1 Thinking Globally

In 1968, three American astronauts became the first human beings ever to see Earth's full disk from space. President Lyndon B. Johnson mailed framed copies of the Apollo mission's photographs to the leaders of every nation as an allegory of the inevitable unity that encompasses all human division and diversity and binds us to the natural world.

By then, of course, representations of Earth as a globe were already centuries old. Nevertheless, many saw a transfiguring power in the awesome beauty of those famous photographs. That small blue ball, spinning alone in darkness: it hit you like a thunderclap, a sudden overwhelming flash of insight. You saw, all at once, the planet's fragility, its limits, and its wholeness, and it took your breath away. The law professor Lawrence Tribe once called it a "fourth discontinuity," as massive a perspectival shift as those brought on by Copernicus, Darwin, and Freud.[1] By 1969, according to rumor, David Brower, founder of Friends of the Earth, had distilled Tribe's "fourth discontinuity" into four words: "Think globally, act locally."[2]

Whatever you think of it as a political principle, "Think globally, act locally" remains arresting in its boldness. It captures an entire philosophy, complete with ontology, epistemology, and ethics, in a bumper-sticker slogan. It asserts an intimate relationship between two vastly different scales: macro, world-scale environmental and economic systems, on the one hand, and the micro sphere of individual choice and action, on the other. It extends an arrow of agency, comprehending macro effects as the results of vast aggregations of micro causes. Thus it locates the meaning of individual action in its relationship to the gigantic whole. Finally, it affirms that global change matters so deeply that it should occupy the intimate corners of everyday awareness and guide each person's every choice.

"Thinking globally" meant seeing the world as a knowable entity—a single, interconnected whole—but in a sense that lacked the secure stasis

Figure 1.1
Photograph of Earth taken from Apollo 8, December 1968.
Image courtesy NASA.

of maps, parlor globes, or pre-Darwinian cosmologies. Instead, it meant grasping the planet as a dynamic system: intricately interconnected, articulated, evolving, but ultimately fragile and vulnerable. Network, rather than hierarchy; complex, interlocking feedbacks, rather than central control; ecology, rather than resource: these are the watchwords of the new habit of mind that took Earth's image for its emblem.

Those photographs and that slogan conveyed all this, and more, not just because of what they said but also because of when they said it.[3] They fell directly into an overdetermined semiotic web prepared by (among other things) the post-World War II "One World" movement; the United Nations; the 1957–58 International Geophysical Year, with its scientific internationalism and powerful popular appeal; the Earth-orbiting satellites Sputnik, Telstar, and TIROS; the many variants of systems thinking descending from operations research, cybernetics, and early computer science; scientific ecology; and what I have called the "closed world discourse" of Cold War politics.[4] Long before the astronauts stared down in awe from outer space, notions of a "global Earth" had begun to emerge in language, ideology, technology, and practice.[5]

How did "the world" become a *system*? What made it possible to see local forces as elements of a planetary order, and the planetary order as directly relevant to the tiny scale of ordinary, individual human lives? How did the complex concepts and tools of global thinking become the common sense of an entire Western generation? How has systems thinking shaped, and been shaped by, the world-scale infrastructures that have emerged to support knowledge, communication, and commerce? How did global thinking become a bumper-sticker slogan? No book could ever resolve such huge questions completely. But by exploring one of today's most prominent objects of global knowledge and politics—global warming—in relation to the infrastructure that supports it, I hope to sketch at least the outlines of some answers.

Global Climate as an Object of Knowledge

If you really want to understand something, I tell my students, you have to ask an elemental question: *How do you know*? At first you may think you have answered that question when you have reviewed the evidence behind the claim. But if you keep asking the question long enough, you will begin to wonder where that evidence came from. If you are talking about a scientific problem, you will begin to care about things like instrument error, sampling techniques, statistical analysis. (*How* do you know?) And if you have the soul of a scientist—or a defense attorney—you will go further still. Who collected that evidence? Why did they see it as evidence, and where did they get the authority to say so? (How do *you* know?) Finally, you will begin to ask how evidence comes to count as evidence in the first place. How do communities interweave data, theories, and models, within their tapestries of culture and commitments, to make what we call knowledge? (How do you *know*?) When you have gone deep enough, you may surrender your Cartesian dreams of total certainty in favor of trust founded in history, reputation, and fully articulated reasoning. Or you may not. Whatever happens, you are going to have to look under the hood.

So how do we know that the world is getting warmer?

First, notice that to say that the global climate has *changed* implies that we know what it *used to be*. At a minimum, we are comparing the present with some period in the past. We would like to know the details, the trend over time. Since we are talking about climate, not weather, we need a long period, ideally 100 years or more. And since we are talking about *global* climate, we need some kind of picture of the whole planet—from the equator to the poles, across the continents, and over the oceans.

How do we get that? Experience isn't enough. No one lives in a "global" climate. Without scientific guidance, not even the most cosmopolitan traveler could perceive a global average temperature change of about +0.75°C, the amount we have seen so far. Extreme weather events—heat waves, hurricanes, droughts, floods—dominate human experience and memory, and they often create false impressions of average conditions. In the winter of 1981–82, the first year I lived in California, it rained in torrents all day, every day, for weeks. Huge mudslides ripped out mountain roads near my house. The San Lorenzo River overflowed, washing away whole neighborhoods. The next winter, I expected the same. It took me most of the decade to really understand that this wasn't normal.

Year to year, weather averages vary naturally. No extreme event or extreme season necessarily reflects a long-term climate change. Rising global average temperatures will not put an end to unusually cold winters, late-spring ice storms, or other episodes that seem to run against the trend. Further, the temperature change that worries us today is an average rise of 2.5–5°C (4.5–9°F) over the next 50–100 years. In terms of human experience, that is far less than the typical difference between daytime highs and nighttime lows in many parts of the world. Every year, the planet's temperate zones endure temperature changes of ten times this magnitude, as frigid winters in the –10°C range bloom into steamy +30°C summers. Thus we can't rely on experience alone.

Let us look for evidence, then. Data should be easy to get. Since the middle of the nineteenth century, meteorologists have been building a global information system of enormous scope and complexity. Each day, weather stations around the planet, on land and sea, generate hundreds of thousands of instrument readings. In addition, satellites, aircraft, radiosondes, and many other instrument platforms measure variables in the vertical dimension, from the surface to the atmosphere's outer edge. Figure 1.2 illustrates the present-day meteorological information system's three

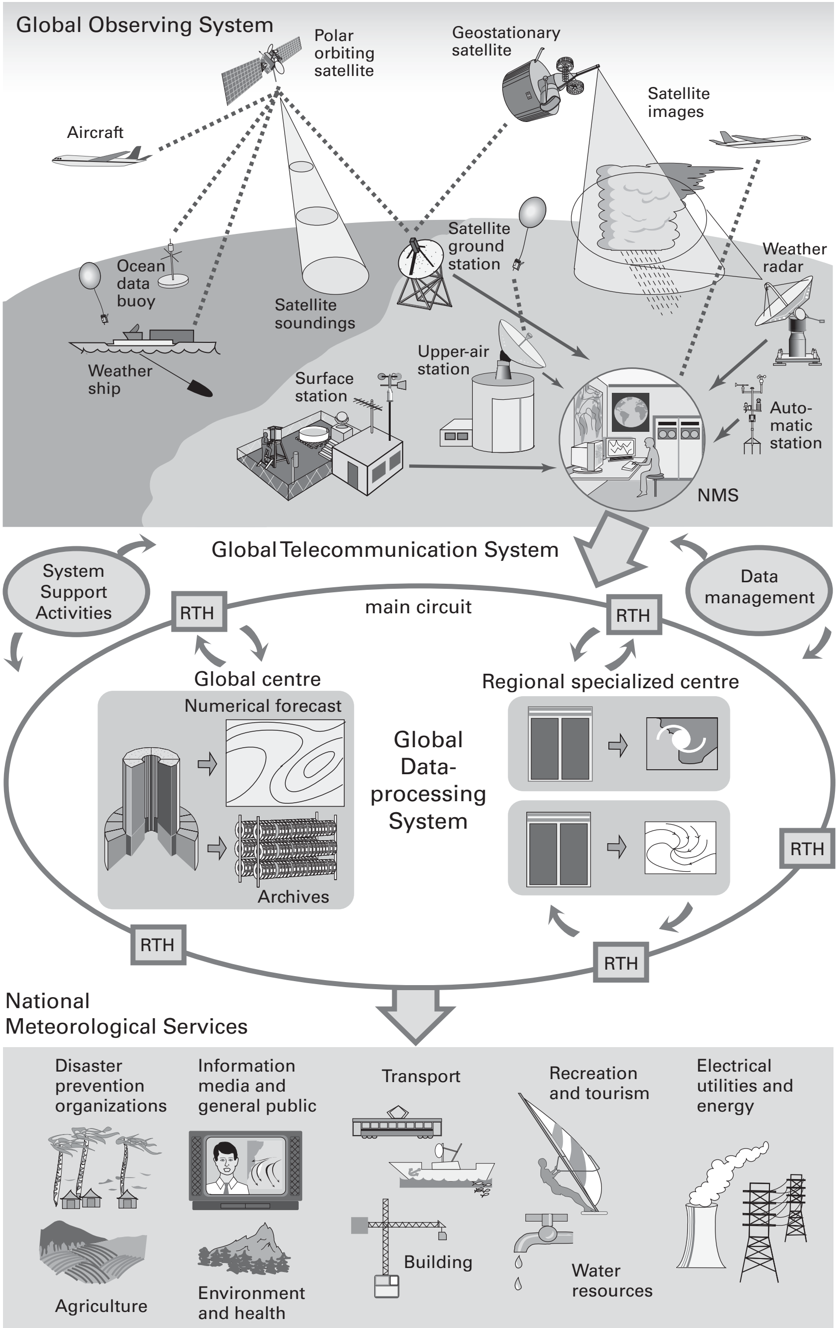

Figure 1.2

The global meteorological data, telecommunication, and forecast network as it looks today. RTH stands for regional telecommunications hub and NMS for national meteorological service.

Courtesy of World Meteorological Organization.

components: the Global Observing System, the Global Telecommunication System, and the Global Data Processing and Forecast System. Together they collect, process, and archive hundreds of terabytes[6] of weather and climate data each year.

With all those numbers, finding evidence of global warming should be simple enough. Collect all the thermometer readings for the world, arrange them by date, average them, graph the results, and *voilà*. But the simplicity of this recipe masks some very complicated problems. To begin with, over the last 160 years (the period of historical thermometer records) practically everything about the weather observing system has changed—often. Weather stations come and go. They move to new locations, or they move their instruments, or trees and buildings rise around them, or cities engulf their once rural environs. They get new instruments made by different manufacturers. Weather services change their observing hours and their ways of calculating monthly averages. These and dozens of other changes make today's data different not only from data collected 150 years ago, but also from data collected 20 years ago, or even (sometimes) last week. It's like trying to make a movie out of still photographs shot by millions of different photographers using thousands of different cameras. Can we reconcile the differences, at least well enough to create a coherent image? Yes, we can, scientists believe. But it isn't easy, and it is never finished.

If we go beyond ground-level air temperature to look for evidence of global climate change—including all the other elements that constitute the climate (sea surface temperatures, ocean currents, rainfall, snow, sea ice, etc.)—the data predicament created by constantly changing observing systems goes from very bad to even worse. And if you want to understand not only what is happening to the climate but also why it is happening, you have to parse out human influences (such as greenhouse-gas emissions), natural factors (such as volcanic eruptions and changing solar output), and random variability. To do this, you need a way to understand the whole system: where its energy comes from; where it goes; how it moves around in the atmosphere and oceans; how land surfaces, snow, and ice affect it; and many other things. We can do this too, with computerized climate models. But the models have their own difficulties, and they depend significantly (for their parameterizations) on observational data.

Thus assembling stable, reliable, long-term evidence of climate change is difficult indeed. Nonetheless, a consistent scientific consensus on climate change had developed by the early 1990s. Though some of the details have shifted since then, in general this consensus holds that some global warming has already occurred, and that human activities are responsible for a substantial part of it. A 2007 assessment by the Intergovernmental Panel on Climate Change (IPCC), the world's most authoritative climate knowledge institution, concluded that the planet warmed by about 0.75°C over the period 1906–2005. Models predict that we are in for much more warming (2–6°C) by 2100, depending on greenhouse-gas emissions, deforestation, and many other factors. Some of this future warming is already "committed," in this sense: even if all emissions of greenhouse gases were to cease tomorrow, warming would continue for several decades as the oceans come into equilibrium with the atmosphere. In 2007, the IPCC and former US Vice President Al Gore shared the Nobel Peace Prize for their work in creating knowledge and spreading awareness of the threat of global warming.

"Consensus" does not mean that all scientists agree on every detail, and noisy protests of even the most basic facts continue. Yet most scientists agree on the essential elements just mentioned. Their consensus has held for nearly 20 years now, and the message has sunk in. Today most people in developed countries believe that global warming is happening, and happening to them; they think it will directly affect their lives. Since the turn of the millennium, opinion surveys consistently show that Americans and Europeans believe that global warming is real, that human activity is its principal cause, and that press reports on the issue correctly reflect, or even underestimate, its dangers. Large majorities (four fifths) support the Kyoto Protocol.[7] Not only governments and environmental organizations, but also major insurance, energy, and automobile corporations have publicly accepted the reality of global warming and announced efforts to address it. Toward the end of the twentieth century, then, global warming became an established fact. This book is about how we came to know this fact and what it means to say that we know it.

This should not be the only book you ever read about global warming, because there are many things I do not cover. In particular, I focus only on atmospheric temperature and circulation. There are many other important lines of evidence for global warming, including paleoclimate studies, the rapid melting of glaciers and continental ice sheets, and ocean temperature and circulation. Spencer Weart's book and website *The Discovery of Global Warming* reviews much of this larger range of evidence from a historical perspective. For authoritative scientific treatments, turn first to the IPCC's assessment reports. If you are looking for responsible discussions more accessible to non-scientists, try Stephen Schneider's *Laboratory*

Earth, Sir John Houghton's *Global Warming: The Complete Briefing*, Andrew Dessler and Edward Parson's *The Science and Politics of Global Climate Change*, or Joseph DiMento and Pamela Doughman's *Climate Change: What It Means For Us, Our Children, and Our Grandchildren*.

A Vast Machine is also not really about scientific uncertainty, the uptake of science into politics, or public understanding of science. Studies of these topics now exist in large numbers, and there are a lot of very good ones, with more appearing almost daily.[8] Nor does it address the impacts of climate change, how to mitigate its effects, or how we can slow its progress, though all of these are, of course, matters of great importance.

Instead, what you are about to read is a *historical account* of *climate science as a global knowledge infrastructure*. Climate science systematically produces knowledge of climate. As Ruskin put it in 1839 (see my epigraph), it is "a vast machine": a sociotechnical system that collects data, models physical processes, tests theories, and ultimately generates a widely shared understanding of climate and climate change. This knowledge production begins with observations, but those are only raw materials. Transforming them into widely accepted knowledge requires complex activity involving scientific expertise, technological systems, political influence, economic interests, mass media, and cultural reception. Even the question of what counts as a valid observation in the first place requires considerable negotiation. This knowledge-production system delivers not only specifics about the past and likely future of Earth's climate, but also the very idea of a planetary climate as something that can be observed, understood, affected by human wastes, debated in political processes, cared about by the general public, and conceivably managed by deliberate interventions such as reforestation or gigantic Earth-orbiting sunshades. Ultimately, this knowledge infrastructure is the reason we can "think globally" about climatic change.

Dynamics of Infrastructure Development

To be modern is to live within and by means of infrastructures: basic systems and services that are reliable, standardized, and widely accessible, at least within a community. For us, infrastructures reside in a naturalized background, as ordinary and unremarkable as trees, daylight, and dirt. Our civilizations fundamentally depend on them, yet we notice them mainly when they fail. They are the connective tissues and the circulatory systems of modernity. By linking macro, meso, and micro scales of time, space, and social organization, they form the stable foundation of modern social worlds.[9]

Infrastructure thus exhibits the following features, neatly summarized by Susan Leigh Star and Karen Ruhleder:

• *Embeddedness*. Infrastructure is sunk into, inside of, other structures, social arrangements, and technologies.
• *Transparency*. Infrastructure does not have to be reinvented each time or assembled for each task, but invisibly supports those tasks.
• *Reach or scope* beyond a single event or a local practice.
• *Learned as part of membership*. The taken-for-grantedness of artifacts and organizational arrangements is a sine qua non of membership in a community of practice. Strangers and outsiders encounter infrastructure as a target object to be learned about. New participants acquire a naturalized familiarity with its objects as they become members.
• *Links with conventions of practice*. Infrastructure both shapes and is shaped by the conventions of a community of practice.
• *Embodiment of standards*. Infrastructure takes on transparency by plugging into other infrastructures and tools in a standardized fashion.
• *Built on an installed base*. Infrastructure wrestles with the inertia of the installed base and inherits strengths and limitations from that base.
• *Becomes visible upon breakdown*. The normally invisible quality of working infrastructure becomes visible when it breaks: the server is down, the bridge washes out, there is a power blackout.
• *Is fixed in modular increments, not all at once or globally*. Because infrastructure is big, layered, and complex, and because it means different things locally, it is never changed from above. Changes require time, negotiation, and adjustment with other aspects of the systems involved.[10]

Most entities typically classified as "infrastructure," such as railroads, electric power grids, highways, and telephone systems, are network technologies. They channel flows of goods, energy, information, communication, money, and so on. Many infrastructures are transnational, and a few have effectively gone global: for example, by 2008 there were over 4 billion mobile phone accounts and 1.3 billion fixed telephone lines, most of which could (in principle) call any of the others.[11]

In the 1980s and the 1990s, historians and sociologists of technology began studying the infrastructure phenomenon intensively. These researchers developed a "large technical systems" (LTS) approach to telephone, railroads, air traffic control, electric power, and many other major infrastructures.[12] Around the same time, some scholars began to identify infrastructure as a key analytic category.[13] The LTS school of thought generated new insights into questions of organizational, social, and historical change. Recently, investigators have applied this and related infrastructure-oriented approaches to urban development, European history, globalization, scientific "cyberinfrastructure," and Internet studies.[14]

Where do infrastructures come from? The LTS approach identified a series of common stages in infrastructure development:

- invention
- development and innovation
- technology transfer, growth, and competition
- consolidation
- splintering or fragmentation
- decline.

In the invention, development, and innovation phases, "system builders" create and promote linked sets of devices that fill a functional need. As elaborated by Thomas Parke Hughes, the paradigmatic LTS example of a system builder is Thomas Edison. Neither the light bulb nor electric power alone accounted for Edison's remarkable commercial success. Instead, Hughes argued, Edison conceived and delivered a lighting *system*, comprising DC generators, cables, and light bulbs. Establishing a new LTS such as Edison's demands more than technical ingenuity; it also requires organizational, economic, political, and legal innovation and effort in order to resolve the host of heterogeneous problems that inevitably arise. Finance capital, legal representation, and political and regulatory relationships become indispensable elements of the total system. Over time, the LTS becomes sociotechnical, rather than merely technological.[15]

Technology transfer to other locations (cities or nations) follows the initial system elaboration phase. Typically, developers respond to new local conditions by introducing variations in the system's original design.[16] Hughes, referring to the distinctive look and feel of the "same" LTS in differing local and national contexts, called this "technological style." In the growth phase, the system spreads quickly and opportunities for both profit and innovation peak. New players may create competing systems with dissimilar, incompatible properties (for example, DC vs. AC electric power, or the Windows operating system vs. Macintosh and Linux).

During consolidation, the quasi-final stage of LTS development, competition among technological systems and standards may be resolved by the victory of one over the others. More often, however, "gateway" technologies emerge that can join previously incompatible systems, allowing them to interoperate.[17] AC-DC power converters for consumer electronics and telephone adapters for international travel are examples, as are (in the world of information technology) platform-independent standards such as HTML and PDF. Gateways may be dedicated or improvised (that is, fitted specifically to a particular system), or they may be generic (standardized sockets opening one system to interconnection with others) or meta-generic or "modeled" (protocols for creating new generic standards, without restricting design in detail).[18]

Gateway technologies and standards spark the formation of networks. Using gateways, homogeneous and often geographically local systems can be linked to form heterogeneous networks in which top-down control is replaced by distributed coordination processes. The shift from homogeneous systems to heterogeneous networks greatly increases flexibility and creates numerous opportunities for innovation. In a later phase, new gateways may connect heterogeneous networks to one another (as in the Internet, a network of networks whose principal gateway technologies are packet switching and the TCP/IP protocol suite). Container shipping (which joins road, rail, and shipping networks) and the linkage of cellular with land-line telephony are examples of internetworks in other domains. Gateways need not be, and often are not, technological. For example, far more important than hardware in linking global financial markets into a single infrastructure were institutional, legal, and political gateways that permitted trans-border stock trading, currency exchange, and so on.

No system or network can ever fulfill all the requirements users may have. Systems work well because of their limited scope, their relative coherence, and their centralized control. System builders try to expand by simply increasing their systems' scale to reach more potential users, thereby excluding competitors. On the other hand, though users appreciate greater scale, they also want greater scope as well as custom functionality. Therefore, they continually cast about for ways to link incompatible systems and networks. Gateway developers (who may be users themselves) try to find ways to automate these links. When they succeed, gateway innovations and shared standards create *networks* or, at a higher level, *webs* (networks of networks, or internetworks). From the user's viewpoint, a network or a web links stand-alone systems (or networks), providing greater functionality. This was the case with the World Wide Web, which began as a protocol for exchange of hypertext documents but rapidly subsumed numerous pre-existing Internet file sharing mechanisms, including ftp, gopher, and nntp. From the operator's viewpoint, networks or webs shift the focus from control to coordination with the systems or networks on the other side of the gateway. The formation of a network or a web usually benefits users, but it can have unpredictable effects on the owners and operators of underlying systems.[19] The standardization process is a rocky road—even in information technology, where it is often easier than in other domains.[20]

To sum up: System builders seek to find or create well-defined niches that can be served by centrally designed and controlled systems, but users' goals typically include functions that may be best served (for them) by linking separate systems. The fundamental dynamic of infrastructure development can thus be described as a perpetual oscillation between the desire for smooth, system-like behavior and the need to combine capabilities no single system can yet provide. For these reasons, in general *infrastructures are not systems* but networks or webs.[21] This means that, although infrastructures can be coordinated or regulated to some degree, it is difficult or impossible to design or manage them, in the sense of imposing (from above) a single vision, practice, or plan.

Infrastructure formation is never tension-free. Emerging infrastructures invariably create winners and losers. If they are really infrastructures, they eventually make older ways of life extremely difficult to maintain: think of family farms against industrial agriculture, or newspapers against the Internet. Every choice involves tradeoffs and consequences. Infrastructures have victims and "orphans" (people and groups who are unable to use them or to reap their benefits because of their circumstances)—for example, people with rare diseases ignored by pharmaceutical research, blind people unable to navigate graphics-based websites, and the 5 billion people still without access to the Internet.

Even in meteorology, a field in which it is hard to discern many victims, one can find tensions that have real human consequences. When I visited the National Severe Storms Center in Norman, Oklahoma, a few years back, the director could barely contain his bitterness. His research budget had barely held steady even as budgets for climate-change research skyrocketed. From his point of view, advancing tornado or hurricane warnings by even a few hours could save thousands of lives and prevent millions of dollars' worth of property destruction. But the money he needed to improve his prediction models was drained by long-term climate research. Every stage of infrastructure development is marked by struggle.[22]

Weather and Climate Information Infrastructures

The world weather and climate information infrastructure, described briefly above (and much more extensively throughout this book), exhibits all the classic features of this well-established development pattern.

National weather services inaugurated a system building phase, based on then-new telegraphy, in the latter half of the nineteenth century. With rapid technology transfer and growth, each national weather service created its own technological style, including various systems and standards for data collection and forecasting. Attempts at consolidation began as early as the 1870s, when some meteorologists sought to create a formal international network. They established the International Meteorological Organization (IMO) to negotiate technical standards and promote network development. By 1900, a Réseau Mondial (worldwide network) for real-time weather data exchange via telegraph had been proposed. For decades, however, consolidation remained elusive.

As both system builders and network users, the national weather services experienced conflicting pressures. Answerable to their governments, their highest priority lay in improving national systems and services. Yet as forecasting techniques improved, most nations needed data from beyond their own borders. So coordinating with other nations was in their interest. On the other hand, getting dozens of weather services to agree on and conform to common standards and techniques often cost more in time, money, and annoyance than it seemed to be worth. The tension between sovereign national systems and voluntary international standards severely limited the IMO's potential, and two world wars did nothing to improve the situation. Meanwhile, in the first half of the twentieth century the telegraph-based weather data network rapidly morphed into an tremendously complicated web, integrating both new instruments (such as radiosondes) and new communications media (such as telex and shortwave radio) through a proliferation of improvised gateways. During that period, most data network development was driven by the internal system-building dynamics of national weather services. International data networks remained a secondary priority. IMO standards acted as guidelines, routinely violated but nevertheless producing considerable convergence. As predicted by the LTS model, this phase of technology transfer and growth resulted in numerous different systems, some linked and others not, all governed by a loose patchwork of conflicting national, regional, and international standards. By the 1920s, the klugey pre-World War II network made worldwide data *available* to forecasters almost in real time. But forecasters' ability to use those data remained limited, in part because of the extreme difficulty of sorting out the numerous formats and standards used by various national weather services.

A consolidation phase began around 1955 and lasted for several decades. On the technical side, consolidation was driven by the arrival of computer models for weather forecasting, first used operationally in 1954. Instantly perceived as a superior technique despite early weaknesses, computer modeling brought with it a voracious appetite for data. Weather forecasters adopted computer modeling immediately. Starting out with regional models, they switched to hemispheric models by the early 1960s and global models by that decade's end. As scales grew, these models needed increasingly heroic quantities of data, demanding huge new efforts in standardization, communication systems, and automation. These developments required not only technological but also institutional innovation. The World Meteorological Organization (WMO), founded in 1950 on a base laid by the International Meteorological Organization, gained new authority for standards as an intergovernmental agency of the United Nations. In the 1960s the WMO directed its principal energies toward systems, standards, and institutional mechanisms for the World Weather Watch (WWW), which became operational in the late 1960s.

World Weather Watch planners wisely adopted a network perspective, promoting more unified development within the existing framework of linked national weather services—a web of institutions. The weather information infrastructure is also a web of instrument networks. Weather satellites—capable of observing the entire planet with a single instrument—began to realize the ideal of a fully global observing system. Satellite data sharing and the WWW concept grew directly out of Cold War politics, promoted as a counterweight to military and ideological tensions. Satellites and radiosondes, especially, generate data that differ dramatically in form from data generated by traditional surface stations. In the long run, numerous gateways—primarily in the form of software—made it possible to reconcile disparate forms of data from the many different platforms. Today weather forecast models and data assimilation models serve as the ultimate data gateways, relating each kind of data to every other one through modeled physics, rather than simply correlating unconstrained measurements in space and time. (See chapter 10 for a fuller explanation.)

The networking of national *climate* observing systems into a global climate information infrastructure took much longer. Weather data systems are built for real-time forecasting. Their priority is speed, not precision, and they absorb new instrumentation, standards, and models quite quickly. In contrast, climatology requires high precision and long-term stability—almost the opposite of the rapidly changing weather observing system—as well as certain kinds of data that weather forecasters do not collect. From the nineteenth century on, climate data networks overlapped with weather networks, but also included their own, separate observing systems, such as the US Historical Climatology Network. Central collectors established rudimentary *global* climate data networks in the late nineteenth century. These gained durability in the early twentieth century in the Réseau Mondial and the Smithsonian Institution's *World Weather Records*, which formed the primary basis of most knowledge of global climate until the 1980s.

Meanwhile, climate modeling developed along lines parallel to weather forecasting, but over a longer period. Because they must simulate decades rather than days while remaining realistic, three-dimensional global climate models remained essentially research tools until the late 1970s. They first gained a foothold as predictive tools around 1970 during the controversy over the supersonic transport, but full acceptance did not come until they achieved a rough consensus on greenhouse warming predictions in the late 1970s.

Under the spur of global warming concerns, national climate observing systems finally begin to consolidate into a global internetwork. The WMO initiated a World Climate Programme in 1980 (after the first World Climate Conference, held in 1979), but full consolidation at the technical level did not really begin until 1992, when the Global Climate Observing System (GCOS) was established in support of the Framework Convention on Climate Change. Today GCOS remains, in the eyes of climatologists, at best an incomplete skeleton for what may one day become a fully adequate climate observing network.[23] Very recently, increasing demands from many quarters for reliable climate forecasts have led US agencies to begin discussions on changing the orientation of the climate observing system from a research orientation to an operational—in my terms, infrastructural—one.

Yet while we can consolidate the climate observing system further as time goes on, making sense of the data we already have presents a different, very special issue of consolidation. We are stuck with whatever data we have already collected, in whatever form, from whatever sources with whatever limitations they might have. We have to consolidate a global climate observing network not only prospectively but *retrospectively*, reassembling the motley collection of weather and climate records and reprocessing them *as if* they all existed only to help us in this moment. Since the 1980s, through a meticulous process of infrastructural inversion (see below), scientists have slowly and painfully consolidated these data, unearthing previously uncollected records and metadata (contextual information) and using them to create more comprehensive global datasets, to reduce inhomogeneities, and to render highly heterogeneous data sources into a common form.

The most ambitious version of this consolidation, known as "reanalysis," also represents a consolidation of the weather and climate information infrastructures. In reanalysis, past weather records (not climate data) are run through complex data assimilation models—originally designed for weather forecasting—to produce a single, uniform global data set for 50 years or more. Traditional climate data consist mostly of averages for single variables (temperature, precipitation, etc.) over periods of a month or more. Reanalysis produces a much different kind of data: all-variable, physically consistent data sets containing information for millions of gridpoints every six hours. Although biases in the models prevent them from displacing traditional climate data, climate statistics calculated from reanalysis data can reveal "fingerprints" of climate change not detectable in traditional data.

A final aspect of consolidation in the climate data infrastructure is the Intergovernmental Panel on Climate Change, founded in 1988 to provide periodic assessments of climate knowledge for parties to the UN Framework Convention on Climate Change, who now include almost every country in the world. The IPCC conducts no research of its own. Yet it represents the most important institutional innovation in the history of climate science. The periodic assessments demand regular comparisons of climate models and of all the various climate datasets. Not only does this process reveal weaknesses in both models and data; it also creates a mechanism for surfacing, reviewing, and merging (wherever possible) every element of climate knowledge. Their very title, Synthesis Reports, represents their consolidating role. The ongoing cycles of IPCC assessment also promote increased coupling across domains as diverse as oceanography, ecology, agriculture, and demography. Today the practical outcomes of this coupling are typically suites of linked computer models, such as Earth system models and integrated assessment models, that combine the knowledge and techniques of many disciplines in a single, many-faceted simulation.

An LTS-based analysis, then, helps us to periodize the history of global meteorological networks as technical systems. It also directs us to attend closely to the political, legal, economic, and institutional dimensions of network formation. To understand global warming as an object of knowledge, however, we need more than this. We want to know not just how weather and climate data get moved around—like conversations in the telephone system or electric power through transmission lines—but also how they get created in the first place, how they are transformed into intelligible and reliable information, and, most important, how that information becomes knowledge.

Knowledge Infrastructures

If we see objects of knowledge as communal, historical products, we can readily extend the concept of infrastructure we have just discussed. The LTS approach to infrastructure always began with a technology base. Yet it also invariably found that to explain a technical system's development one had to understand its social elements—hence its cornerstone phrase, "*socio*technical systems."

If we take this notion seriously, it applies directly to knowledge. Instead of thinking about knowledge as pure facts, theories, and ideas—mental things carried around in people's heads, or written down in textbooks—an infrastructure perspective views knowledge as an enduring, widely shared sociotechnical system. Here is a definition: *Knowledge infrastructures comprise robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds*.

Consider how we produce the specific type of knowledge we call science.[24] If you want to be a scientist, you probably are going to need some technological items, such as instruments and computers. If you are going to share what you learn, you will want the Internet, or at least the telegraph (postal mail, in a pinch). By themselves, however, such tools and media will only get you started. Once you have a result, you still need to convince people that it is true, useful, and consistent with other things they already know. To do that, you need authority and trust. Those can come only from being connected—in both a present-tense sense and a historical sense—with a community that understands what you have found and what you think it means. Thus, if you want to create and maintain scientific *knowledge*, you are also going to need at least the following:

- enduring communities with shared standards, norms, and values
- enduring organizations and institutions, such as libraries, academic departments, national science foundations, and publishers
- mathematics
- specialized vocabularies
- conventions and laws regarding intellectual property
- theories, frameworks, and models
- physical facilities such as classrooms, laboratories, and offices
- "support" staff: computer operators, technicians, secretaries

Let me elaborate this a bit further. Science emanates from a set of respected institutions, including university departments, research laboratories, national academies, and professional organizations. These institutions evolve and sometimes fail, but many of them have endured over long periods of time (decades or even centuries). In addition to instruments, computers, libraries, and so on, these institutions rely on suites of well-accepted models and theories. They generate specialized vocabularies and mathematical techniques, which all practitioners must learn. Professional training in science is long and demanding. It teaches would-be scientists to think according to prevailing standards of logic, to interpret and judge evidence according to disciplinary norms, to use and trust particular instruments and research methods (and reject others), to design experiments around well-established (often community-specific) principles, and to communicate with others according to certain kinds of protocols and conventions. Those who cannot master these practices cannot receive crucial credentials (typically a PhD degree).

Scientific knowledge is transmitted through a variety of material and human forms—journals, conferences, websites, students, postdoctoral fellows, and professional organizations, among others. Only some of this communication is ever condensed into formal publications. Libraries and online depositories store and provide access not only to published results but also (increasingly) to raw data, preprints, and other intermediate products of scientific investigation; this storage and maintenance activity represents a major commitment of human and financial resources. To keep the whole thing going, large institutions such as national science foundations transfer money from taxpayers to researchers. Along the way, they impose numerous practices and policies regarding peer review, ethical behavior, data sharing, credentialing, and so on. Vast legal structures govern and enforce intellectual property rights, informed consent for human subjects, and other forms of scientific integrity.

The infrastructural quality of this edifice appears vividly in the daily routines of scientific work. Consider writing grant applications, posting a new result to an Internet preprint site, keeping track of recent journal articles via Internet connection to a library, attending professional meetings, manipulating experimental data with computerized statistics packages or modeling software, getting one's laptop repaired by a local technician, and teaching a class how to use a simple model. Each of these activities both relies upon and helps reproduce the knowledge infrastructure. That infrastructure is a production, communication, storage, and maintenance web with both social and technical dimensions. Instruments, disk drives, and Internet links blend seamlessly with thinking, talking, and writing. Journals and websites mirror community life. The complex forms required for grant proposals reflect the routines of funding organizations and act as gatekeepers to reduce the number of proposals. Computer software embodies theories and facts. All the features of infrastructure discussed above appear here: embedded in everyday life, transparent to users, wide reach and scope, learned as part of membership, linked with conventions of practice, built on an installed base, and so on.

I intend the notion of knowledge infrastructure to signal parallels with other infrastructures, such as those of communication, transport, and energy distribution. Yet this is no mere analogy or metaphor. It is a precise, literal description of the sociotechnical supports that invariably undergird facts and well-accepted theories.

Get rid of the infrastructure and you are left with claims you can't back up, facts you can't verify, comprehension you can't share, and data you can't trust. Without the infrastructure, knowledge can decay or even disappear. Build up a knowledge infrastructure, maintain it well, and you get stable, reliable, widely shared understanding. The concept of knowledge infrastructure resembles the venerable notion of scientific paradigms, but it reaches well beyond that, capturing the continuity of modern science, which keeps on functioning as a production system even while particular theories, instruments, and models rise and fall within it.[25] This is not an entirely new idea in science and technology studies, where scholars sometimes use the word 'technoscience' to capture the technological dimension of science as a knowledge practice. Ethnographic studies of laboratories and "epistemic cultures" have looked at science as a production system characterized by "inscription devices," document flows, and other material-technical features.[26] I prefer the language of infrastructure, because it brings home fundamental qualities of endurance, reliability, and the taken-for-grantedness of a technical and institutional base supporting everyday work and action.

Further, and perhaps most important, the idea of infrastructure captures the notion of extensibility. Climate knowledge once came from a few relatively uniform and similar scientific disciplines, but that has not been true for decades. Since the 1960s the climate knowledge infrastructure has been extending itself by building gateways linking different fields. Computer models are its most important technical gateways; since the 1960s modelers have progressively linked models of the atmosphere to models of the oceans, the cryosphere, the biosphere, and human activities. Since the late 1980s, the primary institutional gateway joining disparate elements of the climate knowledge infrastructure has been the Intergovernmental Panel on Climate Change, whose regular cycles of comparison, assessment, and integration link numerous scientific fields in a common knowledge project.

Infrastructural Inversion

To understand an infrastructure, you have to invert it. You turn it upside down and look at the "bottom"—the parts you don't normally think about precisely because they have become standard, routine, transparent, invisible. These disappearing elements are only figuratively "below" the surface, of course; in fact they *are* the surface. But as with anything that is always present, we stop seeing them after a while.[27]

This book is going to invert the climate knowledge infrastructure for you, but scientists themselves do it often. Infrastructural inversion is, in fact, fundamental to how scientists handle data. Climate scientists put it this way:

> For long-term climate analyses—particularly climate change analyses—to be accurate, the climate data used must be *homogeneous*. A homogeneous climate time series is defined as one where variations *are caused only by variations in weather and climate*. Unfortunately, most long-term climatological time series have been affected by a number of non-climatic factors that make these data unrepresentative of the actual climate variation occurring over time. These factors include changes in: instruments, observing practices, station locations, formulae used to calculate means, and station environment.[28]

In other words, data aren't data until you have turned the infrastructure upside down to find out how it works. Other "non-climatic factors" in historical data stem from garbled communication, coding errors, and other noise. To decide whether you are seeing homogeneous data or "non-climatic factors," you need to examine the history of the infrastructure station by station, year by year, and data point by data point, all in the context of changing standards, institutions, and communication techniques.

That history, as I intimated earlier, has been deeply problematic for climatology. By the early twentieth century, weather forecasting and climatology had diverged. Most national weather services, focused on providing short-term forecasts, paid scant attention to the observational needs of climatology. New observing stations often did not measure important climatological variables, such as precipitation. Meanwhile, existing stations changed location, replaced old instruments with new ones of a different type, disappeared, or saw their originally rural settings slowly transformed into (warmer) urban ones. These changes and many more affected the continuity, stability, and quality of their data records. As a result, only about one fourth of stations in the US Cooperative Observer Network meet the US Historical Climatology Network's standard that a station have provided "at least 80 years of high-quality data in a stable environment."[29]

Since the 1950s, standardization and automation have helped to reduce the effect of "non-climatic factors" on data collection, and modeling techniques have allowed climatologists to generate relatively homogeneous data sets from heterogeneous sources.[30] But it is impossible to eliminate confounding factors completely. Indeed, since the late 1990s the temporal and spatial consistency of surface weather data has been undermined by technological changes and by a reduction in the number of surface stations and ocean platforms.[31] Such an infrastructural change produces not only quantitative but also qualitative effects. For example, today's climate information system collects much more information than was collected in the past. Surface data for (say) 1890–1900 were produced by a much smaller, much less well-distributed station network than data for (say) 1990–2000. In addition, however, today's data network collects new *kinds* of data, including measurements from radiosondes (weather balloons) and satellite radiometers, which monitor the atmosphere's vertical dimension. Among other things, this means that no 1890–1900 time series will have any data at all from high above the ground, whereas a 1990–2000 series might have much more data from the upper air than from the surface. As we will see, climate scientists have found numerous ingenious ways to confirm, correct, combine, and reject data. Yet these methods, too, have evolved. With each iteration in the cycle of reexamination, correction, and analysis, *the climate data record changes*. As a result, we have not one data image of the planetary climate, but many—very many.

How can this be? Aren't data supposed to be the stable cornerstone of the entire edifice of knowledge? In the strange and wonderful world of computational meteorology, the answer can, in fact, be "not quite." In modern weather forecasting, for example, only about ten percent of the data used by global weather prediction models originate in actual instrument readings. The remaining ninety percent are synthesized by another computer model: the analysis or "4-dimensional data assimilation" model, which creates values for all the points on a high-resolution, three-dimensional global grid. This isn't as crazy as it sounds. Put very simply, the analysis model starts with the previous weather forecast, then corrects that forecast with current observations, producing values for every gridpoint. At the same time, the analysis model checks the observations for errors and inconsistencies, rejecting some observations and modifying others. Thus the raw readings from the observing system constrain, *but never fully determine,* the data that serve as forecast inputs. In empirical tests, these synthetic data sets produce far better weather forecasts than could be achieved using observations alone.[32]

This strange situation raised hopes among climatologists for a technique known as "reanalysis." Analyzed weather data aren't of much use to climatologists because forecasters frequently revise their analysis models (as often as every six months in some cases). Each change in the analysis model renders the data it produces incommensurable with those produced by the previous model. Reanalysis eliminates this problem by using a single "frozen" model to analyze historical observational data over some long period (40–50 years or even more). Because analysis models are built to combine readings from all available observing systems, reanalysis also overcomes the otherwise thorny problem of comparing instruments such as radiosondes and satellite radiometers. The result is a physically self-consistent global data set for the entire reanalysis period. Potentially, this synthetic data set would be more accurate than any individual observing system.[33]

Reanalysis would deal in one fell swoop with many of the data inconsistencies caused by infrastructural change. Yet climatologists currently regard reanalysis data sets as problematic for climate trend studies. Biases in the analysis models—too small to matter in forecasting—accumulate to produce significant errors when applied over the long periods needed to track climatic change. Nonetheless, some scientists hope that reanalysis will eventually generate definitive data sets, useable for climate trend analysis, that will be better than raw observational records. For the moment, however, they are stuck with infrastructural inversion—that is, with probing every detail of every record, linking changes in the data record to social and technical changes in the infrastructure that created it, and revising past data to bring them into line with present standards and systems.

Inverting the weather and climate knowledge infrastructures and tracing their history reveal profound relationships, interdependencies, and conflicts among their scientific, technological, social, and political elements. Over time, as knowledge production becomes infrastructural, these relationships become increasingly invisible, even as they continue to evolve. The difference between controversial claims and settled knowledge often lies in the degree to which the production process is submerged. Thus, *an established fact is one supported by an infrastructure.* In the rest of this book, I explore the meaning and implications of this claim for knowledge about weather, climate, and global warming.

Meteorology as Infrastructural Globalism

Clearly what I am talking about belongs with the larger phenomenon of globalization, a subject that has consumed scholarship, historiography, and political discourse in recent years. Is globalization old or new, a long slow trend or a sharp discontinuity? What are its causes and its consequences? Was the Age of Empire more "global" than the present? Does globalization really link the whole world, or does it disconnect and disenfranchise the poorest people and their nations? No one who has followed these debates can fail to notice the prominence of information and communication technologies in virtually all accounts. Marshall McLuhan long ago described the "global village," the shrinkage of space and time through printing, literacy, and mass media.[34] More recently, Manuel Castells defined the global economy as one "whose core components have the institutional, organizational, and technological capacity to work *as a unit in real time, or chosen time, on a planetary scale*" through information and communication infrastructures.[35] Every chapter in a recent survey of the literatures on political, economic, and cultural globalization systematically addressed the role of communication infrastructures.[36] Similar examples could be multiplied ad infinitum.

In an important variation on this theme, Martin Hewson proposed a notion of "informational globalism." The concept refers simultaneously to systems and institutions for transmitting information around the world, and to systems and institutions for creating information about the world as a whole.[37] Hewson sees informational globalism as developing in three phases. First, during the nineteenth century, national information infrastructures such as telegraph systems, postal services, and journalism were linked into interregional and intercontinental (if not fully global) networks. Between 1914 and 1960 (Hewson's second phase), the pace of infrastructural linking diminished, and some delinking occurred. Yet simultaneously, world organizations such as the League of Nations and the International Monetary Fund "established the legitimacy of producing globalist information"—that is, information about the whole world—in such areas as health, armaments, and public finance (although they did not yet achieve that goal). Hewson's third phase brought generalized attainment of the two previous eras' aspirations, beginning with worldwide civil communication networks (from the 1967 inauguration of the Intelsat system) and global environmental monitoring (from the UN Conference on the Human Environment, 1972). Hewson sees global governance institutions such as the United Nations and the International Telecommunications Union, rather than an autonomous technological juggernaut, as chiefly responsible for the rise of informational globalism.

The story this book tells confirms the pattern Hewson discerned, but it also has special characteristics. The weather data network, along with its cousins in the other geophysical sciences, especially seismology and oceanography, is arguably the oldest of all systems for producing globalist information in Hewson's sense. When Ruskin wrote, in 1839, that meteorology "desires to have at its command, at stated periods, perfect systems of methodical and simultaneous observations . . . to know, at any given instant, the state of the atmosphere on every point on its surface," he was only giving voice to his contemporaries' grandest vision. By 1853 the Brussels Convention on naval meteorology had created a international standard meteorological logbook for ships at sea; these logs now constitute the oldest continuous quasi-global meteorological record. The International Meteorological Organization, despite its endemic weakness, represents an early international governance institution, while the Réseau Mondial and its successors reflected the ambition to build a global weather information infrastructure.

By 1950 the informational-globalist imperative was already far stronger in meteorology than in many other putatively "global" systems that emerged around the same time. Though rudimentary, a planetary monitoring network had been functioning for decades, and had gained speed and scope in the 1920s with the arrival of shortwave radio, which untethered the data network from telegraph cables. Computerized weather forecast models, operational in 1955, covered continental and (soon) hemispheric scales, displaying an insatiable thirst for data from every corner of the world. By the early 1960s, satellites brought the once unthinkable realization of the God's-eye view: the ability to observe the entire planet with a single instrument. Unifying the existing global observing system, improving the communication network, and preparing meteorology for satellite data became the World Meteorological Organization's fundamental goals in its World Weather Watch program. Simultaneously, as a global governance institution operating within the UN system, the WMO actualized a new commitment by governments throughout the world to link their weather services through shared investment in a worldwide weather network. Intergovernmental status meant national government involvement, bringing the political dimensions of weather science into the open.

I contend that the history of meteorology from the 1850s to the present illustrates a profoundly important, albeit messy and incomplete transition: from voluntarist internationalism, based on an often temporary confluence of shared *interests*, to quasi-obligatory globalism based on more permanent shared *infrastructure*. Therefore, I will speak not only of informational globalism but also of *infrastructural globalism*: projects for permanent, unified, world-scale institutional-technological complexes that generate globalist information not merely by accident, as a byproduct of other goals, but by design.[38] Enduring, reliable global infrastructures build scientific, social, and political legitimacy for the globalist information they produce. Meteorology as infrastructural globalism sought to establish permanent sociotechnical systems for monitoring the weather, modeling its processes, and preserving planetary data as scientific memory.[39]

Infrastructural globalism is about creating sociotechnical systems that produce knowledge about the whole world. It may be driven by beliefs about what such knowledge can offer to science or to society, but it is not principally an ideology. Instead it is a *project*: a structured, goal-directed, long-term practice to build a world-spanning network, always including a worldwide epistemic community as well as a technical base.[40] If such a project succeeds, it creates an infrastructure that endures far beyond individual careers, social movements, or political trends. This endurance itself legitimizes the knowledge it produces, and becomes self-perpetuating.

Such projects were never, of course, unique to meteorology. The other geophysical sciences (seismology, oceanography, etc.), the epidemiology of infectious diseases, financial markets, and the American and Soviet intelligence agencies of the Cold War era exemplify other disciplines and organizations that built infrastructures for generating globalist information. They too built monitoring and communication networks, created models of large-scale system behavior, and kept long-term records for the purpose of identifying global trends. Few, however, had either meteorology's need to engage the entire planet, or its great age.

2 Global Space, Universal Time: Seeing the Planetary Atmosphere

Today we see world maps almost everywhere we go. Backdrops to the nightly news, they appear transparent, obvious, unmediated. We seem to grasp their God's-eye view intuitively, without thought. GPS receivers in our phones and our cars pinpoint us precisely on the global grid. In all their incarnations, from Mercator projections to parlor globes to interactive GPS, maps are information technologies of the first order. They are "objects to think with," in Sherry Turkle's felicitous phrase.[1]

Behind the seeming immediacy of global maps and images lie vast bodies of complex and expensive collective and collaborative work and social learning accomplished over many centuries. This labor and this learning included not only invention, exploration, and surveying but also the slow spread, through practical use and formal education, of the graphical conventions, iconography, and social meaning of global maps. Projections of Earth's spherical surface onto a rectangular page, systems of latitude and longitude, the North Pole as the world's "top," ways of depicting geographical features—these conventions and many more evolved and spread along with Western empires. While learning to "see" the whole world with maps, people also imagined traveling its farthest reaches, flying high above its surface, or peering down on it from space long before they could actually do so.[2] World maps undergird our ability to conceive global space. They are an infrastructural technology, a principal material support for "thinking globally."

Like other cartographic concepts, the idea of mapping weather data took centuries to develop. Graphical conventions for showing weather relationships in space emerged many decades after the first international weather data networks. Drawings illustrating the global circulation—the prevailing structure of atmospheric motion—appeared rather suddenly in the middle of the nineteenth century. From then on, graphical representations of weather, climate, and global circulation became core technologies of the emerging climate knowledge infrastructure.

Universal time is basic to the texture of modern life. Seconds before your morning alarm goes off, you awaken to an inner clock nearly as accurate as the one beside your bed: you have internalized the infrastructure. Your world runs on time, in both senses. Like the latitude-longitude grid, today's universal time is a widely shared convention that exists in and through technology (watches, clocks), political decisions (adopting a national standard time, the Greenwich prime meridian), commercial interests (railroads, airlines), and social practices (the different meanings of "on time" in Switzerland, Brazil, and South Africa). We constantly re-create and reaffirm the infrastructure of universal time simply by using it, whenever somebody, somewhere, checks her watch to keep an appointment or catch a train.

Yet for most of human history, the only time that really mattered was the one marked by the sun. In medieval Europe, one daytime "hour" equaled one-twelfth of the time between sunup and sunset: accordion-like, hours shrank in the winter and expanded in the summer.[3] Mechanical clocks fixed the length of the hour, but "noon" still meant the moment when the sun crossed the zenith wherever you were. The present system of universal time, where "noon" is kept by the clock within a broad zone running (mostly) along lines of longitude from pole to pole, was not even conceived until the late nineteenth century. It did not become a worldwide infrastructure until the second half of the twentieth. The momentous change from a plethora of local times to a single universal time began when one emerging infrastructure, the telegraph, made it possible to synchronize clocks across large distances, while another, the railroad, made that synchronization necessary.

Similarly, modern meteorology arose when new infrastructures, including a potent combination of widely shared mapping conventions, telegraphic data transmission, and new time standards, made it possible to create data images of the atmosphere in motion—permitting wide-area forecasting for the first time. Because this capability resonated with national military and commercial interests, it led quickly to the formation of national weather services and telegraph-based international data networks. This chapter examines the origins of these elements of the weather and climate knowledge infrastructure.

Global Space

Eratosthenes (third century BCE), Ptolemy (second century CE), and other ancient astronomer-geographers deduced Earth's spherical shape and accurately estimated its circumference. They also devised latitude-and-longitude systems and mapped the lands they were aware of according to those coordinates. Ptolemy's famous map of his known world covered about 80 degrees of latitude, from the equator to the Arctic, and 180 degrees of longitude, from China to the Canary Islands.[4]

The ancients tied their ideas of climate directly to their conceptions of global space. The English word 'climate' derives from the Greek word *klima*, which is also the root of 'inclination'. *Klima* means "sloping surface of the earth," linking climate to latitude, which governs the inclination of the sun's rays. Ptolemy based his system of fifteen climatic zones on the lengths of their longest day—a quantity that also served him to express latitude, taking the place of degrees.[5] Then, and in succeeding centuries, many natural histories began with descriptions of local and regional climates. Even today, common language terms such as 'tropical', 'desert', and 'temperate' refer interchangeably to geographic regions and their typical weather patterns. Often these are directly associated with latitude (e.g., "the tropics").

In 1686, the British astronomer Edmond Halley published one of the first theories to go beyond the Ptolemaic view of climate as a simple function of latitude. Halley sought to understand the physics of the trade winds, which blow from the northeast in the northern hemisphere and from the southeast in the southern. He proposed a planetary-scale, three-dimensional explanation. "Having had the opportunity of conversing with Navigators acquainted with all parts of India, and having lived a considerable time between the Tropicks, and there made [his] own remarks," Halley theorized that solar heating caused air to rise near the equator.[6] This "rareified" air caused denser air from higher latitudes to "rush in," creating the trade winds.

Halley had identified a fundamental mechanism of weather: the movement of heat from the equator toward the poles. Scientists today still use Halley's term 'circulation' to describe global patterns of air movement, and still use his notion that the atmosphere must "preserve the Æquilibrium." Standard texts cite Halley as the originator of these ideas, but Halley's own discussion makes clear that even earlier work by the geographer Bernhard Varen and by "several" unnamed others sparked his thinking.[7] Halley

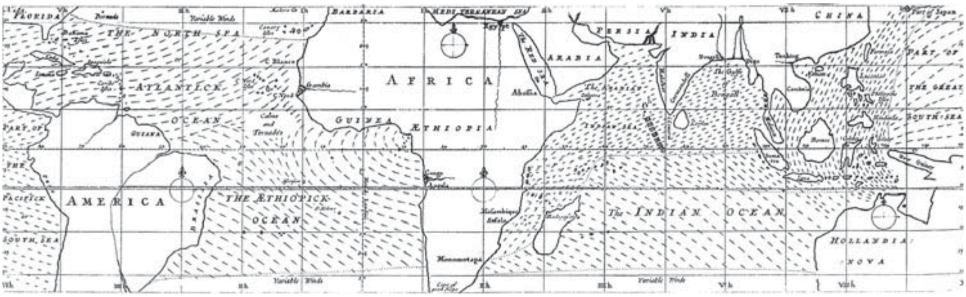

Figure 2.1

Halley's 1686 map of the trade winds in the Atlantic and Indian Oceans.

Source: E. Halley, "An Historical Account of the Trade Winds, and Monsoons, Observable in the Seas Between and Near the Tropicks, With an Attempt to Assign the Phisical Cause of the Said Winds," *Philosophical Transactions of the Royal Society of London* 16, no. 183 (1686), opposite 151.

included a map of the trade winds—reputedly the first meteorological chart ever published—to bolster his explanation (figure 2.1).

Half a century later, when George Hadley modified Halley's explanation to take account of the Coriolis effect, he employed no maps or diagrams of any kind.[8] The absence of graphical elements typified seventeenth-century and eighteenth-century meteorology. Even simple graphs—among today's most ubiquitous tools of data analysis—saw little use before about 1890. Instead, early weather scientists typically published their observations in long tables, which often combined quantitative with qualitative information.[9] Poring over such tables, early meteorologists hoped to discover regularities in weather phenomena. They were sorely disappointed. As Frederik Nebeker put it, "the tabulation of data was forceful in *diminishing* belief in virtually all simple correlations involving meteorological phenomena" (emphasis added).

The nineteenth century witnessed a virtual explosion of scientific cartography, including the first systematic use of mapping as a tool of data analysis (what we would now call "scientific visualization"). In the early 1800s the German scientist Alexander von Humboldt traveled much of the world, over land and sea, measuring, recording, and classifying nearly everything he saw. Humboldt's famous 1817 chart of the northern hemisphere deployed a new graphical technique: "isotherms," smooth lines demarcating zones of similar average temperature (figure 2.2). This chart showed average temperatures curving away from latitude lines, thus defying the ancient theory of *klimata* and posing a climatological problem.[10]

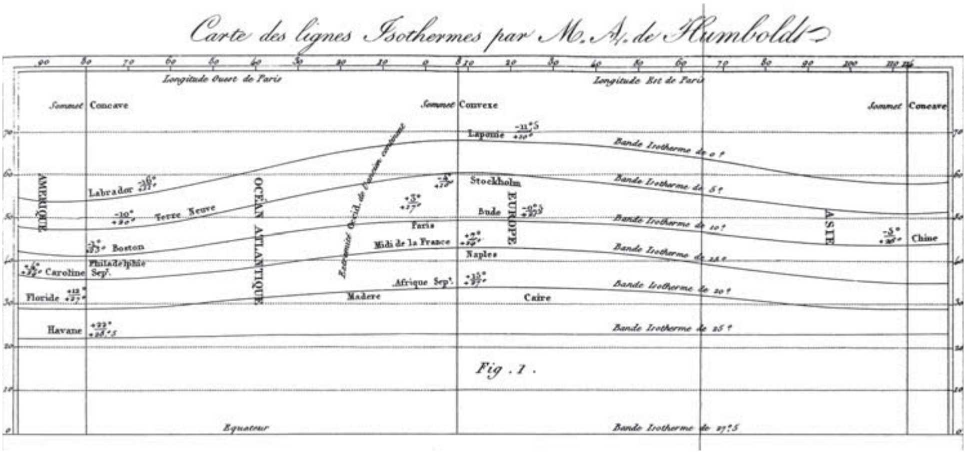

Figure 2.2
Humboldt's "chart of isothermic lines," covering the northern hemisphere from approximately 100°W (the Mississippi river) to 100°E (Thailand).
Source: A. von Humboldt, "Sur Les Lignes Isothermes," *Annales de Chimie et de Physique* 5 (1817): 102–12.

Almost simultaneously (between 1816 and 1819), independent of Humboldt, another German physicist, Heinrich Wilhelm Brandes, produced what were probably the first weather maps. Brandes's original maps are lost, but evidence suggests that they employed "isobars," lines indicating regions of similar barometric pressure.[11]

The meteorologist Heinrich Wilhelm Dove, a close colleague of Humboldt's, soon adopted his method and used it, in part, to discover the relationship of atmospheric pressure to wind direction during the passage of storms.[12] In 1852 Dove published isothermal charts for the entire Earth (figure 2.3).

The isoline—the general term for this technique of mapping relationships among data points—was a crucial innovation in weather and climate data analysis. Its importance can hardly be exaggerated. Isolines were the first practical technique for visualizing weather patterns *from data* over large areas: pictures worth a thousand numbers. Little changed since the days of Humboldt, Brandes, and Dove, isolines remain a basic convention of weather and climate maps today.

The data tables created by seventeenth- and eighteenth-century scientists recorded information from points—that is, individual places. By contrast, isotherms, isobars, and similar cartographical tools displayed

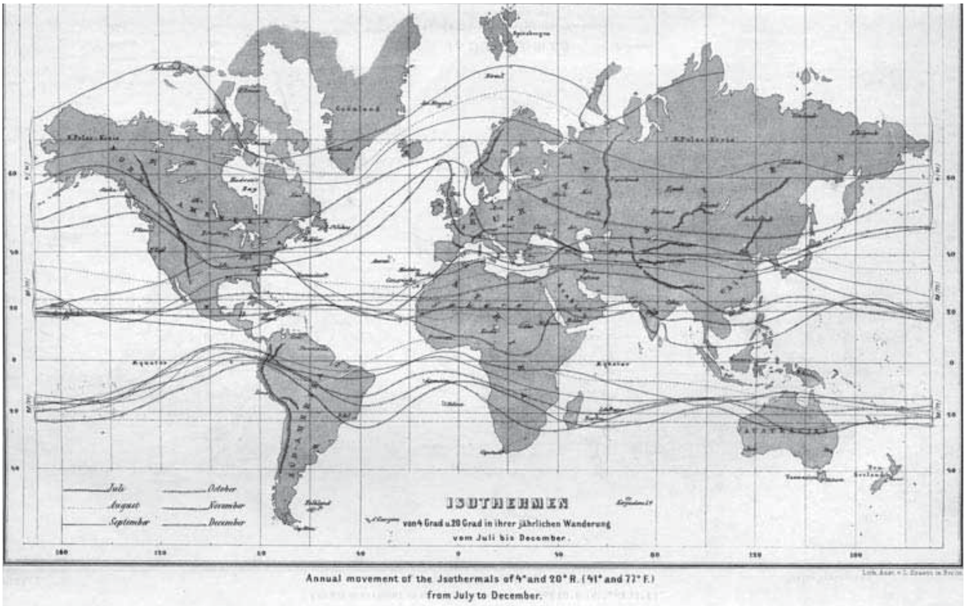

Figure 2.3

Dove's map showing isotherms for July through December at three latitudes. Lines above 40°N are isotherms for 4°C (one line for each monthly average). Lines around 20°N and 20°S are isotherms for 20°C.

Source: H. W. Dove, *The Distribution of Heat Over the Surface of the Globe* (Taylor and Francis, 1853), opposite 27.

spatial continuities or regions. At the same time, however, isolines brought awareness of the stark limitations of available data. One drew a smooth line connecting measurements—but what was actually going on between the points, often hundreds of kilometers apart? To bring the tool closer to the reality it represented, meteorologists knew, they were going to need more data.

In the seventeenth and eighteenth centuries, meteorological observing networks arose sporadically across Europe, America, and Russia, including northern Asia. (See box 2.1.) Until the middle of the nineteenth century, however, none of these networks endured for more than about 20 years. Before the telegraph, these networks communicated via postal mail, taking weeks or months to assemble a data set. Such data had no economic or military value, since they could not be used in forecasting. With every reason to exchange information and none to keep it secret, early meteorologists shared weather data freely. Data sharing became a deeply entrenched norm, which Nebeker named the "communality of data."[13]

Box 2.1
Pre-Nineteenth-Century Meteorological Data Networks

The Accademia del Cimento

From 1654 to 1667, under the patronage of Ferdinand II, Grand Duke of Tuscany, the Accademia del Cimento organized a pan-European weather network using comparable (and in some cases even redundant) instrumentation. The ten stations in this network extended across Italy from its base in Florence, as well as northward to Paris, Warsaw, Innsbruck, and Osnabrück in what is now northern Germany.

James Jurin's Network

Jurin invited European observers to submit weather records for publication, based on his recommended observing scheme.[a] He collected data submitted for the period 1724–1735, publishing them in the British Royal Society's *Philosophical Transactions* between 1732 and 1742. These data included some from the American colonies.[b]

The Great Northern Expedition

Scientists participating in the 1733 Great Northern Expedition, which explored northern Russia seeking sea trade routes, established a network of meteorological stations as far east as Yakutsk at 130°E.[c]

The Palatine Meteorological Society

From 1780 to 1795 the Societas Meteorologica Palatina, based in Mannheim, organized a network of 37 weather stations scattered across Europe and the United States. Thirty-one of these stations carried out synchronous observations.

a. J. Jurin, "Invitatio Ad Observationes Meteorologicas Communi Consilio Instituendas," *Philosophical Transactions of the Royal Society of London* 32, no. 379, 1723: 422–27.
b. A. K. Khrgian, *Meteorology: A Historical Survey* (Israel Program for Scientific Translations, 1970), 71–73.
c. D. C. Cassidy, "Meteorology in Mannheim: The Palatine Meteorological Society, 1780–1795," *Sudhoffs Archiv* 69, 1985: 8–25.

This communality of data helped make meteorology among the most open and cosmopolitan of sciences.

The communality of data set meteorology and climatology apart from the laboratory or "bench" sciences. Laboratory experiments produce data. Usually, numerous failures and false starts precede a "successful" experiment (one whose data confirm a hypothesis). Data from "failed" experiments are mostly discarded, and no one outside the laboratory ever sees them. During this process, the laboratory functions as a private space; no one need know how many mistakes you made along the way. Only data that can be explained by theory get published, and even these usually appear only in highly processed form.[14] This special power not only to isolate and concentrate natural forces but also to multiply mistakes and conceal its own internal processes has made the laboratory one of modernity's most potent inventions.[15] In meteorology and in other field sciences, by contrast, data can't be generated in some closed, private room. Instead, meteorology has to spread itself through large-scale geographical space, distributing its network of people, instruments, and knowledge widely. Few sciences have had such fundamental reasons to make themselves "omnipresent over the globe," as Ruskin put it in 1839.

"Data Guys": The Network Structure of Meteorology

A network such as that of meteorology is known to historians of technology as an "accumulative" infrastructure or infrasystem.[16] Its goal is to accumulate many observations at some central point (or points), where they can be analyzed, charted, and then distributed. In meteorology, in contrast with the laboratory sciences, one can gain professional recognition simply for accumulating a substantial data set. Even in present-day weather science, in which theory and modeling have taken pride of place and gigantic data sets circulate effortlessly across the Internet, the men and women responsible for collecting, "cleaning," and archiving large data sets are held in high esteem, as I learned while interviewing scientists for this book. Climatologists call them "data guys."

Among the first "data guys" to try to build a global data set was Matthew Maury, a US Navy officer. Maury made it his mission to collect and map ships' logs of winds and currents at sea. Beginning in 1848, he cranked out a prodigious series of publications—some 200 volumes.[17] They remained standard works well into the twentieth century.

In the beginning, Maury's project suffered mightily from the lack of standard metrics and measuring practices in existing ships' logs. The metric system, then gaining popularity among scientists, competed with other units of measure—especially the British imperial system adopted by (or forced upon) many countries around the world. Fahrenheit and Celsius temperature scales both remained in common use. Later, when he became director of the US Naval Observatory, Maury used the office to promote "an universal system of meteorological observations by sea and land," to which every government in the world would (he hoped) contribute.[18] He organized the first intergovernmental conference on standardized observing systems, held at Brussels in 1853 and attended by representatives from nine European nations and the United States.

Participants in the Brussels conference settled on a standard logbook format and a standard set of instructions for taking observations. By 1858, nineteen countries had joined the Brussels convention. As a global standard, the agreement saw only partial success. It required, for example, that vessels using the Fahrenheit scale also record temperatures in Celsius; many captains simply ignored this and other inconvenient obligations.[19] Nonetheless, the US Naval Observatory, the British Meteorological Office, and the Netherlands Meteorological Institute each processed the collected naval data to produce important series of marine maps.[20] Guided by such maps, ships shaved 33 days off the average ocean transit from New York to San Francisco.[21] Though Maury became justly famous for his superhuman collecting effort, even more important in the long run was the data network he established. Naval logs remain the longest continuous quasi-global data record.

Two decades later, *HMS Challenger's* four-year scientific voyage renewed Maury's vision of data-based global charts of prevailing winds, currents, and temperatures. Between 1872 and 1876 the *Challenger* sailed more than 127,000 km, traversing most of the world's oceans, with the explicit mission of comprehending "the terraqueous globe taken as one whole." Observers on the *Challenger* recorded weather data every two hours throughout the entire mission. The scientific reports and charts they produced occupied some 50 volumes. This was the nineteenth-century equivalent of a weather satellite: an attempt to observe the entire planet from a single platform using well-calibrated instruments and consistent techniques.

Another "data guy," a meteorologist named Alexander Buchan, took up the task of analyzing the *Challenger* data. Any serious discussion of the oceanic circulation, Buchan wrote, would require "maps showing for the various months of the year the mean temperature, mean pressure, and prevailing winds of the globe, with carefully prepared and extensive tables of the observational data required for the graphic representation of the results." *Challenger* data could contribute to that project, but the majority of data would have to come from weather stations. Yet, as Buchan lamented, "the only works [previously] available were Dove's isothermals, 1852; Buchan's isobars and prevailing winds, 1869; and Coffin and Wojekof's winds of the globe, 1875—*all of which were based necessarily, when written, on defective data*."[22] Buchan was already inverting the data infrastructure, reviewing and revising existing knowledge.

In a story endlessly repeated in subsequent decades, Buchan's effort proved a monumental project. It took him and his assistants seven years to complete their *Report on Atmospheric Circulation*. He tabulated temperature data from 1620 surface stations covering the period 1870–1884.[23] The 52 beautiful color maps illustrated global and hemispheric average temperatures, pressures, and winds (figure 2.4).

In subsequent decades the project of collecting, filtering, and mapping global climate data would be repeated over and over. Each new collector

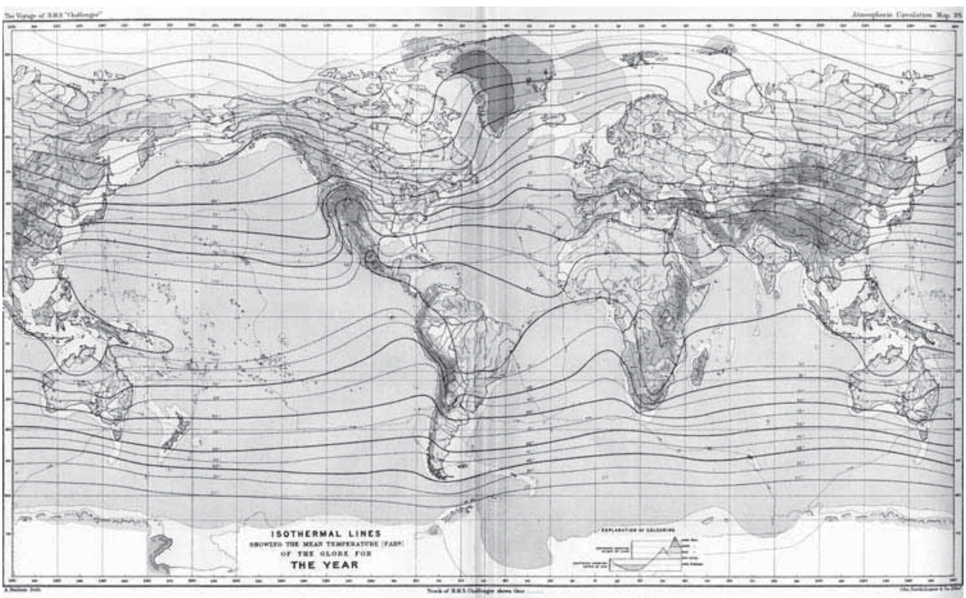

Figure 2.4
Global isothermal lines of mean annual temperatures (°F), constructed from HMS *Challenger* data plus annual averages at 1620 surface stations in 1870–1884 (many series incomplete).
Source: A. Buchan, *Report on Atmospheric Circulation Based on the Observations Made on Board HMS* Challenger *During the Years 1873–1876, and Other Meteorological Observations* (HMSO, 1889).

would invert the infrastructure anew, adding some data and rejecting others. Often collectors would frame some new way to refine the data, correct for systematic errors, or create a set more evenly distributed in global space.

These early maps and charts were strictly climatological. They were attempts to chart average conditions over years or decades—whatever the available data would support. Meteorologists also began to visualize—for the first time—the vertical motions of the planetary atmosphere as well as its horizontal ones. For example, Maury combined the theoretical work of Halley, Hadley, and others with his own knowledge of surface winds to create the diagram in figure 2.5.[24] Both the tropical Hadley cells and the

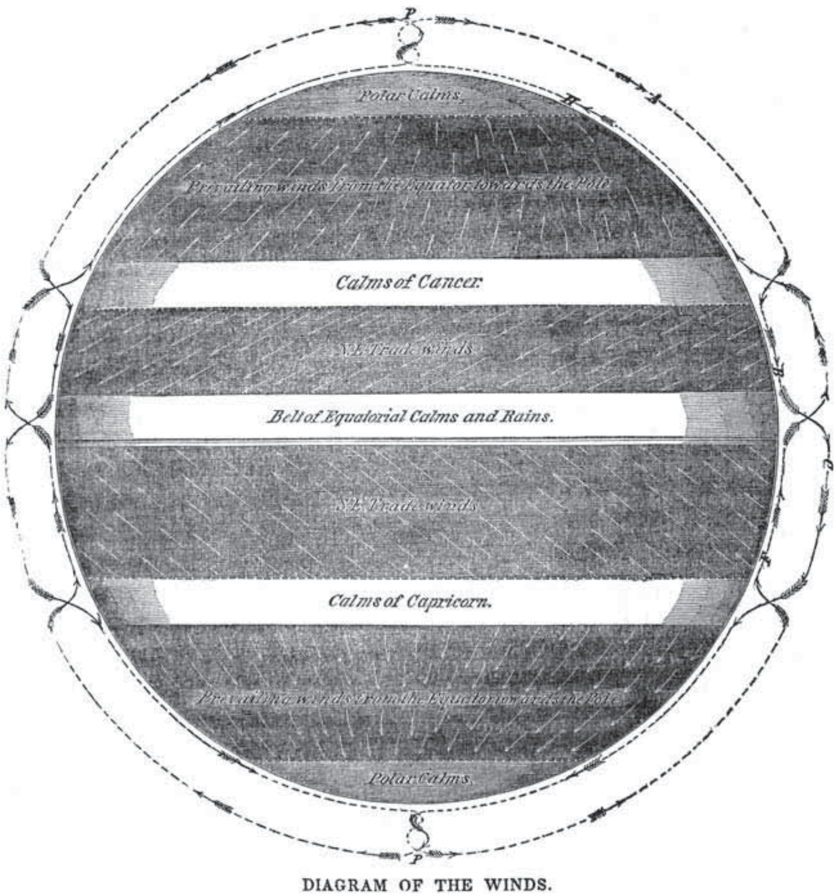

Figure 2.5
Maury's two-cell diagram of the global circulation.
Source: M. F. Maury, *The Physical Geography of the Sea* (Harper, 1855), 70.

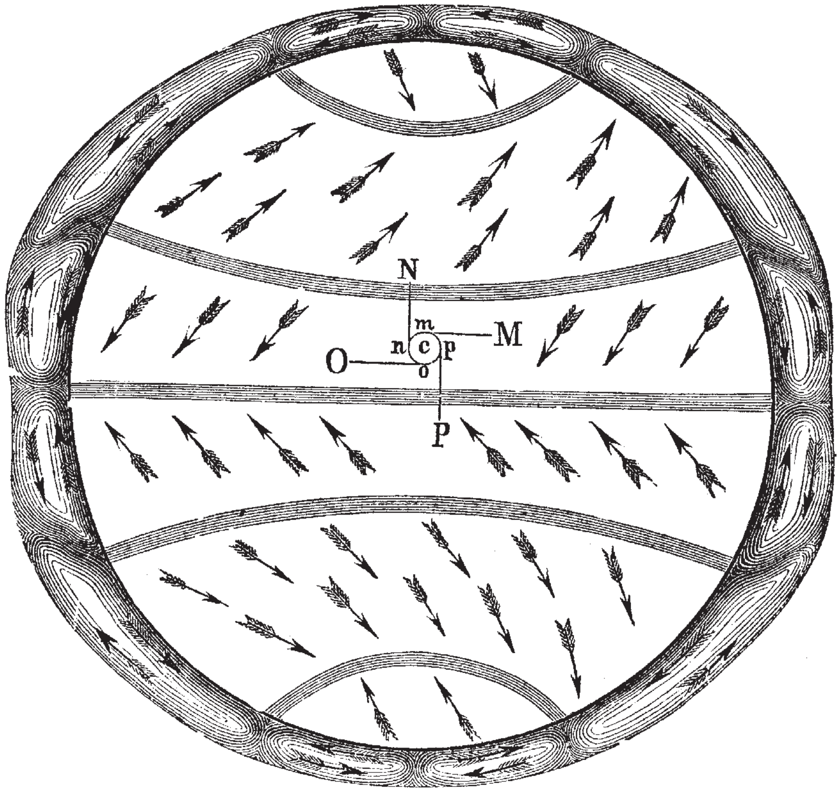

Figure 2.6
Ferrel's three-cell global circulation diagram.
Source: W. Ferrel, "An Essay on the Winds and Currents of the Ocean," *Nashville Journal of Medicine and Surgery* 11, no. 4–5 (1856), 290.

high-latitude circulatory cells proposed by Dove are readily visible.[25] The diagram relates the vertical circulation to the prevailing winds, and also to the calmer areas between the circulatory cells.

William Ferrel soon modified Maury's two-cell diagram, proposing a third cell to account for prevailing winds near the poles.[26] Meteorology's picture of the atmospheric circulation has changed little since then, as one can see by comparing Ferrel's diagram (figure 2.6) with the recent representation shown here in figure 2.7. These images captured the prevailing understanding of large-scale atmospheric motion, explaining the prevailing winds, the horse latitudes (or "calms of Cancer and Capricorn"), and some other fundamental phenomena. Unlike the climatological maps dis-

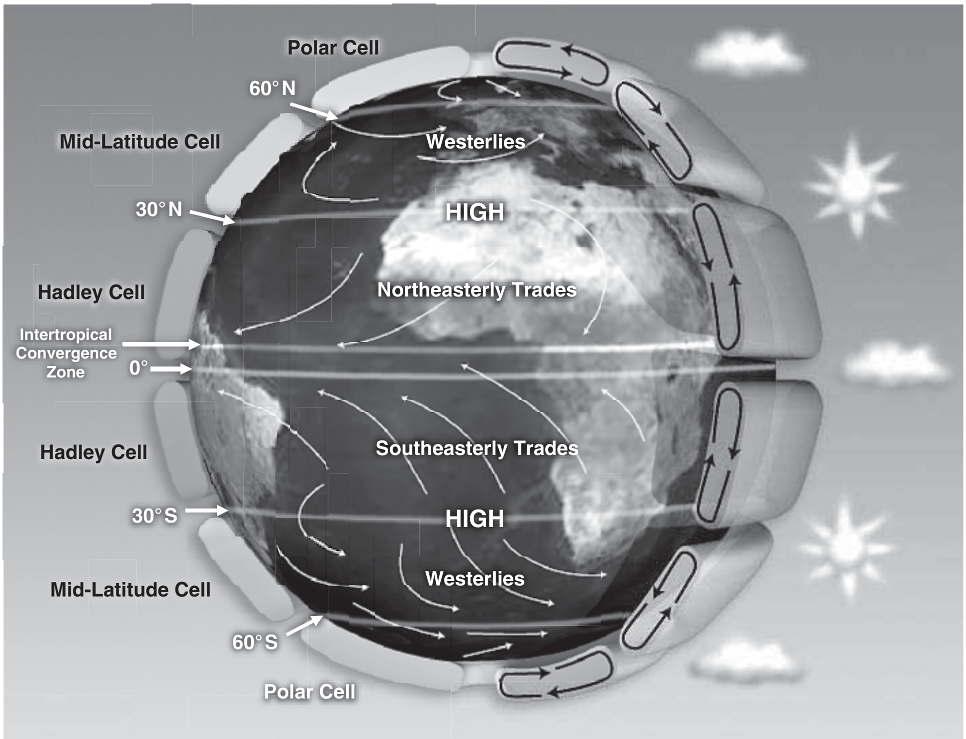

Figure 2.7
An idealized picture of the global circulation. Note the strong similarity to Ferrel's 1856 diagram.
Image courtesy of NASA.

cussed above, however, these were pictures of *theory*. Meteorologists had no way to test these theories, since all their measurements were taken at the surface. Although the physics were compelling, the existence of these vertical structures could only be inferred. Confirming their presence and charting their details would have to wait for the radiosonde, the airplane, and the satellite.

Thus, by the middle of the nineteenth century meteorology had created two crucially important ways to visualize the global atmosphere. The two-dimensional *data image*, as I will call it, sketched continuities in space by mapping averages of instrument readings from weather stations on land and from ships at sea. Meanwhile, the much cruder *theory image* pictured a three-dimensional, constantly moving circulation driven by solar heat; it was literally imagined rather than measured. The seemingly simple conventions of the climate data image, in particular, are technical achievements of the first order—fundamental elements of the emerging climate knowledge infrastructure.

Through these images, meteorology participated in the larger scientific project of envisioning "the world" as a whole—a single, dynamic, coherent physical system, knowable as a unit even though far beyond the scale of individual perception. In pursuit of this project, meteorology sought to occupy global space, distributing people, instruments, and knowledge to every corner of the Earth and its seas. Many other sciences also traveled widely in the Age of Empire, but few had such strong reasons to make themselves "omnipresent over the globe," as Ruskin put it in 1839—or, in more current terminology, "distributed" and "networked."

Universal Time

We think of the present as an era of extremely rapid, even overwhelming, technological change. A perpetual, inexorable acceleration seems to rule our lives.[27] Yet when it comes to overwhelming technological transformations, people living between 1840 and 1890 probably had a wilder ride. Within their lifetimes, railroads and steamships multiplied transport speeds many times over. Petroleum, natural gas, and electricity offered new, potent, flexible sources of energy. Electric light extended the working day. By comparison, almost everything that has happened since looks merely incremental.[28]

The most mind-bending new technology of all was the telegraph. Instantaneous communication over very long distances broke the ancient link between the speed of information and the speed of bodies moving through space. Invented simultaneously during the 1830s in Europe and the United States, the electric telegraph quickly came into worldwide use not long after Samuel Morse demonstrated a practical long-distance technique in 1844. The annihilation of distance and the rise of global virtual community, trumpeted today as consequences of television and the Internet, were felt even more vividly by those who experienced, for the first time ever, the arrival of news from across the oceans on the same day events occurred.[29]

At the dawn of electric telegraphy, scientific meteorology remained chiefly a pastime for gentlemen, academics, and amateur scientists. Forecasting was one goal, but not yet the main focus. Available forecasting techniques offered very limited accuracy and scope. Barometers gave generic clues to imminent local weather shifts, but beyond a day or so their skill was little better than chance. Rather than predict the future, then, most meteorologists studied the past, simply recording temperature, pressure, rainfall, wind direction, wind speed, and so on.

The telegraph, meteorologists immediately realized, would change all that. Now they could begin to realize Ruskin's dream of "perfect systems of methodical and simultaneous observations." Exchanging data across far-flung observing networks almost in real time, they could map the weather over very large areas. The resulting "synoptic" maps of simultaneous observations functioned like snapshots.[30] The maps charted pressure, temperature, and other weather conditions at each observing station. Wind direction and speed told which way the weather was moving, and how fast. All this provided a basis for at least a rational guess at what would happen next, and where. "Weather telegraphy," as it was known, proved considerably more effective than the barometer alone.

At the dawn of the telegraph era, meteorology was not yet professionalized. Except for a few university professors, mostly in Europe, there were no full-time meteorologists. Meteorology had little money, organization, or political power. So when the telegraph appeared on the scene, meteorologists never contemplated a dedicated weather telegraphy system. Instead, they planned to piggyback on the networks built by railroads, armies, and public or private telegraph companies.

Only governments and military forces, with their geographic reach, financial resources, and interests in practical weather prediction, could provide the necessary stability, scale, and funding for serious weather telegraphy. These networks exemplified an emerging social contract between science and the state. The United States' network was established in 1849 by Joseph Henry as one of the new Smithsonian Institution's first projects. Henry secured the agreement of commercial telegraph companies to transmit weather data free of charge. Ten years later, the Smithsonian Institution's weather telegraph network comprised about 500 observing stations.[31]

Europeans developed weather telegraphy around the same time, in similar ways. In 1854, during the Crimean War, a disastrous storm destroyed a French fleet near Balaklava on the Black Sea. Since observers had seen the same storm moving across the Mediterranean the previous day, it was clear that advance warning (by telegraph) might have prevented the debacle. In response, the French astronomer-meteorologist Urbain Jean-Joseph le Verrier proposed to Napoleon III that France sponsor an international weather telegraphy network. A few months later, in mid 1855, the network began operating in France. By 1857, Paris was receiving daily telegraph reports from Russia, Austria, Italy, Belgium, Switzerland, Spain, and Portugal. Not to be outdone, Japan developed a weather telegraphy network in the 1870s.[32]

In 1870, the US Congress established a Division of Telegrams and Reports for the Benefit of Commerce (also known as the Signal Service) within the War Department. It subsumed the Smithsonian's weather telegraphy network, marking the increasing value of weather forecasts for both military and commercial interests. The military network soon spanned the continent, comprising around 200 stations by the 1880s. As early as the 1880s, the Signal Service employed facsimile transmission techniques, such as "autographic telegraphy" and a crude facsimile cipher system, to transmit weather maps directly over telegraph lines (figure 2.8). In 1891, Congress placed the network on an entirely civilian basis, under the US

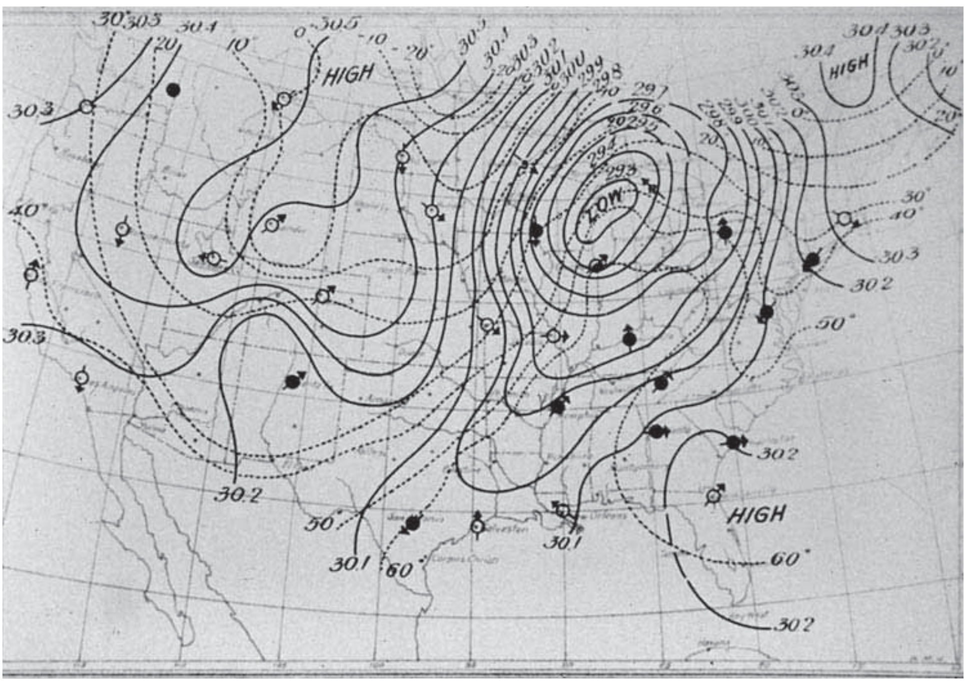

Figure 2.8
A US Signal Service weather map depicting a huge storm over the Great Lakes region of the United States in 1889. The map charts isobars (solid lines), isotherms (dashed lines), and wind direction.
Source: Signal Service, U.S. War Department, "Weather Map of United States." Image courtesy of National Weather Service Historical Photo Collection.

Weather Bureau within the Department of Agriculture. The Signal Service soon distributed daily synoptic charts of the continental United States as well as individual station data. Early in the twentieth century, some city newspapers began publishing these charts on a daily basis. However, high costs and technical problems with reproduction gradually caused newspaper weather maps to die out in the United States. Publication ceased almost entirely during World War I.[33]

By 1900, many countries possessing substantial telegraph networks also sponsored national weather services that conducted empirically based synoptic weather forecasting. Telegraph organizations throughout the world, both public and private, contributed to this project by transmitting weather data at no cost.[34] Forecasts based on weather telegraphy were not very accurate by today's standards, but they were better than local barometers alone, especially for storm warnings. They served important public interests, especially in shipping and agriculture. With the stability of state financial backing and the increased accuracy provided by weather telegraphy, meteorology began to professionalize, moving away from primarily amateur volunteer networks and toward a state-sponsored, technology-based, institutionalized infrastructure.

Telegraphy also catalyzed another event of major importance for the future of meteorology: the general standardization of time. Before about 1800, the norm was solar time, with noon meaning literally the middle of the day—i.e., the precise moment at which the sun crosses an observer's zenith. Time thus varied with longitude. Furthermore, though highly accurate pendulum clocks and chronometers did exist, most ordinary clocks and watches remained quite imprecise. For most purposes, "what time it is" was settled locally, marked by church bells and public clocks. The small differences in solar time between nearby locations caused few difficulties. Moving at relatively low speeds, long-distance travelers on land had little need of universal time.[35] With the advent of railroads, however, transportation speeds reached a point where even small differences mattered not simply for passengers' convenience, but for network coordination and safety. In early single-track rail systems, a southbound train would wait on a siding for the northbound train to pass; when trains failed to meet their schedules, terrible accidents often occurred. For these reasons, most of Great Britain's railways adopted Greenwich Mean Time for their operating schedules in 1847. Expanding telegraph networks made this possible by allowing near-instantaneous transmission of time signals by which conductors and stationmasters throughout the network could set their timepieces. Indeed, railroad companies built many telegraph lines themselves, their railbeds serving as ready-made long-distance rights-of-way. Railroad and telegraph rapidly became tightly coupled, taking on an interdependent web structure. Integrating transport and communication systems helped railroads to become the first widely distributed, large-scale business organizations.[36]

A different set of interests stemmed from the developing needs of science. Traditionally, astronomical observatories had performed a number of important practical functions in addition to scientific activities. These included recording the weather and signaling the precise moment of solar noon to their local communities by means of "time balls" (figure 2.9) or guns. These signals worked well if you were somewhere nearby, but if your town had no observatory your watch was probably going to be wrong. In

Figure 2.9
A time ball atop the Charing Cross telegraph station in London, 1852. The time ball would be raised to the top of the mast, then dropped to mark the exact hour. Note the public clock in the square outside the station.

the 1850s, soon after telegraph networks began to spread, observatories teamed with telegraph companies throughout the United States to sell time signals much further afield. Clients for this service included railroads, jewelers (who sold watches), and municipalities. Observatories calibrated their highly accurate clocks to solar time at their locations, then used them to deliver regular signals marking the hour. Before long, some 100 entities in the United States sold time-signal services. A cacophony of different time standards emerged, including local solar time, local civil time, railroad standard time, and Washington mean time. For a while, local knowledge sufficed to manage the various parallel systems; people simply added or subtracted minutes to accomplish the necessary conversions.

Meteorologists had long recognized the desirability of uniform observing times. Yet despite repeated calls for a consistent international system, each national weather service still established its own observing hours. Further, in these systems weather observers generally used local (solar) time. Before weather telegraphy, this didn't matter much. But once it became practical to gather weather data from a large area in near real time, differences in observing times could affect forecast quality. Among the first to recognize this was Cleveland Abbe. Formerly director of the Cincinnati Observatory (which sold time signals), Abbe became first head of the new Signal Service's weather department in 1870. Abbe often emphasized the need for *simultaneous* observation (same universal time), as opposed to the then common practice of *synchronous* observation.[37] When Abbe took over the Signal Service, standing instructions fixed observing hours by local solar time. Abbe immediately instituted a new system. The Naval Observatory in Washington would now telegraph time signals to Signal Service observers across the United States, thus establishing a uniform continental time standard in meteorology.

Abbe initiated a general campaign for time reform beyond the Signal Service. He chaired the American Metrological Society's committee on the subject.[38] Eventually he also chose, strategically, to advance his efforts through the powerful railroad companies (most of which had already implemented their own time standard), telegraph companies, and the American Association for the Advancement of Science. Abbe promoted standard, simultaneous observing times not only in the United States but internationally. One result was the Signal Service's monthly *Bulletin of International Observations Taken Simultaneously*, published for the entire northern hemisphere from 1875 to 1884.[39] Abbe later called this work "undoubtedly the finest piece of international cooperation that the world has ever seen."[40] In 1883 most of the United States adopted the present system of standard time zones, with Greenwich as the prime meridian. In subsequent decades the rest of the world gradually embraced this time standard.[41]

In any infrastructure, replacing an old standard with a new one requires overcoming the "inertia of the installed base."[42] And indeed, despite Abbe's efforts, international meteorology proved very slow to accept standard time. Just a year before Abbe's time-reform campaign began, the first 1873 International Meteorological Congress had agreed to fix observing hours according to the mean solar day at each station.[43] So synchronous observation became the norm, and it remained the international standard in meteorology well into the twentieth century. The International Meteorological Organization's 1910 Conference of Directors noted the potential value of global simultaneous observations, but merely recommended using Greenwich Mean Time (GMT) on international balloon days, when simultaneous observations aloft were attempted. On all other days, according to this recommendation, observers should simply note which time system they used.[44]

Not all scientists shared Abbe's enthusiasm for simultaneous observation. In 1918, Sir Napier Shaw, director of the British Meteorological Office, explained the scientific rationale for solar time in meteorology: ". . . the diurnal variations of weather are controlled by the sun, and for climatological purposes the fundamental principle of meteorological work is to note the conditions day by day at the same interval before or after true [solar] noon. . . ."[45] Daylight saving time, introduced during World War I as "summer time," injected what many meteorologists viewed as another dangerous confusion. Charles Marvin, chief of the US Weather Bureau, wrote of the "grave doubts surrounding the chronology and history of events resulting from the arbitrary advancement and retardation of clocks involved in [this] scheme. . . ."[46] Shaw agreed, noting that "in spite of very careful instructions a great deal of confusion arose with the observers . . . , and the continuity of many series of observations has been interrupted . . . There is now no possibility of placing beyond dispute the exact time of any event, except those dealt with by the telegraph, which occurred between May 21 and September 30, 1917."[47] Not until 1946 did the International Meteorological Organization officially designate standard observing hours using Greenwich Mean Time.

Global standard time bound continuous space to simultaneous time. It positioned people and communities relative to huge regions defined purely by their longitude. Its adoption required the infrastructures of instantaneous communication and accurate clocks. Standard time also marked a deep conceptual shift in the fundamental meaning and experience of time. Where solar time was tied to one's exact location, universal standard time created large, abstract zones within which time would be the same at all latitudes and all times of year. Time itself became a fundamentally globalist form of information, well suited to a meteorology already far along the road to globalism.