The Advent of Climate Science

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Subject: History of Climate Science Online Publication Date: Jan 2020
DOI: 10.1093/acrefore/9780190228620.013.716

Summary and Keywords

The advent of climate science can be defined as the historical emergence of a research program to study climate according to a modern definition of climate. Climate in this sense: (1) refers not simply to the average state of the atmosphere but also to its variability; (2) is multiscalar, concerned with phenomena ranging from the very small and fast to the very large and slow; and (3) is understood to be influenced by the oceans, lithosphere, cryosphere, and biosphere. Most accounts of the history of climate science to date have focused on the development of computerized general circulation models since World War Two. However, following this definition, the advent of climate science occurred well before the computer age. This entry therefore seeks to dispel the image of climate science as a recent invention and as the preserve of an exclusive, North American elite. The historical roots of today's knowledge of climate change stretch surprisingly far back into the past and clear across the world, though the geographic focus here is on Europe and North America. The modern science of climate emerged out of interactions between learned and vernacular knowledge traditions, and has simultaneously appropriated and undermined traditional and indigenous forms of climate knowledge. Important precedents emerged in the 17th and 18th centuries, and it was in the late 19th century that a modern science of climate coalesced into a coordinated research program in part through the unification of divergent knowledge traditions around standardized techniques of measurement and analysis.

Keywords: climatology, historiography, geography, empire, climate dynamics, Julius Hann, Wladimir Köppen

Introduction: Reassessing the Origin of Climate Science

If skeptics' attacks on the science of global warming have "seeped" into the scientific community and, in some cases, redirected climate research (Lewandowsky, Oreskes, Risbey, Newell, & Smithson, 2015), it would not be surprising to find that denialism has also colored how scientists and their advocates narrate the history of climate science. The public clash over the reality of global warming has become a filter through which early 21st-century observers glimpse a distorted view of the past. Controversy has swayed climate scientists to distance their field from its “pre-modern” forerunners. In response to the skeptics’ onslaught, most historical accounts have foregrounded the recent development of computerized predictions of global average temperature change. They have done so at the expense of attention to other forms of climate knowledge in other contexts and eras. They have exaggerated ruptures and ignored important continuities. New historical research is bringing into focus quite a different picture of the origin of climate science.

What makes modern climate science modern? When 21st-century practitioners reflect on the discipline’s history, they often emphasize just how different contemporary “climate science” is from what went by the name of “climatology” in earlier times. Historians, too, have remarked that old-fashioned climatology was not really a science, just a clutter of empirical data (Weart, 2003). Today’s climate science is often defined against earlier incarnations as predictive and global in scale—as a physical and, specifically, a geophysical science. This all appears familiar and unobjectionable at first glance. And yet this contrast between pre-modern climatology and the modern geophysical science of climate is misleading in several respects. First, modern climate science is not exclusively geophysical. Scientific understanding of anthropogenic climate change in the 21st century hinges on knowledge drawn from the life sciences (and even the social sciences). Interactions between the atmosphere and living things are programmed into “Earth system models,” the primary means of generating predictions of the planet’s climate in the future. Second, the modern concept of climate is not simply global, but resolutely multiscalar. Scientists study micro- and meso-climates alongside the planetary climate, tracking interactions across scales, from aerosol particles to hemispheric circulations. In short, histories that associate climate science with a global, physicalist vision fail to do justice to the richness and complexity of this field of knowledge. While such histories focus on the development of the capacity to predict the future state of the global atmosphere, many of the most important lessons that climate science teaches address the human scale and do not necessarily take the form of predictions. A historical account of the advent of climate science must broaden its scope to match the multidimensionality of this discipline.

Freed from these constraints, we can begin to make out a deeper, broader history of climate science. It is a history of the study of climate as a variable, multiscalar, and holistic concept, and its origins lie not in the late 20th century but in the early modern period. This science emerged from interactions among many different cultures. While this article focuses on European and North American contexts, it will hopefully stimulate research by historians with expertise on other regions and make way, ultimately, for a less Eurocentric account.

Writing Histories of Climate Science

For historical purposes, it is important to distinguish between the science of climate and that of weather—or, in pre-20th-century terms, between climatology and meteorology. Historically, these fields developed to serve different purposes. Meteorology grew up largely around efforts to forecast storms, while climatology informed the long-term adaptation of human activities (agricultural, industrial, medical, and military) to regional conditions. Surprisingly, historians often fail to make any distinction between the two. Those who do often introduce another misconception. For their definitions of meteorology and climatology, they often turn to the Austrian scientist Julius Hann's *Handbuch der Klimatologie* (1883), the first textbook of "climatology." There Hann distinguished climatology as a descriptive enterprise from meteorology as an explanatory one. In other words, in the terms coined by the neo-Kantian philosophers of Hann's generation, climatology was idiographic, while meteorology was nomothetic. To hold strictly to these definitions, however, would be misleading in light of the continuation of Hann's definition. He went on to indicate that no clear boundary could be drawn between meteorology and climatology. Accordingly, Hann and his colleagues practiced climatology in close coordination with meteorological research. A generation after Hann, the philosopher of science Viktor Kraft explained that climatology had a "dualistic" character. It sat at the intersection between the idiographic methods of geography and the nomothetic methods of meteorology (Coen, 2018A; Randalls, 2017). That is to say, climatology studied the climate of a given region both to grasp its unique, local qualities, and as a case study in the operation of the laws of atmospheric processes most generally. Contemporary "climate science" is similarly dualistic. Its practitioners tend to embody dual identities: as scientists concerned with universal laws, and as geographers concerned with particular regions and their characteristics.

Thus climate science deserves its own history, one that recognizes its multifaceted character. The history of climate science forms a complement to the more established historical study of efforts at weather prediction from the 19th century to today (Anderson, 2005; Friedman, 1989; Harper, 2008; Nebeker, 1995). To some degree, historians of science have lagged behind the reversal in status between meteorology and climate science that occurred in the 1990s (Weart, 2013). Only since the late 1990s have professional historians begun to write the history of climate knowledge.

Major early studies of the history of climate science followed the wave of right-wing denialism in the 1990s. Two of the earliest and most influential contributions came from James Fleming (1998) and Spencer Weart (2003). Superficially, these books shared a geographical focus on North America, as well as agreement on the defining features of the modern understanding of climate change (including the greenhouse effect, theories of the Earth's climate history, and the instrumental time series) and on many of the central actors in the story. At a deeper level, the two books diverged in telling ways. Weart's book (and the linked hypertext website) portrayed climate science as a discipline forged in the aftermath of World War Two, when the first electronic computers made possible the development of numerical weather prediction and then simple general circulation models. Weart's was a story of scientific heroism, offered in support of the scientists against their skeptics. Accordingly, it stressed the radical disjuncture between "climatology" before 1950, no more than a "scientific backwater," and modern "climate science." Fleming, by contrast, a 19th-century historian by training, devoted most of his book to the period before World War Two. He located the origin of "modern climatology" in the early 19th century, when the question of the stability or variability of climate was already in play, and when men of science began to insist that such claims refer to instrumental measurements, rather than hearsay and ancient texts. While Weart saw a sea change in ideas of climate change ca. 1950, Fleming stressed continuity in social attitudes toward climate change over two centuries. Yet Fleming's (1998, p. 136) story, too, was ultimately progressive, one in which a "culture-bound discussion of climatic change was superseded by more or less objective attempts to examine the atmosphere and its changes."

Research into the history of climate science has been stimulated in part by the field of historical climatology, which uses historical sources like weather diaries and ship logs to generate proxy weather data. In order to interpret such sources, historical climatologists need to understand the culture-bound assumptions that informed the conventions of recording meteorological phenomena in the past. In other words, they rely on the history of science.

The International Commission for the History of Meteorology was founded in 2001, a sign of growing interest in the history of atmospheric science. Since then, two new avenues of research have enriched our understanding of the political and cultural stakes of climate knowledge. In the field of science and technology studies, scholars such as Paul Edwards, Sheila Jasanoff, and Clark Miller have examined the interdependent emergence of the science of global warming and of institutions and infrastructures of global governance, a process they refer to as the "co-production" of science and politics (Edwards, 2010; Edwards & Miller, 2001). Meanwhile, anthropologists and cultural historians have demonstrated the complex relationships between ideas of climate and concepts of health, race, civilization, and colonial power (Cruikshank, 2005; Golinski, 2007; Jennings, 2006; Strauss & Orlove, 2003).

In the 2000s, a standard narrative had congealed that identified the history of climate science with the development of certain components of the theory of anthropogenic global warming, focusing on the disciplines of atmospheric chemistry and atmospheric physics (e.g., Le Treut et al., 2007). Yet this taxonomy is incomplete. Historians are just beginning to recapture the role of other fields of knowledge in the making of climate science, from geology and geography to botany and balneology.

Historians are also beginning to devote more attention to traditional environmental knowledge (TEK), including the knowledge traditions that have sustained indigenous communities through earlier periods of climate change (Cruikshank, 2005; Whyte, 2018). TEK is an important component of modern scientific knowledge of climate change, especially in parts of the world without written records of past conditions. TEK also functions as an alternative knowledge system, one implying an ethical critique of the instrumental rationality characteristic of much modern science. Tellingly, it was in the 19th century that naturalists began to appreciate indigenous traditions of natural knowledge. Ecology, which was institutionalized as a discipline ca. 1900, was deeply indebted to native epistemologies (Cañizares-Esguerra, 2006; Cushman, 2011; Grove, 1995; Mulcahy, 2006).

Before Climate Science, 1600–1750

Important precedents for the science of climate arose before 1800, during the so-called scientific revolution (roughly 1600–1750), but these did not yet constitute a research program. Rather, they formed "a broad field of ideas and activities which engaged diverse communities and interests and yielded different understandings of weather and climate" (Heymann, 2010, p. 583).

Concepts of Climate

In early modern discourse, "climate" retained its ancient Greek meaning of the angle of the Sun's inclination or latitude. According to Aristotle, three climate zones neatly banded each hemisphere: frigid at the poles, temperate at mid-latitudes, and torrid at the equator. More holistic concepts of terrestrial conditions figured prominently in medicine and cosmography, but were not usually linked to the term climate.

Hippocratic medicine attributed the health of human bodies to the qualities of their milieux, as shaped by the seasons, prevailing winds, hydrography, topography, and vegetation. This way of thinking persisted well into the 19th century, particularly in vernacular medical cultures, as documented by Conevery Bolton Valencius (2002) and other historians of "medical geography" or "medical topography."

The Renaissance discipline of "cosmography" also employed a concept of place defined by terrestrial and cosmic circumstances, rather than simply by latitude (Barry, 2013). Some historians view cosmography as the predecessor to deterministic theories of the influence of climate on human societies, which became popular in the 18th century, closely tied to the rise of biological theories of race. However, Franz Mauelshagen (2018) cautions that it is misleading to refer to 18th-century theories of the geographical determination of human diversity as "climate theories," in the sense of attributing a causal influence to the atmosphere, since "climate" still often meant nothing more than latitude.

Historians disagree about when the meaning of climate shifted. Sam White (2015) argues, contra Mauelshagen, that European experiences in the New World began to throw the latitudinal definition into question as early as the 16th century (see also Kupperman, 1982). Early European explorers noted that the North American continent did not adhere to the Aristotelian scheme that equated climate with latitudinal zones. Shocked at first by the frigid winters and steamy summers of the East Coast of North America, settlers began to reimagine the geography of climate and to redefine what counted as "temperate" (Zilberstein, 2016). Already in the 16th century, some writers in North America were using climate to refer not only to a latitudinal zone but also to the character of a region as determined by its prevailing weather. Nonetheless, many commentators continued to use climate in the narrow sense of latitude into the early 19th century (Fressoz & Locher, 2015). By 1700, then, multiple meanings of climate coexisted: latitudinal climate, climate as a medical factor, and climate as determined by local circumstances (White, 2015).

Meanwhile, in the course of the 17th and 18th centuries, climate acquired another meaning: that of an agency or active force in its own right. Thus a given climate could be said to “produce” certain goods and not others, or to “mold” the character of a nation. That is, climate became synonymous with the factors that determined human wellbeing and national economic productivity. What’s more, according to the doctrine of “improvement,” climate in this sense could be actively steered by human interventions (Jankovic, 2010; Miglietti, 2016).

Practices of Observation

The direct observation of weather took on new significance in the early modern period. The discipline of meteorology, as taught at Renaissance universities, centered on remarkable events in the sublunary sphere, such as floods, earthquakes, and comets. Unlike Aristotelian disciplines resting on deductive reasoning, Renaissance meteorology was conjectural and open to revision. Yet it did not offer predictions and did not depend on observations of particular instances (Martin, 2009). By contrast, “astrometeorology,” which furnished weather forecasts on the basis of astronomical observations, was both predictive and empirical. Astrometeorology flourished at Renaissance courts and prompted the first empirical records of weather, as a means of judging the accuracy of forecasts. Vladimir Janković (2000) uses the phrase “meteoric reportage” to describe empirical attention to *unusual* atmospheric phenomena in the early modern period. In the course of the 18th century, as Jan Golinski (2007) has shown, meteoric reportage gave way to consistent records of *ordinary weather*. Only in the 18th century did the discipline of meteorology reorient itself around weather in this sense (Daston & Park, 1998). Yet astrometeorology survived. It flourished in the 18th century as a Newtonian program to correlate atmospheric phenomena with the positions of celestial bodies. Its legacy is also evident in successful 19th- and early-20th-century theories, such as those of James Croll and Milutin Milanković, which attributed climatic changes to variations in the Earth’s orbit.

The spread of Copernicanism bestowed new significance on empirical observations for meteorology. Galileo, for instance, offered the trade winds as evidence that the Earth does not stand still. It thus became possible to explain winds dynamically, that is, with reference to the Earth’s rotation. With new practices of “collective empiricism” in the 17th and 18th centuries, a more complete picture emerged of prevailing winds across the surface of the Earth. With it came early theories of the forces powering the circulation of the atmosphere on a planetary scale (Daston, 2011).

Empirical attention also turned to what 17th- and 18th-century commentators called “accidental” influences on climate. This referred to factors that brought about deviations from the climate that would be expected based solely on latitude. Such accidental factors included the distribution of continents and oceans, as well as local topography and its effects on wind, humidity, and sunlight. In colonial North America, settlers began to refer to accidental factors to explain the deviation of regional climates from expectations based on the Aristotelian scheme. Settler colonialism also propelled the science of acclimatization, which studied the effects of transplantation on living things (Osborne, 2000).

Finally, the 18th century saw the spread of consistent, instrumental weather records, primarily in the form of "weather diaries." Thermometers and barometers became fixtures in bourgeois homes, part of a new culture of weather observation that was recognizably modern in its insistence on self-discipline (Daston, 2011). Golinski (2007, p. 90) describes the 18th-century practice of keeping a weather diary as a form of asceticism, "a peculiarly self-denying form of self expression." He argues that familiarity with instrumental measurements gave rise to the modern concept of weather in the sense of the continuity and regularity of atmospheric phenomena.

Concepts of Climate Change

Before 1750, the phrase "climate change" most often referred to movement from one climatic zone to another, a concept of significance to physicians due to the presumed impact of travel on health. Yet the idea that the climate of a region could undergo change was hardly unknown; indeed, Aristotle held that a region's climate would periodically cycle between wet and dry (Dal Prete, 2019). Early modern observers not only found evidence of changes of climate on a regional or even global scale; more surprisingly, they occasionally invoked human agency to explain such shifts. Indeed, recent research suggests that there is a long history to the belief that humans can cause climate change.

This idea dates back to the 4th century BCE, when Aristotle's student Theophrastus documented changes in air temperature due to the removal of forests and the drainage of lakes (Hughes, 1985). The writings of Theophrastus became a point of reference for European travelers of the late 15th century. Christopher Columbus recorded that he knew "from experience" that rain fell more plentifully in forested regions. He noted that the deforestation of the Canary Islands, Madeira, and the Azores by the Spanish and Portuguese had reduced cloud cover and rainfall on these islands (Fressoz, 2016). Columbus inferred from this evidence that human activities may have altered climate in unexpected ways. However, other European visitors to the Americas reported that forest clearing had the effect of evening out the climatic extremes of this unfamiliar territory. Among Europeans in the New World, anthropogenic climate change was less a cause for concern than a propitious sign of imperial sovereignty (Miglietti, 2016; Zilberstein, 2016).

The idea that humans are capable of radically altering terrestrial conditions on a *planetary* scale is often considered a uniquely 21st-century insight. Remarkably, Lydia Barnett (2019), building on earlier histories by David Livingstone and Steven A. Epstein, shows that this idea originated in the 16th century, an outgrowth of an intellectual tradition at the nexus of theology and natural philosophy. Biblical commentators interpreted the flood recounted in Genesis as the result of a natural, causal chain of events that began with human sinfulness. In this way, Barnett (2019, p. 51) proposes, religion was central to the development of a "global environmental consciousness," as well as to the emergence of a sense of the vulnerability of humanity to the consequences of their own unintended transformations of the nonhuman world.

Interest in climate change took a resolutely empirical turn in 18th-century France. Fressoz and Locher (2015) trace the present-day field of historical climatology back to the efforts of French savants to compensate for the unreliable meteorological data of their day. They did so by identifying what 21-century scientists call climate “proxies.” They sought to ascertain how the onset of seasonal phenomena, such as the freezing of rivers and the ripening of fruit, correlated with air temperature. They also proposed the use of plants as indicators of climate change, using shifts in what would later be called vegetation lines to track the advance and retreat of climatic boundaries. However, all these investigations proceeded with little sense of the time scale of the Earth’s history, which started to become clear only toward the close of the 18th century.

Consolidating Climate Science, 1800–1914

Only after 1800 did climate science become a coherent research program seeking empirical evidence and causal understanding of the past and present distribution of climatic conditions across the surface of the Earth. By the end of the 19th century, scientists had woven together many of the earlier strands of investigation. In the process, they bridged the gaps between conflicting definitions of climate, different disciplinary approaches, and seemingly incommensurable time-scales of analysis.

Producing and Communicating Data

The consolidating impulse of 19th-century climatology first stimulated the production of standardized data (Edwards, 2010). It was in the 19th century that the first permanent weather-observing networks spread their telegraphic tendrils across the continents. More tentatively, they reached upward to sample the air of the upper atmosphere via kites, balloons, and mountain observatories. Ca. 1900, knowledge of the three-dimensional structure of the atmosphere helped to elucidate the formation of cyclones (though a full appreciation of the role of high-altitude winds in the general circulation only arrived with air travel in the 20th century). The effort to standardize measurements across national borders was a defining act of the new climate science, supported by the founding of the International Meteorological Organization in 1873.

Climatologists also invented useful forms, both visual and written, with which to communicate climate data to the public. Histories of atmospheric science often refer to the introduction of isotherms (lines connecting points of equal temperature) by Alexander von Humboldt in 1817. Far less well known is the wide range of alternative cartographic techniques that climatology developed in the 19th century. By the time of the 1873 Vienna World’s Fair, nearly every country participating in the agricultural exhibit displayed a map showing average temperature and rainfall by region. Such a simple scheme no longer satisfied professional climatologists, however (Lorenz, 1874, p. 21). In order to characterize a climate for agricultural or medical purposes, the variability of those elements was as important as their averages. It was in this context that the German-Russian meteorologist Wladimir Köppen began to develop a series of classification schemes, based largely on the correlation between temperature and vegetation, in order to make apparent the climatic similarities between regions far removed from each other in space, such as deserts on separate continents. Köppen's climate maps became ubiquitous in the 20th century, but they represented climate as a static variable; only recently have they been adapted to display climate *change* (Greene, 2015). Other 19th-century climatologists made different representational choices, some of which generated a more dynamic image of climate. Those concerned with depicting physical–geographical relationships of interdependence *between* climatic regions incorporated factors like orography and winds into their maps (Supan, 1884). Alongside such maps, scientists also communicated climate information via the new genre of climatography, which sought to translate quantitative data into descriptions at once evocative and of practical use to non-scientists (Coen, 2010).

Reconciling the Meanings of Climate

In a second act of synthesis, scientists resolved the dichotomy that had emerged in the 18th century between two definitions of climate, "solar" and "physical." Ever since the 16th century, European explorers and medical and agricultural researchers had been compiling evidence that atmospheric conditions are rarely consistent along lines of latitude. In this way, a new, empirical concept of climate, "physical climate," had grown up alongside the traditional meaning of solar inclination. Earlier scholars had treated these as independent concepts, but 19th-century scientists set out to reconcile them. They thought the oceans, ice, vegetation, soil, and surface relief as factors that "modify" the solar climate. More importantly, researchers began to tackle the question of *how* these factors influence the state of the atmosphere. Drawing on the new physical theory of thermodynamics, they began to explain why it was that oceanic climates differed from continental climates, mountain climates from valley climates, the climate of a forest from that of an open field. The definition of climate now encompassed the influence of "accidental" factors. This in turn necessitated a third feat of synthesis: 19th-century scientists reconciled two competing approaches to the study of climate, physical and geographic.

Joining Physics to Geography

In the 18th century, physical and geographical investigations had been largely independent of each other. On the physical side, theorists like George Hadley, working solely from sailors' observations of winds, had speculated about the physical mechanisms driving the atmospheric circulation. Simultaneously, explorers were amassing detailed descriptions of local climates around the world. Little thought was given to the relation between one project and the other until the 19th century. Then, in the middle of the 19th century, the work of physical explanation latched on to that of geographical observation, so that the two proceeded hand in hand.

Consider in this light once again the opening of Hann's 1833 climatological handbook. Following his initial distinction between climatology and meteorology, he went on to elaborate on their relationship. Climatology's task was primarily descriptive, namely to attend to nature’s variability. Yet that task was coupled to a quest for understanding, a “need” to explain the reciprocal relationships responsible for maintaining this diversity:

> We also demand from climatology that it furnish not merely a patchwork image of the varied climates of different locations, but rather that it satisfy our intellectual need for order and unity in the representation of diversity by means of a systematic representation, by grouping related climates together—further that it demonstrate the interaction and mutual determination of these climates. Only in this way does climatology become a scientific discipline.
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> (Hann 1883, p. 3)

The study of climate did indeed become a “science” in the 19th century, but *not* because climate became a strictly physical concept. As Hann suggested, climatology united physical and geographical modes of investigation.

This conjoined approach generated the first “dynamic” theories of climate, in the sense of the application of the physics of heat and fluid motion to explain the influence on climate of what early modern commentators had called “accidental” factors, such as the shape and constitution of the Earth’s surface. These efforts originated in the 1860s with the investigations of mountain winds by Julius Hann and Hermann von Helmholtz in the eastern and western Alps, respectively. This successful demonstration of the applicability of thermodynamics to the atmosphere stimulated efforts to develop a mathematical physics of the atmosphere. Over the course of the next 50 years, researchers worked out the basic equations describing the flow of atmospheric mass, energy, and momentum (Friedman, 1989). Precise solutions to these equations would not be possible until the invention of digital computers. Ca. 1900, however, researchers relied on a different kind of model. Often nothing more than a dishpan filled with fluid and set on a rotating turntable, analog models made it possible to visualize the implications of these equations (Edwards, 2011).

Modern climate models still rest on the mathematical description of atmospheric motion worked out over a century ago. The fusion of physics and geography gave rise to dynamical meteorology, concerned with physical explanation and prediction of weather events. Meanwhile, dynamical *climatology* constituted a related yet separate legacy. It sought to explain not events but trends, namely the long-term patterns of the atmosphere’s behavior. While dynamic meteorology developed as an aid to forecasting, dynamic climatology was concerned with *understanding* the distribution of climates and their stability.

In this sense, dynamic climatology was characteristic of the 19th-century turn to statistical thinking (Porter, 1986). One can trace a direct line, in fact, from the social statistics of the early 19th century, to Boltzmann’s statistical mechanics of gases, to the climatological concept of *Austausch* or exchange. Introduced during the First World War, *Austausch* was the earliest mathematical treatment of the role of atmospheric turbulence in the regulation of climate on micro and macro scales (Darrigol, 2005, p. 262; Schmidt, 1925).

Dynamic climatology was also an outgrowth of 19th-century technologies and infrastructures. These included the rail, steamship, and telegraph networks that enabled global transport and communication. These also encompassed the infrastructure that supported the penetration of extractive industries—such as whaling, trapping, and mining—into unmapped regions of the Arctic (Stuhl, 2016).

One strain of dynamic climatology became known in the 1930s as “air-mass climatology.” Associated initially with the Swedish scientist Tor Bergeron (1930), air-mass climatology relied on the concept of an air mass—a portion of the atmosphere with horizontally uniform temperature, humidity, and pressure—to define typical regional weather patterns. The idea was to track the trajectories of such bodies of air and their modifications as they passed over warmer or cooler surface regions. One could then define the climate of a given region in terms of the characteristics and frequencies of its incident air masses. This had an intuitive appeal, since it echoed the ancient idea that the character of a locale depends on the place of origin of its prevailing wind. This qualitative approach caught on during World War Two because it was quick to carry out, though it was often criticized for relying on subjective judgment. From a historical perspective, air mass climatology represents yet another legacy of the 19th century’s fusion of physics and geography in the service of the study of climate.

Bridging Disparate Scales

It proved more difficult to narrow the gulf between inquiries into shifts in climate over historical and geological time-scales. When the first historical-climatological studies launched in the late 18th century, geologists were just beginning to learn to read the antiquity of the Earth in the stratigraphic record (Rudwick, 2005, 2008). For much of the 19th century, scientists considered evidence of glaciation in the deep past irrelevant to the question of the stability of climate in the present. While many in the early 19th century worried that human activities like deforestation, swamp drainage, and urbanization could have detrimental impacts on local climates, few if any connected this concern to growing evidence of radical shifts in climate in the Earth’s distant past.

It took a leap of the imagination to begin to compare processes unfolding on such different temporal scales, to see human history in relation to geological history. It is not a coincidence, for instance, that one of the first individuals to pose the question of anthropogenic change in these comparative terms was the French architect Eugène-Emmanuel Viollet-le-Duc. Architects rely on a feel for the relationship between small scale and large, shifting between the ground-level perspective and the distant overview. Bringing this knack for scaling to bear on Earth history, Viollet-le-Duc (1876) argued that every large-scale change was the result of countless small causes, and so by small means human actions could bring about planetary change. In this vein, researchers like George Perkins Marsh, Eduard Brückner, and Anton Kerner von Marilaun mined historical records alongside the evidence of fossils and strata in pursuit of a seamless account of climate history (Brückner, 1890; Kerner, 1879; Marsh, 1864).

Explaining Climate Variability

Attempts to explain apparent variations of regional or global climate often focused on those factors that 18th-century savants had called “accidental,” that is, regional changes such as shifts in land use or geological transformations like elevation and subsidence. At the same time, scientists began to ask what other, as yet unsuspected mechanisms may account for climate change—as seen, for instance, in Europeans’ inquiries into the mysterious climatic disruptions now associated with the eruption of Mount Tambora in 1815 (Bodenmann, Brönnimann, Hadorn, Krüger, & Weissert, 2011).

The earliest of these new theories of climate change focused on fluctuations in solar activity, which astronomers had linked to the appearance and disappearance of sunspots. In 1801 William Herschel first proposed tracking the influence of the Sun on Earth’s climate by comparing the annual number of sunspots to the price of grain. In the 1840s an astronomer confirmed that variations in the number of sunspots followed an 11-year period. Soon many people claimed to have found cycles of this same length in meteorological records. Yet many others claimed that climate fluctuations occurred with periods of 8, 19, 24, 425 years or more (Brückner, 1890, pp. 36–38). The data was simply inconclusive (Lehmann, 2015).

Another cosmic theory of climate change focused on variations in the Earth’s orbit around the Sun. According to this idea, first proposed in 1842, the shifting distribution of sunlight over the Earth’s surface depends on three factors: the variable elongation of the Earth’s orbit, the greater or lesser tilt of its axis with respect to the plane of its orbit, and the precession or wobbling of its axis. In the 1860s, a self-educated Scotsman named James Croll reconsidered this hypothesis. He realized that variations in solar insolation alone could not directly alter Earth’s climate, but that they could do so indirectly, by modifying the character of the seasons. The onset of an Ice Age could begin when cosmic factors aligned to produce longer, colder winters in one hemisphere. This initial cooling effect would in turn trigger the operation of what Croll called “physical agents,” known today as positive feedbacks. Thus the growth of ice sheets in the winter hemisphere would reflect more sunlight back into space, driving temperatures lower. At the same time, the exaggerated temperature difference between the hemispheres would redirect ocean currents, further accentuating this North–South contrast and potentially even shutting down the Gulf Stream (Sugden, 2014). Croll’s theory thus emphasized the interaction between cosmic and terrestrial causes. Although Europe’s leading geologist, Charles Lyell, resisted the idea of cosmic agency, Croll himself saw his work as a fusion of physical and geological reasoning (Fleming, 2006).

Other scientists looked for a control on climate closer to home. In the 1820s Joseph Fourier used the emerging theory of thermodynamics to find an explanation for average temperatures on Earth. His calculations suggested that the Earth is warmer than it would be if the atmosphere were not somehow preventing the Sun’s heat from escaping back into space. John Tyndall took up Fourier’s question in the late 1850s. His laboratory investigations concluded that neither oxygen nor nitrogen were capable of blocking the passage of heat rays. Then it occurred to him to test a gas that was increasingly common in industrializing England: coal gas. It proved to be opaque to heat, as did pure carbon dioxide. Tyndall worked out that even a low concentration of CO_2 in the atmosphere could have a warming effect on the surface. In the 1890s, Svante Arrhenius conceived the idea that this effect could be magnified by what is called today positive feedbacks. He supposed that, if volcanic eruptions suddenly spewed more CO_2 into the atmosphere, the subsequent rise in air temperature would cause the atmosphere to hold more moisture. Since water vapor is particularly opaque to heat rays, the presence of more moisture in the atmosphere would further accentuate the warming trend. On the other hand, a decrease in atmospheric CO_2 would reduce water vapor in the atmosphere. Arrhenius speculated that the subsequent cooling effect may even be strong enough to bring on an ice age. He realized that this science held a lesson for the industrial age: burning coal could potentially make the planet warmer (Archer & Pierrehumbert, 2011, pp. 1–77).

As an inhabitant of a cold northern country, Arrhenius viewed the possibility of warming complacently. Many of his contemporaries likewise remained unconcerned about rising levels of CO_2 in the atmosphere. First, it was easy for scientists at the time to suggest that Arrhenius' model of the atmosphere was too simple to be realistic. It would also have been hard for them to foresee the acceleration of fossil-fuel consumption in the 20th century. In addition, scientists assumed that excess CO_2 in the atmosphere would be absorbed by the oceans. Not until the 1950s did scientists begin to recognize that the oceans' uptake of this gas is subject to strict limits. Finally, many scientists maintained a religiously inspired attitude of providentialism: they took for granted that, on balance, the Earth would remain suited to human habitability.

That is not to say, however, that the subject of climate change generated little concern in the 19th century. On the contrary, evidence of regional climate change was a matter of intense anxiety and debate. The possible climatic impact of deforestation, in particular, prompted vigorous policy debates in newspapers and parliamentary assemblies after 1850. Indeed, this highly public conversation was a major incentive for scientists to take up climate change as a research question. One will not find their expressions of concern in the journals of physics and chemistry in which men like Tyndall and Arrhenius published. Rather, to hear the voices of those who worried about climate change, the historian must turn to writings on geography, agriculture, forestry, and medicine. These disciplines took seriously both the possibility of anthropogenic impacts on climate and the consequences of climatic fluctuations for human wellbeing (e.g., Kropotkin, 1904; Ficker, 1921).

Researchers also paid careful attention to what they called weather "anomalies," meaning deviations from long-term averages. This was in keeping with Hann's insistence that variability was a defining characteristic of a regional climate. For instance, in the 1920s there was a spell of unusually mild winters in northern Europe, which drew the curiosity of many scientists at the time. Jacob Bjerknes still remembered it 40 years later, when he presented his theory of the relationship between variations in ocean surface temperature and the intensity of the atmospheric circulation (Kapala, Mächel, & Flohn, 1998). An early model for this avenue of research came from Hann's studies of extreme winters in Vienna and Greenland, begun in the 1870s. Drawing on the records of Protestant missionaries along the west coast of Greenland, Hann demonstrated the coincidence between unusually cold (warm) winters in Greenland and unusually warm (cold) winters in Vienna. Hann identified Greenland as a "center of action," that is, a region where anomalies tend to be most pronounced. This line of research made plausible the notion of "teleconnections," or see-saw effects between distant climates. Hann's statistical analysis rested on a simple contingency table. Just two years later, Francis Galton introduced the method of correlation, which Gilbert Walker first applied to questions like this in India in 1909. Ultimately, in the 1980s, the study of centers of action led to the first reliable seasonal forecasts, which play a vital role in agriculture throughout the global South today (Hense & Glowienka-Hense, 2010).

Science in the Service of Empire

What was responsible for inspiring this efflorescence of climate knowledge in the 19th century? The new science was, first and foremost, a practical endeavor, supported by modernizing states, concerned with climate in its relation to human life, and stressing human vulnerability to environmental conditions. Climatologists worked closely with government ministries of agriculture, trade, and health to produce vital information about the length of seasons, the likelihood of frost, the navigability of waterways and mountain passes, and the association of climatic conditions with dominant illnesses. Climatology was also a subject of research at non-governmental observatories founded by Jesuits in Asia, Africa, Latin America, and the Middle East, although more is known about their contributions to storm-forecasting than to climatology (see, e.g., Udías 1996). These practical goals were reflected in the focus on economically and physiologically relevant measurements, such as the distribution of rainfall and the duration of sunshine, as well as in the introduction of new variables, such as the "wintriness" of a region (defined, for the purposes of the winter tourism industry, as the number of snow days as a fraction of total precipitation days).

More specifically, climate science grew out of the political context of 19th-century empire-building (Amrith, 2018; Mahony & Endfield, 2018; Moon, 2013; Morgan, 2018). Because the overseas empires depended for navigation on knowledge of the winds and forecasts of storms, meteorology flourished in particular in London and Paris, as well as in colonial ports like Bombay, Madras, Hong Kong, and Singapore (Locher, 2008; MacKeown, 2011; Williamson, 2015; on monsoon science, see Amrith, 2018; on meteorology as a Japanese imperial science, see Zaiki & Tsukahara, 2007). In the course of the 19th century, both the British and the French empires consolidated what had been a loose network of intermittent weather informants into a modern meteorological network, in which military officers and medical professionals played key roles. As Richard Grove (1995) argued in a classic study, the British imperial network was critical to the emergence of a global vision of the Earth's climate. Correlations became apparent, for instance, between periods of drought in India and Australia. Colonial power and its hunger for raw materials likewise propelled European investigations of climate in the Arctic (Stuhl, 2016).

Throughout the colonial world, indigenous guides proved essential to the making of climate science.

However, settler colonial cultures rarely maintained a clear vision of climate. Often they found it difficult to relinquish expectations formed in a very different environment, expectations that clashed with indigenous understandings of climate and that inhibited their ability to learn from their surroundings (Davis, 2007; Endfield & Nash, 2002; Morgan, 2018). Continental empires, such as those of the Romanovs and Habsburgs, created different incentives for climate science. In these contexts, in which the line between colonizer and colonized was rarely sharply defined, climate science developed as a means of reasoning about the interdependence of an empire's parts. Climatology offered a schematization of the multiethnic state as an empire of complementary regions, each climatically suited to different crops and industries (Coen, 2018B).

Conclusion: Expanding the Horizons of the History of Climate Science

Climate science crystallized in the 19th century in part due to its unification of divergent knowledge traditions around standardized techniques of measurement and analysis. Yet its practitioners remained captivated by phenomena that eluded this synthetic program. In this respect, they were the descendants of the Romantics, of Goethe, Humboldt, Karl Ritter, and Luke Howard (Dettelbach, 1999), to whom many of them made frequent reference. They inherited the Romantics' sense of the splendor of clouds and storms. They too spoke of the Earth as a body with breath and pulse. Even as they sought to capture the workings of the atmosphere in differential equations, they maintained their appreciation for the variety, complexity, and reciprocity of natural phenomena.

It remains to explore exactly how this research program coalesced. Climate science was constructed out of a panoply of different ways of knowing. We need to understand better how this science emerged from exchanges across cultures and disciplines: between physicists and geographers, colonists and indigenous peoples, collectors and travelers, scholars and peasants, European writers and translators around the world. These processes continue to unfold today: increasingly, researchers studying the impacts of climate change are turning to local and indigenous experts as collaborators in the production of information tailored to their communities' needs. Yet such processes of exchange began more than a century ago. If we can see more clearly the historical roots of what we know today, we might be better equipped to design knowledge for the future.

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