

Early History of Climate Modeling in the British Meteorological Office*

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Introduction

In June 1988, over 300 scientists and policymakers around the world gathered at the World Conference on “The Changing Atmosphere: Implications for Global Security” held in Toronto, Canada, jointly organized by the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP). The conference proclaimed that, in order to prevent human-induced global warming, there was a need to reduce global carbon dioxide (CO₂) emissions by 20% from their 1988 levels before the year 2005—a conclusion that garnered significant international attention.¹ Six months later, at its 43rd General Assembly, the United Nations passed a resolution on the “Protection of Global Climate for Present and Future Generations of Mankind” and endorsed the establishment of the Intergovernmental Panel on Climate Change (IPCC). The IPCC was tasked to “provide internationally coordinated scientific assessments of the magnitude, timing and potential environmental and socio-economic impact of climate change and realistic response strategies.”²

The IPCC was launched with three Working Groups: (a) Working Group I (WGI) assesses the scientific aspects of the climate system and climate change, specifically the role of greenhouse gases in these phenomena, and the observed and projected changes in the earth’s climate; (b) Working Group II (WGII) assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it; and (c) Working Group III (WGIII) assesses options for limiting greenhouse gas emissions and oth-

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¹ WMO/UNEP, *The Changing Atmosphere: Implications for Global Security* (Geneva: WMO, 1989).

² UN General Assembly, *Protection of Global Climate for Present and Future Generations of Mankind*, A/Res/43/53 (1988).

erwise mitigating climate change. In the initial stage of the IPCC, given its responsibility to provide the crucial scientific basis anchoring the assessments of WGII and WGIII, WGI was considered most important.³ As expected, there was substantial international interest in how WGI would be structured and administered, and which scientific groups would assume leadership roles.

After negotiations, Sir John Houghton, then director-general of the British Meteorological Office (hereafter, the Met Office), was appointed to chair WGI. Though Houghton was a distinguished atmospheric physicist with international recognition, and his work certainly had some relevance to the study of climate change, his appointment largely hinged on his leadership role at the Met Office. The Office, at that time, was highly regarded for its world-leading expertise in the state-of-the-art physico-mathematical modeling of global climate and its extensive experience in conducting climate simulation experiments. To manage the considerable work associated with WGI assessments, a technical support unit was formed within the Met Office. Later, in 1990, with financial backing from the UK Department of Environment, the Met Office established the Hadley Centre for Climate Prediction and Research. The Centre not only served as a technical support unit for WGI but also contributed important climate simulation results, underpinning the publication of the IPCC Scientific Assessment reports until the early 2000s.⁴

However, while the internationally acclaimed activities of the IPCC have shed light on the Met Office's climate modeling work since the late 1980s, it is less well-known how such research began in the first place and the contexts in which it has evolved. For the last several decades, the emergence of global environmental change as a worldwide concern has led to an array of rich historical studies of earth and environmental sciences.⁵ In line with this trend, the history of numerical modeling of the atmosphere, of climate modeling, as well as of research into CO₂-induced

³ For the history of the IPCC, see S. Agrawala, "Context and Early Origins of the Intergovernmental Panel on Climate Change," *Climatic Change* 39 (1998), 605-620.

⁴ See, e.g., C.K. Folland et al., "History of the Hadley Centre for Climate Prediction and Research," *Weather* 59:11 (2004), 317-323; M. Mahony and M. Hulme, "Modelling and the Nation: Institutionalising Climate Prediction in the UK, 1988-92," *Minerva* 54:4 (2016), 445-470.

⁵ See, e.g., J. Cloud, ed., "Special Issue: Earth Sciences in the Cold War," *Social Studies of Science* 33:5 (2003), 629-819; C. Kwa, "Local Ecologies and Global Science: Discourses and Strategies of the International Geosphere-Biosphere Programme," *Social Studies of Science* 35:6 (2005), 923-950; J.D. Hamblin, *Oceanographers and the Cold War: Disciples of Marine Science* (Seattle: University of Washington Press, 2005); J. Vetter, ed., *Knowing Global Environments: New Historical Perspectives on the Field Sciences* (New Brunswick: Rutgers University Press, 2010); R. Launius et al., eds., *Globalizing Polar Science: Reconsidering the International Polar and Geophysical Years* (London: Palgrave Macmillan, 2011); R.E. Doel et al., eds., *Exploring Greenland: Cold War Science and Technology on Ice* (London: Palgrave Macmillan, 2016); N. Oreskes, *Science on a Mission: How Military Funding Shaped What We Do and Don't Know about the Ocean* (Chicago: University of Chicago Press, 2021).

global warming, has also been explored extensively.⁶ On the other hand, these studies have concentrated mainly on research efforts in the US, only briefly touching upon the British case. Even though some recent studies have examined the history of weather forecasting and climate modeling at the Met Office in the pre-1980s period, they tended to be more concerned with how the use of those models was influenced by the immediate British political and policy contexts.⁷ The detailed and deeper historical trajectory of the development of general circulation models at the Office and its broader transnational dimensions have yet to be fully explored.

The current paper aims to fill this gap by tracing the history of climate modeling at the Met Office from the 1950s through to the early-to-mid 1970s. It will explore how a combination of diverse factors—i.e., the institutional objectives and organizational culture of the Met Office, the national and global political climates, burgeoning environmental concerns, and international scientific initiatives—forged a distinctive path and style of climate modeling. The paper will begin by examining the advent of numerical weather prediction in the 1950s. At that time, climatology—the study of climate—was generally viewed as a descriptive endeavor, having a low status in the hierarchy of sciences. As one British climatologist put it, “climatology was looked upon merely as the dry-as-dust book-keeping branch of meteorology.”⁸ Within a few decades, however, climatology transformed itself into a highly physico-mathematical science. Built upon the fundamental equations of hydrodynamics and thermodynamics, complex numerical models were constructed to simulate the general circulation of the atmosphere. These new approaches would soon dominate

⁶ See, e.g., P.N. Edwards, “A Brief History of Atmospheric General Circulation Modeling,” D.A. Randall, ed., *General Circulation Model Development, Past Present and Future* (New York: Academic Press, 2000), 67–90; *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge: MIT Press, 2010); C.A. Miller and P.N. Edwards, eds., *Changing the Atmosphere: Expert Knowledge and Environmental Governance* (Cambridge: MIT Press, 2001); S.R. Weart, *The Discovery of Global Warming*, revised edition (Cambridge: Harvard University Press, 2008); “The Development of General Circulation Models of Climate,” *Studies in History and Philosophy of Modern Physics* 4 (2010), 208–217; J. Fleming, *Fixing the Sky: The Checkered History of Weather and Climate Control* (New York: Columbia University Press, 2010); K.C. Harper, *Weather by the Numbers: The Genesis of Modern Meteorology* (Cambridge: MIT Press, 2008); *Make It Rain: State Control of the Atmosphere in Twentieth-Century America* (Chicago: University of Chicago Press, 2017); M. Heymann et al., eds., *Cultures of Prediction in Atmospheric and Climate Science: Epistemic and Cultural Shifts in Computer-based Modelling and Simulation* (London: Routledge, 2017).

⁷ J. Martin-Nielsen, “Scientific Forecasting?: Performing Objectivity at the UK’s Meteorological Office, 1960s–1970s,” *History of Meteorology* 8 (2017), 202–221; “Computing the Climate: When Models Became Political,” *Historical Studies in the Natural Sciences* 48:2 (2018), 223–245. See also J. Agar, “‘Future Forecast: Changeable and Probably Getting Worse’: The UK Government’s Early Response to Anthropogenic Climate Change,” *Twentieth Century British History* 26:4 (2015), 602–628. Agar, however, focused on the Central Policy Review Staff of the UK Cabinet Office and did not examine the history of climate science.

⁸ H.H. Lamb, “Our Changing Climate, Past and Present,” *Weather* 14 (1959), 299.

the field of climate research. But the basic capability to model the atmosphere had to be built first.

Pre-History of Climate Modeling

(1) Beginning of Numerical Weather Prediction

In 1946, John von Neumann, a prominent mathematician and pioneer of scientific computing, turned his attention to weather prediction as a test base for the newly developed electronic computer. From his experiences in weapons research, von Neumann well understood how important weather was to the military. He managed to persuade the US Navy to support his Meteorology Project, based at Princeton's Institute for Advanced Study (IAS), and in 1948 invited Jule Charney to become its leader. By that time, Charney had developed the concept of quasi-geostrophic approximation and opened the possibility of using barotropic equations for numerical weather prediction (NWP). The first 24-hour numerical forecast was successfully accomplished in 1950, using a barotropic model on the ENIAC computer.⁹ A series of trial forecasts were made in the following years. In 1954, the Joint Numerical Weather Prediction Unit (JNWPU) was set up by the US Weather Bureau, the Air Force, and the Navy. A year later, the JNWPU began to issue regular, real-time daily numerical weather forecasts using a barotropic model. As computer technology and forecast algorithms improved, baroclinic models were also being constructed, though they were not yet used by the forecasters. A new era of numerical meteorology unfolded.¹⁰

NWP developed somewhat slowly in Britain. When World War II was over, Nelson Johnson, director-general of the Met Office, was able to strengthen the research side of the Office. In 1948, he established the Forecasting Research Division alongside the Central Forecasting Office at Dunstable. Reginald Sutcliffe was appointed to lead the Division, which at first consisted of two branches—Short-Range and Long-Range Forecasting Research.¹¹ In the same year, the Meteorological Research

⁹ F. Nebeker, *Calculating the Weather: Meteorology in the 20th Century* (New York: Academic Press, 1995), 135-151.

¹⁰ Ibid., 152-172. In 'barotropic' models, no vertical wind shears were allowed and there was uniform temperature at all heights. 'Baroclinic' models, on the other hand, assumed that temperature varies vertically, allowing atmospheric disturbances to grow by converting potential energy to kinetic energy. These models were designed to yield a prediction at two or more levels.

¹¹ R.C. Sutcliffe, Interview by J.M.C. Burton (Royal Meteorological Society, 1983).

Committee discussed the possible application of electronic computers in meteorology as the National Physical Laboratory planned the Pilot ACE computer project.¹² The Met Office's NWP research really began in 1950, when the Forecasting Research Division sent Fred Bushby to Imperial College to attend a course on numerical methods. Bushby was again sent to Cambridge in 1952, where the EDSAC computer had been developed. Soon he completed 2-level baroclinic atmospheric model equations, together with John Sawyer, head of the Short-Range Forecasting Research Branch.¹³ The first 12-hour experimental forecast using this model produced encouraging results. Numerous trials followed in 1953-54.¹⁴

Interestingly, the Met Office meteorologists were more cautious about the future of NWP. In 1952, the annual report of the Office stated that "there is still no evidence that the computer will do as well as the conventional forecaster".¹⁵ While such a response might indicate the more generally conservative nature of the British Scientific Civil Service, it also reflected the institutional setting in which the Office scientists carried out their research. Many of those involved in the Met Office's NWP project, including Sutcliffe, Sawyer, and Bushby, were trained as mathematicians, and they appreciated the use of rigorous dynamical methods. Even so, they tended to be less concerned with theoretical elegance or with dynamical studies that had little impact on practical applications. O.G. (later Sir Graham) Sutton, the new director-general of the Office, summarized this mood in 1953:

Even if the methods were infallible (which it is not [*sic*]) the services of the meteorologist, as distinct from the mathematician, would still be required to 'put into the weather,'...¹⁶

This pragmatic approach to dynamical meteorology, in turn, underpinned the modeling philosophy that particularly emphasized the 'physical realism' of atmospheric models. For the Met Office scientists, the barotropic treatment that applies only in the mid-troposphere was intellectually stimulating and academically important, but not suitable for weather forecasting. At one of the Royal Meteorological Society discussion meetings in 1951, Sutcliffe, who was directing the Forecasting Research

¹² J.S. Sawyer, "Electronic Computing Machines and Meteorology," *Meteorological Magazine* 81 (1952), 74.

¹³ Both Bushby and his superior Sawyer were trained in mathematics. See B.J. Mason, "Retirement of Mr. F. H. Bushby," *Meteorological Magazine* 113 (1984), 29-31; H. Taba, "The Bulletin Interviews: J.S. Sawyer," *WMO Bulletin* 46:2 (1997), 104-115.

¹⁴ M.K. Hinds, "Computer Story," *Meteorological Magazine* 110 (1981), 70-75.

¹⁵ Met Office, Annual Report of the Meteorological Office 1951-52 (London: HMSO, 1952), 30.

¹⁶ G. Sutton, "The Development of Meteorology as an Exact Science," *Nature* 173 (1954), 1114. Sutton himself had been trained as a mathematician. After World War II, he served as professor of mathematical physics at the Royal Military College of Science, and in 1953, succeeded Nelson Johnson as director-general of the Met Office. See F. Pasquill et al., "Sir Oliver Graham Sutton," *Biographical Memoirs of Fellows of the Royal Society* 24 (1978), 529-546.

Division, argued that a future solution to the three-dimensional atmospheric problem would “derive little or nothing from the barotropic model”.¹⁷ Unlike the US and Swedish NWP groups, the Met Office worked on baroclinic models from the very beginning, thus permitting the prediction of both surface and upper-air charts.

Partly due to this distinct style of numerical modeling, operational NWP in the Met Office was delayed for some time. However, more immediate concerns for the Office scientists were insufficient computing power and time. The Met Office did not then have its own electronic computer. The calculations were made using the LEO 1, a copy of EDSAC at J. Lyons & Co., a catering company, and later the Ferranti Mark 1 at Manchester University. This significantly constrained the modeling work in the Office. In 1954, recognizing the potential of NWP, the Meteorological Research Committee requested that the Met Office should acquire an electronic computer for research purposes. Financial approval was given in the next year for the purchase of the Ferranti Mercury although the machine was actually installed only in 1959. With the Mercury computer, the 2-level Sawyer-Bushby model was extended to the 3-level Bushby-Whitelam model. As forecasting models became more advanced, attempts to introduce secondary physical processes were begun. In 1960, the Met Office launched a full-scale, real-time NWP experiment using the 3-level model.¹⁸

(2) Towards General Circulation Modeling

Weather prediction models were regional in their scope. The Met Office’s trial forecasts in the 1950s usually covered Europe and the North Atlantic Ocean. In 1954, Norman A. Phillips, a meteorologist at the IAS, went further and suggested to Jule Charney the possibility of applying a baroclinic model to the general circulation of the atmosphere.¹⁹ The idea was not to attempt a deterministic prediction of weather patterns over a long period, but rather to generate the statistical features of the atmosphere’s general circulation. By mid-1955, Phillips was able to construct a 2-level quasi-geostrophic, hemispheric model that could sustain a stable integration for a reasonably long simulated time. Phillips’ model, often referred to as the first general circulation model (GCM), was simplistic in many respects and the numerical calculations broke down after 30 days. Nevertheless, its results showed a remarkable agreement with the observed monthly and seasonal statistics of the real atmosphere. Von Neumann was very impressed. A few months later, he organized a conference

¹⁷ R.C. Sutcliffe et al., “Dynamical Methods in Synoptic Meteorology: Discussion,” *Quarterly Journal of the Royal Meteorological Society* 77 (1951), 472.

¹⁸ M.K. Hinds, op. cit., 76.

¹⁹ J.M. Lewis, “Clarifying the Dynamics of the General Circulation: Phillips’ 1956 Experiment,” *Bulletin of the American Meteorological Society* 79 (1998), 46.

on “The Application of Numerical Integration Techniques to the Problem of General Circulation” in Princeton.²⁰ He subsequently submitted a proposal to the US Weather Bureau to form a new GCM research division. The new group, the General Circulation Research Section led by Joseph Smagorinsky, was set up in the next month and began to develop a primitive equation GCM without barotropic or baroclinic assumptions.²¹

The British and American meteorological communities had had a close relationship. The Met Office and the US Weather Bureau routinely exchanged views on the problems arising in their numerical modeling work. Sutton, Sutcliffe, and Sawyer were all aware of new developments initiated by Phillips’ experiment. In 1956, Phillips also published his simulation results in a British journal, the *Quarterly Journal of the Royal Meteorological Society*, and became the first recipient of the Society’s Napier Shaw Memorial Prize.²² Phillips was invited to deliver a lecture in London, where his lecture was received with great interest by British meteorologists, including senior scientists from the Office. Probably inspired by Phillips’ work, the Met Office assigned a small group of scientists to embark on dynamical studies of the general circulation of the atmosphere. Hemispheric charts were produced and integrated to reveal the long waves in atmospheric circulation. Andrew Gilchrist, a scientific officer at the Long-Range Forecasting Branch, looked into the use of barotropic equations and whether large-scale atmospheric motions could be usefully represented in terms of spherical harmonic functions.²³ At the Climatological Research Branch, extending the work of Charles Priestley, Brian Tucker and his co-workers started to conduct observational studies of the transport of heat, momentum, and moisture on a large scale.²⁴

In American universities, meteorology became firmly established by the early to mid-1950s. The US Weather Bureau and governmental agencies such as the Air Force Cambridge Research Center commonly used their research expenditures for

²⁰ R.L. Pfeffer, ed., *Dynamics of Climate: The Proceedings of a Conference on the Application of Numerical Integration Techniques to the Problem of the General Circulation* (London: Pergamon Press, 1960).

²¹ The General Circulation Research Section was first established as a joint project between the US Weather Bureau, the Air Force, and the Navy. A year later, the Air Force and the Navy withdrew their support and the Weather Bureau assumed full responsibility. See J. Smagorinsky, “The Beginnings of Numerical Weather Prediction and General Circulation Modeling: Early Recollections,” *Advances in Geophysics* 25 (1983), 3–37.

²² N.A. Phillips, “The General Circulation of the Atmosphere: A Numerical Experiment,” *Quarterly Journal of the Royal Meteorological Society* 82 (1956), 123–164.

²³ A. Gilchrist, Interview by the author, 1999.6.9. Gilchrist was also trained in mathematics before joining the Met Office in 1951. As already noted, the Met Office scientists were skeptical about the use of barotropic equations in weather models. But the skepticism did not apply to general circulation models.

²⁴ G.B. Tucker, “Some Developments in Climatology during the Last Decade,” *Weather* 16 (1961), 394–399.

joint projects or contracts awarded to university meteorologists, as von Neumann's Meteorology Project demonstrates. In Britain, the post-war growth of meteorology was mostly confined to the Met Office. Even in the late 1950s, Imperial College was the only British university with an independent meteorology department. Elsewhere, meteorology training and research were carried out as a minor part of the activities of geography, physics, or mathematics departments. Besides, like other branches of the British Scientific Civil Service, and as part of the Air Ministry, the Met Office had a relatively hierarchical, closed culture.²⁵ It tended to train its scientific staff in-house and did not encourage them to collaborate with the universities. In 1958, the Secretary of State for Air set up a special committee with Lord Brabazon as chairman to review the work and organization of the Office.²⁶ The committee's recommendation led to a substantial reorganization and an increase in the research budget. This did not, however, bring about close cooperation between the Met Office and the universities.

Outside the Met Office, Eric Eady at Imperial, in addition to elaborating his mathematical theory of the general circulation, was using the Manchester computer to develop a simple 2½-dimensional, baroclinic model of the atmosphere. He also began to advocate going beyond empiricism in traditional studies of climate and applying the dynamical understanding of the general circulation to climatology.²⁷ Eady's theoretical and numerical work was highly respected by the meteorological community, especially those engaged in NWP research at Princeton's IAS. In fact, it was during a short visit to Eady in 1953 that Phillips first came to envisage the general circulation numerical experiment.²⁸ But for the reason already mentioned, and since his work was conceived by the Met Office as too theoretically oriented, Eady failed to secure the institutional and financial support that Jule Charney was enjoying in the US. Eady's modeling did not last long because of illness. Percival Sheppard, head of Imperial's meteorology department, urged his academic colleagues to follow up on this work, but without much success.

The Met Office carried on the synoptic analysis of upper-air climatology and dynamical-observational studies of large-scale atmospheric processes throughout the late 1950s. These studies proved useful in understanding certain features of the general circulation. And yet, there was still no strong institutional commitment to GCM development in the Met Office. With the highest priority given to short-range

²⁵ For the general history of the Met Office, see M. Walker, *History of the Meteorological Office* (Cambridge: Cambridge University Press, 2011).

²⁶ Met Office, *Annual Report of the Meteorological Office 1957-58* (London: HMSO, 1958), 6-7.

²⁷ E.T. Eady, "Note on Weather Computing and the So-called 2½-Dimensional Model," *Tellus* 4 (1952), 145-156.

²⁸ H. Taba, "The Bulletin Interviews: N. Phillips," *WMO Bulletin* 44:3 (1995), 215-224. Lewis, on the other hand, argued that Phillips first started to think about the general circulation experiment while he was involved in the barotropic forecasting experiments in Sweden. See J.M. Lewis, *op. cit.*, 46.

weather forecasting, the Office's research activities on other aspects of the subject were considerably inhibited by the limited availability of resources—above all, computing power and time. The Ferranti Mercury computer had a relatively low calculation speed (*ca.* 3 *kFLOPS*) and did not much improve the Office's computational setup for numerical modeling. Gilchrist accordingly had to use the computer at Manchester for his early calculations. Moreover, the Met Office preserved the generalist tradition of the British Civil Service and frequently moved its staff around across a range of different research and service divisions. Gilchrist, the only scientific officer working full-time on mathematical investigations of the general circulation, was transferred to the Central Forecasting Office in 1958. It took several years before he was released from other duties to work again on GCM development.²⁹

(3) Atmospheric Radiation and Climate

While major advances in numerical modeling of the atmosphere were underway during the 1950s, there were also several important developments in atmospheric physics. In the US, utilizing the Northern Hemispheric upper-air data noted above, Henry G. Houghton at MIT and Julius London at New York University estimated the radiation budget of the globe. This required detailed calculations of radiative transfer—*i.e.*, emission and absorption—by various atmospheric constituents such as ozone, water vapor, and CO₂, which were extensively carried out by Lewis Kaplan at Princeton throughout the 1950s.³⁰ Outside the meteorological community, Gilbert Plass, an infrared physicist at Johns Hopkins, computed the atmospheric radiation flux for ozone and CO₂. In Germany, parallel studies were conducted by Fritz Möller at Mainz. Their results had implications for the study of climate. Plass in particular, attempted to renew the discussion of the connection between climate and atmospheric CO₂ in 1956.³¹ His argument was not accepted by most scientists but indicated that global physical climatology might be developed. These works were followed in the early 1960s by the studies of Syukuro Manabe at the Weather Bureau's General Circulation Research Laboratory, who collaborated with Möller.³²

²⁹ A. Gilchrist, Interview by the author, 1999. 6. 9.

³⁰ For the work of Kaplan, Plass, and Möller, see S.R. Weart, "Global Warming, Cold War, and the Evolution of Research Plans," *Historical Studies in the Physical and Biological Sciences* 27:2 (1997), 319-56 and references therein.

³¹ G.N. Plass, "The Carbon Dioxide Theory of Climatic Change," *Tellus* 8 (1956), 140-154. Plass contended that doubling atmospheric CO₂ would lead to greater absorption of infrared radiation and raise the earth's surface temperature by 3.6 °C.

³² However, it is important to note that Manabe's primary aim was to develop the radiative scheme for GCMs. See S. Manabe and F. Möller, "On the Radiative Equilibrium and Heat Balance of the Atmosphere," *Monthly Weather Review* 89 (1961), 503-532. The US Weather Bureau's General

In Russia, the study of the earth's energy balance was developed, from early on, in connection with the development of global physical climatology. Mikhail Budyko at the Main Geophysical Observatory began in the late 1940s to calculate annually the heat budget components for certain parts of the Soviet Union. By 1956, he was able to publish a world atlas of the earth's heat balance which included net radiation maps for every month and for the entire year. Budyko's work became widely known to Western scientists when his book was translated into English by the US Weather Bureau in 1958.³³

Atmospheric physics research was also actively pursued in British universities. In 1952, with the help of Charles D. Walshaw, Richard Goody in Cambridge formulated a simplified method for effectively calculating infrared radiative transfer in the atmosphere. A year later, he joined Imperial College as a reader in meteorology, where he investigated the interaction between radiation and convection as well as the thermal structure of the stratosphere until he left for Harvard in 1958.³⁴ Dobson and his collaborators at Oxford continued to be preoccupied with ozone measurements throughout the 1950s as they became intensely involved in creating a global network of ozone observing stations for the International Geophysical Year (IGY) 1957-58.³⁵ In the early 1960s, led by J.T. (later Sir John) Houghton, who in 1983 became director-general of the Met Office, the Oxford group began to move away from ozone measurements.³⁶ Although its new research focus turned to the instrumental development for remote sounding from satellites, numerous works on atmospheric radiation calculations were also produced by Walshaw and his former student Clive Rodgers, who joined the group from Cambridge.

All these research projects could have been readily linked to the study of climate. Goody's ideas, for instance, were later taken up by climate modelers. Yet, at the time in Britain, atmospheric radiation experts in universities had little interest in the bigger questions concerning climate or even the global radiation budget. They were inclined to identify themselves as applied physicists rather than meteorologists, not to mention climatologists, placing their emphasis almost entirely upon individual atmospheric phenomena. While they knew and valued Plass and Kaplan's infrared radiation research, the climatological aspects of their work were rarely discussed. Guy Callendar, a British engineer and amateur meteorologist, advocated the theory

Circulation Research Section changed its name to General Circulation Research Laboratory in 1959, and a few years later, it was renamed again as the Geophysical Fluid Dynamics Laboratory.

³³ M.I. Budyko, *The Heat Balance of the Earth's Surface* (Washington, DC: US Weather Bureau, 1958).

³⁴ M. Goody, Interview by F. Taylor (Royal Meteorological Society, 1994).

³⁵ G.M.B. Dobson, "Forty Years' Research on Atmospheric Ozone at Oxford: A History," *Applied Optics* 7 (1968), 401-403.

³⁶ J.T. Houghton, Interview by the author, 1999. 10. 4.

of enhanced greenhouse effect up to the early 1960s,³⁷ but only succeeded in drawing the attention of a few climatologists. Budyko's energy balance climatology also failed to resonate with British atmospheric physicists. To them, Budyko's mathematical treatments were not rigorous enough. His insights into the physics of climate were, however interesting they might be, something to be appreciated by geographers, not by themselves.

In the Met Office, atmospheric radiation studies were organized under the Physical Research Division by George D. Robinson, who returned to Kew Observatory after World War II. In the early years, much work had to be done to improve the accuracy and precision of radiometers. The surface measurements of terrestrial radiation were instigated in 1946, along with aircraft and surface measurements of solar radiation.³⁸ The local radiation balance and albedo were then estimated from the observed data. Radiation balance was one of the elements proposed for wide-scale study during the IGY. The Met Office took the initiative in expanding its radiation measurements, setting up a surface radiation station at Kew Observatory for IGY field experiments and instituting continuous radiation measurements at sea. The radiative properties of clouds and atmospheric aerosol were also investigated. The link between atmospheric physics and climatology was perhaps better recognized in the Met Office. Robinson suggested in 1962 that "a mapping of the flux of energy in its various forms as comprehensive as that mapping of temperature and wind" was needed.³⁹ But the Office's radiation work was basically oriented toward observations and instrumentation. The development of a new physics-based climatology was left to dynamical meteorologists working on GCMs.

Constructing General Circulation Models (GCMs)

(1) Establishment of the Dynamical Climatology Branch

The British GCM research really started when the Met Office set up the Dynamical Climatology Branch in 1963. For many dynamical meteorologists, the GCM development was a natural extension to the previous NWP work. The Met Office's Dynamical Climatology Branch was not created, however, on purely scientific grounds. It was also a by-product of growing political and economic interest in climate-related

³⁷ G.S. Callendar, "Can Carbon Dioxide Influence Climate?," *Weather* 4 (1949), 310-314; "On the Amount of Carbon Dioxide in the Atmosphere," *Tellus* 10 (1958), 243-248; "Temperature Fluctuations and Trends over the Earth," *Quarterly Journal of the Royal Meteorological Society* 87 (1961), 1-12.

³⁸ G.D. Robinson, "Physical Meteorology: Achievements and Prospects," *Meteorological Magazine* 91 (1962), 321-326.

³⁹ *Ibid.*, 326.

problems.

During the mid to late 1950s, the likelihood and ramifications of deliberate climate modification were being discussed in the US and Russia. In 1955, von Neumann pointed out that nuclear explosions could affect the earth's albedo and eventually its weather and climate. He claimed that climate might be modified deliberately by changing the earth's albedo in a similar way and warned that this could be used as a weapon of war.⁴⁰ Around the same time, it became public that Russian hydraulic engineers were discussing the prospect of constructing a large dam across the Bering Straits. They speculated that, by pumping water from the Arctic Ocean into the Pacific, and thereby drawing warm water up from the Atlantic, they might be able to remove the Arctic ice to warm Siberia.⁴¹ While some scientists were more interested in the negative consequences of such plans, British meteorologists, including the Met Office's senior scientists, were skeptical of the very possibility of deliberate climate modification. Sutton, director-general of the Office, contended in 1958 that "man cannot control weather on any substantial scale, and this state of affairs may persist for a long time to come, perhaps forever".⁴² Nonetheless, the Office scientists had to respond to the government's concern over the issues. Their answer was that a quantitative understanding of the general circulation of the atmosphere using numerical models should be achieved before any realistic assessments could be formed.

Another impetus for the development of GCMs, more important from the Office's point of view, was the prospect of dynamical long-range weather forecasting. The Met Office had long been concerned with the potential economic value of monthly and seasonal forecasts.⁴³ Despite the skepticism, the Office continued to develop long-range forecasting techniques based on empirical and statistical methods. Since the late 1950s, experimental monthly forecasts had been routinely produced using such techniques. However, although these forecasts showed tolerably good results, they were not issued to the governmental agencies and the public. The Office's senior scientists concluded that the empirical and statistical methods used for these forecasts were not scientifically grounded.⁴⁴ As NWP began to attest to the power of dynamical methods, they increasingly came to believe that long-range forecasting should be best handled in the same way, but with a focus on the general circulation. In 1962, Sutcliffe, now director of research, wrote:

⁴⁰ C. Kwa, "The Rise and Fall of Weather Modification: Changes in American Attitudes Towards Technology, Nature, and Society," C.A. Miller and P.N. Edwards, op. cit., 141-142.

⁴¹ J. Fleming, *Fixing the Sky: The Checkered History of Weather and Climate Control* (New York: Columbia University Press, 2010), 198-204.

⁴² G. Sutton, "Man's Attempts to Control the Weather," *New Scientist* 4:94 (1958), 746.

⁴³ R.C. Sutcliffe, "Are Long-range Weather Forecasts Possible?" *New Scientist* 11:245 (1961), 211-213.

⁴⁴ The 1959-60 annual report of the Met Office stated that "... no method of long-range forecasting is yet accepted as good enough for the public service ...". Met Office, *Annual Report of the Meteorological Office 1959-60* (London: HMSO, 1960), 29.

The question then arises whether success in long-range forecasting will come only by improving and extending the methods used for short-range forecasting ... success, if it is to come, requires a great deal more work to be done on the scientific study of the general circulation of the atmosphere.⁴⁵

Ironically, the inception of the Met Office's GCM work owed much to the political pressure to enhance old-style long-range forecasting activities. In the winter of 1962-63, the weather was exceptionally cold and had a marked effect on the British economy. The severe winter had actually been predicted by the Met Office monthly forecast, but the results were as always not issued. On the other hand, the US Weather Bureau, using comparable techniques, had been issuing monthly weather forecasts, and in that particular year, its success in predicting the cold winter attracted huge media attention both in the US and Britain. Facing public dissatisfaction, the British government and parliament intervened and instructed the Met Office to publish its monthly weather forecasts.⁴⁶ This opportunity was taken to reorganize climatological research in the Office. Rather than passively expanding its long-range forecasting activities, the Met Office divided the existing Climatological Research Branch (Met.O.13) into two new branches. The Met.O.13 was renamed as the Synoptic Climatology Branch, retaining the responsibility of the preparation of monthly forecasts, and the newly formed Dynamical Climatology Branch (Met.O.20) was commissioned to perform dynamical research into the general circulation and large-scale features of the atmosphere.⁴⁷

By that time, Smagorinsky's group at the Geophysical Fluids Dynamics Laboratory (GFDL) had constructed a 2-level hemispheric, primitive equation GCM, incorporating the complete form of the equations of motion and model physics, and began to design a truly global, 9-level model. The primitive equation GCMs were also being developed at UCLA's Department of Meteorology, the Lawrence Livermore National Laboratory, and the National Center for Atmospheric Research (NCAR).⁴⁸ Like those involved in US GCM groups, the Met.O.20 scientists considered it very important to take into account the effects of baroclinic scales on atmospheric motions and acknowledged early on that the construction of a full primitive equation GCM should be their ultimate goal. The problem was that most of the computing time available in the Met Office was being consumed by the Forecasting Research Division. Nor did the Met.O.20 have enough scientific manpower to undertake the complexity of the problem, having started as a small research branch, initially comprising George Corby, Andrew Gilchrist, and a few ancillary staff members. Given

⁴⁵ Quoted from the Directorate of Research section of Met Office, *Annual Report of the Meteorological Office 1962* (London: HMSO, 1963), 47-48.

⁴⁶ Met Office, *Annual Report of the Meteorological Office 1963* (London: HMSO, 1964), vii, 51.

⁴⁷ R.C. Sutcliffe, "Expansion of Meteorological Office Research in Dynamical Climatology," *Meteorological Magazine* 93 (1964), 3-4.

⁴⁸ P.N. Edwards, "A Brief History of Atmospheric General Circulation Modeling," 73-79.

the immense computational difficulties that would arise with GCMs, the Met.O.20 followed John Sawyer's suggestion to first build a simple 2-level quasi-geostrophic barotropic model in terms of Fourier series—*i.e.*, ordinary harmonics.⁴⁹ The model was designed to examine the behavior of the planetary waves of low-wave numbers, in which smaller-scale disturbances of the circulation were treated statistically. The Met.O.20 scientists thought that this approach would allow them to introduce the effects of geographic differences in topography and temperature into a relatively simple model.⁵⁰

Even before the Met.O.20 was established, the shortage of computing power was by no means a trivial problem. The real-time tests using the 3-level Bushby-Whitelam model were well in progress. The Forecasting Research Division also initiated research into the primitive equation NWP models. In 1961, when the headquarters moved from Dunstable to Bracknell, the Met Office, therefore, made a decision to replace the Ferranti Mercury with a moderately powerful English Electric KDF9 (with a computing speed of 50 *kFLOPS*).⁵¹ A new computer was installed in the summer of 1965, enabling two forecast runs per day. Later in the same year, however, the Met Office's numerical forecasts became officially operational, making full use of the KDF9 computer. Other trial calculations, including that of a new Bushby-Timpson 10-level primitive equation NWP model, were fitted into the time available when the KDF9 was not heavily engaged by operational NWP. More often, they were executed using the much faster ATLAS computer, first at Manchester and later at the Rutherford Laboratory. The Met.O.20 was no exception. Its barotropic model still required several hours on the ATLAS computer for each integration and had to be run at night.

(2) Expansion of Numerical Modeling at the Met Office

Operationalization of the Met Office NWP was chiefly due to the initiative of B.J. (later Sir John) Mason, the new director-general of the Office. Since his arrival in 1965, Mason had been very keen to establish the Met Office not only as an efficient weather service agency but also as one of the world's leading meteorological research institutions.⁵² This was the era of the so-called "white heat" of the scientific

⁴⁹ G.A. Corby, Personal communication with the author, 2000. 4. 10.

⁵⁰ G.A. Corby and A. Gilchrist, *A General Circulation Experiment (Planetary-wave Model)*, Met.O.20 Technical Note, No. 1 (Bracknell: Met Office, 1965).

⁵¹ M.K. Hinds, *op. cit.*, 77.

⁵² John Mason was then Professor of Cloud Physics at Imperial College. B.J. Mason, "Some Thoughts on the Future," *Weather* 20 (1965), 273-274; Interview by the author, 1999. 7. 5.

and technological revolution in Britain.⁵³ Optimism for the potential of science and technology was at its height. They were portrayed as a vehicle for modernizing Britain. Within the first five years of his directorship, new research branches—*e.g.*, on cloud physics and geophysical fluid dynamics—were set up; many young science graduates were recruited into the Office, and more attention was directed to the importance of computing and telecommunication facilities and the potential of meteorological satellites.⁵⁴ Mason was also very enthusiastic about the use of the numerical modeling approach in atmospheric sciences. In the face of some scientists' reservations about the feasibility of real-time NWP, both inside and outside the Office, he strongly insisted that the Met Office should begin to issue operational numerical weather forecasts.

These developments in the Met Office were further aided by growing international collaborations in meteorological services and research. Since the successful launching of the first artificial satellite, Sputnik-I, in 1957 and of the first man in space in 1961 by the Soviet Union, the US had been anxious to accelerate its own space program and to bring the Russians into some forms of international scientific cooperation.⁵⁵ The US meteorological establishment quickly took this opportunity and prepared a position paper for the President's Science Advisory Committee (PSAC). As a result, President Kennedy, in his second State of the Union address in May 1961, appealed for "at the earliest possible time a satellite system for worldwide weather observation".⁵⁶ Later in September that year, Kennedy addressed the UN General Assembly and called for "further cooperative efforts between all nations in weather prediction and eventually in weather control".⁵⁷ The UN then adopted Resolution 1721 (XVI), which requested the World Meteorological Organization (WMO), in consultation with other international bodies, to draw up recommendations on appropriate arrangements to improve the meteorological services of member states and to advance the state of atmospheric sciences. The WMO responded in 1963 with an outline plan for the World Weather Watch (WWW), a global network of world and regional weather service centers and data processing and telecommunication systems. On the research side, UN Resolution 1802 (XVII) was adopted in 1962, inviting the WMO and the International Council of Scientific Unions (ICSU) to devise

⁵³ In 1963, Harold Wilson, then leader of the Labour Party, asserted at the party conference that a "New Britain" should be forged in the "white heat" of a scientific and technological revolution. See M.W. Kirby, "Blackett in the 'White Heat' of the Scientific Revolution: Industrial Modernisation under the Labour Governments, 1964-1970," *Journal of the Operational Research Society* 50 (1999), 985-993.

⁵⁴ Met Office, *Annual Report of the Meteorological Office 1969* (London: HMSO, 1970), 31-34, 51-61, 63-66.

⁵⁵ R.G. Fleagle, "From the International Geophysical Year to Global Change," *Reviews of Geophysics* 30 (1992), 305-313.

⁵⁶ John F. Kennedy, Address to Joint Session of Congress, May 25, 1961.

⁵⁷ P.N. Edwards, *A Vast Machine*, 223.

an extensive program of research in atmospheric sciences to complement the programs being prepared by the WMO. From this was born the Global Atmospheric Research Programme (GARP).⁵⁸

Both GARP and WWW took several years of lengthy negotiations over the planning and implementation programs. The differences of interests among member states, as well as rivalries between the government weather services and the academics, had to be resolved. The final plan for the WWW was laid in April 1967 at the WMO 5th Congress. Significant for the Met Office was that, the Bracknell headquarters became a Regional Meteorological Center and a Regional Telecommunications Hub as part of the WWW.⁵⁹ This greatly helped Mason persuade the Treasury to provide the resources to procure an IBM 360/195 computer, improve telecommunication facilities, and expand education and training schemes. It was GARP, however, which had a more direct relevance to the work of the Met.O.20. GARP was formally approved by the WMO and ICSU in October 1967. The WMO/ICSU Joint Organizing Committee was subsequently established, with John Sawyer, director of research, being one of its members. The objectives of GARP centered on an improved understanding of the physical and dynamical processes that would govern the global circulation of the atmosphere.⁶⁰ In the hope of providing a sound scientific basis for extended-range weather forecasting over periods of up to several weeks, their efforts were concentrated on the development of physico-mathematical models of the global atmosphere, and of an optimum global observing system that would supply the input data for those models. The importance of studying climate was also recognized. Through GARP, senior scientists of the Met.O.20, including George Corby and Andrew Gilchrist, participated in a series of international workshops and study conferences on global circulation modeling.

(3) The First Met Office GCM

By the time John Mason joined the Met Office, the Met.O.20 decided to develop its own primitive equation GCM. After several months of examination, it became evident that no fruitful outcome could be achieved from a barotropic model.

⁵⁸ B. Bolin, "Progress on the Planning and Implementation of the Global Atmospheric Research Programme," G.A. Corby, ed., *The Global Circulation of the Atmosphere* (London: Royal Meteorological Society, 1969), 235-255.

⁵⁹ For the importance of GARP and WWW for the Met Office, see B.J. Mason, "Global Atmospheric Research Programme: Contribution to the Numerical Simulation and Prediction of the Global Atmosphere," *Earth-Science Reviews* 7 (1971), 165-186.

⁶⁰ Ibid., 166-167.

Mason became more interested in GCMs later,⁶¹ but he was supportive of the Met.O.20 from the beginning and provided it with several of the best young scientists in the Office. With this extra manpower, the Met.O.20 boosted its GCM development. In 1966, numerical experiments were conducted to determine suitable grid and vertical levels for a new model. The 5-level hemispheric form was finally adopted, with a horizontal resolution of 3° latitude $\times$ 5° longitude.⁶² As for other GCMs, the Met.O.20 model simulated the major physical processes controlling atmospheric motions over a long-time scale. Many of these processes were still poorly understood, and in some cases, there were no known laws for them. For some other processes, their scales were too small to be represented within the model grid. Thus, they had to be included as their statistical effects either by using the climatologically observed values or by using “parameterizations”—i.e., representing complex processes as functions of other easily measurable variables without explicitly considering the details. For example, in the Met.O.20 model, sea surface temperatures were prescribed, along with seasonal and diurnal variations of solar radiation.

Trial computations were completed at each introduction of a new physical process. By 1967 about two-thirds of the program was written. A full program became available in 1969, and simulations using the Met.O.20 5-level GCM were started. In order to achieve computing efficiency, compromises had to be made concerning the model resolution, effectiveness of parameterizations, and length of integration of the model. At first, the calculation was carried forward to 35 simulated days. The results showed an encouraging degree of realism—the model successfully simulated the major features of the general circulation as well as the seasonal distributions of temperature, pressure, wind, and rainfall observed in the real atmosphere. In 1970, the integration was extended to 60 days.⁶³ The careful analysis of the 60-day simulation was carried out in the following years, leading to a number of changes in the model which were mainly of a purely mathematical kind, and some concerning the mathematical representation of the physical processes.

GCM was thought to provide a theoretical tool for assessing the length of time over which short-range weather forecasts would ultimately be possible and the observational network that would be needed to achieve them. The importance of GCM development was also being stressed in the context of a growing interest in deliberate or inadvertent climate modification. The US National Academy of Sciences (NAS) appointed a Panel on Weather and Climate Modification in 1963 to review the status

⁶¹ See, e.g., B.J. Mason, “Towards the Understanding and Prediction of Climatic Variations,” *Quarterly Journal of the Royal Meteorological Society* 102 (1976), 473–498; “Recent Advances in the Numerical Prediction of Weather and Climate,” *Proceedings of the Royal Society of London A* 363:1714 (1978), 297–333.

⁶² G.A. Corby et al., “United Kingdom Meteorological Office Five-Level General Circulation Model,” J. Chang, ed., *General Circulation of the Atmosphere, Methods in Computational Physics*, Vol. 17 (New York: Academic Press, 1977), 67–110.

⁶³ Met Office, *Annual Report of the Meteorological Office 1970* (London: HMSO, 1971), 71.

and activities in the field and issued a final report in 1966.⁶⁴ GFDL, the leading GCM research group, was involved in the assessment, although GCMs were not actually used. These events highlighted various potential applications of GCMs. There was some general concern that Britain might fall behind in state-of-the-art meteorological research.⁶⁵ The Met.O.20's primary aim at this stage, however, was to develop a GCM for investigating anomalies of the presently observed climate. The Met.O.20 scientists believed that this was a logical way to proceed in the early stage of model development. For testing against observable and well-documented atmospheric phenomena would enable model characteristics and possible shortcomings to be identified, and the performance of GCMs in any future perturbed simulations should be judged against the control ones. But the tendency to lay more emphasis upon relatively short-term and regional natural climatic variations was, as has already been noted, closely related to the Met Office's interest in the prospect of long-range forecasting for about a month ahead by means of dynamical methods.

The Met.O.20's emphasis on the detailed variations of the presently observed climate was visible in its approaches to some of the most difficult parts in developing a GCM—for example, the transfer of heat by radiation. It was generally believed that the net radiative flux at any level in the atmosphere depended on the temperature and concentration of the radiatively active constituents at all levels. Hence, while the theory had been available to account for many of these processes, its full exploitation in numerical simulations would be computationally very expensive.⁶⁶ Furthermore, if the effects of radiation were specified climatologically, the feedback aspects of the processes would not be fully taken into account. The Met.O.20 took the middle-way approach, and in collaboration with Walshaw and Rodgers at Oxford, formulated a non-interactive scheme based on long-wave cooling and solar heating rates derived from mean climatological data.⁶⁷ This approach omitted—or at best only indirectly and insufficiently incorporated—the effects of clouds on the radiation field. So it was seen as having disadvantages in simulating climate perturbations due to external forcings such as changes in solar radiation, changes in the composition of the atmosphere, land-use changes, or volcanism. But the scheme was very fast and effective, giving good results when radiation was not the essence of the problem—*i.e.*, the simulation of natural climate, especially in the troposphere.

Throughout the 1970s, the Met.O.20's GCM development continued to be dominated by the emphasis on simulation of the presently observed climate. The rationale was the importance of GCM's 'physical realism'—that is, "before the model can

⁶⁴ US NRC, *Weather and Climate Modification: Problems and Prospects*, Vol. 2. *Research and Development* (Washington, DC: National Academy of Sciences, 1966).

⁶⁵ R.C. Sutcliffe, "Control of Weather and Climate," *Nature* 210 (1966), 459-460.

⁶⁶ Corby et al., *op. cit.*, 92.

⁶⁷ C.D. Rodgers and C.D. Walshaw, "Computation of Infra-Red Cooling Rate in Planetary Atmospheres," *Quarterly Journal of the Royal Meteorological Society* 92 (1966), 67-92.

represent changes in climate correctly, it must reproduce the present climate correctly".⁶⁸ In a similar way as in the NWP work, this reflected both a cautious and conservative style of the British Scientific Civil Service and the Met Office's pragmatic approach to dynamical meteorology.

Even with the whole power of the ATLAS computer, running a hemispheric model was too expensive. The 60-days integration of the Met.O.20 5-level GCM took about 120 hours.⁶⁹ With the new IBM 360/195 computer (with a computing speed of 4×10^3 *kFLOPS*) installed in 1971, however, the same integration took less than ten hours. The Met.O.20 could therefore pursue its modeling work, for the first time, relatively free from computational constraints. The model was now run both on a hemispheric and a global scale.⁷⁰ In the course of re-writing the program for the IBM 360/195, the Met.O.20 introduced a new grid and finite differences system, in which the zonal grid length was more nearly constant than in the previous system. A new higher-resolution global 11-level GCM also began to be developed.⁷¹ By the mid-1970s, the Met.O.20 expanded to have five independent research groups of its own, covering 5- and 11-level GCM developments, tropical meteorology, stratospheric modeling, and global data processing, with more than twenty scientific staff members. GCM was finally becoming a major part of British climate science.

Toward Modeling Global Climate

(1) Effects of Atmospheric Pollution on Global Climate

Meanwhile, outside Britain, interest in the effects of pollution on the global atmosphere continued to grow. In 1965, the Environmental Pollution Panel of the US President's Science Advisory Committee (PSAC) issued its official report *Restoring the Quality of Our Environment*, which had a chapter on the climatic effects of increased atmospheric CO₂.⁷² Around that time, Syukuro Manabe of GFDL was asked by the NAS Panel on Weather and Climate Modification to examine the dependence of the earth's surface temperature on the atmospheric CO₂ content.⁷³ By using a 1-D radi-

⁶⁸ B.J. Mason, Interview by the author, 1999. 7. 5.

⁶⁹ G.A. Corby et al., "A General Circulation Model of the Atmosphere Suitable for Long Period Integrations," *Quarterly Journal of the Royal Meteorological Society* 98 (1972), 809-832.

⁷⁰ A. Gilchrist et al., "A Numerical Experiment Using a General Circulation Model of the Atmosphere," *Quarterly Journal of the Royal Meteorological Society* 99 (1973), 2-34.

⁷¹ Met Office, *Annual Report of the Meteorological Office 1972* (London: HMSO, 1973), iv.

⁷² R. Revelle et al., "Atmospheric Carbon Dioxide," PSAC, *Restoring the Quality of Our Environment* (Washington, DC: The White House, 1965), 111-133.

⁷³ US NRC, op. cit., 87-88.

ative-transfer model with a convective adjustment—or as it was usually called a radiative-convective model (RCM)—devised in their GCM development, Manabe and his co-worker Richard Wetherald estimated that a doubling CO₂, with a fixed absolute humidity assumption, would increase the mean surface temperature by *ca.* 1 °C. Later in 1967, when they used a given distribution of relative humidity, the figure doubled to *ca.* 2 °C.⁷⁴ In Russia, based on the results of his simple energy balance model (EBM), Mikhail Budyko insisted that the increase of atmospheric CO₂ content might cause the Arctic ice to disappear. William D. Sellers at the University of Arizona-Tucson, who followed Budyko's approach but developed his own 1-D EBM, came to a similar conclusion.⁷⁵

Anthropogenic factors other than CO₂ also began to be considered. Manabe's model calculations included a five-fold increase in stratospheric water vapor. These results were used in assessing the effects of water vapor exhausted by supersonic transports (SSTs) on climate. Some scientists proposed yet another anthropogenic cause of climate change. In 1971, S. Ichtiaque Rasool and Stephen H. Schneider of the NASA Goddard Institute of Space Studies (GISS) compared the effects on global climate of large increases in atmospheric CO₂ and aerosols, utilizing a different 1-D radiative-transfer model developed for studies of other planetary atmospheres. While Rasool and Schneider were concerned with the bigger issue of human impact on climate, their study, like Manabe's work, was basically a climate sensitivity experiment and did not attempt to "predict" the future climate. But they contended that the projected rate of increasing aerosol injection could lead to a decrease in global temperature by *ca.* 3.5 °C, which "is believed to be sufficient to trigger an ice age", and that, even with the effects of doubling CO₂ considered, the net result could be a "cooling of Earth".⁷⁶

Within a very short period, anthropogenic climate change had been transformed from a subject that concerned only a few research groups to a potentially far-reaching environmental threat. Manabe presented his results in 1968 at the American Association for the Advancement of Science (AAAS) symposium on the Global Effects of Environmental Pollution, the participants of which included not only renowned scientists such as Roger Revelle but also scientist-activists such as Barry Commoner.⁷⁷ More significant in framing anthropogenic climate change as a global environmental

⁷⁴ S. Manabe and R.T. Wetherald, "Thermal Equilibrium of Atmosphere with a Given Distribution of Relative Humidity," *Journal of the Atmospheric Sciences* 24 (1967), 241-259.

⁷⁵ M.I. Budyko, "Effect of Solar Radiation Variations on Climate of Earth," *Tellus* 21 (1969), 611-619; W.D. Sellers, "A Global Climate Model Based on the Energy Balance of the Earth-Atmosphere System," *Journal of Applied Meteorology* 8 (1969), 392-400.

⁷⁶ S.I. Rasool and S.H. Schneider, "Atmospheric Carbon Dioxide and Aerosols: Effects of Large Increases on Global Climate," *Science* 173 (1971), 138-141.

⁷⁷ S.F. Singer, ed., *Global Effects of Environmental Pollution* (Dordrecht: D. Reidel, 1970).

problem were the two workshops held in 1970 and 1971: the Study of Critical Environmental Problems (SCEP) and the Study of Man's Impact on Climate (SMIC).⁷⁸ The SCEP's Work Group on Climatic Effects, chaired by William W. Kellogg of NCAR, reviewed the state of knowledge on possible human-induced causes of climate change, from atmospheric CO₂, aerosols, and land surface changes, to SSTs. Having been organized more focused, SMIC extended SCEP's discussions and affirmed that humankind could already be influencing the climate on a global scale.

SMIC was also an American initiative but more international than SCEP and was held in Wijk, Sweden. Some of the leading foreign scientists in the field—*e.g.*, Budyko from Russia and Bert Bolin from Sweden—were invited. It is noteworthy that there was no British participant except George D. Robinson, who, together with William W. Kellogg, served as joint secretary. To a large degree, this reflected the status of British climate research in the early 1970s. There were few climatologists who were interested in anthropogenic climate change. Many dynamical meteorologists were indifferent to the very subject of climate and its change. The Met.O.20 was preoccupied with developing their first GCM and was yet to expand its manpower and computing capabilities. But there was another reason as well. Hart and Victor suggest that SMIC was carefully cultivated to link science and environmental politics; its final report was prepared as a kind of background paper for the Stockholm Conference.⁷⁹ For many British meteorologists, SMIC did not carry the authority to convey an essentially political message on behalf of the scientific community. In his review of the SMIC report, Sutcliffe rather cynically wrote:

[It] read like the report of a Royal Commission except they are addressed to no responsible executive body. 'We recommend ...' appears so often in the text, perhaps a hundred times, perhaps several hundred, that we at once ask to whom the advice is tendered ...⁸⁰

This skeptical stance had much to do with the fact that the senior scientists at the Met Office were highly critical of simple climate modeling extensively used in the SMIC report.⁸¹ The development and use of GCMs were, without a doubt, embraced

⁷⁸ SCEP, *Man's Impact on the Global Environment: Report of the Study of Critical Environmental Problems* (Cambridge: MIT Press, 1970); SMIC, *Inadvertent Climate Modification: Report of the Study of Man's Impact on Climate* (Cambridge: MIT Press, 1971).

⁷⁹ D.M. Hart and D.G. Victor, "Scientific Elites and the Making of US Policy for Climate Change Research, 1957-74," *Social Studies of Science* 23:4 (1993), 643-680.

⁸⁰ R.C. Sutcliffe, "Book Review: Inadvertent Climate Modification: Report of the Study of Man's Impact on Climate," *Quarterly Journal of the Royal Meteorological Society* 98 (1972), 708.

⁸¹ In fact, by the time the SMIC was held, Manabe did have the GCM results for a CO₂-doubling experiment. Scientists within the modeling community were aware of his early GCM results. However, Manabe did not present or publish them until the mid-1970s. Manabe first presented his GCM results at the GARP Study Conference held in 1974. See S. Manabe, "The Use of Comprehensive General Circulation Modeling for Studies of the Climate and Climate Variation,"

by dynamical meteorologists elsewhere. This was the main theme of the “Global Circulation of the Atmosphere” conference jointly held by the Royal, American, and Canadian Meteorological Societies in 1969.⁸² The final reports of SCEP and SMIC, among other things, recommended the expansion of GCM developments. Because GCMs were in a primitive stage of development, however, 1-D and 2-D models were widely used for climate sensitivity studies during the late 1960s and 1970s even though they treated atmospheric dynamics only in a crude parameterized form. The Met Office scientists did not approve of such a direction.

In fact, even academic meteorologists who had difficulty acquiring computing power and time considered Budyko and Sellers’ 1-D EBMs as overly simplistic. Often dubbed “toy models”, these models were typically seen as something belonging to geographers.⁸³ It should be pointed out that radiative-transfer models (RCMs) were treated differently since they were viewed as involving more rigorous mathematical techniques and comprehensive knowledge of atmospheric physics. The 1967 work of Manabe and Wetherald at GFDL, in particular, was highly regarded. Important to the Met Office scientists, however, was that the use of RCMs was an integral part of GCM developments. Whereas Manabe and Wetherald did use a 1-D RCM to study the climatic effects of increased CO₂, their major research goal was the formulation of a radiative transfer scheme for GFDL’s GCM. The NAS request to assess the greenhouse effect was secondary to this goal. The Met Office scientists’ respect for their results also had less to do with the CO₂-doubling experiment. By then, Clive Rodgers and Charles D. Walshaw at Oxford had developed a similar radiative transfer scheme for the Met.O.20 GCM. Not surprisingly, it was not understood as the use of a simple model for climate research.⁸⁴

(2) Early Climate Modeling Work at the Met Office

The Met Office scientists’ skepticism toward simple climate modeling does not mean that the issue of human impact on climate was simply ignored. The Met Office’s early motivation for setting up the Met.O.20, as previously mentioned, was closely tied to the development of dynamical long-range weather forecasting. However, the prospect of dynamical long-range forecasting was already being called into question during the mid to late 1960s. Tests by US GCM research groups including

WMO/ICSU, *The Physical Basis of Climate and Climate Modeling* (Geneva: WMO, 1975), 148-162.

⁸² G.A. Corby, ed., *The Global Circulation of the Atmosphere*.

⁸³ R.S. Harwood, Interview by the author, 1999. 2. 25.

⁸⁴ C.D. Rodgers and C.D. Walshaw, op. cit., 67-92.

GFDL, UCLA, and NCAR indicated that the limit of deterministic atmospheric predictability was about 2 weeks.⁸⁵ In 1967, George D. Robinson, president of the Royal Meteorological Society, raised the same issue in his presidential address, discomfiting scientists from the Met Office.⁸⁶ This realization, at least partly, led the Met Office to engage more in exploring GCM uses other than extended-range weather forecasting—e.g., the studies of long-term climate changes and the assessment of large-scale, deliberate or inadvertent, climate modifications. The Global Atmospheric Research Programme (GARP) also began to put more emphasis on its second objective (of understanding the physical basis of climate) in addition to its first objective (of extending the range of dynamical weather forecasting), thereby underpinning this shift.

By the early 1970s, the first Met.O.20 5-level GCM had been prepared. The new, faster IBM 360/195 computer became available a year later, overcoming the problem of lack of computing power and time for climate modeling. The first GCM climate sensitivity experiment, conducted by Roger Newson, was a simplified simulation of how the northern polar climate would react to a removal of the Arctic ice-cap.⁸⁷ The results showed that the lowered albedo of the polar cap would result in higher temperatures and disturb atmospheric circulation patterns. These were comparable to those obtained from another ice-free Arctic GCM experiment by the RAND Corporation in the US. RAND was then running a program called “Climate Dynamics for Environmental Security”.⁸⁸ Built upon Joseph Fletcher’s previous work on polar climates, it was developed in reaction to the concern of the defense community that the US might be harmed by changes in the climate elsewhere on the globe. The Met.O.20’s simulation was also inspired by the debates over the Russian river diversion plan. As yet, however, the model was premature, and the aim of this experiment was to demonstrate the superiority of GCM over other approaches rather than to produce complete assessments. Mason wrote a few years later that these results

⁸⁵ E.N. Lorenz, “The Future of Weather Forecasting,” *New Scientist* 42:648 (1969), 290-291; A.L. Hammond, “Global Meteorology (II): Numerical Models of the Atmosphere,” *Science* 174 (1971), 393-395.

⁸⁶ G.D. Robinson, “Some Current Projects for Global Meteorological Observation,” *Quarterly Journal of the Royal Meteorological Society* 93 (1967), 409-418.

⁸⁷ R.L. Newson, *An Ice-Free Experiment with the Met.O.20 General Circulation Model*, Met.O.20 Technical Note, No. II/7 (Bracknell: Met Office, 1972); “Response of a General Circulation Model of the Atmosphere to Removal of the Arctic Ice-cap,” *Nature* 241 (1973), 39-40.

⁸⁸ R.R. Rapp, *Climate Modification and National Security* (Santa Monica: Rand Corporation, 1970); M. Warshaw and R.R. Rapp, *An Experiment on the Sensitivity of a Global Circulation Model: Studies in Climate Dynamics for Environmental Security* (Santa Monica: RAND Corporation, 1972). The Rand program on climate dynamics for environmental security was initiated in 1970 against the backdrop of the Cold War, prompted by apprehensions about how changes in climate in other nations could pose threats to U.S. national security. However, it was short-lived as broader scientific and political concerns shifted to the climatic effects of pollution, transcending national boundaries.

served “to illustrate the limitations of intuitive judgments in dealing with such highly interactive, nonlinear systems.”⁸⁹

The Met Office’s first official scientific assessment of climate change was, in fact, on the potential climatic impact of SSTs. This issue became hotly debated in the US. Syukuro Manabe’s early study noted above implied that the effects on the earth’s temperature of added water vapor in the stratosphere would not be significant. Subsequent photochemical studies in the late 1960s suggested that water vapor exhaust from SSTs might catalytically destroy stratospheric ozone, and in turn, increase the penetration of biologically harmful ultraviolet (UV) radiation. In 1971, atmospheric chemists, Paul Crutzen at Stockholm and Harold Johnston at UC Berkeley, each claimed that NO_x emission from SSTs could also play a catalytic role in the destruction of stratospheric ozone.⁹⁰ While Crutzen and Johnston were doing their calculations, the US Congress and Senate voted against further funding for the Boeing SST. In the end, the Boeing project was killed mainly on economic grounds, but the issue of human impact on climate received substantial coverage in the US media.⁹¹ This series of events prompted the US Department of Transportation to establish the Climatic Impact Assessment Program (CIAP) in 1971.⁹²

By the late 1960s, the Anglo-French SST project, Concorde, was well underway and the test flights of prototype aircraft were being carried out in Britain and France. At first, the Met Office’s Special Investigations Branch concentrated only on the problems associated with the forecasting requirements for successful SST flights such as turbulence, icing, landing, or the distribution of cumulonimbus clouds.⁹³ Many dynamical meteorologists, both at the Met Office and elsewhere, were skeptical that SSTs could pose serious threats to stratospheric ozone. The conclusions of Crutzen and Johnston were based entirely on 1-D photochemical calculations, and virtually ignored atmospheric dynamics, which meteorologists believed would dominate the stratospheric distribution of ozone and NO_x.⁹⁴ Furthermore, despite the

⁸⁹ B.J. Mason, “Recent Advances in the Numerical Prediction of Weather and Climate,” 320.

⁹⁰ P. Crutzen, *On Some Photochemical and Meteorological Factors Determining the Distribution of Ozone in the Stratosphere: Effects of Contamination by NO_x Emitted from Aircraft*, MISU Report AP, No. 6 (Stockholm: Meteorological Institute, 1971); H. Johnston, “Reduction of Stratospheric Ozone by Nitrogen Oxide Catalysts from Supersonic Transport Exhaust,” *Science* 173 (1971), 517-522.

⁹¹ J. Rosenbloom, “The Politics of the American SST Programme: Origin, Opposition and Termination,” *Social Studies of Science* 11 (1981), 403-423.

⁹² J. Mormino et al., *Climatic Impact Assessment Program: Development and Accomplishments, 1971-1975* (Washington, DC: US Department of Transportation, 1975).

⁹³ A.F. Crossley, “Atmospheric Environment of Supersonic Transport Aircraft,” *Quarterly Journal of the Royal Meteorological Society* 95 (1969), 784-788.

⁹⁴ The SMIC reports thus stated that “... the problem of stratospheric ozone distribution is very complex and must be studied in an atmospheric model in which proper treatment is given to dynamical processes [air motions] before any definitive results can be considered reliable.” See SMIC, *Inadvertent Climate Modification*, 272.

growing public concern over pollution, the environmental aspect of SSTs did not emerge as an important issue in Britain, except for that of a sonic boom. But Concorde was designed for international flights, and the Met Office was in due course asked to give advice on the problem of the NO_x/ozone connection. In 1972, the Met Office set up the Committee on Meteorological Effects of Stratospheric Aircraft (COMESA).⁹⁵

COMESA directed a three-year multi-disciplinary project. This was Britain's first systematic attempt to organize research into climate-related issues. Unlike CIAP, in which the biological, social, and economic aspects of SSTs were also studied, COMESA was confined to atmospheric research. Part of the work was contracted out to university groups, but the overall coordination was left within the Met Office. Thus, a strong emphasis was placed upon atmospheric modeling. The Met.O.20 devised a 13-level GCM for COMESA by adding the extra vertical resolution in the stratosphere to the existing 5-level model. The problem was that computing constraints prohibited the GCM calculation of a full 3-D distribution of NO_x with interactive photochemistry. COMESA's final estimates for SST-induced ozone depletion were more conservative than those of CIAP—calculating that several hundred Concorde, each flying five hours per day, would reduce the stratospheric ozone content by less than 0.5%.⁹⁶ These results, in which the British government was most interested, were actually based largely on laboratory investigations, observational studies, and 1-D photochemical and 2-D dynamical-chemical models. Yet, the Met Office maintained the importance of GCM, and used the 13-level model to simulate the natural stratosphere and to study the likely climatic effects of stratospheric ozone depletion.⁹⁷

⁹⁵ R.J. Murgatroyd, ed., *Report of the Committee on Meteorological Effects of Stratospheric Aircraft* (Bracknell: Met Office, 1975).

⁹⁶ Ibid. Martin-Nielsen suggested that COMESA marked the beginning of a period in which the Met Office's "climate models themselves were transformed by political agendas." See J. Martin-Nielsen, "Computing the Climate: When Models Became Political," 233. However, as demonstrated in this paper, the development of climate models was shaped by the institutional, social, cultural, and political contexts from its very inception. Furthermore, climate modelers at the Met Office were not simply passive; they often actively engaged with these contexts. A more nuanced perspective is needed to consider the mutual shaping of climate modeling and its surrounding institutional, social, cultural, and political contexts, going beyond the "balancing and construction of rhetorical boundaries."

⁹⁷ See, e.g., R.L. Newson, "An Experiment with a Tropospheric and Stratospheric Three-Dimensional General-Circulation Model," A.J. Broderick and T.M. Hard, eds., *Proceedings of the Third Conference on the Climatic Impact Assessment Program* (Washington, DC: US Department of Transportation, 1974), 461-473.

(3) Slow Expansion of Climate Modeling at the Met Office

The central role of GCMs in climate research was further highlighted when WMO and ICSU convened the GARP study conference on “Physical Basis of Climate and Climate Modeling” in Stockholm in July 1974.⁹⁸ This conference was designed to provide a basis for the implementation of GARP’s second objective. Its important aspect was that it aimed at developing international consensus on how to model climate and its change. Faced with rising concern over potential climate threats, the political significance of climate modeling was being recognized by the participants. There was what one science reporter described as a “new sense of urgency” to construct models capable of predicting climate change.⁹⁹ Many participants thus showed great interest in the GCM simulations of climate change presented at the conference. Policy discussions were largely sidelined, however, except for the call for setting up an international climate research program. A few scientists such as Schneider attempted to raise climate policy issues more directly, without much success.

Still, the topic of anthropogenic climate change was extensively discussed at the conference. For example, Syukuro Manabe reported his results for the GCM study of CO₂-doubling, while Jule Charney reviewed his GCM results for the effects of overgrazing on desert and drought in the Sahel.¹⁰⁰ Bert Bolin of Stockholm University presented a paper on the role of the carbon cycle in climate change.¹⁰¹ This was partly because so many climate disasters within a very short period gave rise to speculation that these developments might have causes other than natural variability. Another important context was that the effects of external forcings, especially those agents under human control, were seemingly less problematic for modeling than were the effects of internal forcings or unknown periodicities in nature.

The Met.O.20 scientists adopted a more conservative stance. They maintained a cautious view on GCMs, arguing that, without the models’ ‘physical realism’, any perturbation experiments (*i.e.*, simulations of climate change due to external forcings) could not be trusted. Consequently, they focused on ensuring that their GCMs realistically simulated the presently observed climate and its short-term variability. The 5-level GCM was extensively used to study the effects of sea surface temperature

⁹⁸ WMO/ICSU, *The Physical Basis of Climate and Climate Modeling*.

⁹⁹ A.L. Hammond, “Modeling the Climate: A New Sense of Urgency,” *Science* 185 (1974), 1145-1147.

¹⁰⁰ S. Manabe, “The Use of Comprehensive General Circulation Modeling for Studies of the Climate and Climate Variation”; J. Charney “Dynamics of Deserts and Drought in the Sahel,” WMO/ICSU, *The Physical Basis of Climate and Climate Modeling*, 171-175.

¹⁰¹ B. Bolin, “A Critical Appraisal of Models for the Carbon Cycle,” WMO/ICSU, *The Physical Basis of Climate and Climate Modeling*, 225-235.

anomalies, which were believed to influence weather systems on a large scale.¹⁰² Substantial efforts were made to develop and test an 11-level GCM for the GARP Atlantic Tropical Experiment (GATE), which took place in June–September 1974 with the aim of understanding the tropical atmosphere and its role in the general circulation. During GATE, a series of extended weather predictions were performed using the Met.O.20 11-level model, covering parts of the Atlantic, Africa and South America. A group of scientists was also assigned to manage the GATE Synoptic Subprogramme Data Centre.¹⁰³ By the time GATE was launched, the Met.O.20 had been enlarged to accommodate around 20 scientific and 13 ancillary staff. Apart from those involved in the COMESA project, only two scientists and two programmers were working full-time on the GCM studies of climate sensitivity. In fact, no one from the Met.O.20 attended the GARP climate modeling conference. The only participants from the Met Office were John Sawyer, who was on the GARP Joint Organizing Committee, and Raymond Hide, head of the Office’s Geophysical Fluid Dynamics Laboratory (Met.O.21).

In the case of the observational studies of climate, which were often overshadowed in the Met Office’s climate research, the program at the Climatological Research Branch (Met.O.13) was re-structured with particular emphasis on data collection and processing, rather than interpretation. This approach was designed specifically to support and complement the Met.O.20’s development of GCMs. The Met.O.13 carried on experimental monthly and seasonal weather forecasts using analogous methods. For this, long time series of temperature and rainfall records over the last 100 years, and much of the northern hemisphere, were being constructed. The data were processed with a statistical analysis, in order to reveal periodicities in their amplitude and any variations from epoch to epoch, and were assembled on magnetic tape for computer use. In 1973, Met.O.13 embarked on a major program for extracting sea surface temperatures from a variety of sources and subjecting them to quality control.¹⁰⁴ This work was particularly important as it aimed to improve understanding of the relationship between sea surface temperature anomalies and ensuing atmospheric anomalies, a relationship that was vital to enhancing the Met.O.20’s GCM development.

The need for assessing climate change nonetheless continued to grow. The priority of the Met Office’s climate research remained on the model development, but gradually its research focus shifted toward climate change studies. The Met Office had, as described earlier, been involved in the COMESA project, and new concerns were also beginning to arise. For example, when in 1973 the first oil crisis prompted the

¹⁰² P.R. Rowntree, “The Influence of Tropical East Pacific Ocean Temperatures on the Atmosphere,” *Quarterly Journal of the Royal Meteorological Society* 98 (1972), 290–321.

¹⁰³ D.E. Parker, “The Synoptic-scale Subprogram,” *Bulletin of the American Meteorological Society* 55 (1974), 720–730.

¹⁰⁴ C.K. Folland, Interview by the author, 1999. 10. 5.

British and other Western governments to consider large-scale utilization of nuclear energy, there emerged some questions about the effects of releasing waste heat into the atmosphere and oceans. In 1975, Andrew Gilchrist, who was now head of the Met.O.20, began to investigate this issue using the 5-level GCM, in collaboration with the International Institute for Applied Systems Analysis (IIASA), Austria.¹⁰⁵ A year earlier, M.J. Molina and F.S. Rowland at UC Irvine in the US proposed that chlorofluorocarbons (CFCs) might also lead to ozone destruction.¹⁰⁶ As a response, using the 13-level COMESA GCM, the Met.O.20 conducted research into the climatic effects of CFCs and other stratospheric trace constituents such as aerosol, in conjunction with a national research program coordinated by the Central Unit on Environmental Pollution, the Department of the Environment.¹⁰⁷

Soon climate change studies were in full swing around the world. In the US, the White House Domestic Council proposed in December 1974 a “United States Climate Program” with funding of \$240 million for 1975-78.¹⁰⁸ When in August 1975 the symposium on long-term climatic fluctuations was held in East Anglia, sponsored by the WMO and the International Association of Meteorology and Atmospheric Physics (IAMAP), 250 scientists from over 30 countries attended.¹⁰⁹

In the Met Office, director-general John Mason became personally interested in the studies of climate change. In early 1976, he gave a Symons Memorial Lecture “Towards the Understanding and Prediction of Climatic Variations” at the Royal Meteorological Society, reviewing past climates, possible causes of climate change and various GCM results from the Met.O.20. He underlined the potential importance of, and the need to implement, a sustained research program into climate change. And yet, he was very reserved in his assessment of the status of climate change research:

I think that the likelihood of major and potentially catastrophic changes in climate has been grossly exaggerated. ... Unfortunately our understanding of the mechanisms and causes of climatic trends and fluctuations is inadequate to allow of their

¹⁰⁵ A. Gilchrist, *Some Results from the UK Meteorological Office Model Relevant to the Waste Heat Experiments*, Met.O.20 Technical Note, No. II/59 (Bracknell: Met Office, 1975); A.H. Murphy et al., *The Impact of Waste Heat Release on Simulated Global Climate*, RM-76-079 (Laxenburg: IIASA, 1976).

¹⁰⁶ M.J. Molina and F.S. Rowland, “Stratospheric Sink for Chlorofluoromethanes: Chlorine-Atom Catalyzed Destruction of Ozone,” *Nature* 249 (1974), 810-812.

¹⁰⁷ Met Office, *Annual Report of the Meteorological Office 1974* (London: HMSO, 1975), 77; *Annual Report of the Meteorological Office 1976* (London: HMSO, 1977), 101-102.

¹⁰⁸ A.D. Hecht and D. Tirpak, “Framework Agreement on Climate Change: A Scientific and Policy History,” *Climatic Change* 29 (1995), 371-402.

¹⁰⁹ WMO/IAMAP, *Proceedings of the WMO/IAMAP Symposium on Long-term Climatic Fluctuations* (Geneva: WMO, 1975).

prediction. It is not even clear whether they are brought about by internal changes in the atmospheric-oceanic system or by changes in external factors.¹¹⁰

Despite these reservations, Mason, while repeatedly pointing out that GCMs still had serious deficiencies, tended to have more faith in the model results. Hence, the preliminary results from the Met.O.20 13-level model were enough for him to discredit the potential connections between climate and volcanic eruptions, which had been advocated by some observational climatologists. As part of preparing his discussion on long-term climate change, he also asked the Met.O.20 scientists to carry out GCM experiments on the effects of changes in the earth's orbit.¹¹¹

Mason's position was that not only was further scientific research required, but also that this research should be carried out using complex physico-mathematical models. Until then, one should be very careful in making any claims about climate change. It was coming from this background that he declined, a few years earlier, to join the production of *The Weather Machine*, a BBC documentary, as its scientific advisor. Mason decided to withdraw when he found out that Nigel Calder, the writer of the documentary, had already completed the script before consulting the Met Office scientists.¹¹² While the script did report the state-of-the-art development in GCMs, it devoted considerable space to empirical studies of climate and the possibility of a new ice age. This was unacceptable to Mason. Calder later recalled the tension between the Met Office and *The Weather Machine*'s production team:

The UK Met Office was extremely cross about our TV show. It demanded equal airtime to say that talk about a coming ice age was nonsense. For 18 months angry letters went to and fro between the BBC and the Met Office.¹¹³

Mason also believed that human impact was still too small to cause noticeable disruptions to climate. For him, the climate system was "so robust, and contains so much inherent stability through the presence of negative feedback mechanisms".¹¹⁴

Such a cautious stance, especially on the possible effects of alterations in the radiation balance on the global climate, did not weaken Mason's enthusiasm for the Met Office's climate change research. But it did encourage the Office's research to

¹¹⁰ B.J. Mason, "Towards the Understanding and Prediction of Climatic Variations," 473, 475.

¹¹¹ J.F.B. Mitchell, *The Effect on Climate of Changing the Parameters of the Earth's Orbit: Two Summer Integrations Incorporating a Fully Interactive Surface*, Met.O.20 Technical Note, No. II/72 (Bracknell: Met Office, 1976).

¹¹² B.J. Mason, Interview by the author, 1999.7.5. Nigel Calder, the former editor of *New Scientist* (1962-66), was an independent science writer and screenwriter. *The Weather Machine* was aired by BBC Two on November 20, 1974.

¹¹³ N. Calder, "The Climate Wars: Reporting from the Battlefield," CLOUD meeting at Abingdon, 2000. 4. 16.

¹¹⁴ Quoted from J. Gribbin, "Man's Influence Not Yet Felt by Climate," *Nature* 264 (1976), 608.

proceed in a very specific direction. From 1976 onward, with Mason's strong support, the Met Office rapidly expanded its climate change research. Around this time, the Met.O.20 had also developed new radiation schemes with a sophisticated treatment of clouds, thought to be more suitable for both controlled and perturbed climate simulations.¹¹⁵ With these developments, the conservative, pragmatic, and GCM-oriented approach described here became further entrenched, dominating future climate change research at the Met Office.

Concluding Reflections

As I have attempted to show in this paper, throughout the 1960s and 1970s, the Met.O.20 developed a distinctive style of climate modeling, evident both in the construction and use of GCMs.

The Met.O.20 was then the only GCM research group in the world that was a direct branch of the national meteorological service, whose primary task was operational weather forecasting. One of the initial rationales for establishing the Met.O.20 was to explore the possibility of constructing dynamical long-range weather forecasting models for periods extending to a month ahead or even seasons. The Met.O.20's strong commitment to the 'physical realism' of GCMs—i.e., the model's ability to realistically simulate the detailed variations of the presently observed climate—was shaped by this institutional objective of the Office. By the early-to-mid 1970s, it became evident that the theoretical limit of long-range weather forecasting was no more than a few weeks, thus rendering such forecasting impractical. Consequently, and in conjunction with the need to respond to growing environmental awareness, the Met.O.20's research focus shifted toward the numerical simulations of anthropogenic or long-term climate changes. But the emphasis on the model's physical realism remained an essential constituent of the Met.O.20's climate modeling work. Although GCM research groups elsewhere likewise pursued the development and refinement of GCMs that could simulate the present climate, the Met.O.20 considered it particularly imperative.

Scientists at the Met Office also adhered to a pragmatic and yet hierarchical view of climate modeling. Their choice of modeling methodology was guided, in part, by whether it would have practical use for the intended purposes. For instance, simple models such as 1-D RCMs could not be used for simulating the regional or seasonal variations

¹¹⁵ See, e.g., G.E. Hunt and S.R. Mattingly, *Atmospheric Radiation Studies*, Met.O.20 Technical Note, No. II/31 (Bracknell: Met Office, 1974); *Infrared Radiative Transfer in Planetary Atmospheres I: Effects of Computational and Spectroscopic Economies on Thermal Heating/Cooling Rates*, Met.O.20 Technical Note No. II/60 (Bracknell: Met Office, 1976); J. Walker, *Interactive Cloud and Radiation in the 11-Layer model: Part I. Radiation Scheme*, Met.O.20 Technical Note No. II/91 (Bracknell: Met Office, 1977); P.R. Rowntree and J. Walker, *Radiation Schemes in the Met.O.20 Models*, Met.O.20 Technical Note No. II/93 (Bracknell: Met Office, 1977).

of climate. 3-D GCMs were necessary. On the other hand, the Met.O.20 scientists firmly believed that, as a matter of principle, climate and its change could only be scientifically studied by using complex physico-mathematical models, i.e., GCMs. The acceptance of GCMs as a major methodology did not necessarily exclude other modeling techniques. In the US, simple climate models of various kinds were widely used. Syukuro Manabe, among others, actively carried out RCM studies of the climatic effects of increased CO₂, even though his original goal was to develop a radiative transfer scheme for GCMs. Interestingly, Manabe was later awarded the 2021 Nobel Prize in Physics for his CO₂-doubling simulations including those using RCMs.¹¹⁶ However, the Met.O.20 scientists disapproved of the use of simple models for the purpose of studying climate change. They did regard Manabe's experiments highly, but primarily because his work was part of GCM developments and was physico-mathematically advanced.

The GCM-centered approach espoused by the Met Office was, in addition, tied to a deep-rooted conservative attitude held by its senior scientists toward the role of science in policy. Undoubtedly, rising global environmental concerns served as an important catalyst for the expansion of the Met.O.20's climate modeling work. Nevertheless, for the Office's senior scientists, not only were the domains of science and policy strictly demarcated from each other, but policy discussions should also be premised on 'sound' science. Policy-oriented research based on hasty scientific analysis was to be avoided at all costs. Simple models, such as 1-D RCMs, were recognized as possessing their own scientific values, yet they were deemed inappropriate for the rigorous study of climate change. The Met Office instead prioritized the development of more sophisticated GCMs. This approach contrasted with that of Manabe, who maintained that the use of RCMs was legitimate as long as the overall climatic effects of increased CO₂ or other trace gases could be investigated.¹¹⁷ Hence, while the cultural hierarchy of science that privileged GCMs was prevalent in both the US and Britain, the specific ways in which this manifested diverged. And this difference did not simply stem from technical concerns but was intertwined with the Met Office's unique stance on policy-relevant science.

Such a cautious, conservative approach to the science-policy interface was perhaps expected. The Met Office regularly issued weather forecasts to government agencies, industry, and the public, which had potentially significant societal consequences. This brought in a culture of conservatism at the Office. As part of the British Scientific Civil

¹¹⁶ Syukuro Manabe was awarded the Nobel Prize in Physics in 2021, jointly with Klaus Hasselmann and Giorgio Parisi, for his contributions to "the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming." Nobel Prize Outreach AB. 2021. (Accessed 2023. 2. 1.) <https://www.nobelprize.org/prizes/physics/2021/summary/>.

¹¹⁷ Manabe was also happy to use low-resolution GCMs with relatively simple physical parameterizations in his CO₂-doubling simulations. See S. Manabe, "Estimates of Future Change of Climate Due to the Increase of Carbon Dioxide Concentration in the Air," W.H. Matthews et al., eds., *Man's Impact on the Climate* (Cambridge: MIT Press, 1971), 249-264. The Met.O.20 scientists ruled out using such models in their simulations.

Service, the Met Office also had a closed and hierarchical organizational culture. The Met.O.20's research priorities and activities were controlled at the level of the directorate of research and the deputy directorate of dynamical research. Policy matters were handled exclusively by a select group of senior staff. As the model development advanced and commitment to climate research increased, the Met.O.20 expanded both in size and scope, integrating more junior scientists. While the scientists working for climate modeling worked in an academic-like environment, they were closely supervised by the assistant director of the Met.O.20 and other senior scientists. Naturally, the Met.O.20 scientists were quite cautious in changing their style of doing things or in adopting new theories or techniques even when they thought there were scientific reasons for the changes. The potential diversity of research interests and practices within the Met.O.20, therefore, tended to be suppressed.¹¹⁸

This is by no means to suggest that climate modeling work at the Met Office had been distorted or contaminated by non-scientific factors. The Met.O.20's development and use of GCMs for climate simulations gained acclaim from the international climate science community and would later contribute significantly to building the scientific basis for the IPCC. However, it is crucial to acknowledge that some of the most scientifically advanced features of the Met.O.20's climate research would not have been possible without its conservative, pragmatic, and hierarchical style of modeling. This distinctive style of science was very much a product of the institutional, social, cultural, and political contexts in which it was embedded and developed.¹¹⁹ Recently, a group of environmental social scientists, deeply frustrated by the persistent deadlock in addressing the climate crisis despite the ever-increasing climate research, have called for a moratorium on climate change science to direct our attention toward the urgent need for immediate action.¹²⁰ The moratorium on climate change science is certainly an overstated idea. Nevertheless, a more nuanced understanding that climate science has always been inseparable from its social, cultural, and political contexts could perhaps help us ponder the pressing climate crisis we face today.

¹¹⁸ This organizational culture was closely intertwined with the cultural hierarchy of science that privileges GCMs, leading to a more complex picture than the "'hard science' culture" Martin-Nielsen discussed. J. Martin-Nielsen, "Scientific Forecasting?: Performing Objectivity at the UK's Meteorological Office, 1960s-1970s," 209.

¹¹⁹ If we are to examine climate modeling as an anchor of what Mahoney and Hulme call the nation's "epistemic sovereignty," it is necessary to first comprehend how this distinctive style of climate modeling has been historically constructed. M. Mahony and M. Hulme, "Modelling and the Nation: Institutionalising Climate Prediction in the UK, 1988-92," 466.

¹²⁰ B.C. Glavovic et al., "The Tragedy of Climate Change Science," *Climate and Development* 14:9 (2022), 829-833.

Abstract

The study of climate and its change had traditionally been descriptive and regionally oriented and regarded as a minor branch of meteorology. With advances in computing technology, however, climate studies gradually moved towards highly mathematical endeavors. By the mid-1970s, climate research became dominated by dynamical meteorologists, atmospheric physicists, and physical oceanographers armed with complex numerical modeling as a principal methodology. The observational studies of climate, as well as simple climate modeling studies focusing on climate sensitivity and feedback processes, continued to play an essential role in raising the issue of climate change – both natural and anthropogenic – in the 1960s and early 1970s. On the other hand, many meteorologists firmly believed that climate and its change could only be properly studied using numerical models of the large-scale atmospheric circulation – i.e., general circulation models (GCMs). This tendency was particularly strong in Britain. From early on, the British Meteorological Office devoted much of its climate research efforts to developing GCMs. This paper traces the history of GCM developments at the British Meteorological Office from the 1950s to the mid-1970s and also explores how particular styles of scientific practice, disciplinary traditions, institutional cultures, and broader political environments shaped these developments.

Keywords: climate science, climate modeling, cultural hierarchy of science, general circulation models, Meteorological Office, environmental politics