

Paul N. Edwards, "The World in a Machine: Origins and Impacts of Early Computerized Global Systems Models"

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THE WORLD IN A MACHINE: ORIGINS AND IMPACTS OF
EARLY COMPUTERIZED GLOBAL SYSTEMS MODELS

Paul N. Edwards

INTRODUCTION

The idea of “the world” is probably as old as language, with as many meanings and connotations as there are cultures. For much of human history “the world” must have seemed boundless, beyond the grasp of mortal understanding. Even long after the Scientific Revolution, when “the world” had become for many an immense but finite globe, comprehending the forces that act upon it as a whole—as a system—remained for the most part beyond reach.

Although scientists began to develop theories of world-scale processes at least as early as Copernicus, grounded empirical knowledge of geophysical features and processes remained in a rudimentary state until the Second World War. This was even more the case in the social arenas of politics, economics, and culture. The short-lived era of the League of Nations notwithstanding, it is really only since the Second World War that “the world” has *become* a system in political, economic, and cultural terms. Phrases like “global economy,” “global village,” “world system,” and “global warming,” mundane elements of modern discourse, would have been little more than rhetoric even in 1939.

Without the articulated, developed concepts of global systems that underlie these phrases, “the world” might remain in an important sense merely a symbol or icon. Yet in our society, we are regularly exhorted by bumper stickers and political leaflets to “think globally,” to see ourselves as part of a larger, *knowable* whole. How did “the world” become a system? What kind of science made it possible to know the planet as a unit, to disentangle the vast array of interlocking forces that determine its characteristics as a system? As the politico-economic world became increasingly integrated, from where did the conceptual tools for grasping that integration come? This chapter begins to address these questions by looking at the first concerted efforts to simulate complex, global dynamic systems. I focus on *comprehensive mathematical*

simulation models of global dynamic processes. Unlike maps, globes, and other simple models with one or a few dimensions, these models attempt to capture all of the major elements of time-evolving, world-scale systems.¹

The chapter explores the origins of two types of simulation models: (1) numerical models of weather and climate, and (2) world dynamics models (offshoots of a general method known as “system dynamics”). In the 1950s, the forecasting of weather by means of mathematical models became feasible for the first time with the advent of electronic digital computers. By the 1960s, increasing computer power made possible detailed simulations of the general circulation of Earth’s atmosphere. This, in turn, allowed scientists to simulate weather and climate—genuinely global systems. During approximately the same period, computer pioneer Jay Forrester created techniques for simulating the dynamic behavior of large socio-technical systems. He began in the late 1950s with factories, proceeded to cities, and published a book on the general “principles of systems” in 1968. Finally, in the early 1970s, he modeled “world dynamics.” Under Forrester’s aegis, the MIT System Dynamics Group used world-dynamics models as the basis for the controversial best-seller *The Limits to Growth* (1972).² According to the System Dynamics Group, imminent global collapse could be prevented only by sweeping, long-term, world-scale planning, based on computer modeling. In the 1980s these two kinds of models became directly linked, in part through concerns over human impacts on the global environment, such as global warming and ozone depletion.

While their historical origins and purposes are largely distinct, these two kinds of world-modeling practices overlapped in some interesting and surprising ways. Here I outline these origins and overlaps, focusing primarily on the period 1945–72. Bringing them together reveals patterns in the construction of “the world” through a systems approach to science and science-based policy.³

The notion of “system” played a more important role in the world dynamics case, where it served as a central, explicit organizing concept (even, some have said, an ideology), than in weather and climate modeling. But the actual models had much in common. In both cases, feedbacks among system components lay at the core of the models’ design. In both cases, computers made possible the numerical solution of nonlinear dynamic equations and the vast iterative processing required to simulate the interaction of many closely linked factors

over long periods of time. In both cases, the acquisition and coding of global data for model validation, calibration, and forecasting became a central, critical, and controversial issue. Finally, in both cases, computer models became the core not only of an epistemology of global systems, but also of a new policy analysis paradigm.

PART 1. 1945–56: COMPUTERS FOR SIMULATION AND CONTROL

Simulation: Weather Prediction, Weather Control, and Climate Models

Military agencies became deeply interested in the universe of possibilities opened up by digital computers after World War II. As was the case in many other areas, this interest developed through a process I have called “mutual orientation.” Scientists and engineers who had worked on the military projects of the war continued, after the war, to consider military problems as part of their research agenda. The fact that most research funding in the postwar period came from military agencies amplified this effect. Scientists and engineers oriented their military sponsors toward new techniques and technologies, while the agencies oriented their grantees toward military applications. This “mutual orientation” mostly produced general directions rather than precise goals. Often there was only a very loose linkage between funding and military utility, rather than a tightly focused dollars-for-products regime.⁴

One area of mutual orientation was numerical weather prediction (NWP). Weather prediction has great military value, since weather affects virtually every aspect of battlefield operations (especially, in World War II and after, air warfare). Indeed, the data networks that made possible the first numerical weather predictions came into existence because of the need of World War II military aviators for information about conditions in the upper atmosphere. The much-increased extent and more systematic character of upper-air observations—using radiosondes (weather balloons incorporating radio transmitters), aircraft, rockets, and other techniques—gave weather forecasters the crucial ability to map activity at several atmospheric levels. Radar, another World War II product, also increased the observational abilities of meteorologists, for example, through rawinsondes (radar-tracked radiosondes).⁵

If weather could be predicted, it might also be controlled, and this too could have profound military implications. General George C. Kennedy of the Strategic Air Command claimed, in 1953, that “the

nation which first learns to plot the paths of air masses accurately and learns to control the time and place of precipitation will dominate the globe.”⁶ Cloud seeding by dry ice and silver iodide, discovered and developed in 1946–47, seemed to some—including Nobel Prize winner Irving Langmuir, a major proponent—to offer the near-term prospect of complete control of precipitation. Respected scientists, both American and Soviet, believed in the mid-1950s that a new struggle for “meteorological mastery” had become a salient element of the Cold War arms race. Proponents of weather control frequently drew analogies between the energy released by atomic weapons and the (even larger) energy contained in weather systems, and they sought the ability to alter climate as a possible weapon of war. By January 1958, in the aftermath of Sputnik, *Newsweek* magazine warned readers of “a new race with the reds” in weather prediction and control.⁷

Numerical Weather Prediction

The key to numerical weather prediction (the only part of this story I will pursue here) was the digital computer, itself a product of World War II military needs. The chief American computer project—the University of Pennsylvania ENIAC—was designed for the Army’s Aberdeen Proving Ground, where ballistics table production had fallen far behind schedule, but it was not completed until the fall of 1945. John von Neumann, a member of the ENIAC team and also a consultant to the Manhattan Project, suggested the ENIAC’s first application: a mathematical simulation of a hydrogen bomb explosion.

Von Neumann also foresaw the computer’s application to weather prediction. The hydrogen-bomb problem and the issue of weather prediction were conceptually linked, as both were essentially problems of fluid dynamics, an area of particular scientific interest to von Neumann.⁸ But von Neumann’s concern with the weather prediction issue was connected to the bomb in other ways as well. Like many other scientists in the postwar years—and as a Hungarian emigré with bitter memories of communism—von Neumann remained dedicated to the application of science to military problems as the Cold War intensified.⁹

Von Neumann became deeply interested in weather prediction after World War II—era encounters with Carl-Gustav Rossby, a leading meteorologist, and Vladimir Zworykin, an RCA electrical engineer involved in meteorological instrumentation work.¹⁰ Early in 1946, while the ENIAC was still churning out the Los Alamos H-bomb

calculation, von Neumann attended a meeting of the U.S. Weather Bureau and began to plan for work on the weather prediction problem at Princeton's Institute for Advanced Study (IAS). Under grants from the Weather Bureau and the navy and air force weather services, he assembled a group of theoretical meteorologists at the IAS.

Among the IAS Numerical Meteorology Project's initial goals was "to examine the foundation of our ideas concerning the general circulation of the atmosphere, with the intention of determining the steady state of the general circulation of the atmosphere and its response to arbitrarily applied external influences."¹¹ The group spent the next three years developing numerical methods for various aspects of general-circulation and weather problems. Under von Neumann's direction, in late 1949 the group prepared to perform the first computerized weather prediction using the ENIAC. In March and April 1950, members of von Neumann's team carried out two 12-hour and four 24-hour retrospective forecasts using observational data. The calculations required about 800 hours of ENIAC computer time, with each 24-hour forecast taking about 24 hours to perform once the methods had been settled and the programs debugged.¹² Results, while far from perfect, seemed to justify further work. By 1954 the civilian Weather Bureau, the Air Weather Service of the Air Force, and the navy's Naval Weather Service had established computerized weather prediction programs. Routine computerized national weather forecasting began in Sweden in 1954, and in the United States in 1955.

NWP models, then as now, work by breaking up the atmosphere into a set of "grid boxes," tens to hundreds of kilometers square and hundreds to thousands of meters deep. Within each grid box, conditions such as temperature, humidity, and pressure are assumed homogeneous. The models simulate what happens to the air mass in each grid box on a periodic "time step" (today, typically about twenty to thirty minutes; in early models, sometimes as much as three hours). For example, part of a warm air mass might move upward into an adjacent grid box, becoming cooler in the process. Thus the model as a whole simulates how the specified initial conditions will change over time. However, the chaotic nature of weather processes limits forecasts based on this method to a maximum of about two weeks.

The 1950 ENIAC forecasts used some 270 grid points approximately 700 km apart, laid out in a two-dimensional 15×18 grid covering North America and much of the surrounding oceans at a single high-altitude atmospheric level. The forecasts used a three-hour time

step. Wind speed, wind direction, vorticity, and barometric pressure were the sole forecast elements. A subsequent experimental forecast, using a somewhat more refined model, employed a grid of 361 points spaced approximately 320 km apart, while the initial Weather Bureau production forecast models used a 600-point grid at three altitudes.¹³ These resolutions meant that only gross factors affecting weather (regional barometric pressure, temperature, and high-altitude wind speed and direction, for example) could be predicted. As computer models slowly matured, human forecasters used a combination of the computer-produced regional weather maps, radar images, and especially their own experiential, “subjective” knowledge of local conditions in preparing their forecasts.

Gathering Global Data

One of the great challenges of this era turned out to be the collection of data and, especially, its entry into the computer in a form suitable for calculations.

International agreements to share weather observations date to the 1878 founding of the International Meteorological Organization (IMO), one of the oldest intergovernmental organizations in the world. Telegraph, and later telephone, radio, and teletype, allowed rapid transmission of information. Long before World War II, standard coding systems had been worked out that allowed relatively smooth, coordinated transfer of this information. In 1947, as part of the general organization of the United Nations, the IMO became the World Meteorological Organization (WMO)—from the point of view of this chapter, a significant name change that marks a new, global approach.¹⁴ A central purpose of both organizations was to develop and promote data distribution systems and standardized observational techniques.¹⁵

With the advent of computerized NWP came new needs for data and for ways to handle them. As computer models grew in sophistication, they required information about the state of the atmosphere from ground level to very high altitudes and from locations as near as possible to points on their regular grids, which covered very large areas (continents, eventually hemispheres). Data collection for global forecasting suffered particularly from a lack of observation stations over the oceans, which cover some 70 percent of the Earth’s surface, and from irregularly spaced stations, especially in sparsely populated areas such as Siberia, Canada, and much of the Southern Hemisphere.

As for data entry, at the outset of computerized weather prediction “gathering, plotting, analyzing and feeding the necessary information for a 24-hour forecast into a computer [took] between 10 and 12 hours,” with another hour required for computation, plus additional time for transmitting the results from the central computer facility at Suitland, Maryland, to local forecasters.¹⁶ Well into the 1960s, much weather data were hand recorded and hand processed before being entered into computers.¹⁷ Much of this work, such as the interpolation of grid-point data from hand-drawn maps, was difficult, time-consuming, and error-prone. Despite international standards for data coding, data distributed in potentially machine-readable form, such as teletype, often arrived in a Babel of different formats, necessitating conversions.¹⁸ A great deal of available data was never used at all, since the time required to code it for the computer would have delayed forecasts beyond their very short useful lifetimes. In 1962, a WMO report predicted that “the principal meteorological benefits of high-speed automatic computing machines during the next few years will lie as much in the processing of large assemblages of data as in numerical forecasting.”¹⁹

Meteorologists had always engaged in the “smoothing” of data, in which errors and anomalous data points were eliminated from the data. In the 1950s, this process was based both on “subjective” readings of observations (using the meteorologist’s judgment to reject probable errors) and on explicit theories of large-scale atmospheric behavior. Another standard practice was the interpolation of intermediate values (in both time and space) from known ones. Both smoothing and interpolation were now increasingly automated; as computerization continued, virtually all of it was automated. The methods themselves did not really change, but their automation forced meteorologists to develop explicit, computer-programmable theories of error, anomaly, and interpolation. The effect was simultaneously to render invisible the data “massage” necessary for forecasting.²⁰

In other words, the data themselves were subjected to processing based on models of physical behavior (for interpolation), and/or on the needs of NWP models for correctly gridded and time-stepped data. Eventually, the NWP models themselves were actually used to “produce” standard data sets. Today, for example, the widely used twice-daily atmospheric analyses of the National Meteorological Center (in the United States) and the European Center for Medium-Range Weather Forecasts “incorporate observational data from both the

surface and from satellites into a 4-D data assimilation system that uses a numerical weather prediction model to carry forward information from previous analyses, giving global uniformly gridded data."²¹ Thus the twice-daily periods of actual observation are transformed into 24-hour data sets *by computer models*; these data sets, in turn, become inputs to other weather and climate models.²²

Models as an Experimental Domain

In the period I have been discussing (1945–56), the utility of digital computers—huge, power-hungry, unreliable, and expensive—remained an open question for many. According to William Aspray, von Neumann “regarded [the computer’s] application to meteorology as the crucial test of its scientific value, in large part because the hydrodynamics of the atmosphere is a prime example of those complex, nonlinear phenomena that were previously inaccessible to mathematical study.”²³ The success of NWP proved this value, which involved changes much more fundamental than faster calculation. As one of its key members, Jule Charney, explained in an address to the National Academy of Sciences in 1955, “the radical alteration that is taking place [in meteorology] . . . is due . . . to [the computer’s] ability to serve as an *inductive device*. . . . The machine, by reducing the mathematical difficulties involved in carrying a physical argument to its logical conclusion, makes possible the making and testing of physical hypotheses in a field where controlled experiment is still visionary and model experiment difficult, and so permits a wider use of inductive methods.”²⁴ In other words, modelers had already begun to experience the appeal of computer models as an alternative experimental domain.

Having successfully fostered the emerging program of numerical weather prediction, von Neumann and his colleagues turned their attention to modeling the atmospheric general circulation (i.e., its global motion and state) in 1953. By mid-1955 Norman Phillips had completed the first, two-layer “quasi-geostrophic” model.²⁵ Von Neumann and Harry Wexler of the U.S. Weather Bureau immediately proposed a substantial research program on numerical methods for the general circulation problem. In response, the Weather Bureau created a General Circulation Research Section, under the direction of Joseph Smagorinsky; his group eventually became the Geophysical Fluid Dynamics Laboratory (GFDL), now located at Princeton University. Starting in 1959, the laboratory developed a nine-level hemispheric general circulation model (GCM).²⁶ Groups at UCLA and Lawrence

Livermore National Laboratory also began building GCMs around the same time.²⁷ In addition to their weather prediction applications, GCMs would later become the crucial proving grounds—the experimental domain—for theories of anthropogenic climate change.

As the grid scales of weather models and their time-steps began to shrink, and as meteorologists sought to model the entire globe, the lack of global uniformly gridded data increasingly became a problem. By the end of the period discussed here, it was beginning to dawn on atmospheric scientists that the core issue of their discipline had been turned on its head by the computer. Whereas in the very recent past, through the data networks built for World War II military aviation, they had rather suddenly acquired far more data than they could ever hope to use, now they could see that in the not-too-distant future they might not have enough—at least not in the standard formats (computer processable), from the right places (uniform grid points), at the right times (uniform time-steps). The computer, which had created the possibility of NWP in the first place, now also became a tool for refining, correcting, and shaping data to fit the models' needs.

Control: Computers for Military Systems

While von Neumann was leading the drive to build weather and climate models, another computer pioneer of similar stature, Jay Forrester, was learning to apply computers to a much different kind of problem. Like von Neumann's, Forrester's project had military sponsors. But his became much more directly focused on a Cold War military problem: the defense of North America against nuclear-armed Soviet bombers. Forrester was among the first to envision the application of computers to an integrated information and control system on a continental scale.

The Semi-Automatic Ground Environment (SAGE) system, conceived by Forrester and others in the early 1950s and completed by 1961, was capable of using radar data to plot intercept courses for fighter aircraft automatically, of remote control of the latter's autopilots to guide them to their targets, and even in principle of controlling the release of air-to-air missiles. SAGE marked the first effort to apply computers to large-scale problems of real-time *control*, as distinct from calculation and information processing.²⁸

Control has since become one of the primary applications of computers. But in the 1940s, when Forrester initiated the digital computer project known as Whirlwind, this was far from an obvious use of the new technology. It was dismissed or resisted by many for reasons

ranging from reliability problems and expense to the availability of alternatives (primarily analog techniques).²⁹ Long before Whirlwind became the core of SAGE, Forrester had sought out and studied possible military applications, in a process of “mutual orientation” like that described above vis-à-vis weather prediction and control. His source of funding (the Office of Naval Research and the Navy Special Devices Center), the political climate, and their personal experiences oriented Forrester’s group toward military applications, while the group’s research eventually oriented the military toward new concepts of command and control. When the first Soviet atomic test and the outbreak of the Korean War shook the nation’s confidence in its defenses, Forrester was ready. In the new political context, Forrester’s then-unusual agenda of digital computers for control could suddenly fill a vast, newly perceived gap.

In building the SAGE system, Forrester and his engineers were dealing with issues quite similar to the problem faced by meteorologists of this period, albeit in a much different domain. They too needed to gather data on an enormous (continental) scale, and they needed to find a way around the immensely time-consuming and error-prone activity of human reading and interpretation of data. They solved the former problem with a widely dispersed network of radar stations as far north as the Arctic Circle; eventually, just as with meteorology, much of the data for the system came from satellites. Like the meteorologists, the SAGE engineers solved the problem of automatic data conversion by creating new ways—sensors, interpretation programs, modems—to acquire and input data in numerical form. In both cases time pressures were intense; although weather prediction is not *quite* a “real-time” problem, like air defense, every hour’s delay between data collection and forecast output rendered weather predictions less useful.

In the late 1950s and beyond, SAGE spawned dozens of similar computerized real-time command-control systems, including SACCS (the Strategic Air Command Control System), the many computer systems built for NORAD (the North Atlantic Air Defense Command), NADGE (the NATO Air Defense Ground Environment), and WWMCCS (the World Wide Military Command and Control System). These projects extended the SAGE concept to create a world-encompassing surveillance, communications, and control system. It is perhaps, then, not surprising that Forrester—like von Neumann before him—eventually turned to modeling the world, as we will see below.

PART 2. 1957–69: BUILDING GLOBAL MODELS

By 1957, computers were exhibiting the remarkable combination of steep climbs in capability and declines in price that have characterized their development ever since.³⁰ As capabilities increased, so did expectations. Computer-based numerical weather prediction had become a routine element of U.S. weather forecasting, although NWP models were still continental (vs. hemispherical or global) in scale. Von Neumann's long-term goal of modeling climate was beginning to seem feasible. Meanwhile, the SAGE system was on the verge of its first operational tests, in 1958. Both NWP and SAGE proved the value of computers, in different but related ways: NWP for near-real-time simulation models of physical processes, SAGE for real-time data analysis and control of complex human-machine systems. Within a decade, computer simulation techniques were adopted by many other sciences—including the social sciences, where models of economies and cities were just two of the myriad applications. Part 2 discusses the maturation of global general circulation models, on the one hand, and the precursors of world dynamics in Forrester's turn to socio-technical modeling, on the other, during this period.

Climate Models Mature

The Geophysical Fluid Dynamics Laboratory (GFDL) was the direct descendant of von Neumann's vision for weather and climate modeling. During the 1960s, this laboratory developed the crude models of Phillips and Smagorinsky into the first global, three-dimensional atmospheric GCMs. The National Center for Atmospheric Research (NCAR) in Boulder, Colorado, founded in 1960 under NSF sponsorship, developed expertise in climate modeling a few years later.

GCMs are simply global versions of the NWP models discussed above. When used to forecast weather, they are initialized with observational data and run to simulate short periods (up to two weeks). But GCMs can also be used to study climate. In this case, they are usually *not* initialized with actual weather data. Instead, they start with physical constants such as the amount of solar energy striking the atmosphere, the speed of Earth's rotation and wobble on its axis, and the atmosphere's chemical composition. The models are run until they achieve a stable ("equilibrium") state, understood to be their model "climate."³¹ This simulated climate may then be compared to observed climatological averages of the actual Earth. Physical parameters may be altered

to simulate other planets, to simulate climates of ancient times (“paleoclimate”), or to project future trends. Thus climate models are simulations in a more profound sense than are numerical weather forecasts.

Even more than weather prediction, climate modeling demands enormous computational power. A typical model must compute changes for many thousands of grid boxes some 20,000 times to simulate the global climate for a single year. In 1971, GFDL’s Syukuro Manabe estimated that a model with a 500-km grid and nine atmospheric layers required about 120 hours of computer time to simulate a single year of climate.³² By the early 1980s, supercomputers had reduced the time to about twelve hours per simulated year.³³ Computer speed limitations meant that early climate simulations were usually run for only a simulated few months—at most, for a year or two. But because climate is by definition a long-term (multiyear) statistical average, because of the strong effect of the ocean “heat sink” on atmospheric behavior, and because the models take several “years” to settle into reliable patterns, runs of 20–100 years are necessary to determine their equilibrium states.³⁴ Even in the early 1980s, a single complete GCM run thus required 1,200 hours—fifty continuous days—of expensive supercomputer time. Despite vast increases in computer power, full runs of today’s state-of-the-art GCMs still require hundreds of supercomputer hours, since modelers add complexity to the models even more rapidly than computers improve.

By the end of the 1960s, GCMs had become the central tool of climate science, despite their still-primitive state. By that point, as we will see below, the issue of carbon dioxide accumulation in the atmosphere had started to acquire some urgency among a small but influential group of scientists. This combination set the stage for the still-continuing debate over human-induced global climate change.

The International Geophysical Year

As computerized NWP models began to dominate weather forecasting in the late 1950s, with GCMs looming on the scientific horizon, the need for global data sets became increasingly apparent. The first attempts to construct genuinely global data networks for meteorological observation came with the International Geophysical Year (IGY). During the “year” between July 1957 and December 1958, scientists from some fifty nations conducted global cooperative experiments to learn about world-scale physical systems, including Earth’s atmosphere,

oceans, ionosphere, and geological structure. Among the major scientific participants and organizers was the WMO.

As the IGY began, the theory of carbon dioxide (CO_2)-induced global warming was becoming the focus of considerable scientific attention. Scientists—primarily oceanographers—had begun to explore the fate of carbon dioxide released into the atmosphere by fossil-fuel consumption. They knew that the oceans absorbed CO_2 , but whether and how fast the oceans could absorb all of the fossil-fuel carbon remained in question. In the early 1950s Hans Suess used the radioactive carbon injected into the atmosphere by nuclear blasts to trace the circulation of carbon from fossil fuels, concluding that some but not all of this excess carbon remained in the atmosphere.³⁵ A widely cited article by Gilbert Plass, published in 1956, aroused renewed interest in carbon dioxide as a factor in climate change.³⁶ Suess and Roger Revelle, head of the Scripps Institute of Oceanography, predicted that fossil fuels might soon induce a rapid change in world climate. In a now-famous phrase, they wrote that humanity was conducting, unawares, “a great geophysical experiment” on the Earth’s climate.³⁷

To track the “experiment’s” progress, Revelle proposed to build a monitoring station for atmospheric CO_2 at Mauna Loa, Hawaii, as part of the IGY. This station, initially opened in Antarctica, has operated on a continuous basis ever since. It is the chief source of what is probably the only undisputed fact in the global warming debate: the steady rise in the atmospheric concentration of CO_2 , from about 280 ppm at the beginning of the industrial era in the mid-nineteenth century to about 370 ppm today. Revelle and others also sought to build a global network of monitoring stations for atmospheric chemistry.³⁸

The IGY’s meteorological component focused most of its attention on the global general-circulation problem. Three pole-to-pole chains of atmospheric observing stations were established along the meridians 10°E (Europe/Africa), $70^\circ\text{--}80^\circ\text{W}$ (the Americas), and 140°W (Japan/Australia). Dividing the globe roughly into thirds, these stations coordinated their observations to collect data simultaneously on specially designated “Regular World Days” and “World Meteorological Intervals.” An atmospheric rocketry program retrieved information from very high altitudes. An extensive effort was made to gather information about the Southern Hemisphere from commercial ships, as well as (for the first time) from the Antarctic continent. Data from all

aspects of the IGY were deposited at three World Data Centres: one in the United States, one in the Soviet Union, and a third divided between Western Europe and Japan.³⁹

The IGY efforts thus represent the first global data networks for constant, consistent, structured observation on a scale and grid to match the emerging atmospheric models. Some, but not all, of these efforts continued after 1958; rising Cold War tensions during this period undoubtedly contributed to their incomplete success. Within a few years, Revelle's hopes for a global atmospheric-chemistry network fell by the wayside, and even the Mauna Loa station experienced severe funding difficulties.⁴⁰

Nevertheless, the cooperative activities of the IGY began a trend toward global programs such as the World Weather Watch (WWW) and the Global Atmospheric Research Program (GARP). Conceived about 1960, WWW took another decade to enter into practice. It coordinated global data collection from satellites, weather rockets, ocean buoys, ocean-launched radiosondes, and commercial aircraft as well as conventional observing stations. This was necessary, according to one participant, because "currently conventional methods . . . will never be sufficient if the state of the atmosphere over the whole globe is to be observed at reasonable cost with the time and space resolution which can be used with advantage in computer-assisted research and forecasting."⁴¹ GARP had its roots in a 1961 proposal by John F. Kennedy to the United Nations for "further co-operative efforts between all nations in weather prediction and eventually in weather control."⁴² It, too, took most of the decade to implement. With the participation of American, Soviet, and many other nations' scientists, GARP sponsored a series of regional and global observations and experiments.⁴³ Data gathered by these programs were especially important for global weather and climate models, because they included the first detailed observations of equatorial weather, which (in part since it is so constant and predictable) had never been carefully observed.

Mirror Worlds: Models and Data

By the end of the 1960s, global, three-dimensional climate models had emerged as the central tool of climate science. Modelers had begun to speak routinely of "experiments with the models." Just as with weather prediction, acquisition of global uniformly gridded data became a necessity.

But because of the long-term nature of climate processes, climate models posed especially severe data problems. How could they be empirically validated? The seasonal cycle, because of its extreme variability compared with climate change, provides a well-known, reasonably well-understood benchmark against which to test climate models, but this is not enough. Unlike weather models, which are easily checked against observations over very short periods, comparing climate models with reality demands data on long time scales—ideally, at least 100 years.

Records of land and sea surface temperature exist for large areas over the last hundred years. But changes over time in thermometer quality, location, number, and measurement technique create uncertainties. For example, most thermometers are located on land and clustered in and near urban regions, where “heat island” effects raise local temperatures above the regional average. Temperature records at sea come primarily from shipping lanes, ignoring the globe’s less traveled areas. Records from the atmosphere above the surface exist only for the last few decades, but until quite recently these too came mostly from populated land areas in the Northern Hemisphere. Paleoclimatic data from a variety of “proxy” sources (tree rings, ice cores, fossilized pollen, etc.) are also available, though naturally the accuracy and level of detail in this data is far lower than in direct instrumental observations. Model inputs can be set to the different conditions (orbital precession, trace gas concentration, etc.) of past periods and validated by how well they simulate the paleoclimatic record.

During the 1960s, orbiting weather satellites began to provide the first truly global pictures of the atmosphere. The global coverage of satellite data makes them almost fatally attractive to climate modelers. “We don’t care about a beautiful data set from just one point,” one modeler recently told me. “It’s not much use to us. We have one person whose almost entire job is taking satellite data sets and putting them into files that it’s easy for us to compare our stuff to.”⁴⁴ Yet even the satellite data are problematic. They provide only proxy measurements of phenomena at low altitudes, which may be distorted by optical effects and orbital drift.⁴⁵ In addition, their lifespans are short (two to five years), and their instruments may drift out of calibration over time.

The way in which most of these problems were resolved was by filtering the actual observations through other models, which smoothed, interpolated, and gridded the scattered, uncertain, and often absent

data. Some of this was done by hand or by eye, but in many situations—and routinely in the case of satellite data—computer models provided automatic conversion of instrument readings into standard data sets. Without this much lesser known and appreciated class of intermediate models, validation and calibration of NWP models and GCMs could not proceed. In this seemingly paradoxical mirror world, data used to validate one class of models are themselves partly the product of other models. There was (and is) no real alternative.

From Industrial Dynamics to World Dynamics

Jay Forrester's "world dynamics" models were to gain an enormous influence as the basis for *The Limits to Growth*, a popular best-seller that predicted the catastrophic collapse of socio-economic systems by 2050.⁴⁶ Their origins lay in Forrester's mid-career shift from computer engineering to management science, where he brought his expertise with comprehensive computerized systems to bear on the problems of factories, cities, and eventually the world as a whole.

As the research phase of the SAGE project drew to a close in the mid-1950s, Forrester grew restless. He had enjoyed a virtually unique position as one of the most important pioneers of digital computing. Now he sought some new area in which he could once again be a pioneer.⁴⁷ The opportunity came when he was invited to join MIT's Sloan School of Management, whose mission was to develop a "scientific" approach to management. There he began to explore the problem of the causes of cyclical change in factory production and employment. He published his first study (of General Electric factories in Kentucky) in 1958. There he argued that a company should be viewed "not as a collection of separate functions but as a system in which the flows of information, materials, manpower, capital equipment, and money set up forces that determine the basic tendencies toward growth, fluctuation, and decline."⁴⁸ By 1961 he had refined this approach into a comprehensive, model-based theory of company activity he called "industrial dynamics."

Forrester's industrial models typically showed a "roller-coaster effect,"⁴⁹ later known as an "overshoot-and-collapse" mode. Production and employment, for example, tended to rise high, then rapidly fall back to very low levels, creating employee layoffs and idle factories in a "boom-bust" cycle. This pattern, according to Forrester, had less to do with cyclical change in the larger economy than with the built-in

“delays” and “amplifications” in the “information-feedback system” of company management. Managers, inclined to attribute such fluctuations to external factors, typically tried to dampen these swings. But the policies they introduced often, Forrester believed, actually made the roller-coaster effect worse.

The introduction to *Industrial Dynamics* (1961) demonstrates the profound influence of the first phase of Forrester’s career on his later management-science work. Over and over he points to the automation and simulation of military systems by means of digital computers as the root of current modeling capabilities. The industrial dynamics approach was built, he wrote, on “four foundations” which were “primarily . . . a by-product of military systems research” since 1940:

- the theory of information-feedback systems
- a knowledge of decision-making processes
- the experimental model approach to complex systems
- the digital computer as a means to simulate realistic mathematical models⁵⁰

For Forrester, the primary sources of simulation models were “the design of air defense systems,” which he noted had “received tens of thousands of man-years of effort in the last decade,” and engineering studies such as the simulation of river basin development in the context of hydroelectric power plant construction. Recognizing that simulations of economic systems, electric power grids, and other complex phenomena had been attempted on analog computers starting in the 1930s, he pointed out—echoing von Neumann—that “these analog computers . . . do not readily deal with nonlinear systems” and that they were incapable of sufficient size and complexity for simulation of economic and corporate problems. For him, the development of digital computers from 1945–60 represented “a technological change greater than that effected in going from chemical to atomic explosives.”⁵¹

Throughout the text of *Industrial Dynamics*, Forrester frequently noted that although his examples came primarily from industry, his models relied on “orderly underlying principles from which system behavior derives.” Forrester argued that “systems of information-feedback control” were the essential organizing principle of all complex organized entities, from biological organisms to machines and computers.⁵²

Over the next decade, Forrester refined these general principles of systems and applied them to areas of increasing complexity and scale.

He first turned his attention to modeling cities. Like *Industrial Dynamics*, Forrester's *Urban Dynamics* (1969) argued that systems as complex as cities are "counterintuitive," in the sense that policies developed to correct problematic behavior often end up making problems worse. In effect, policy makers tend to see and treat symptoms rather than causes of problematic system functions. This occurs because "a complex system is not a simple feedback loop where one system state dominates the behavior, [but] a multiplicity of interacting feedback loops ... controlled by nonlinear relationships."⁵³ The issue of nonlinearities and multiple feedbacks made complex systems virtually impossible, in Forrester's view, for unaided minds to grasp, since people think mainly in terms of linear relationships and simple feedbacks.

Forrester's models tended to be insensitive to changes in most parameters, even of several orders of magnitude—indicating to him that "complex systems resist most policy changes."⁵⁴ Effective policies usually followed a counterintuitive "worse before better" pattern. A system's short-term responses to change tended to be of opposite sign from long-term responses, so that policies which produced desirable effects for a couple of years would end up creating negative effects in the long run (and vice versa). In short, Forrester's slogan for policy makers was "no pain, no gain."

Forrester argued that there were only two possible solutions to the insensitivity of systems to most parameter changes. The first was to find, through modeling, those few parameters and structural changes which *could* produce desirable effects. The second was to design—again with the help of models—comprehensive policies which took into account the complex interactions among all the different elements of a system. Models thus became, for him, virtually a sine qua non of effective policy making in any complex system.

The *Urban Dynamics* models also reflected three other interesting and unusual characteristics of Forrester's approach. First was his strikingly cavalier attitude toward empirical information. Forrester wrote that "the barrier to progress in social systems is not lack of data. We have vastly more information than we use in an orderly and organized way. The barrier is deficiency in the existing theories of structure." Rather than gathering more data, Forrester thought it much more important to model as many important system relationships as could be incorporated. "It is far more serious," he wrote, "to omit a relationship that is believed to be important than to include it at a low level of accuracy that fits within the plausible range of uncertainty." He noted

that this modeling approach "follows the philosophy of the manager or political leader more than that of the scientist. If one believes a relationship to be important, he acts accordingly and makes the best use he can of the information available. He is willing to let his reputation rest on his keenness of perception and interpretation."⁵⁵ These sentiments reflected Forrester's lifelong belief that tools should always be forged through actual practice, never only in academic laboratories.

Second was Forrester's insistence that models for policy should be comprehensive. This demanded interdisciplinary and cross-disciplinary work. "The barriers between disciplines must melt away.... Within the same system we must admit the interactions of the psychological, the economic, the technical, the cultural, and the political."⁵⁶

Finally, in a theme that became enormously important during the *Limits to Growth* controversies, Forrester argued that growth was a developmental phase rather than a constant of urban systems. *Urban Dynamics* focused on the "life cycle" of cities over a 250-year period, in which empty land is settled and developed until fully inhabited. Then it proceeds through a series of socio-economic "realignments" until it reaches an "equilibrium" state of stagnation.⁵⁷ "Continued exponential growth," Forrester asserted unequivocally, "is impossible."⁵⁸

These three features of Forrester's modeling techniques and modeling philosophy were indeed pioneering. Although many of his contemporaries regarded his models' lack of empirical data as an extremely serious if not a fatal problem, Forrester was among the first to insist that computer models could serve important policy purposes even in the absence of good data. Like the climate scientists, ecologists, and other systems scientists whose work also matured during the 1960s, Forrester believed that sorting out the structure and dynamics of a system using a computer model was the key to understanding. Data could come later, in part because a systems model could help reveal *which* data might be most important. His models' far-reaching, interdisciplinary character foreshadowed many later developments, such as the rise in the late 1980s of Earth systems models, which encompass atmosphere, oceans, agriculture, and ecology, and of integrated assessment models, which incorporate economics, energy, and human social systems as well. Though Forrester was far from the first to articulate the theme of inherent limits to growth—his critics invariably compared him to Malthus—his models drew attention to ways in which a many-dimensional world system might be more finite and fragile than it appeared.

PART 3. 1970–72: MODELS FOR POLICY

Between 1970 and 1972, as the environmental movement came of age in the United States, world models of both sorts rather suddenly became the focus of substantial public controversy. Climate modelers went public with claims that human activities were likely to alter the climate, and world dynamics modelers predicted imminent collapse of human societies in a world ravaged by overpopulation and over-extraction of limited resources.

I do not have space here to give the political aspects of these controversies the attention they deserve. Instead, I focus on the relationships between models and data, especially the role of modeling projects in provoking the creation and extension of global data networks. In the end, I argue, these models and data networks have played a major part in creating “the world” as we know it today.

SCEP and SMIC

Most of the series of “experiments with models” carried out in the 1960s showed a global warming somewhere in the range of 1–6 °C with a doubling of atmospheric carbon dioxide over the preindustrial era. This was in fact a very old scientific result, dating to the work of Svante Arrhenius in 1896.⁵⁹ But three things about the 1960s findings were new. First, there were the Mauna Loa CO₂ measurements, which showed exponentially increasing levels of CO₂ far from the urban pollution centers of the developed world. Second, the 1950s had seen an extremely rapid rise in the rate of fossil fuel consumption, the chief anthropogenic source of CO₂. Finally, there were the GCMs. In climate science as in many other fields, computers lent their enormous scientific and popular cachet to the GCM results. Together, these developments led to rising alarm about human tampering with the atmosphere. According to Hart and Victor, “by 1968 the notion that pollution could modify the climate was a commonplace.”⁶⁰

In 1969, the WMO called for extending the global atmospheric data network in a new direction: to monitor pollutants that might change the climate, such as CO₂ and particulate aerosols.⁶¹ That call was soon underscored by two important scientific working groups, the Study of Critical Environmental Problems (SCEP, 1970) and the Study of Man’s Impact on Climate (SMIC, 1971). The SCEP and SMIC reports are widely cited by scientists and policy makers alike as the first

point at which anthropogenic climate change began to become a major public issue. They also mark the point at which the climate modeling story and the world dynamics story begin to converge.

Both studies were organized by the entrepreneurial professor Caroll Wilson of MIT's Sloan School (where Forrester had worked since 1956). Wilson had been involved in science policy for decades; he began his career as Vannevar Bush's assistant during World War II and later served as general manager of the Atomic Energy Commission. He planned the month-long summer conferences on which the reports were based as contributions to the UN Conference on the Human Environment, scheduled for Stockholm in June 1972.

SCEP focused on world-scale environmental problems, conceived as "the effects of pollution on man through changes in climate, ocean ecology, or in large terrestrial ecosystems."⁶² NCAR and Scripps—important centers of atmospheric and ocean modeling respectively, and both loci of important work on the carbon dioxide theory of climate change—were both heavily represented among the invitees. Smagorinsky of GFDL attended on a part-time basis, and Revelle (now at Harvard) consulted.

The climatic effects section of the report cited GCMs as "indispensable" in the study of possible anthropogenic climate change. The report pointed to two key uses of models: as "laboratory-type experiments on the atmosphere-ocean system which are impossible to conduct on the actual system," and as a way of producing "longer-term forecasts of global atmospheric conditions."⁶³ While noting their many deficiencies, the report argued that models were "the only way that we now conceive of exploring the tangle of relations" involved in climate. It therefore recommended an expanded program of climate, ocean, and weather modeling research.⁶⁴

SCEP's recommendations focused heavily on the problem of uniform global data. The report noted that "critically needed data were fragmentary, contradictory, and in some cases completely unavailable. This was true for all types of data—scientific, technical, economic, industrial, and social."⁶⁵ It recommended three initiatives: (1) "new methods" for global information gathering, which would integrate economic and environmental statistics, along with "uniform data-collection standards," (2) "international physical, chemical, and ecological measurement standards," administered through a "monitoring standards center," and (3) integration of existing monitoring programs to produce an "optimal" global monitoring system.⁶⁶

Where the majority of SCEP participants were Americans, SMIC—less than a year before the Stockholm UN meeting—included a much more international cast of characters. SMIC provided a detailed technical discussion of GCMs and other, simpler climate models. The study reached conclusions very similar to those of SCEP with respect to human impacts on climate, including possible effects of then-controversial supersonic commercial aircraft. The body of the SMIC report reflects relative confidence in the availability of global uniform data, citing the WMO data network, the Global Atmospheric Research Program, and the increasing body of observations gathered by satellites. Nevertheless SMIC recommended a global monitoring program even more elaborate than the one proposed the year before by SCEP, including a global network of 100 monitoring stations to sample air and precipitation chemistry, measure solar radiation, and gather other meteorological data. SMIC estimated that an adequate program could be established for a yearly budget of about \$17.5 million. Wilson's project had at least one direct outcome: at the UN Stockholm conference, the SCEP and SMIC calls for a global monitoring network were approved "with little discussion."⁶⁷

These urgent calls for more and more data to feed the global models illustrate the process of data/model interaction for which I have been arguing. Climate and weather models increasingly gave a picture of "the world" as a whole, an interconnected set of systems whose interactions could be understood only through a combination of simulation and observation. The needs of each one drove the other forward. Without complete global data sets, modelers could neither validate nor parameterize their models. Without computers and models, data collection on that scale would have been not only pointless but meaningless. The models were what *made sense* of the data; they made a coherent world from collections of bits. In a certain important epistemological sense, they gave us "the world" as an ecological and physical unity.

THE LIMITS TO GROWTH

Around the same time as Wilson's SCEP and SMIC, a new kind of global model was being built by another Sloan School professor: Forrester. In June 1970 Forrester attended the first general meeting of the Club of Rome, a small international group of prominent businessmen, scientists, and politicians organized by Italian industrialist Aurelio

Peccei. His invitation came at the behest of Carroll Wilson, himself a new member of the Club of Rome.

The Club of Rome, founded in 1968, had at this point been considering for a year a proposal to model what it called the world *problématique*—global, systemic problems—in cybernetic terms.⁶⁸ The Volkswagen Foundation had rejected the modeling proposal for methodological vagueness. Forrester suggested that his approach might overcome this objection, and invited Club members to attend a workshop on industrial dynamics. By the time the Club of Rome's executive committee arrived at MIT three weeks later, Forrester had worked up and programmed on the computer a rough model, "World 1." The model divided world systems into five major subsystems (natural resources, population, pollution, capital, and agriculture) and incorporated some sketchy data and guesses about relationships among these variables. This very rapid work-up of the world model again reflected Forrester's fundamental belief that system structure and dynamics were more important than precise data.

Perhaps not surprisingly, World 1's characteristic modes resembled those of the industrial and urban models Forrester had already developed, especially the phenomenon of "overshoot and collapse." Eduard Pestel recalled that Club of Rome founder Peccei was tremendously impressed "by the fact that all computer runs exhibited—sooner or later at some point in time during the next century—a collapse mode regardless of any 'technological fixes' employed. Peccei obviously saw his fears confirmed. . . ."⁶⁹ The Club of Rome returned to the Volkswagen Foundation with a new proposal. This time, with Forrester's clear and well-developed methodology in hand, the application for an eighteen-month modeling project at MIT was approved.

Forrester's former student Dennis Meadows led the System Dynamics Group, with Forrester acting as consultant.⁷⁰ The team developed two successor models, known as World 2 and World 3.⁷¹ World 3 incorporated over 120 strongly interdependent variables. Attempts were made to calibrate the models by starting model runs in the year 1900 and adjusting parameters until the model results roughly matched actual historical trends. World dynamics' essential conclusion was that many existing trends (resource consumption, pollution increases, population growth, etc.) displayed exponential growth rates that a finite planet could not possibly sustain. The world dynamics models continued to show, after refinement and even on the most optimistic assumptions, that natural resources would be rapidly

exhausted, that pollution would rapidly increase to life-threatening levels, and that catastrophic collapse, including massive famine, would follow around the year 2050. *The Limits to Growth* became an international phenomenon, selling over seven million copies worldwide in some thirty languages.

The System Dynamics Group's self-described "bias" followed Forrester in favoring comprehensive model structure and dynamics over precise data. Indeed, the data used in the world models were generally poor in quality. In many cases, they were simply guessed. Although reviewers attacked them savagely for this apparent sin,⁷² the situation was more complicated than it first appeared.

Like the weather and climate modelers before it, the System Dynamics Group had a great deal of difficulty acquiring high-quality information in the right form. Since the central idea of the world models was to produce very long runs (up to 150 years), in order to project long-term consequences of current trends, they could be validated only with very long time series. As Meadows put it in an interview, "it was hard in those days to find the kind of comprehensive, cross-national time series data on the issues we wanted to see, except on population. So we were looking where we could, with the United Nations and the World Bank as principal sources of information."⁷³ But the United Nations and the World Bank were only a quarter-century old. Where were Meadows and his colleagues to find *world-scale* information on pollution, agriculture, trade, and so forth, going back more than twenty-five years? The scant available information, such as population figures, was mostly either in a highly aggregated form that prevented analysis using the model categories, or at a level of disaggregation that would have taken the small modeling group years to organize. So Meadows's group chose the path Forrester had blazed for them: model the structure and worry about the data later.

Irving Elichirigoity's analysis of this situation bears careful attention: "The Meadows team had problems finding globally oriented information because information of that type was not normally collected within a framework of scientific practice that did not conceptualize the global as an entity on which information needed to be collected."⁷⁴ Just as with weather and climate modeling, one indirect effect of *The Limits to Growth* and its successors was to create an epistemological framework in which gathering global information became necessary and made sense.

All the models drew heavy fire from some sectors of the scientific community and, especially, economists. Within a couple of years most scientists regarded them with indifference or even contempt. Many in the policy community found the world-models approach—in an era when computer simulation was far less widely understood and accepted than today—technocratic in the extreme. This impression was only amplified by the Club of Rome's elite character and by the perceived arrogance and insensitivity of some of the modelers. Nevertheless, during the rest of the 1970s the Club of Rome commanded considerable international respect. It convened a series of meetings among senior politicians to discuss global resource concerns. The meetings, held in major world capitals, sometimes included the presidents and prime ministers of such nations as Canada, Sweden, the Netherlands, and Mexico.⁷⁵

The Limits to Growth and the Club of Rome had few, if any, direct policy impacts. Nevertheless, through its models, popular books, meetings, and person-to-person canvassing of politicians, the Club succeeded in communicating, to both a broad public and a policy elite, its two basic conclusions: (1) that population, pollution, and consumption levels could not continue to grow indefinitely, and (2) that attempts to control problems piecemeal, without taking into account the interconnected nature of world socio-technical-environmental systems, would not work and might actually backfire. It is safe to say that these principles achieved the status of shared background assumptions for a large subset of the world policy community. In addition, the world dynamics modelers helped to establish computer simulation as an important technique of policy analysis. In the process they—like today's global change modelers—established a hybrid science/policy community for which the models were a key focal point.⁷⁶

SCEP, SMIC, and *The Limits to Growth* are important because they mark the moment in the history of environmentalism when global issues first became salient not only to scientists, but also to the general public. Before this point, virtually the only issue discussed as *global* was population. The Club of Rome played a major part in building awareness of the integrated character of world systems, and especially of natural resources with human economies. From this point on, a growing minority of scientists, environmentalists, economists, and concerned citizens moved beyond the "pollution paradigm" to conceive of some environmental problems as global in scope.

CONCLUSION

During the past decade, computerized global modeling has become a widely accepted paradigm in science, in policy forecasting, and especially in science-based policy analysis. Earth systems models based in the physical sciences are including human systems (such as agriculture and forestry) in climate modeling, while integrated assessment models are combining GCM outputs with models of energy and resources to analyze climate policy options. Some of these, such as the Dutch integrated assessment model IMAGE, descend directly from Forrester's world dynamics.⁷⁷ The history of these modeling techniques thus holds some important lessons for the present.

In each case, computer models represented a fundamentally new approach to the phenomena in question. Detailed simulation models of global dynamic processes were, in general, not possible before the advent of electronic digital computers, for two reasons. One of these is obvious: the scale of calculation involved was prohibitive. The second reason—not nearly so obvious as the first—is that the global data required to construct, calibrate, and validate such simulations were largely unavailable.

From the mid-1950s on, efforts to build global atmospheric models and efforts to gather global uniformly structured data sets proceeded in tandem, each one driving the other's progress. The modeling efforts provided the rationale for the creation of global data networks. In addition, the models' requirements for time-stepped, gridded data shaped the technical structure of those networks. In turn, models were increasingly used (especially in weather and climate science) to refine rough, sparse, and poorly gridded data sets, resulting in increasingly blurred boundaries between models and data.

The profound interdependence of models and data in these cases suggests an important epistemological issue, namely the question of what is "global" about global models.⁷⁸ For both climate modeling and world dynamics, none of the available data sets remotely approach what might be construed as a minimal requirement for truly "global" data. Instead, coverage is spotty, inconsistent, poorly calibrated, and temporally brief. Rather, it is the *models* that are "global"; the data, with the exception of the (problematic) satellite measurements and population figures, are local or regional at best. Part of the work of the models, then, is to make those data *function as* "global" by providing an overarching reference frame.

As in many other areas of science, the U.S. high-technology Cold War strategy made immense financial and technical resources (especially computers and satellites) available to scientists and influenced research directions, particularly in the 1950s. In the case of weather and climate modeling, both the necessary equipment and the requisite data networks were direct products of military efforts during World War II and the early Cold War. Contests to achieve accurate weather prediction and weather control developed as part of the general Cold War arms race. In the case of the world dynamics models, Forrester's systems thinking had early precursors in his 1944–56 work on World War II and Cold War military projects, especially the SAGE continental air defense system. Forrester and his research group envisioned comprehensive solutions to world-scale military problems featuring digital computers as the focal technology. These concepts and technologies of global systems control had a profound influence on Forrester's later world modeling projects.

In both cases, international cooperative ventures were catalytic. The UN-sponsored World Meteorological Organization, the World Weather Watch, the Global Atmospheric Research Program, and other projects produced a variety of data and data networks that became crucial to weather and climate model development. The 1957 International Geophysical Year, which produced the first global uniform meteorological data sets, was a hybrid scientific/political response to Cold War tensions. The world dynamics models grew out of the Club of Rome's efforts to promote understanding of the world "*problématique*." They employed data gathered by various UN agencies, but also focused a glaring light on the inadequacy of world-scale socio-economic information sources. The importance of uniform data for these kinds of models has only grown with time.

Thus the second crucial aspect of the "global" character of global models is their role in generating and extending global data networks. The worldwide spread of scientific instrumentation for atmospheric observations, and of the knowledge and practices required to make such instrumentation function reliably, is one form of globalization rarely mentioned in the modern litany of "global" activities. This is equally true for the less developed, but also extremely extensive, data networks for collecting information about population, energy use, agriculture, trade, and other socio-economic activities. Global data networks require high levels of standardization, creating new commonalities in practice and understanding worldwide.⁷⁹

With the emergence of global environmental politics, these data networks are among the forces creating concepts of global systems, global problems, and global common interests. From the perspective of this chapter, these are among the most important globalizations of all. For it is with models and data networks that modern concepts of "the world" have been built.

NOTES

1. An ordinary globe is a "model" of the world, and global maps were very important in colonial empire building. Scientists engaged in a variety of efforts at global mapping (e.g., of vegetation and average climatic conditions) in the nineteenth century, and possibly before. See, e.g., Jane Camerini, "The Physical Atlas of Heinrich Berghaus: Distribution Maps as Scientific Knowledge," in *Non-Verbal Communication in Science Prior to 1900*, ed. Renato G. Mazzolini (Florence: Olschki, 1993): 497–512. In the nineteenth century, Malthus speculated on the problem of the world's maximum population; Fourier and Arrhenius developed theories of global temperature as determined by the chemical composition of the atmosphere. In the twentieth century, meteorologists (among others) built a variety of analog models of global processes, such as "dishpan" experiments with rotating trays of colored liquids exposed to a heat source. "Weather Now Computed," *Science News Letter* 64 (1953): 196.
2. Donella H. Meadows et al., *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (New York: Universe Books, 1972).
3. This chapter is a preliminary study for a book, tentatively entitled *The World in a Machine: Computer Models, Data Networks, and Global Atmospheric Politics* (Cambridge: MIT Press, in preparation).
4. See chap. 3 of Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge: MIT Press, 1996).
5. Joseph J. Tribbia and Richard A. Anthes, "Scientific Basis of Modern Weather Prediction," *Science* 237 (1987): 493–499.
6. Kennedy, cited in James R. Fleming, "'Cloud Wars': Weather Modification and the U.S. Military, 1947–1977" (forthcoming), ms. p. 10. Ms. available from James Fleming, Colby College, Waterville, Maine, 04901. On this subject see also James R. Fleming, ed., *Historical Essays on Meteorology, 1919–1995* (Boston: American Meteorological Society, 1996), and R. G. Fleagle and others, *Weather Modification in the Public Interest* (Seattle: University of Washington Press, 1974).
7. Fleming, "Cloud Wars," ms. p. 5.
8. In addition to his work on shock waves and aerodynamics for Los Alamos, von Neumann was "consultant to BRL (Ballistics Research Laboratory) on hydro-

dynamical and aerodynamical problems associated with projectile motion." J. G. Brainerd, ENIAC project supervisor, cited in William Aspray, *John von Neumann and the Origins of Modern Computing* (Cambridge: MIT Press, 1990), 37.

9. Aspray quotes von Neumann, during hearings on his nomination to the AEC: "I am violently anti-Communist, and I was probably a good deal more militaristic than most. . . . My opinions have been violently opposed to Marxism ever since I remember, and quite in particular since I had about a three-month taste of it in Hungary in 1919." *Ibid.*, 247.

10. Rossby was among the early promoters of cloud seeding for military weather control. He chaired a 1947 Panel on Meteorology for the Joint Research and Development Board of the Department of Defense, which recommended an "intensive research and development effort." Fleming, "Cloud Wars," ms. p. 2. Zworykin had previously proposed building an *analog* computer for weather prediction.

11. Aspray, *John von Neumann*, 132, quoting Rossby.

12. J. G. Charney, R. Fjörtoft, and J. von Neumann, "Numerical integration of the barotropic vorticity equation," *Tellus* 2 (1950): 237–254; G. W. Platzman, "The ENIAC computations of 1950—Gateway to numerical weather prediction," *Bulletin of the American Meteorological Society* 60 (1979): 302–312.

13. "The Man Who Works the Weather Machine," *U.S. News & World Report*, 20 May 1955, 16.

14. See Clark A. Miller, "Scientific Internationalism in American Foreign Policy: The Case of Meteorology, 1947–1958," in Paul N. Edwards and Clark A. Miller, eds., *Changing the Atmosphere: Science and the Politics of Global Warming* (Cambridge: MIT Press, in preparation).

15. "Convention on World Meteorological Organization, 1947," in *The Encyclopedia of the United Nations and International Agreements*, ed. Edmund Jan Osmańczyk (Philadelphia: Taylor and Francis, 1985), 923–925.

16. "Long-Range Weather Forecasts by Computer," *Science News Letter*, 12 June 1954, 376.

17. Lt. Col. John R. Collins Jr., "Automated Data Processing at the United States Air Force Environmental Technical Applications Center," in *Data Processing for Climatological Purposes: WMO Technical Note No. 100*, ed. World Meteorological Organization (Geneva: World Meteorological Organization, 1969), 26.

18. B. Bolin et al., *Numerical Methods of Weather Analysis and Forecasting: WMO Technical Note No. 44* (Geneva: World Meteorological Organization, 1962), 3.

19. *Ibid.*, 2.

20. On these methods see, for example, *ibid.*; Collins, "Data Processing"; and V. V. Filippov, "Quality Control Procedures for Meteorological Data," in *Data Processing for Climatological Purposes: WMO Technical Note No. 100*, ed. World

Meteorological Organization (Geneva: World Meteorological Organization, 1969), 35–38.

21. Jeffrey T. Kiehl, "Atmospheric General Circulation Modeling," in *Climate System Modeling*, ed. Kevin E. Trenberth (Cambridge: Cambridge University Press, 1992), 367–368.

22. See Naomi Oreskes, Kristin Shrader-Frechette, and Kenneth Belitz, "Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences," *Science*, 4 February 1994, 641–646; Paul N. Edwards, "Data-Laden Models, Model-Filtered Data: Uncertainty and Politics in Global Climate Science," *Science as Culture* (forthcoming); and Stephen D. Norton and Frederick Suppe, "Epistemology of Atmospheric Modeling," in Edwards and Miller, *Changing the Atmosphere*.

23. Aspray, *John von Neumann*, 152.

24. Charney, cited in *ibid.*, 152–153.

25. Norman A. Phillips, "The General Circulation of the Atmosphere: A Numerical Experiment," *Quarterly Journal of the Royal Meteorological Society* 82, 352 (1956): 123–164.

26. Joseph Smagorinsky, "General Circulation Experiments with the Primitive Equations," *Monthly Weather Review* 91, 3 (1963): 99–164.

27. Cecil E. Leith, "Numerical Simulation of the Earth's Atmosphere," in Berni Alder et al., eds., *Methods in Computational Physics*, vol. 4 (New York: Academic Press, 1965), 1–28; Yale Mintz, "Design of Some Numerical General Circulation Experiments," *Bulletin of the Research Council of Israel* 76 (1958): 67–114.

28. See chap. 3 of Edwards, *The Closed World*.

29. The interpretation of SAGE offered here is detailed in *ibid.* Also see Kent C. Redmond and Thomas M. Smith, *Project Whirlwind: The History of a Pioneer Computer* (Boston: Digital Press, 1980); and Kenneth Schaffel, *The Emerging Shield: The Air Force and the Evolution of Continental Air Defense 1945–1960* (Washington, D.C.: Office of Air Force History, United States Air Force, 1991).

30. Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: Brookings Institution, 1988).

31. "Weather," for the atmospheric sciences, refers to actual meteorological events, while "climate" refers to long-term averages such as seasonal temperature change, annual rainfall, and so forth.

32. Syukuro Manabe, private communication, cited in Study of Man's Impact on Climate (SMIC), *Inadvertent Climate Modification* (Cambridge: MIT Press, 1971), 143.

33. Robert M. Chervin, "High Performance Computing and the Grand Challenge of Climate Modeling," *Computers in Physics* (May–June 1990): 235.

34. SMIC, *Inadvertent Climate Modification*, 143.

35. Hans E. Suess, "Natural Radiocarbon and the Rate of Exchange of Carbon Dioxide between the Atmosphere and the Sea," in *Nuclear Processes in Geologic Settings*, ed. National Research Council Committee on Nuclear Science (Washington, D.C.: National Academy of Sciences, 1953): 52–56.

36. G. N. Plass, "The Carbon Dioxide Theory of Climatic Change," *Tellus* 8 (1956): 140–154.

37. R. Revelle and H. E. Suess, "Carbon Dioxide Exchange between the Atmosphere and Ocean and the Question of an Increase of Atmospheric CO₂ during the Past Decades," *Tellus* 9 (1957): 19.

38. David M. Hart and David G. Victor, "Scientific Elites and the Making of US Policy for Climate Change Research," *Social Studies of Science* 23 (1993): 643–680. This article provides an insightful look into the surprisingly slow development of a public debate over the climate change issue.

39. Sir Harold Spencer Jones, "The Inception and Development of the International Geophysical Year," in *Annals of the International Geophysical Year*, ed. Sydney Chapman (New York: Pergamon Press, 1959), 393–395, 410–411 et passim; Comité Spécial de l'Année Géophysique Internationale, "The Fourth Meeting of the CSAGI," in *Annals of the International Geophysical Year*, ed. M. Nicolet (New York: Pergamon Press, 1958), 300–313, 350–353 et passim. The geopolitical structure of this division is intriguing; note especially the absence of a "World" Data Centre in the Southern Hemisphere.

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41. G. D. Robinson, "Some Current Projects for Global Meteorological Observation and Experiment," *Quarterly Journal of the Royal Meteorological Society* 93, 398 (1967): 410.

42. Kennedy, cited in *ibid.*, 409.

43. See for example "Report of the Fifth Session of WMO Executive Committee Inter-Governmental Panel on the First GARP Global Experiment," GARP Special Report No. 26 (World Meteorological Organization Executive Committee, 1978).

44. Anonymous interviewee, interviewed by Paul N. Edwards at NCAR in 1994.

45. James W. Hurrell and Kevin E. Trenberth, "Spurious Trends in Satellite MSU Temperatures from Merging Different Satellite Records," *Nature* 386, 6621 (1997): 164–166.

46. Meadows et al., *Limits to Growth*.

47. Jay W. Forrester, interviewed by Marc Miller, 1977. MIT Archives, *Computers at MIT Oral History Collection*, Acc. no. 78-106, transcript pp. 44-45, 48 et passim.
48. Jay W. Forrester, "Industrial Dynamics: A Major Breakthrough for Decision Makers," *Harvard Business Review* 36, 4 (1958): 52.
49. Jay Forrester, *Industrial Dynamics* (Cambridge: MIT Press, 1961), 41.
50. *Ibid.*, 14.
51. *Ibid.*, 18-19.
52. *Ibid.*, 15.
53. Jay Forrester, *Urban Dynamics* (Cambridge: MIT Press, 1969), 9.
54. *Ibid.*, 110.
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57. *Ibid.*, 38.
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60. Hart and Victor, "Scientific Elites," 665.
61. *Ibid.*
62. Study of Critical Environmental Problems (SCEP), *Man's Impact on the Global Environment* (Cambridge: MIT Press, 1970), 5.
63. *Ibid.*, 78.
64. *Ibid.*, 88.
65. *Ibid.*, 6.
66. *Ibid.*, 7.
67. Hart and Victor, "Scientific Elites," 664.
68. Irving Fernando Elichirigoity, "Towards a Genealogy of Planet Management: Computer Simulation, *Limits to Growth*, and the Emergence of Global Spaces" (Ph.D. diss., University of Illinois, Urbana, 1994), 149ff.
69. Eduard Pestel, *Beyond the Limits to Growth* (New York: Universe Books, 1989), 24, cited in *ibid.*, 174.

70. Forrester himself moved on to other projects and was not deeply involved in the work of the System Dynamics Group. In 1971 he published a technical report on the world models as *World Dynamics* (Cambridge: MIT Press, 1971).
71. In addition to the rudimentary discussion in *Limits to Growth*, the System Dynamics Group's world models are exhaustively described in Dennis L. Meadows et al., *Dynamics of Growth in a Finite World* (Cambridge, Mass.: Wright-Allen Press, 1974).
72. The canonical critique is H. S. D. Cole et al., eds., *Models of Doom: A Critique of The Limits to Growth* (New York: Universe Books, 1973), but there were many others. A reasonably comprehensive retrospective look at the debate is Brian P. Bloomfield, *Modelling the World: The Social Constructions of Systems Analysts* (Oxford: Basil Blackwell, 1986).
73. Meadows, interviewed by Irving Elichirigoity, quoted in Elichirigoity, *Planet Management*, 175–176.
74. Ibid.
75. Alexander King, "The Club of Rome and Its Policy Impact," in *Knowledge and Power in a Global Society*, ed. William M. Evan (Beverly Hills: SAGE Publications, 1981), 205–224.
76. Paul N. Edwards, "Global Comprehensive Models in Politics and Policy-making," *Climatic Change* 32 (1996): 149–161.
77. Jan Rotmans, *IMAGE: An Integrated Model to Assess the Greenhouse Effect* (Boston: Kluwer Academic Publishers, 1990).
78. An especially insightful look at this problem appears in Peter Taylor and Fred Buttel, "How Do We Know We Have Global Environmental Problems?" *Geoforum* 23, 3 (1992): 405–416.
79. Peter M. Haas, "Obtaining International Environmental Protection through Epistemic Consensus," *Millennium* 19, 3 (1990): 347–364; Peter M. Haas, Robert O. Keohane, and Marc A. Levy, eds., *Institutions for the Earth: Sources of Effective International Environmental Protection* (Cambridge: MIT Press, 1993).