[1] Wiener's book drew attention to feedbacks and the stability or collapse of systems. These were timely topics in an era when electronics opened possibilities ranging from automated factories to novel modes of social communication and control. Through the 1950s, the educated public got used to thinking in cybernetic terms. Climate scientists were swimming with the tide when they directed their attention to feedback mechanisms, whereby a small and gradual change might trigger a big and sudden transition.

At the start of the 1960s, a few scientists began to think about transitions between different states of the oceans. Study of cores drilled from the seabed showed that water temperatures could shift more quickly than expected. A rudimentary model of ocean circulation constructed by Henry Stommel suggested that under some conditions only a small perturbation might shift the entire pattern of deep currents from one state to another. It was reminiscent of the shifts in the dishpan fluid models.[2] All this was reinforced by the now familiar concept that fluctuations in ice sheets and snow cover might set off a rapid change in the Earth's surface conditions.[3]

Similar ideas had been alive in the Soviet Union since the 1950s, connected to fabulous speculations about deliberate climate modification—making Siberia bloom by damming the Bering Straits, or by spreading soot across the Arctic snows to absorb sunlight. According to the usual ideas invoking a snow albedo, if you just gave a push at the right point, feedback would do the rest. These speculations led the Leningrad climatologist Mikhail Budyko to privately advance doubts about how feedbacks might amplify human influences. His entry-point was a study on a global scale. Computing the balance of incoming and outgoing radiation energy according to latitude, Budyko found the heat balance worked very differently in the snowy high latitudes as compared with more temperate zones. It took him some time, Budyko later recalled, to understand the importance of this simple calculation.[4] It led him to wonder, before almost any other scientist, about the potentially huge consequences of fossil fuel burning as well as more deliberate human interventions.

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[1] Heims (1980); Wiener (1956b); Wiener (1948).

[2] Stommel (1961).

[3] E.g., Weertman offered calculations of ice cap instability in support of Ewing-Donn, Weertman (1961).

[4] Budyko, interview by Weart, March 1990, AIP. Smagorinsky, interview by Weart, March 1989, AIP, credits Budyko for introducing snow-albedo feedback with "hand-waving".

In 1961, Budyko published a generalized warning that the exponential growth of humanity's use of energy will inevitably heat the planet. The next year he followed up with more specific, if still quite simple, calculations of the Earth's energy budget. His equations suggested that climate changes could be extreme. In the nearer term, he advised that the Arctic icepack might disappear quickly if something temporarily perturbed the heat balance. Budyko did not see an ice-free Arctic as a problem so much as a grand opportunity for the Soviet Union, allowing it to become a maritime power (although he admitted the longer-term consequences might be less beneficial).[1]

Even setting aside ice-albedo effects, interest in feedbacks was growing. Improvements in digital computers were the main driving force. Now it was possible to compute feedback interactions of radiation and temperature along the lines Arrhenius had attempted, but without spending months grinding away at the arithmetic. A few scientists took a new look at the old ideas about the greenhouse effect. Nobody fully grasped that the arguments about "saturation" of absorption of radiation were irrelevent, since adding more gas would make a difference in the crucial thin layers from which radiation did escape into space. But the way radiation traversed the high, thin layers was attracting increasing scientific attention. New data showed that there was not enough water vapor and CO_2 in the atmosphere to saturate the gases' absorption of radiation in the upper atmosphere (actually it was not even saturated at lower levels, although that didn't matter). A few physicists decided that it was worth their time to calculate what happened to the radiation in detail, layer by layer up through the atmosphere. *(The details are discussed in the essay on Basic Radiation Calculations.)*

In 1963, building on pioneering work by Gilbert Plass, Fritz Möller produced a model for what happens in a column of typical air (that is, a "one-dimensional global-average" model). His key assumption was that the humidity of the atmosphere should increase with increasing temperature. To put this into the calculations he held the relative humidity constant, which was just what Arrhenius had done long ago. (The simplest alternative would have been to assume that the water vapor concentration, the actual amount of water held in the world's air, remained unchanged as climate changed. That was roughly equivalent to the old assumption that a little global heating would make more clouds, which would promptly cool things back to equilibrium.)[2] Möller got the same amplifying feedback that Arrhenius had found. As the temperature rose more water vapor would remain in the air, adding its share to the greenhouse effect.

When he finished his calculation, Möller was astounded by the result. Under some reasonable assumptions, doubling the CO_2 could bring a temperature rise of 10°C—or perhaps even higher, for the mathematics would allow an arbitrarily high rise. More and more water would evaporate from the oceans until the atmosphere filled with steam! Möller himself found this result so implausible that he doubted the whole theory (in fact it failed to include essential features of the

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[1] Budyko (1961); Budyko (1962).

[2] Möller (1963); Arrhenius (1896), p. 263.

atmosphere). Yet others thought his calculation was worth noticing. The model, as one expert noted, “served to increase confusion as to the real effect of varying the CO_2 concentrations.”[1]

Increased confusion is valuable when it pushes scientists to get a better answer. Möller’s disturbing calculation was one stimulus for taking up the challenging job of building full-scale computer models that would take better account of key processes. By 1967 a team in Princeton had removed the runaway by adding more realism to a one-dimensional model (they allowed heated air to rise, included some effects of clouds, etc.).But it would take another decade or two of hard work before computer models would offer a reasonably convincing simulacrum of the present global climate, let alone a changing one.[2]

Crude models of climate change became common during the 1960s, and some of them showed uncomfortably plausible possibilities for disaster. One reason these drew attention was that climate scientists were beginning to admit that there was no such thing as a “normal” climate. By now they had many good long-term weather records, and analysis showed that weather patterns did not always swing back and forth around a stable average. The traditional model of a self-regulating balance of nature was gradually yielding to a picture in which climate continually changed. Feedbacks were no longer seen as invariably helpful, ever restoring an equilibrium. Rather, they might push the system into a fatal runaway.

The scientists were not causing a change of attitude so much as reflecting one that was sweeping through the world public. Many people were taking up the idea that humanity was liable to bring down global disaster on itself, one way or another. Crude calculations pointed to ruinous consequences from the spread of pesticides, radioactive materials, and above all nuclear war. People no longer saw all this as mere science fiction for teenagers, but as plain scientific possibility.

Alongside the occasional models of spectacular climate catastrophes, scientists continued to develop more workaday studies of how this or that force or feedback might influence climate. The subject remained a minor out-of-the-way field, salted with individualists who dreamed of winning honor by discovering the key to the ice ages or a way to predict droughts. As the Director of Research of the United Kingdom Meteorological Office remarked in 1963, nobody had yet produced a quantitative model that could show even “that the climate of the Earth should be distributed as it is.” Without such a model for the present state of climate, so much the worse for understanding climate change—any discussion “is necessarily conjectural and inconclusive.” That was no wonder, he pointed out, when even the most basic data, like the Earth’s budget of incoming and outgoing radiation energy, were known only approximately. “With theory so

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[1] Eriksson (1968), p. 74.

[2] Manabe and Wetherald (1967) still used constant relative humidity. Stimulus: cited by Manabe and Wetherald (1975).

rudimentary and the data so incomplete... the subject has largely been left as a topic for armchair speculation."[1]

Another expert tallied significant theories about causes of climate change extant in 1960 and came up with 54 distinct hypotheses. When a colleague looked again in 1968, he found the total had mounted to 60. "There is nothing to suggest that an end to the speculation on climatic change is in sight," he sighed. "It seems that we have a long way to go before the correct answer can be affirmed."[2] The few and scattered scientists who tried to do scientific work on climate change usually distrusted all the primitive models, including their own. Hardly anyone pursued a given idea except the author, who usually just presented a paper or two before moving on to more productive work.

As the 1960s proceeded, scientists found it harder to get any respect at all for a physical model unless it incorporated at least a few equations and numerical results. Such calculations, involving ice sheets or CO_2 or whatever, became increasingly common, even if the product was often little better than hand-waving dressed up with graphs. As the power of computers rose, people began to think about building models that would calculate out the whole three-dimensional general circulation of the atmosphere. The main impetus was to predict daily weather, but some hoped eventually to learn something about climate. The early models did give a recognizable climate, but it was more qualitative than quantitative, no close reproduction of the Earth's actual climate. One problem was that computers were too slow to handle millions of numbers in a reasonable time. But a worse problem was pure ignorance of how to build a general circulation model. An infinitely fast computer would be no use unless it began with the correct equations for complex effects like the way moisture in the air became raindrops or snowflakes.

Many people preferred to keep on developing simple models of climate instability. Such models were easy and satisfying to grasp, and however qualitative and speculative they might be, they offered genuine insights. The best of these insights would eventually be incorporated into the gigantic computer models. Meanwhile some climate scientists took advantage of computers in a less expensive and arduous way, putting them to work on simple models and working out the numbers in minutes instead of weeks.

Among various simplified models that were written down in a few equations and run through a calculation, the most important was built in the late 1960s by Budyko. He continued to worry about the climate modification proposals that had concerned Soviet climatologists since the 1950s, the grand schemes to divert rivers from Siberia or spread soot over the icepack. Budyko and his colleagues recognized that existing models were far too primitive to predict how such activities might alter climate. At first, they tried instead to make predictions using the simplest sort of empirical model. They would study past climates, compiling statistics on what had

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[1] Sutcliffe (1963), pp. 276-78.

[2] Eriksson (1968), p. 68; the earlier source he cites was Schwarzbach (1963).

happened during years when the icepack was a bit smaller, the temperatures a bit warmer, the atmosphere a bit dustier. The way weather patterns had shifted in the past might well indicate how they would shift in response to future interventions. This resembled the traditional weather prediction method of "modeling" tomorrow's weather by comparing today's weather with similar maps from the past. The approach was also a natural extension of traditional climatology, with its piles of statistics and its idea of climate change as a simple question of changed weather patterns.

In service of this program, Budyko's institute in Leningrad had been laboriously compiling old temperature figures from around the world. He noticed an apparent correlation over the past century between fluctuations in global temperature and variations in atmospheric transparency, due to dust from occasional volcanic eruptions. Other climatologists reported similar findings in the late 1960s. Apparently temperature was sensitive to any haze of particles that lingered in the atmosphere. Budyko was well aware of vigorous ongoing debates over the general warming trend that had been reported for some regions, and he already expected that human industry would cause an accelerated warming. Moreover, studying new satellite data on the albedo of different parts of the Earth, he found dramatic differences depending on snow cover. Combining these separate concerns, he worried that a change in sea ice, or a similar feedback mechanism, "can multiply a comparatively small initial change in air temperature created by men's activities."[1]

To pin down the idea, in the mid 1960s Budyko constructed a highly simplified mathematical model. It was a "zero-dimensional" model that looked at the heat balance of the Earth as a whole, summing up radiation and albedo over all latitudes. When he plugged plausible numbers into his equations, Budyko found that for a planet under given conditions—that is, a particular atmosphere and a particular amount of radiation from the Sun—more than one state of glaciation was possible. If the planet had arrived at the present after cooling down from a warmer climate, the albedo of sea and soil would be relatively low, and the planet could remain entirely free of ice. (In particular, as Donn was continuing to insist, once the Arctic Ocean was free of its ice pack it would be less likely to freeze over in winter).[2] But the Earth had come to the present by warming up from an ice age, keeping some snow and ice that reflected sunlight, and so it could retain its chilly ice caps.

Under present conditions, the Earth's climate looked stable in Budyko's model. But not too far above the present temperatures and snow cover, the equations reached a "critical point." The global temperature would shoot up as the ice melted away entirely. That would give a uniformly and enduringly warm planet with high ocean levels, as seen in the time of the dinosaurs. And if the temperature dropped not too far below present conditions, the equations hit another critical point. Here temperature could drop precipitously as more and more water froze, until the Earth reached a stable state of total glaciation—the oceans entirely frozen over, the Earth transformed

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[1] Volcanoes: Budyko (1969); his interest in the observed warming is reported by Kondratyev (1988), p. 4; quotes and satellite data in Budyko (1972), p. 869.

[2] Donn and Shaw (1966).

permanently into a gleaming ball of ice! Budyko thought it possible that our era was one of "coming climatic catastrophe... higher forms of organic life on our planet may be exterminated."[1]

Others were on the same trail, independently of Budyko's work in Leningrad—communications were sporadic across the Cold War frontiers. Already in 1964, a New Zealand ice expert, Alex Wilson, had offered some thought-provoking if schematic calculations. Antarctic ice sheets might be unstable enough to collapse so that icebergs would spread across vast tracts of the southern oceans, then melt away, raising and then lowering the Earth's albedo. He proposed that this "provides the 'flip-flop' mechanism to drive the Earth into and out of an ice age."[2] The following year Erik Eriksson in Stockholm wrote a set of differential equations involving temperature and ice cover. The mathematics revealed instabilities that might lead to either "an explosive growth" or "a very rapid retreat of ice." As Eriksson explained in a 1965 conference on climate change, the system had a "'flip-flop' mechanism."[3]

That was an extreme example of what the American meteorologist Edward Lorenz had begun to call "intransitive" effects. Under given external conditions, the atmospheric system could get itself locked into one persistent state or into another and quite different state. The choice might depend on only minor variations in the starting-point. These ideas were no doubt provocative, but so blatantly primitive and speculative that few scientists spent much time thinking about them.

What did at last catch attention was the drastic outcome of an energy-budget model published in 1969. The author, William Sellers at the University of Arizona, built on Budyko's and Eriksson's ideas. Rather than attempt another grand but rudimentary global model, Sellers computed possible variations from the average state of the actual atmosphere, separately for each latitude zone. The model was still "relatively crude," as Sellers admitted (adding that this was unfortunately "true of all present models"), but it was straightforward and elegant. Climatologists were impressed to see that although Sellers used equations different from Budyko's, his model too could approximately reproduce the present climate—and that it too showed a cataclysmic sensitivity to small changes. If the energy received from the Sun declined by 2% or so, whether because of solar variations or increased dust in the atmosphere, it might bring on another ice age. Beyond that, Budyko's nightmare of a totally ice-covered Earth seemed truly possible. At the

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[1] Budyko (1968); Budyko (1969), quote p. 618.

[2] Wilson (1964), p. 148; he pointed out that buildup of the Antarctic ice sheets was one of the few features of the Earth with a time constant that might match the long Milankovitch periods, Wilson (1969).

[3] The model was only mentioned casually at the conference, not as the main point of Eriksson's presentation, was not published until 1968, and attracted little notice aside from helping to stimulate Sellers' work. Eriksson (1968), "flip-flop" p. 77.

other extreme, Sellers suggested, “man’s increasing industrial activities may eventually lead to a global climate much warmer than today.”[1]

The striking results published by Budyko and Sellers kindled increased interest in simple models. While some scientists gave them no credence, others felt that such models were valuable “educational toys”—a helpful starting point for testing assumptions, and for identifying spots where future work could be fruitful.[2] But did the Budyko-Sellers catastrophes reflect real properties of the global climate system? That was a matter of brisk debate.[3]

In the early 1970s, some scientists did find it plausible that feedbacks could build up a continental ice sheet more rapidly than had been supposed. The ice’s albedo was not the only feedback that might contribute. Ewing continued to defend his theory that a North American ice sheet could build up over only a few thousand years because of the increase in snowfall if the Arctic Ocean became ice-free. Other climate experts consistently rejected the idea. Aside from specific details, many continued to doubt the basic picture of a climate sensitive to small perturbations. For example, a 1971 climatology textbook pointed out that the Arctic Ocean occupied less than 5% of the globe’s surface, and asked, “Is it not inherently improbable that the freezing and thawing of this surface should have major repercussions over the whole globe?”[4] Whether such magnified consequences were truly improbable got different answers from different scientists. Some went so far as to take seriously the idea offered by C.E.P. Brooks back in the 1920s, that thanks to feedback, frigid winds sweeping down from snow fields could move the snowline rapidly southward year by year.[5] Such a runaway freeze might possibly be triggered soon, according to some, as smog and smoke emitted by human industry increasingly shaded the Earth.[6]

The opposite extreme—a self-sustaining heating of the planet—might be even more catastrophic, according to another set of calculations from a few equations. In the early 1960s, telescope measurements had revealed that the planet Venus was at a temperature far above the boiling point of water. It stayed so hot because a dense blanket of water vapor and CO_2 maintained a

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[1] Sellers (1969), quote p. 392, “rapid transition to an ice-covered Earth” p. 398.

[2] Robinson (1971), pp. 209, 214; cited with approval e.g. by Schneider and Dickinson (1974).

[3] Budyko (1972); Sellers (1973); North (1975).

[4] Crowe (1971), p. 493.

[5] Ives (1957); see also Ives (1958); Ives (1962); wind feedback: Lamb and Woodroffe (1970).

[6] Rasool and Schneider (1971); Lockwood (1979), p. 162.

ferociously strong greenhouse effect. The furnace-like conditions not only kept water vaporized in the atmosphere but also kept the CO_2 there, for the surface minerals, red-hot, would not absorb the gas. The system was thus self-perpetuating. Perhaps Venus had originally been similar to the Earth, only just enough warmer to begin evaporating gases into its atmosphere—greenhouse gases, which produced further warming, and so forth. If so, the end had been a "runaway greenhouse." According to one calculation, the Earth would need to be only a little warmer for enough water to evaporate to tilt the balance here as well. If our planet had been formed only 6% closer to the Sun, the authors announced, "it may also have become a hot and sterile planet." This was published in 1969, the same time as the work of Budyko and Sellers.[1]

By 1971, the risks to climate were under vigorous discussion in the small community of climate scientists. When Budyko presided over a large meeting in Leningrad, a rare occasion when most of the leading American, Western European and Soviet experts all met together, he put the issue to them forcefully. At the conclusion of the conference, where the organizer would traditionally sum up with some bland remarks, "Instead of general words," Budyko recalled, "I presented in short form an idea which proved to be absolutely unacceptable to everybody: the idea that global warming is unavoidable... The result was a sensation. Everybody had very strong feelings, and extremely unfavorable... A few very prominent men said, first, that it was absolutely impossible to have any [effect] of man's activity on the climate... And absolutely impossible to predict any climate change."[2] It was not pleasant, Budyko later recalled, to present unconventional ideas and provoke negative feelings, but the risk to the planet seemed so grave that it was important to provoke scientists to study the question and find whether the ideas were valid.[3]

Budyko was not in fact alone in his concerns. They were taken up in an influential report (the "SMIC report") as the consensus of a major scientific meeting held in Stockholm that same year, 1971. The experts concluded that there was a possibility that a mere 2% increase or decrease of solar radiation, helped by albedo feedback, could leave the planet either totally ice-free or totally frozen.[4] Budyko, Sellers, and others pressed ahead, finding that under a variety of simple assumptions, any model that gave a good representation of the Earth's present climate looked

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[1] Ingersoll (1969); Rasool and de Bergh (1970).

[2] Symposium on Physical and Dynamical Climatology, as described in Budyko, interview by Weart, March 1990, AIP.

[3] Budyko, interview by Weart, March 1990, AIP.

[4] For support they pointed to semi-empirical studies of the way polar ice had rapidly disappeared during the warming of the 1930s. Wilson and Matthews (1971), pp. 125-29; they cite Budyko (1971).

unstable and could just as easily produce a radically different climate.[1] In 1972, Budyko calculated that a mere few tenths of a percent increase in solar radiation input could melt the icecaps. More important still, changing the level of greenhouse gases in the atmosphere would have an effect similar to changing the Sun's radiation. His model indicated that a 50% increase in CO_2 would melt all the polar ice, whereas reduction of the gas by half "can lead to a complete glaciation of the Earth." Budyko went on to note that any changes in CO_2 caused by natural geological processes had been overtaken by human activity. Sometime "comparatively soon (probably not later than a hundred years)... a substantial rise in air temperature will take place." As early as 2050, he calculated, the Arctic Ocean's ice cover could be melted away entirely.[2]

A mathematical model like those of Budyko and Sellers, built out of only a few simple equations, is quite likely to predict sharp changes. The more complex processes of the real world, however, might become saturated at some point, or react so as to counter any big shift. Scientists tended to be skeptical about this entire genre of models. As one expert later remarked, many in the 1970s thought the Budyko-Sellers instability was a nuisance—"an artifact of the idealized models, and the usual approach was to dismiss it or introduce additional *ad hoc* mechanisms that would remove it."[3] The few who pursued the calculations found no easy way to avoid the catastrophic instability, but they understood that it would take a much larger and more complete computer model to produce credible results.[4] Sellers himself developed a somewhat more elaborate model (although it still took only 18 seconds on the computer to work out a year of climate change), and again he got a planet that was highly sensitive to perturbations. But he admitted that resolving the question must wait for some future "super-computer."[5] Besides, in the early 1970s the public had become agitated about possible climate shifts, and it could seem irresponsible to talk too loudly about world doom predicted by patently deficient models.

Some senior climatologists, attacking "the glibly pessimistic pronouncements about the imminent collapse of our terrestrial environment," stuck by their traditional model of climate as a self-regulating system. They continued to expect, for example, that a negative feedback from cloudiness would stabilize global temperature. But others were taking a new view of their field. Not only theoretical studies, but a flood of data on past climate changes were hard to reconcile

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[1] Out of five possible states, "The only completely stable climate is one for which the Earth is ice-covered," according to Faegre (1972), p. 4; "multiple steady states do exist," and which one would be found at a given time depended on the previous history, concluded Sellers (1973), p. 253.

[2] Budyko (1972).

[3] North (1984), p. 3390; see also North (1975), p. 1307.

[4] North (1984).

[5] Sellers (1973), p. 241.

with the old definition of "climate" as a long-term average of weather. An average made sense only if you calculated it over a period where things were roughly the same during the first half as during the second half. But was there ever such a period? As one prominent climatologist explained, "it cannot be ruled out... that [climate] varies on all scales of time." He admitted that "it can be argued that the very concept of climate is sterile," unless you gave up "the classical concept of something static."[1]

In 1973, studies in wholly different fields brought new credence to the idea that positive feedbacks could defeat stability, with drastic results. A spacecraft reached Mars and sent back images with dramatic evidence that although the planet was now in a deep freeze, in the past there had been floods of water. Carl Sagan and his collaborators calculated that the planet had two stable states, and ice albedo feedback helped to drive the shift between them. Enormous flips of climate were apparently not a mere theoretical possibility but something that had actually befallen our neighboring planet.[2] *For more on the way studies of other planets supported ideas of radical climate change, see the supplementary essay on Mars and Venus.*

Another field of study produced even more telling news. By the mid 1970s, analysis of layers of clay extracted from the seabed gave unassailable evidence that ice ages had come and gone in a 100,000-year cycle, closely matching Milankovitch's astronomical computations of periodic shifts in the Earth's orbit.[3] Yet the subtle orbital changes in the amount of sunlight that reached the Earth were far too small to have a direct effect on climate. The only reasonable explanation was that there were other natural cycles that resonated at roughly the same time-scale. The minor variations of external sunlight evidently served as a "pacemaker" that pinned down the exact timing of internally-driven feedback cycles.

What were the natural cycles that fell into step with the shifts of sunlight? The most obvious suspect was the continental ice sheets. It took many thousands of years for snowfall to build up until the ice began to flow outward. A related suspect was the solid crust of the Earth. On a geological scale it was not truly solid, but flowed like tar. The crust sluggishly sagged where the great masses of ice weighed it down, and sluggishly rebounded when the ice melted. (Scandinavia, relieved of its icy burden some twenty thousand years ago, is still rising a few millimeters a year.) Since the 1950s, scientists had speculated that the timing of glacial periods might be set by these slow plastic flows, the spreading of ice and the warping of crustal rock.[4]

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[1] Senior climatologists: e.g., Kellogg (1971), pp. 131-32; concept of climate: Mitchell (1971), pp. 134-35.

[2] Sagan et al. (1973).

[3] Especially Hays et al. (1976).

[4] E.g., Emiliani and Geiss (1959). They emphasize these ideas were not especially original with them.

Starting around the mid 1970s, scientists in a variety of institutions around the world, from Tasmania to Vladivostok, devised numerical models that indicted how 100,000-year cycles might be driven by feedbacks among ice buildup and flow, with the associated movements of the Earth's crust, albedo changes, and rise or fall of sea level. They rarely agreed on the details of their models, which of necessity included speculative elements.[1] But taken as a group, the numerical models made it plausible that ice-sheet feedbacks could somehow amplify even the weak Milankovitch sunlight changes (and perhaps other slight variations too?) into full-blown ice ages.

From Small Models to Big Computers (1980s)

Many scientists had converted by now to a new view of climate. No longer did they see it as a passive system responding to the (name your favorite) driving force. Now they saw climate as almost a living thing, a complex of numerous interlocking feedbacks prone to radical self-sustaining changes. It might even be so delicately balanced that some changes would be unpredictable. To be sure, many people stuck to earlier views. In 1976 the Director-General of the United Kingdom Meteorological Office told the public that "sensational warnings of imminent catastrophe" were utterly without foundation. "The atmosphere is a robust system with a built-in capacity to counteract any perturbation," he insisted.[2] That was becoming a minority opinion.

While models of ice-albedo and ice-sheet flow gave the most spectacular results, scientists developed a variety of other simple models. Most important and technically challenging, some labored to improve calculations of how radiation was transferred through a column of the atmosphere. These one-dimensional calculations were the underpinning for simplified energy-budget models incorporating changes in ice cover, atmospheric CO_2, and so forth. Such models also provided basic elements to build into the proliferating full-scale computer models of the general circulation.

The huge computer models were taking over the field from simpler models. By the mid 1970s, everyone understood that it was hopeless to try to understand how climate changed by looking at

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[1] Examples: Weertman (1976a) (Northwestern Univ., IL, and the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH); note also his pioneering calculation of ice sheet buildup and shrinkage times, Weertman (1964); Sergin (1979) (Laboratory for Mathematical Modeling of the Climate, Pacific Institute of Geography of Academy of Sciences, Vladivostok, but written while visiting NCAR, Boulder, CO); Budd and Smith (1981) (Meteorology Dept., U. Melbourne); as a perhaps more typical example, Young (1979) (Antarctic Division, Dept. of Science and Technology, Kingston, Tasmania) conservatively showed a response time of perhaps 20,000 years; an especially influential model involving ice sheet buildup delay was Imbrie and Imbrie (1980); a good review is Budd (1981).

[2] Mason (1977), p. 23; see Gribbin (1976).

just one or another feature, or even several features: you had to take into account all the mutually interacting forces at once. Digital computers were reaching a point where they might be able to do just that. Work increasingly concentrated on developing systems to incorporate as components of comprehensive models. Some scientists nevertheless continued to build elementary stand-alone models of various features, using them to garner insights that would be necessary to grasp the full climate system.

The most outstanding difficulty was the intricate problem of clouds. Among other things, the authoritative 1971 SMIC report noted that a climate change could alter not only the amount of clouds but also their average height. The height determined the temperature of the cloud surfaces, which affected how they radiated heat upward and downward. The authors concluded that "clouds could act as a feedback mechanism" responding to global warming, "but the direction of feedback remains to be determined."[1]

Formerly, everyone had assumed with little thought that more clouds obviously would reflect sunlight, and necessarily cool the Earth. But in the one-dimensional 1967 calculation mentioned earlier, Syukuro Manabe and Richard Wetherald had included the way that clouds not only reflected incoming sunlight but also intercepted radiation rising from below. Like greenhouse gases, the clouds could radiate heat back downward—or as one writer put it, "trap" heat on the surface. (After all, it's common experience that a cloudy night will typically be warmer than a clear one). Also, by absorbing some of the radiation coming from above or below, clouds would warm the layer of atmosphere where they floated. In 1972, Stephen Schneider published a suggestive attempt to discuss the complexities in detail. He argued that while a greater amount of cloud cover would lead to net cooling, an increase in the height of the cloud tops would lead to warming. Overall his model was highly sensitive to small changes—not to mention being sensitive to its simplifying assumptions.[2] Further rudimentary calculations showed that all sorts of subtle and complex influences would determine whether a given type of cloud brought warming or cooling.

Another problem that needed much more work was smoke, dust, and other aerosols. Tiny atmospheric particles would not only strongly influence the formation of clouds, but would interact with radiation on their own. Some observations and primitive calculations showed that aerosols from volcanoes, and perhaps from human activity too, would have to be included in any realistic climate model. By the late 1970s, groups studying aerosols had built simple one-dimensional models and slightly more advanced models that averaged over zones of latitude. The models gave important results: the net effect of injecting aerosols would be global cooling. Confidence in the results was bolstered when James Hansen's group used a simple model to compute the temporary cooling caused by the haze from a volcano that had erupted back in 1963; their results matched real-world data remarkably well. In particular, the model predicted that the

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[1] Wilson and Matthews (1971), p. 122.

[2] Schneider (1972).

> stratosphere should warm up while the lower atmosphere cooled, just what was observed. To be sure, knowledge of aerosols was so uncertain, and the normal fluctuations in climate were so great, that the volcano "experiment" could not prove anything for certain. "Nevertheless," as one reviewer commented, "the good agreement is rather satisfying."[1]

Another essential problem that people studied in simple models was the circulation of the oceans, which computers could not yet handle as part of a full-scale global simulation. Some modelers recognized that real understanding of long-term climate change would require models that coupled the atmosphere and oceans. They continued to offer hand-waving models to suggest how the interaction might behave. For example, in 1974 Reginald Newell offered some ideas about rapid switching between two distinct configurations for heat transport through the oceans. Newell's ingenious mechanism involved the spread of sea ice over the ocean, but he noted that there could also be important Budyko-style albedo feedbacks, and other effects such as changes in the pattern of winds. His suggestions were "speculative," Newell admitted, "as indeed are all previous suggestions concerning the course of the ice ages."[2]

Simple models also remained necessary for studying conditions beyond the range of general circulation models. The big computer models had a problem. Any tiny initial error in the physics or climate data tended to accumulate, adding up through the millions of numerical operations to give an impossible final result. The models gave stable results only when their initial parameters were adjusted ("tuned") until the outcome simulated current conditions realistically within a given range of conditions. Such a model was useless outside its range. By 1976, a full-scale model had been built that not only simulated current climate but also, with the addition of continental ice sheets and other readjustments, gave a rough reproduction of conditions at the peak of the last ice age. (It was good enough to confirm the long-held assumption that ice and snow albedo were indeed important for sustaining an ice age.) But to dynamically compute the whole range of climates as ice ages came and went was far beyond this or any model's capacity. By the 1980s, the strangely regular cycles of ice sheet advance and retreat over the past several hundred thousand years were well determined, thanks to cores drilled from seabeds and icecaps. Scientists who took up the old challenge of explaining the cycles had no recourse but simple models—a few equations including the time-delay for laying down and melting ice sheets, plus feedbacks such as changes in the level of CO_2 in the atmosphere.[3]

Going to still more extreme conditions, only simple models could deal with the runaway changes in temperatures and greenhouse gas concentrations that might make a totally glaciated "snowball

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[1] Examples of useful techniques are Wang and Domoto (1974); Coakley and Chylek (1975); volcano: Hansen et al. (1978); reviewed by Ramanathan and Coakley (1978), quote p. 484; Charlock and Sellers (1980); Coakley et al. (1983).

[2] Newell (1974), p. 126.

[3] Pisias and Shackleton (1984).

Earth." In the 1980s, this threatening scenario became more credible. It had increasingly puzzled computer modelers that their simulations had a strong tendency to wander into this mode. Some began to wonder why it had not actually happened.[1] Now geological evidence turned up indicating that at least once in the very distant past, the Earth's oceans really had frozen over, or mostly so.

For analyzing climate under current conditions, mammoth supercomputer models took over the field toward the end of the 1970s. The last great contribution of primitive one-dimensional and two-dimensional calculations was to provide a check. The most complex three-dimensional computer models seemed plausible once they were found to behave much the same as the simple models. Tests using a variety of small models came up with numbers close to the ones printed out by the biggest ones. In short, introducing the myriad complexities of a full-scale model did not change the plain lesson of global warming contained in the elementary physics that stretched back to Arrhenius.

During the 1980s, many scientists came to believe that the Earth was getting warmer. But that said nothing about the cause. A search got underway for "fingerprints"—specific patterns of climate that would point to the greenhouse effect (or point away from it, to some other cause). As one example, both computer models and simple reasoning declared that when gases in mid-atmosphere blocked radiation coming up from the surface, that would leave the stratosphere above the gases cooler. By 1988, "a number of intriguing candidates are appearing that might be part of a fingerprint," a *Science* magazine report said, but "no one is claiming a certain identification of the greenhouse signal."[2]

Whatever the cause of warming, elementary reasoning could predict some important consequences. Warming would not mean a slightly higher temperature on every day, but a serious increase in "heat waves," runs of days of extreme heat—harmful in many ways but especially to farmers.[3] That was one of the things that attentive journalists picked up from James Hansen's widely reported 1988 testimony to the U.S. Congress: the number of deadly heat waves would shoot up.[4] Furthermore, a warmer atmosphere would hold more moisture, so it seemed likely that the whole grand cycle of weather from evaporation to precipitation would intensify. The effects were debatable, but most experts felt that a warmer world would have worse droughts, worse

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[1] Gleick (1987), p. 170.

[2] Kerr (1988), p. 560.

[3] Mearns et al. (1984).

[4] Hansen (1988).

floods, and perhaps worse storms— possibly all very much worse—although nobody could say just how bad these disasters could be, let alone where they might strike.[1]

A wholly different approach was to "model" the greenhouse world on similar climates of the past. Paleontologists had traditionally studied rocks and fossils to find whether a region had once been jungle, prairie or desert. In the 1980s, Budyko encouraged Soviet geologists to extend this line of work into a detailed mapping of the last warm interglacial period, especially in the territory of the Soviet Union itself. They hoped that this would give an idea of how the world's climate map would appear during global warming in the 21st century.[2] This program was largely overtaken by much more detailed data deduced from studies of ocean floor mud, data precise enough to combine with computer models of climate. Still, the Soviet studies did help to demonstrate that a warmer planet was likely to have a very different geographical distribution of warm, cold, wet and dry regions than at present.

A completely different group of simple models was meanwhile joining the discussion. It was essential to understand how biological systems interacted with both global warming and an increased CO_2 level. What would changes in gases and temperature and precipitation do to forests, wetlands, and so forth? In particular, what changes might come in the emission of methane gas, the absorption of CO_2, the amount of dust in the air, and so forth? This was important to climate science because such things could react back on the climate system itself, perhaps in a vicious circle.

Most people were more interested in another question: what might climate change mean for agriculture, forestry, the spread of tropical diseases, and other matters of human concern? By the early 1980s, some scientists found the risk of climate change great enough to justify an effort to work out preliminary answers. Simple models could give at least a rough idea as to how global warming might affect, say, the production of wheat in North America. A new area of research got underway with the customary features—research grants, conferences, articles in interdisciplinary journals like *Climatic Change*.[3]

Specialists in a variety of fields approached the issues with computer models. They plugged in equations and data on such things as how farmers might be forced to change the crops they grew,

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[1] Hurricanes (50% higher "destructive potential" in future): Emanuel (1987); a trend had been detected of greater storminess in the North Atlantic 1962-1988, Carter and Draper (1988); for more recent work, e.g., Knutson et al. (1998); droughts ("severe drought, 5% frequency today, will occur about 50% of the time by the 2050s" in the U.S.): Rind et al. (1990); Karl et al. (1995) reported a rise in extreme precipitation events; whether the hydrological cycle will intensify is still debated, see Ohmura and Wild (2002).

[2] Zubakov and Borzenkova (1990), pp. ix, 5-7.

[3] For example, Kellogg and Schware (1981); Rosenzweig (1985); Emanuel et al. (1985).

or how higher temperatures might affect electricity production or wildlife. “Impact studies,” as this field came to be called, was rudimentary compared with atmospheric modeling. The underlying data came from only a few acres of woods or fields at a few locations, and the equations did not go far beyond hand-waving. Another and even simpler approach was the one pioneered by Budyko’s Leningrad group, finding what the weather had been like in a given region during past periods of warmer climate, and asking how such weather might affect modern life. Here too the data were sketchy, and extrapolation to our own future little more than a guess.[1] What these studies did show was that it was more likely than not that a few degrees of warming would have important consequences for both natural ecosystems and human society—mostly nasty consequences.

Nobody would be able to predict precisely how the atmosphere would change, nor what the impacts of the change would be, without understanding all the interactions. Such studies required expertise in botany or agronomy or sociology as much as in geophysics. The climate science community dreamed of a grand model computing every factor together, not just the physics and chemistry but the biology (would forests grow farther north and the dark trees absorb more sunlight?) and economics (would a rise of temperature promote more fossil fuel burning, or less?). Such a comprehensive model lay far in the future. Devising its multitude of component parts would take many years of development using simple models.

After 1988

There had always been a range of approaches to modeling. At one extreme were people who aimed for the most realistic and comprehensive maps of climate that could possibly be contrived, building ever more complex systems of parameters. At the other extreme were people fascinated by the dynamics of the system, who would rather play around with an idealized model, running it repeatedly while tweaking this or that feature to see what would happen. Despite the rapid improvement in the huge general-circulation computer models, the lovers of simple models continued to find useful things to do.[2]

For one thing, simple models could lend conviction when critics disputed the incomprehensibly intricate computer models. As statisticians sought a definitive “fingerprint” to demonstrate the arrival of greenhouse warming, of course they compared their observations with the predictions from big models. But the conclusions seemed more solid when they showed features that Tyndall and Arrhenius had long ago predicted from elementary and ironclad principles. In particular, the simplest physical logic said that the blocking action of greenhouse gases would be most effective where outward radiation was most important for cooling the Earth: warming would come especially at night. And indeed a rise in the daily minimum temperature, mainly due to rising

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[1] IPCC (2001), p. 748 includes 1980s references.

[2] Dalmedico (2007), p. 138.

night-time temperatures, was plainly observed world-wide from the 1950s onward.[1] The predicted increase in extreme climate events also seemed to be showing up in statistics, at least for the United States (later, in the mid 2000s, this and other impacts predicted by simple models were observed around the world).[2]

No less persuasive, Arrhenius and eain reason was that even a little warming would melt some of the snow and ice, exposing dark soiveryone since had calculated that the Arctic must warm more than other parts of the globe. The ml and water that would absorb sunlight. Enhanced Arctic warming was a solid feature of models from the simplest hand-waving to the most sophisticated computer studies.[3] And in fact, it was in places like the Arctic Ocean, Scandinavia, and Siberia that global warming became most noticeable in the 1990s. The area of ocean covered by ice declined sharply, so did the thickness of the icepack, treelines moved higher, and so forth. Studies mustering large amounts of data from around the Arctic showed that the 20th-century warming far exceeded anything seen for at least the past 400 years.[4] Humanity's "large scale geophysical experiment," as Roger Revelle had called it back in 1957, was producing data almost as if we had put the Earth on a laboratory bench to observe the effects of adding greenhouse gases. The data seemed to be confirming the basic theories.

These "fingerprints" of the greenhouse effect, combined with more elaborate computer studies and with the evident global surface temperature rise, did much to convince scientists and attentive members of the public that global warming was underway. Nevertheless, as a few critics pointed out, the pattern of modest temperature rise might be caused by other influences in the complex climate system.[5] If computer models agreed with old hand-waving arguments, that did not alter

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[1] Karl et al. (1986); Karl et al. (1991); Easterling et al. (1997). More studies are being published every year. Warming should likewise be seen more in winter than in summer, and there are some indications this is happening.

[2] Karl et al. (1996). More recent work is summarized in IPCC (2007a) and IPCC (2007c).

[3] The effect is much less in Antarctica, whose thick ice cover is not easily changed. Arctic warming is also enhanced by increased transport of heat energy in moisture carried from lower latitudes, and by thinner sea ice, which allows greater conduction of heat from the Arctic Ocean into the air. The first large model to demonstrate polar sensitivity was Manabe and Stouffer (1980); a more recent example is Manabe and Stouffer (1993).

[4] Overpeck et al. (1997).

[5] Singer (1999).

the fact that the modelers were still far from certain about the interactions with cloudiness and so forth.[1]

People who doubted that greenhouse warming was truly a problem continued to devise simple models of their own. Well into the 21st century, one or another critic (typically a person with some scientific training but no experience in the climate field itself) would labor through a simplistic calculation and claim it proved that the entire greenhouse warming theory was a sham. One bizarre example was an effort by John Sununu, chief of staff to President George H.W. Bush. He had heard criticism that climate models did not calculate the mixing of heat into the oceans correctly, and therefore grossly overestimated future atmospheric warming. In 1990 he asked one of the government's top modeling teams to give him a one-dimensional climate model that he could run on his Compaq 386 personal computer. "Sununu did not trust our big climate models," recalled Warren Washington, the team's leader. "He wanted to do the computations himself within the White House." The team did their best to give the powerful politician a usable model, but of course in the end he was unable to disprove (or probably even to understand) their calculations.[2]

The best actual scientific criticism came from a respected Massachusetts Institute of Technology meteorologist, Richard Lindzen. Around 1990 he began to challenge the way modelers allowed for water vapor feedback. This was the crucial calculation showing how a warmer atmosphere would carry more water vapor, which would in turn amplify any greenhouse effect. Lindzen believed the climate system somehow avoided that. He offered an alternative scenario involving changes in the way drafts of air carried moisture up and down between layers of the atmosphere. While Lindzen's detailed argument was complex and partly impressionistic, he said his thinking rested on a simple philosophical conviction—over the long run, natural self-regulation must always win out. His work also became, he confessed, "a matter of being stuck with a role." It was important for *somebody* to point out the uncertainties. However, few scientists found Lindzen's technical arguments convincing. Observations suggested that the way the modelers handled water vapor, although far from perfect, was not wildly astray. Still, it took more than a decade to get observations that proved convincingly that his scenario was flat wrong.[3]

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[1] Wang and Key (2003) subsequently indicated that in fact circulation rather than radiation effects predominated in the arctic warming.

[2] Washington (2007), pp. 96-105.

[3] His essential argument was that warming would make an increase in tropical thunderstorm clouds, whose downdrafts would remove moisture from the upper atmosphere. Lindzen (1990); Kerr (1989a); "stuck with a role," quoted Grossman (2001); Lindzen has been accused of obfuscation, taking extreme ideological positions, and unjust ad hominem attacks, see Gelbspan (1997), pp. 49-54; but the accusation that Lindzen has been in the pay of industry is based only on lecture fees that Lindzen received. For the water vapor argument and other areas of debate with Lindzen, see Hansen et al. (2000a), pp. 154-59. Corrections: Del Genio et al. (1991);

Lindzen remained convinced that all climate models had so many uncertainties that their findings were meaningless, and he kept looking for some demonstrable flaw. Taking up the old idea that a warmer ocean should generate more clouds that would shade the planet, he dug up some data that tended to support his idea that the climate system thus stabilizes itself.[1] The data, however, came only from a limited region of the tropical Pacific Ocean where the effect was especially likely to be seen. Although the question remained unsettled, hardly any other expert thought he was right at last.

Still, nobody could dismiss out of hand Lindzen's complaint that computer results were based on unproven assumptions. Although the models passed many rigorous tests, they also showed significant errors, deviating in various details from one another and from the actual climate. Evidently the modelers had not properly represented all the real-world mechanisms. Simple qualitative arguments would continue to be needed for checking the plausibility of any big model.

Back-of-the-envelope calculations also continued to be useful for circumstances beyond the range of the big computer models. Tuned to match current conditions, they had a hard time reproducing any situation too different. Above all there was the old problem of explaining ice ages—what conditions made a glacial epoch, and within such an epoch just what drove the cyclic ebb and flow of ice? The usual combination of plausible arguments and simple equations was applied in a variety of models, which now incorporated not only ice sheets but also shifts in ocean currents.[2] Although computers were starting to become capable of handling full-scale models for the ocean circulation, here too there was still room for simple plausibility arguments.

Such arguments were also the best way to study the interactions between glaciation and CO_2. Ice core measurements showed that during recent glacial periods, CO_2 and methane had gone up and down roughly in time with the advance and retreat of the ice. Was the cycle driven not by ice or ocean dynamics, but by emissions of gas, as Chamberlin had speculated a century back?[3] Perhaps the gases served as an amplifying feedback, released into the atmosphere from seas and peat beds as a warm period began? There were so many interactions that a climate modeler remarked, "I have quit looking for one cause" of the glacial cycle. The mystery of the ice ages, which had launched a century of studies of greenhouse gases and climate, remained unsolved.

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satellite data show "the water vapour feedback is not overestimated in models," Rind et al. (1991), p. 500; Sun and Held (1996); and the final nail in the coffin, Soden et. al. (2005).

[1] Lindzen (1997) Lindzen et al. (2001).

[2] For a short review and references, see Broecker and Denton (1989), p. 2486.

[3] E.g., "the 100,000-year cycle does not arise from ice sheet dynamics." Shackleton (2000).

Meanwhile the old program of studying ancient climates for hints on future conditions persisted. With computer models disagreeing on how warming would affect specific regions, the experience of past warm periods might give as good a guess as any. For the planet as a whole, some scientists used paleoclimate data to get a rough idea of the climate's "sensitivity"—how much temperatures had actually changed, under the powerful influences that had operated at one time or another in the geological past. The results gave useful and encouraging comparisons with general-circulation computer models[1]

To get farther with the big models, it helped to construct simpler models of the interactions between biological systems and gases. Although actual measurements remained fragmentary, the models of specific processes were improving rapidly. An example (called "one of the most robust predictions of the new dynamic global vegetation models") was a calculation that forests would tend to replace northern tundra as the world warmed. Here, as so often, there were complex and unexpected consequences. The dark evergreens would absorb much more solar radiation than the pale tundra, amplifying the global warming.[2]

Meanwhile ice cores and other indicators showed that greenhouse gas levels during the 20th century were rising much faster than any change detected in the past. Was that why temperatures were likewise climbing, more rapidly than any warming in the past millennium? The big general-circulation computer models with their millions of numerical operations could not reliably churn through a run of ten centuries. There was no way to keep small initial errors from accumulating, a little more each time the model ran through another year, until the whole computation veered off into unreality. But a simple energy-balance model could be adjusted until it responded smoothly to changes in gases, aerosols, and the like in ways that faithfully mirrored the overall average responses of the big models. Thus modeling came full circle, with large computer systems used to calibrate a stripped-down version. The result was some of the most convincing evidence yet that the greenhouse effect was indeed upon us, rapidly growing more serious.[3] No matter how you manipulated any sort of model, if you could get it to simulate the current climate, it was likely to show warming if you put in greenhouse gases.

By now, some of the "simple" models run on desktop computers were comparable to what had been considered state-of-the-art for the most advanced computations in the 1960s. Of course, at that time everyone had recognized that those models were primitive). Such a simplistic model became far more reliable and convincing once it was calibrated against a range of different full-scale general circulation models. Then anyone could run it through a variety of scenarios. It was thus, for example, that scientists could take a set of different assumptions for how much

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[1] Kerr (1999); "quit looking:"Andre Berger. Kerr (2000); A landmark work using paeloclimate data to derive sensitivity was Hoffert and Covey (1992).

[2] Foley et al. (1994); "robust": Melillo (1999).

[3] Crowley (2000).

greenhouse gases humanity might emit over the coming century, and get rough predictions for the range of temperature and sea-level changes likely to result for each proposed policy. Or they could get around the uncertainties in how the biosphere interacted with climate by building models with boxes for various regions and types of vegetation, then running these models through the entire range of plausible responses in each box. Another example: to address the large uncertainties in the parameters used to calculate such things as cloudiness, thousands of people cooperated to run simplified "screensaver" models using every reasonable combination of such parameters (nearly all of them produced global warming, and some got disastrously warm). I'm running such a model in the background on the computer on which this is written.[1]*

Simple models—hardly simple by the standards of 1970, perhaps, but far more comprehensible than the enormous three-dimensional general circulation models—also found increasing use in estimating the impacts of global warming. Specialized models were used, for example, to study how the strength or frequency of storms might change. Others evaluated changes already underway, as when a group calculated that global warming probably had a hand in the unprecedented 2003 heat wave that killed thousands in Europe.[2]

Simple models played a major role in the reports that the Intergovernmental Panel on Climate Change prepared for the world's policy-makers. For its 2007 report the IPCC ordered up an elementary model with one box representing land and one representing ocean in each hemisphere, adjusted so that the exchanges of heat between land and oceans, the responses to an increase in CO_2, and so forth were all similar to the responses of state-of-the-art computer models The model was then run through a variety of scenarios for the emissions that humanity might choose to allow in future, mapping out the range of likely consequences.[3]

The huge global computer models, ever grander and more complex, represented an approach to dealing with the world that some found neither appealing nor convincing. Simple models offered a variety of other approaches, more comprehensible and more easy to verify within their special

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[1] The most important such use has been in the Intergovernmental Panel for Climate Change reports, e.g., IPCC (2001), ch. 9; Randall et al. (2007), section 8.8. For another use see Wigley (2005). Among the simplifications in the distributed model in the initial runs by www.climateprediction.net was a "slab" ocean instead of a circulating-ocean model, see Stainforth et al. (2005); Piani et al. (2005) estimate 5th/95th probability percentiles for future warming at 2.2 and 6.8 K. Similarly, Andreae et al. (2005) used a one-dimensional model with parameters that began with those from a three-dimensional general circulation model and varied them within plausible limits, also finding a possibility of extreme warming. A recent example of use of an energy balance model calibrated against general circulation models is Hegerl et al. (2006).

[2] Knutson and Tuleya (2004); Stott et al. (2004).

[3] IPCC (2007a), pp. 643-44.

domains. If they were not overlooked in the shadow cast by gargantuan computations, they could add flexibility and plausibility to decisions about future policies.[1]

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[1] Shackley et al. (1998).