4 - Deducing Climate

Smagorinsky’s Laboratory

from Part I - The Past

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Summary

The Geophysical Fluid Dynamics Laboratory (GFDL) is a pioneering institution in the field of climate modeling. Its founding director, Joseph Smagorinsky, was a member of the Princeton Meteorology Group. He hired a Japanese scientist, Syukuro Manabe, who formulated a one-dimensional model of climate, known as the radiative–convective model, that was able to calculate the amplifying climate feedback due to water vapor. This model provided one of the first reliable estimates of global warming. Manabe worked with other scientists to build three-dimensional climate models, including the first model that coupled an atmospheric model to an ocean model. The concepts of reductionism and emergentism, which provide the philosophical context for these scientific developments, are introduced.

Keywords

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The Climate Demon

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For the next chapter in the story of climate prediction, we return to Princeton University. Driving southeast out of the main campus, we reach Route 1, the north–south US highway that runs all the way from Florida to Maine. After traveling about three miles northeast along this road, we reach the Forrestal Campus of Princeton University. This sprawling campus was created to host government-sponsored research labs affiliated with the university.

Near the entrance to Forrestal Campus, we see a nondescript, rectangular, two-story office building, vaguely reminiscent of a greenhouse (Figure 4.1a). Within this building is a US government laboratory called the Geophysical Fluid Dynamics Laboratory, or GFDL, which carries out research on fluid dynamics in the atmosphere and the ocean, studying the motions of air and water that control weather and climate. There is a bunker-like annex behind the main GFDL building, which until recently housed state-of-the-art computers used for weather and climate modeling. As computers became more and more power-hungry, they were moved offsite. Now GFDL's computers are hosted remotely, at Oak Ridge National Laboratory (ORNL) in Tennessee.

Figure 4.1

(a) Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton's Forrestal Campus.

(b)

(b) Kirk Bryan (left) and Suki Manabe, with GFDL Director Joseph Smagorinsky (right) in 1969.
(Photos: NOAA/GFDL)

The Geophysical Fluid Dynamics Laboratory originated with a young scientist named Joseph Smagorinsky (Figure 4.1b), formerly of the Princeton Meteorology Project. Smagorinsky, or “Smag” as he was known to his friends, was a forceful and influential figure in meteorology during the second half of the twentieth century.[1] The lab that he founded and nurtured – sometimes known as Smag’s Laboratory – would play a pioneering role in weather and climate prediction.

4.1 General Circulation of the Atmosphere

Joseph Smagorinsky grew up in New York City, in a family of Belarusian refugees,[2] and worked in his father’s paint store. His dream was to become a naval architect, but he failed to gain admission to the prestigious Webb Institute near his home. Smagorinsky settled for his second choice of career, meteorology, and began attending New York University (NYU) in 1941. When the

United States entered the Second World War, Smagorinsky joined the Air Force and was selected for its meteorology training program.

After the war, Smagorinsky completed his master's degree in dynamic meteorology at NYU and joined the US Weather Bureau as an assistant to Harry Wexler, Chief of the Special Scientific Services Division.[3] Wexler was involved with the Princeton Meteorology Group, and, in 1950, Smagorinsky himself joined the group. He worked as a scientific programmer, while simultaneously carrying out his doctoral research in atmospheric weather patterns at NYU.

Smagorinsky returned to the US Weather Bureau in 1953, after receiving his Ph.D. from NYU. There he continued to work on computational weather forecasting. In 1955, another member of the Princeton Meteorology Group, Norman Phillips, carried out an innovative calculation using the IAS computer. Phillips used Charney's simplified three-dimensional equations for the atmosphere, with just two grid levels in the vertical direction, to carry out a 30-day forecast, well beyond the weather prediction horizon. For the first time, the boundary between weather and climate prediction had been crossed.

Phillips's calculation immediately caught the attention of von Neumann. It was a step toward the infinite forecast he had envisioned, which fitted into his grand vision of modifying weather and climate through better understanding of the atmosphere. The infinite forecast would describe the long-term average of atmospheric flow patterns, referred to as the *general circulation of the atmosphere*. For this reason, the earliest atmospheric models were known as *general circulation models* or GCMs. (Today, GCM is more commonly used to denote *global climate model*.)

In August 1955, von Neumann proposed the establishment of a research unit to study the dynamics of the general circulation using state-of-the-art computers.[4] He requested $262,000 per year, or about $2.5 million in today's money. The United States government signed off within a month. The General Circulation Research Section (GCRS) was established soon afterwards in Suitland, Maryland, as a joint Weather Bureau–Air Force–Navy venture, with Joe Smagorinsky as the director.

In 1959, the GCRS unit changed its name to the General Circulation Research Laboratory and moved to Washington, DC.[1] It acquired its current moniker in 1963, and, five years later, it moved to Princeton University's Forrestal Campus, where it continues to operate today. Through the Department of Geosciences, scientists at GFDL were provided with affiliate appointments at Princeton

University, enabling them to teach courses and advise graduate students. The management structure of GFDL, though, is quite different from that of a university department; it operates more like the IAS, where Smagorinsky had worked in the early 1950s. The emphasis is more on long-term research than on the short-term publication of papers.

Princeton Meteorology Group was organized around the ENIAC and then around the IAS computer. Von Neumann wanted Smagorinsky's lab to likewise have as its centerpiece the most advanced computer available. After the success of the ENIAC, private companies had entered the business of building computers. One of them was the Remington Rand corporation, which had acquired a smaller computer company started by Mauchly and Eckert, the designers of ENIAC. In 1951, it released a computer called the UNIVAC, for "universal automatic computer." Around the same time, a competing corporation, International Business Machines (IBM), was creating its own computer, having hired von Neumann as a consultant.[5] This computer, named the IBM 701, followed the design of the IAS computer.

The UNIVAC and the IBM 701 were the first computers that were sold commercially; they were not just one-of-a-kind research computers. Both were large and were built using vacuum tubes, like the ENIAC. Although they were not much faster than their predecessor, they were more reliable and had far more memory for data and programs. These larger computers were referred to as "mainframes," to distinguish them from the smaller computers that followed. Later, the most advanced computers of the day would become known as "supercomputers," as mainframes became commoditized for business uses.

GFDL started out with access to an existing IBM 701 in 1955.[6] Smagorinsky rapidly assembled a team of scientists and programmers. The scientists came up with ideas and algorithms, and the programmers implemented these in code. As the team began to build a comprehensive three-dimensional model of the atmosphere to simulate weather and climate, Smagorinsky recognized the need for additional expertise, beyond fluid dynamics. He was looking for a scientist with a strong background in atmospheric physics to work with him in his new lab.

4.2 From Tokyo with Meteorology

Akira Kasahara was looking for a job. While Smagorinsky was building computer models of weather in Princeton, Kasahara was a graduate student working under Shigekata Syono, an eminent professor of meteorology at the University of

Tokyo.[7] Professor Syono was an excellent researcher, but he did not provide many employment opportunities for his students. In 1952, a scientist from Syono's group, Kanzaburo Gambo, left to work with Jule Charney in Princeton, and Kasahara was able to obtain Gambo's former research position. Gambo wrote excitedly from Princeton about how computers were being used to predict weather. Kasahara and others in his research group closely followed these developments, which were revolutionizing their field. In 1954, Gambo returned from Princeton, and Kasahara found himself out of work.[8]

Kasahara wrote to one of the members of the Princeton Meteorology Group, John Freeman, who had recently moved to Texas A&M University in College Station, Texas, and was in search of a research assistant. Freeman hired Kasahara, and, in 1954, Kasahara took a cargo ship to the United States. Kasahara was among the first of many Japanese scientists who emigrated to the United States in the postwar period and made lasting contributions to weather and climate science.

In 1956, Kasahara took a new position at the University of Chicago, working on hurricane prediction with George Platzman, another former member of the Princeton Meteorology Group.[9] Kasahara needed a computer for his research, but the University of Chicago did not have one at the time, so Kasahara had to travel regularly to locations with computers. Some of the computers he used, such as those at national laboratories, were sensitive installations operated by the US Atomic Energy Commission. Since Kasahara was not a US citizen, and these were restricted facilities, he was not allowed to enter the building with the computer. So, he would leave the deck of punched cards containing his computer program at the guard's office. The deck would then be sent to the computer operators, who would run the program and send the output back to the guard's office. Kasahara would come back later to pick it up.

One of the computers that Kasahara was able to use more easily, through Platzman's Princeton connections, was the IBM 701 at GFDL. During one of Kasahara's frequent visits, Smagorinsky mentioned to him that he was looking for a scientist with a strong background in atmospheric physics to help him build a climate model.[10] Kasahara suggested Syukuro Manabe, a colleague from Professor Syono's group at the University of Tokyo. Impressed with Manabe's work on rainfall prediction, Smagorinsky hired him in 1958.

We will encounter Kasahara once more in a later chapter: He changed jobs again in 1963, at the invitation of another former member of the Princeton Meteorology Group.

4.3 Three-Dimensional Climate Modeling

Syukuro “Suki” Manabe was born in rural Japan, the son and grandson of medical doctors (Figure 4.1b).[11] When he went to the University of Tokyo, it was assumed that he would follow in their footsteps. But Manabe despised biology and soon switched fields to physics. Figuring that he was not smart enough to be a theoretical physicist, and not handy enough to be an experimental physicist, he decided to study geophysics. After obtaining his bachelor’s degree, he couldn’t find a job. He went on to complete a master’s degree and then a Ph.D. in Professor Syono’s group. There still were no well-paying jobs.

At the time, Manabe was working 18-hour days doing rainfall prediction with manual calculations. When Smagorinsky offered Manabe the chance to work on computer modeling in the United States, Manabe immediately accepted it.[12] In the fall of 1958, he moved to Washington, DC, where GFDL was then located. Smagorinsky also ended up hiring two of Manabe’s colleagues from Syono’s group, Kikuro Miyakoda and Yoshio Kurihara, who would go on to become pioneers in extended weather forecasting and hurricane modeling, respectively.

Manabe’s primary task was to work with a team of meteorologists and programmers to build a three-dimensional climate model. Initially, Manabe worked under Smagorinsky’s direction, improving various components of the model. As Smagorinsky became progressively more involved over the years with administrative activities and international projects, Manabe took charge of the team.[13]

The process of constructing three-dimensional weather and climate models starts from the Navier-Stokes equations that govern air motions (Section 1.3), along with thermodynamic equations for air and water vapor.[14] The Earth’s atmosphere is a spherical shell (Figure 4.2). To solve the equations on the computer, the spherical shell is first divided into a two-dimensional grid of cells covering the entire globe in the horizontal (latitude–longitude) dimensions. Then the column of air over each horizontal grid cell is further subdivided into a grid of levels in the vertical (or altitude) dimension, extending from the ground to the stratosphere, to form a three-dimensional grid spanning the entire globe. The horizontal grid cell is typically about 10 × 10 km for weather models and about 100 × 100 km for climate models. The number of levels in the vertical is about 50. This means that a typical climate model has about three million elements in its three-dimensional grid, and weather models can have a hundred times more grid elements. At each grid element, air temperature, humidity, and winds are represented by numbers that change over time, as determined by the equations.

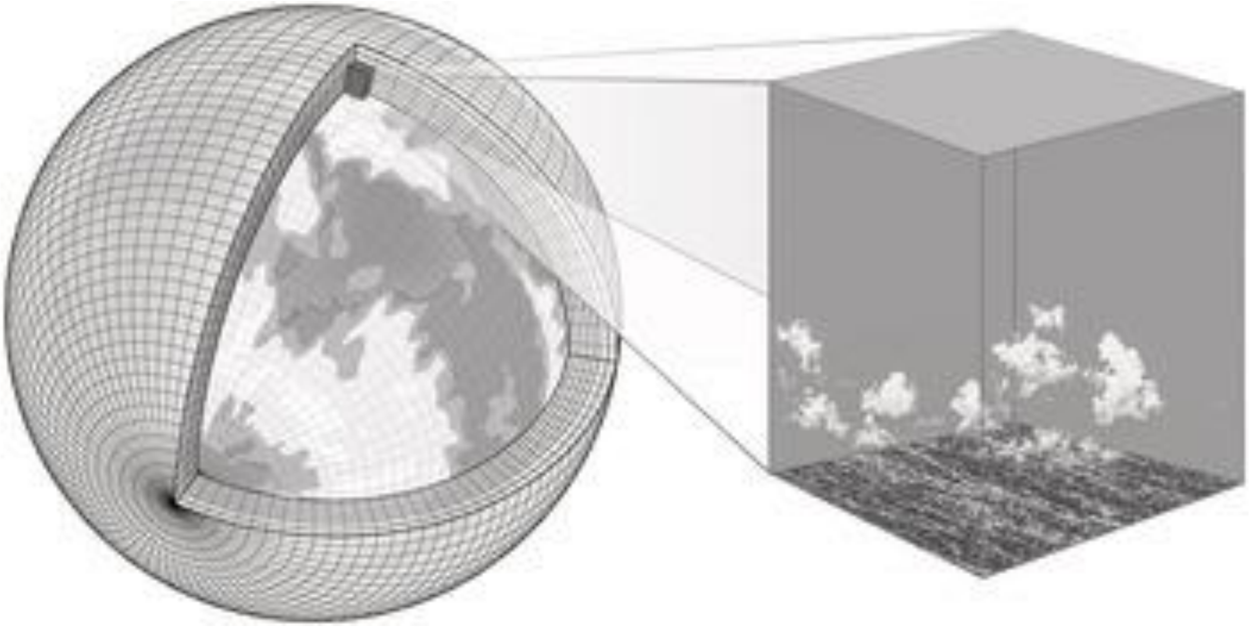

Figure 4.2 Schematic illustration of the three-dimensional spherical grid of a global climate model. The blow-up on the right shows a single column of air over a horizontal grid cell, which is too coarse to capture the details of fine-scale clouds inside the column.

(From Schneider et al., Reference Schneider, Teixeira and Bretherton2017a; reprinted by permission from Springer/Nature Climate Change, © 2017)

The size of each horizontal grid cell is too coarse, even in weather models, to capture the details of individual clouds and other fine-scale processes (Figure 4.2). Instead, approximate mathematical formulas known as *parameterizations* are used to represent clouds and other small-scale processes in the computer model. The equations governing the large-scale air motions represented in the grid, and the parameterization formulas for fine-scale processes not captured by the grid, are solved using a powerful computer, starting from an initial condition and marching forward one time step at a time (Section 1.3).

Although weather and climate prediction share the same computational framework, there are additional challenges when it comes to climate prediction, because many more processes need to be considered. The early weather models used by Charney and von Neumann were focused on simulating the movement of air, a process known as fluid dynamics. But air is warmed by infrared radiation from the Earth’s surface, not directly from the sun (Section 3.1). Water vapor also heats and cools. When water evaporates from the surface, it cools the surface. When water vapor condenses to form clouds, rain, or snow, it heats the air. Like infrared radiation, water vapor also transfers heat from the surface to the air. Radiation and rainfall are two important processes that need to be represented well in climate models.

In 1965, Manabe and Smagorinsky published papers[15] that described their success in building one of the earliest three-dimensional climate models.[16] The model solved the fluid equations in a hemispherical shell, meaning that only the Northern Hemisphere was represented. The horizontal grid cell size was 500 × 500 km, and there were nine levels in the vertical. Even though it had no geography – it was all land and no ocean – the model managed to capture the basic properties of weather and climate. But this state-of-the-art three-dimensional model was complex and computationally expensive, making it hard to tweak it in different ways to understand its behavior.

4.4 Philosophy Break: Reductionism and Emergentism

Little drops of water,
Little grains of sand,
Make the mighty ocean
And the pleasant land.

From the nineteenth-century poem by Julia Carney

When scientifically analyzing a complex system, we might find it simpler to reduce the system to a collection of smaller interacting subsystems and study each of these subsystems separately. This approach to science is known as *reductionism*. An early practitioner of this approach was the Greek philosopher Democritus, who posited in the fifth century BCE that the physical world was composed of indivisible particles called atoms. In the seventeenth century, the French philosopher René Descartes,[17] the namesake of Cartesian geometry, introduced the related concept of *mechanism*. Descartes argued that the world was like a machine, driven by parts that acted as a clockwork mechanism.

One can think of reductionism as a repeated wielding of the analytic knife. Pirsig’s Phaedrus used the analytic knife to “split the whole world into parts of his own choosing, split the parts and split the fragments of the parts, finer and finer and finer until he had reduced it to what he wanted it to be.”[18] The idea is that once the parts of the whole are small enough, they are easy to study and understand.

The opposite of reductionism is *emergentism*. Emergentism says that new properties in a complex system emerge through interactions between other properties. An early proponent of emergentism was the nineteenth-century British philosopher John Stuart Mill, who used properties of chemical compounds as an example. The related concept of *holism* literally means that the whole is more than the mere sum of its parts. In other words, an emergent or holistic complex system exhibits behavior that cannot be understood by simply studying each of its parts.

The distinction between reductionism and emergentism, both of which deal with the physical world, is somewhat orthogonal to the distinction between deductivism and inductivism, which are both concerned with scientific thought. Typically, reductionism is associated with deductivism, and inductivism with emergentism, but other combinations are possible. Among the sciences, physics is more reductionist: Matter is composed of molecules, molecules are composed of atoms, and so on. Biology, on the other hand, is more emergent; the behavior of organs like the brain or the heart cannot be explained by simply studying the properties of individual cells and molecules.

Reductionism forms the basis for the construction of computer models of weather and climate. A computer model is a giant program that is made up of smaller programs, each of which deals with different components – such as atmosphere, ocean, and land – as well as different processes that are too small to be represented on the model grid – such as rain, clouds, and turbulence.

To use the Laplace’s Demon analogy, the Weather Demon can be described as working with lesser demons such as the Air Demon, the Radiation Demon, and the Cloud Demon that interact with each other. Each lesser demon makes a prediction for its domain, and the Weather Demon combines them to make an overall prediction. A reductionist approach would study each of the lesser demons separately, under the assumption that the Weather Demon simply adds up the individual predictions. An emergent approach, on the other hand, would argue that the isolated behaviors of the lesser demons are less important to the overall prediction than are the interactions between these lesser demons.

Weather and climate prediction therefore depend upon the emergent behavior of the atmosphere simulated by models.[19] The models can predict complex phenomena like hurricanes and droughts, even though such phenomena are not explicitly represented in the individual model components. The collective interaction of different components such as air circulation, radiation, and clouds is responsible for generating these phenomena.

4.5 Models of Simplicity in the Garden of Complexity

Big models have little models
To delegate their deductivity
And little models have lesser models
And so on to reductivity

variation of Lewis Fry Richardson’s 1922 poem, itself a variation of Augustus De Morgan’s *Siphonoptera* (1872) derived from Jonathan Swift’s satirical *On Poetry: A Rhapsody* (1733)

In the 1960s GFDL was a hive of research activity in weather and climate modeling. It welcomed a number of international visitors. One of these visitors was a German scientist named Fritz Möller, an expert on radiation.[20] Möller, like Arrhenius before him, was interested in the greenhouse effect that kept the Earth warm. In 1938, a British engineer named Guy Callendar claimed that the Earth had warmed in the previous 50 years and that the concentration of carbon dioxide in the atmosphere had increased in the same period – and that the former was attributable to the latter.[21] This was the first time such a link had been made based on data; Arrhenius’s earlier work merely raised this link as a possibility. Callendar estimated climate sensitivity, long-term warming due to a doubling of the carbon dioxide concentration, to be about 2°C, which appeared to be consistent with the data. His analysis, although groundbreaking, was flawed; it only considered the role of radiation in heating the atmosphere, not the role of water vapor.

Möller revisited the greenhouse effect of carbon dioxide in 1963, using a much more accurate calculation of radiation. He found that estimates of climate sensitivity depended upon how water vapor was handled in the calculation. Manabe, who was working with Möller, was strongly influenced by this result.[22] At the time, Manabe was helping Smagorinsky improve the radiation formulas in the GFDL’s comprehensive climate model. But tweaking the radiation formulas and running the full climate model each time to test it would be very expensive computationally – not to mention very slow because of the wait time between model runs.

What Manabe did, which is a common approach in climate science, was to narrowly focus on the vertical transfer of heat, reducing the complexity of the problem. He constructed a much simpler model of the atmosphere – a one-dimensional climate model that only considered the altitude dimension, ignoring the latitude and longitude dimensions. At first glance, this appears to be a giant leap of faith, approximating the spherical shell of the atmosphere as a single column (Figure 4.2). But it is not as drastic as it sounds. Temperature decreases with altitude at each location on the globe, and local lapse rates, the rates at which temperature falls off with height, do not diverge much from the global average value of 6.5°C/km (Figure 3.1). Mathematically, this means that there is a certain amount of symmetry along latitude and longitude, allowing those dimensions to be averaged out, leaving only the altitude dimension.

Manabe's one-dimensional model, known as the *radiative–convective model,* represents both radiation and moist convection, the turbulent transport of water vapor that causes rain. The effects of radiation were captured through tedious but doable computations using the basic equations of electromagnetic radiation. The model computed solar radiation passing through the atmosphere and reaching the surface, and infrared radiation emitted from the surface passing through the atmosphere back to space. It also calculated the effects of the two main greenhouse gases, water vapor and carbon dioxide, which impede the passage of infrared radiation.

Representing convection, though, was much trickier. Convection is a chaotic and turbulent process, especially when moisture and clouds are included in the mix. During convection, rising air cools due to an effect called *adiabatic expansion* (Section 3.1). If the air contains moisture and its temperature cools below a threshold temperature known as the dew point, the moisture will condense to form cloud droplets and rain. Since this happens at very fine spatial scales – of a few hundred meters – it cannot be captured by the coarse grid of a climate model.

Manabe came up with a clever shortcut to represent rain due to convection. The one-dimensional model followed a parcel of warm, moist air rising upward from the surface as it cooled due to adiabatic expansion. When the temperature of the parcel cooled below the dew point, it could no longer hold all its moisture. The excess moisture would then be condensed and fall as rain. The air parcel's temperature would be continuously readjusted to the dew point as it moved upward, until all its moisture was rained out.[23] This procedure, known as *moist convective adjustment*, is one of the earliest examples of a parameterization – a formula or algorithm used to represent small-scale processes like clouds that are too small to be captured by the spatial grid of the model. Manabe first tested it in his one-dimensional model before including it in the full climate model.

With this convective adjustment parameterization in place, Manabe had a simple, but complete, one-dimensional climate model that could be solved rapidly using a computer. With his colleagues Robert Strickler and Richard Wetherald at GFDL, he published papers in 1964 and 1967 using this model. The latter paper, titled

"Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity," is considered one of the most influential papers in climate science.

Manabe's model is a classic example of the power of the reductionist approach. The model encapsulated the essence of the problem that had previously been studied by Arrhenius, Callendar, and Möller. Building on this prior work, Manabe was able to fix many of its deficiencies. He used the one-dimensional model to study the global warming associated with carbon dioxide, including the amplifying effect of the water vapor feedback. He estimated climate sensitivity to be about 2.3°C, not far from today's estimate of about 3°C.

Manabe's model also showed that, while increasing carbon dioxide warms the lower part of the atmosphere, the troposphere, it actually cools the upper part of the atmosphere, the stratosphere (Figure 3.1).[24] This happens because carbon dioxide is both a good absorber and a good emitter of infrared radiation. In the lower atmosphere, the absorption of strong infrared radiation from the surface plays a bigger role and leads to warming. In the upper atmosphere, where there isn't that much infrared radiation from below to absorb, the emission effect dominates, leading to more cooling with increased carbon dioxide concentration. This counterintuitive stratospheric cooling effect, verified by observations, demonstrates the power of scientific modeling. Many results from Manabe's radiative–convective model have stood the test of time, despite its highly simplified nature – or perhaps because of it.

Like the atmosphere, the ocean is an important component of the climate system. Early climate modelers used a very simple representation of the ocean; they treated the upper ocean as a motionless slab of water, completely ignoring ocean currents. This may be acceptable if one is only interested in predicting the equilibrium climate, but it is a very poor representation if one is interested (as we are) in predicting the evolving climate. In Section 4.6, we discuss the development of a complex ocean model that is an analogue of the complex atmospheric model.

4.6 Flywheel of Climate: The Circulating Ocean

A flywheel is a very heavy wheel that spins, acting as a reservoir of kinetic energy. It's difficult to get it to spin, but, once it is spinning, it is equally difficult to get it to stop. Flywheels are commonly used in exercise machines, like stationary bikes and ellipticals, to maintain momentum.

The ocean is climate’s equivalent of a flywheel, storing heat energy rather than kinetic energy. It can serve as a heat reservoir because of a property called *heat capacity*. Heat capacity is defined as the amount of energy it takes to warm an object by 1°C.

Say you put an empty metal saucepan on a heating stove. The saucepan will heat up rapidly, because the metal of the saucepan has a small heat capacity. Of course, the saucepan is not really “empty” – there is air inside of it – but as air has even smaller heat capacity, this makes little difference in how fast the saucepan heats up. When the saucepan is filled with water, it takes much longer to heat up, because the water has a much larger heat capacity than air. The heat capacity of a saucepan-sized amount of water is about 4,000 times the heat capacity of a saucepan-sized amount of air, accounting for the low mass of the air.[25] We can do a similar calculation for the atmosphere and ocean, taking into consideration the average depth of the ocean and the area it occupies. It turns out that the ocean has about 1,000 times the heat capacity of the entire atmosphere.[26] In other words, it takes 1,000 times more energy to warm the entire ocean by 1°C than it takes to warm the entire atmosphere by 1°C. The ratio is smaller if we only consider the warming of the upper ocean, which is what happens in the short term, over a few decades.

The enormous differential between the heat capacity of the atmosphere and the heat capacity of the ocean has important consequences for the global warming problem. Say the carbon dioxide concentration doubles instantaneously, and the greenhouse effect begins to trap more infrared radiation. As the atmosphere warms up, it begins to transfer excess heat to the upper ocean, through a process known as ocean *heat uptake*. This slows down global warming, resulting in the *transient climate response* that occurs over many decades (Section 3.2). The excess heat from the upper ocean eventually makes it way to the deep ocean, over many centuries, through a process called *thermohaline circulation*. Once the entire ocean has warmed up, the combined atmosphere–ocean system reaches a new equilibrium. The warming at this point is the *climate sensitivity* that we discussed previously. Of course, if the carbon dioxide concentration keeps increasing, the system will not reach equilibrium. (The land has about the same heat capacity as the atmosphere, and therefore does not take up much heat.)

To predict the short-term evolution of global warming, we need to consider the ocean as well as the atmosphere. When Manabe and his predecessors used simple atmosphere models to estimate the warming associated with doubling the amount of carbon dioxide, they worked around the lack of a proper ocean model by considering only the long-term equilibrium response, after the ocean has completely warmed up. It would take the entire ocean thousands of years to reach equilibrium. But since we want to mitigate climate change, we are more interested in knowing what is likely to happen in the next 30–100 years.

Smagorinsky was prescient enough to understand that any climate model used for practical prediction would have to include both the atmosphere and the ocean. His long-term vision was to realize Lewis Fry Richardson's dream of a "forecast factory" for the entire climate system (Figure 1.2a). In 1960, he hired an oceanographer named Kirk Bryan (Figure 4.1b) from the Woods Hole Oceanographic Institution to start building an ocean model at his lab.[27] Back then, oceanographers often had a very different scientific culture from meteorologists; they focused more on regional problems than on global problems, for instance. The ocean was much more poorly observed than the atmosphere, and oceanographers concentrated more on data gathering than on modeling. Due to lack of sufficient data to constrain the three-dimensional structure of the global ocean, efforts to model it were considered premature. But Bryan had originally trained as a meteorologist and had experience with numerical modeling, having completed his Ph.D. under the supervision of Ed Lorenz.[28] This background enabled him to transcend the disciplinary boundary and work more easily with the atmospheric modelers who dominated GFDL.

Bryan worked alongside a talented programmer named Michael Cox to build a model of the ocean that could represent ocean currents like the Gulf Stream or the Kuroshio. Bryan and Cox essentially had to start from scratch because ocean modeling was far less developed than atmospheric modeling: The ocean models then were quite simple and assumed the ocean was in steady state. To develop their three-dimensional model of the ocean, they borrowed computational design ideas from a parallel climate modeling effort underway at the University of California, Los Angeles (UCLA), led by Yale Mintz and Akio Arakawa – the latter being from Professor Syono's group in Tokyo, like Manabe and Kasahara. Later, Bryan and Cox shared the code for their model with scientists around the world, pioneering the open-source tradition that has become increasingly common in climate modeling.[29]

In 1969, Manabe and Bryan constructed a climate model that included both the atmosphere and the ocean, known as a "coupled model" – the first of its kind.[30] It was not a truly global model, given the state of modeling at the time, but it did allow atmospheric winds to interact with ocean currents for the first time ever. This collaboration between the oceanographer and the meteorologist would continue for several decades, as they built more complex models of the climate system.

To use the Laplace's Demon analogy, the Climate Demon needs to work with lesser demons like the Atmosphere Demon, Ocean Demon, Land Demon, and Sea Ice Demon to make predictions. Early versions of the Climate Demon relied mostly on the Atmosphere Demon, interacting with very crude caricatures of the other demons. Manabe and Bryan were the first to get the Atmosphere Demon to talk to a realistic Ocean Demon.

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Many years later, Manabe said of his time at GFDL: "this is one of the fascinating things about this laboratory. We never, I never in my whole life – I never wrote [a] grant proposal for my own research."[31] The success of Smagorinsky's lab owes much to the management philosophy of the man who led it from its inception in 1955 until his retirement in 1983.[1] He hired young, talented scientists like Manabe and Bryan and provided them the resources and the freedom that they needed to grow to be world leaders in their disciplines. Scientists at GFDL were provided a small team of programmers to assist in their work and computer resources to run their model without ever having to write proposals so long as they carried out research broadly consistent with the mission of the laboratory. Apart from the pioneering climate modeling activities discussed in this book, GFDL scientists have also made many groundbreaking contributions in other areas of the atmospheric and oceanic sciences.

During the 1960s, computer models of climate were being built at research centers around the world. Manabe's model at GFDL was just one among them. Jule Charney and John von Neumann, along with the rest of the Princeton Meteorology Group, had already shown how we could use the basic principles of physics in conjunction with a computer to scientifically predict weather. It is then natural to ask whether we can also scientifically predict climate, which is simply the average of many weather events, using those same physical principles. The computer climate models of Manabe and others, as well as the simple model of Svante Arrhenius, essentially aimed to do just that. But recall that Lorenz had shown that we cannot predict weather beyond the next two weeks. How, then, can we hope to predict climate months and years into the future?