Climatology

Julie A. Winkler
Michigan State University, USA

Climatology is a key component of contemporary physical geography. In this contribution to *The International Encyclopedia of Geography*, the evolution of climatology as a field of inquiry is summarized. In addition, the data sources available to climatologists, along with their limitations, are described, and the wide range of statistical methods and numerical models used in climatological research is highlighted. The various subfields of climatology are grouped into two categories, those that represent an analytical perspective and those that are thematic in focus, and are briefly described. Particular attention is paid to recent developments in applied climatology. Finally, the growing popularity of the terminology "climate science" and the consequent implications for the meaning of "climatology" are noted.

Evolution of climatology as a field of inquiry

Climatology is often described as either "the study of climate" or "the science of climate." These broad definitions, however, mask the evolution through time in the perceptions of what constitutes "climate," and the impact of these changes on the foci, objectives, and approaches of climatology. Danish science historian Matthias Heymann argues that climate "cannot be reduced to a clear, neat, and unequivocal definition;" but, rather, "its interpretation is closely linked not only to a state of scientific knowledge, but also to the broader cultural contexts of its time" (Heymann 2010, 82). Changes in the perception and interpretation of climate have not only influenced the nature of climatology as a field of inquiry, but also the positioning of climatology among, and within, other disciplines, including geography.

Climatology before 1900

The term climate originates from klima, a Greek astronomical term for the length of the longest day at different latitudes. In the third century BCE, Greek philosopher Eratosthenes described five latitudinal zones (two frigid zones, two temperate zones, and a tropical zone), distinguished by similar sun angles and day lengths, which he referred to as climates. Early climatological thought was strongly influenced by the philosophy of weather and climate espoused in *Meteorologica*, authored by Aristotle around 340 BCE. Another influential treatise was *On Airs, Waters and Places*, published around 400 BCE by Hippocrates, who attributed common diseases to locations, seasons, winds, and air.

The scientific era of climatology begins in the 1600s, when, as succinctly described by American mathematician H. Howard Frisinger, the study of climate moved "beyond the natural philosopher into the hands of the natural scientist" (Frisinger 1966, 444). Scientific breakthroughs that furthered an understanding of the Earth's climate included French mathematician Blaise Pascal's observations in the seventeenth century of the relationship between atmospheric pressure and elevation, and the

The International Encyclopedia of Geography.
Edited by Douglas Richardson, Noel Castree, Michael F. Goodchild, Audrey Kobayashi, Weidong Liu, and Richard A. Marston.

DOI: 10.1002/9781118786352.wbieg1131

development in the mid-eighteenth century of a conceptual model of the general circulation by British amateur meteorologist George Hadley. The invention, beginning in the late sixteenth century, of key meteorological instruments (e.g., thermometer, barometer, hygrometer, anemometer) led to systematic measurements of the atmosphere and also to the sharing of observations. Observational networks date to the mid-1600s and were commonplace by the late 1800s. According to geographer David Miller, these measurements provided climatology with numerical data for analysis before most other environmental sciences, and the term climatology became synonymous with the "ordering of any variable displaying an annual regime" (Miller 2005, 284). Science historian Heymann (2010) argues that with these new measurements, the intellectual focus of climatology shifted to climate's changeability (i.e., the temporal dimension of climate), with less emphasis on the spatial (i.e., geographical) dimension. Notwithstanding the strides made in providing a foundation for the physical explanation of climate, climate determinism also gained popularity during this period. The underlying belief of climate determinism is that the physical environment, particularly the climate, has a controlling influence on the development of human societies and cultures.

Substantial shifts in climatological thought occurred during the nineteenth century. Alexander Humboldt is often credited for refocusing climatology on the spatial, rather than temporal, variations in climate and, early in the 1800s, Humboldt prepared the first isoline map of the spatial distribution of annual temperature. The introduction in the late 1800s of long-term averages as a reference for comparing typical conditions between locations is attributed to Austrian meteorologist Julius von Hann. Climate classification also was used to describe the spatial variations of climate, and the well-known classification by German geographer Waldimir Köppen was first published in 1884. In the nineteenth century, climatology was primarily a subdiscipline of geography and meteorology and, to a lesser extent, of geology. Climate determinism remained popular among some groups throughout the nineteenth century.

The modern era of climatology

The modern era of climatology begins in the late nineteenth and early twentieth centuries. Early in this period, Norwegian meteorologist Vilhelm Bjerknes outlined the primitive equations (i.e., equations for the conservation of mass, momentum, and energy) for predicting large-scale atmospheric motion, and British mathematician Lewis Fry Richardson provided initial numerical techniques for solving these equations. Bjerknes and his colleagues, including his son Jacob Bjerkness and Halvor Solberg, also were responsible for the first conceptual models of extratropical cyclones, air masses, and frontal systems, providing a platform for relating the climate at a location to the frequency of different types of weather systems. Atmospheric teleconnections, defined as the relationships between distant atmospheric and sea-surface temperature anomalies, were first introduced by British physicist Gilbert Walker in the late nineteenth century, and by the second half of the twentieth century were widely used to explain interannual climate variability.

Energy and water fluxes between the atmosphere and Earth surface were another focus of twentieth century climatological research. The initial conceptualization of the energy budget is attributed to the work of Swedish physicist Anders Ångström in the 1920s, although numerical models of the energy balance were not developed until the late 1960s. In 1955, geographers Charles Thornthwaite and John Mather published their seminal monograph *The Water Balance*, outlining methods to estimate water surpluses, runoff, and recharge. Improvements in observations also contributed to advances in climatology. Regular balloon soundings of the upper atmosphere began in the 1930s and, from the 1970s onward, climatology benefited from the greater spatial and temporal coverage of satellite observations of the atmosphere and land surface.

In the second half of the twentieth century, concerns about anthropogenic contributions to climate change spawned an enhanced interest in climatology. In the 1850s British physicist John Tyndall discovered that atmospheric molecules such as carbon dioxide and water vapor absorbed thermal energy, and in the first half of the twentieth century global temperature was theoretically linked with changing carbon dioxide concentrations by Swedish physicist Svante Arrhenius and British engineer Guy Callendar. Yet, concern regarding the impact on climate of increasing greenhouse gases did not become widespread until after Carl Keeling initiated in 1958 systematic measurements of atmospheric carbon dioxide at the Mauna Loa Observatory in Hawai'i. Soon after, anthropogenic-induced land cover change was recognized as an additional forcing of local, regional, and global climate. With this heightened interest in the anthropogenic influences on climate came a greater interest in the temporal, rather than spatial, variations of climate. Although initial attempts to estimate trends in global surface temperature date to the early work by Köppen in 1881, published time series of globally averaged temperatures were not available until the 1970s and 1980s. These include, for example, the temperature time series produced by scientists at the University of East Anglia Climatic Research Unit in the United Kingdom, and at the US National Aeronautics and Space Administration Goddard Institute for Space Studies.

Climate models became essential tools for studying climate. Meteorologist Norman Phillips is credited with developing, in 1956, the first general circulation model of the atmosphere, and in the late 1960s and early 1970s climatologist Syukuro Manabe and oceanographer Kirk Bryan constructed and refined a coupled atmosphere and ocean model. By the early twenty-first century, global models were widely used to project future climate conditions, and archives of model simulations were established. Interest in paleoclimatic approaches to studying climate also increased during the modern era, in line with an evolving focus of climatology on the temporal variations of climate. As early as 1837, Swiss geologist Louis Agassiz proposed that the Earth had experienced past ice ages, and in 1941 Serbian astronomer Milutin Milankovitch related long-term climate change to cyclic variations in Earth motion (orbital eccentricity, obliquity, and precession). Beginning in the 1800s, proxy measures of climates, such as the growth bands in trees and deposits in lake beds, were recognized as a means to extend the climatological record backwards in time. Ice cores were first drilled in the 1950s, and, around the same time, analyses of deep-water corals suggested variations of ocean temperatures over glacial time scales.

Philosophical paradigms of climatology

The philosophical paradigms of climatology, particularly as practiced within geography, have shifted considerably over time. In the early twentieth century, climatology was heavily influenced by environmental (climatic) determinism, which at that time was a central theory of the discipline of geography. After environmental determinism fell out of favor in the 1920s, climatology as practiced within geography returned to a focus on the spatial differences in climate that was popular during the previous century, whereas the focus of climatology practiced within the discipline of meteorology was on the time-averaged components, or synthesis, of weather. From the mid-twentieth century until recently, philosophical paradigms were not extensively debated by climatologists, whatever the discipline with which they most closely identified. For the most part, climatologists comfortably worked within a positivist framework and employed the scientific method. American geographer Richard Skaggs contends that the lack of a widely accepted orthodoxy during this period, and the diversity of subject matter and methods, contributed to the rapid advancement of climatology from the 1950s onward (Skaggs 2004). But beginning with the early twenty-first century, climatologists became more cognizant of the paradigms that guide their work. Climatologists Gavin Schmidt and Steven Sherwood, for example, recently commented on the influence of climate models on climatological thought, pointing out that these models have led to the dominance of "the paradigm of understanding emergent properties of the complex system via the bottom-up agglomeration and interaction of small scale processes" (Schmidt and Sherwood 2015, 165). Interest in the coupling of climate and human systems also has grown and British geographer Mike Hulme has argued that geography should "reclaim climate from the natural sciences," where it is defined in physical terms only, and, instead, "treat it unambiguously as a manifestation of both Nature and Culture" (Hulme 2008, 6).

Data sources for climatological analyses

A large number of climate variables are used to describe the many facets of climate. Observations of these variables are essential for analyzing the spatial and temporal variability of climate. Climate variables can be measured directly or they can be estimated using remote sensing techniques. Worldwide routine in situ measurements include surface air pressure, maximum and minimum temperature, precipitation, humidity, wind direction and speed, and visibility. A global network of balloon soundings provides upper-air measurements of pressure, temperature, humidity, and wind speed and direction for multiple levels in the upper atmosphere. Satellite observations of the atmosphere began nearly fifty years ago. Observations are obtained from both Earth-orbiting satellites and geostationary satellites. Retrieved variables include, among others, surface land temperature, sea surface temperature, soil moisture, snow and ice cover, and precipitation estimates.

Although climatologists often collect atmospheric observations as part of field campaigns and maintain specialized observational networks for specific applications, the extensive use of historical climate data archives is a hallmark of climatology. Most often, these archives are maintained by national organizations, such as the US National Oceanic and Atmospheric Administration's National Centers for Environmental Information (formerly the National Climatic Data Center). Working with these archived observations can be challenging. Most observational networks were initially designed for short-range weather prediction, where the focus is on the accuracy and precision of measurements. While these qualities are also a consideration for climate monitoring, the temporal and spatial consistency of observations is as, or even more, important. Heterogeneities introduced into the historical climate record by changes in instrumentation, observation protocols such as time of observation, and station location complicate the use and interpretation of climate observations, particularly the interpretation of temporal trends. Consequently, identifying and adjusting for biases in time series of climate observations has been, and continues to be, an important aspect of climatology.

In addition to archives of "raw" observations, gridded fields of historical climate observations also are available. Gridded fields can be obtained by: (i) averaging anomalies or climatological values for stations located within a specified grid box (e.g., the Global Historical Climatology Network (GHCN) global gridded temperature and precipitation products); (ii) spatial interpolation of anomaly and climatological fields based on distance between observing stations, such as the global gridded monthly time series and climatological values of terrestrial air temperature and precipitation developed by the University of Delaware; or (iii) spatial interpolation that, in addition to distance, considers elevation (e.g., the WorldClim and Daymet datasets) or elevation and slope (e.g., the PRISM (parameter-elevation relationships on independent slopes model) gridded fields of temperature and precipitation). As noted by PRISM developer Christopher Daly, an important consideration when using gridded observations is that the fine resolution of many of these datasets can give an appearance of realism that is often not consistent with the spatial resolution of the initial observations (Daly 2006).

Reanalysis fields, first introduced in the late 1990s, are another popular data archive for climate research. These gridded fields are a "blend" of observations and model output. Very generally, for a particular time, the value of a parameter at a location is initially obtained from the short-term forecast of an operational weather forecast model and then modified by the surrounding current observations of the atmosphere. The spatial coverage of reanalyses ranges from regional (e.g., the North American regional reanalysis) to global (e.g., ERA-40 from the European Centre of Medium Range Forecasting), and the horizontal resolution varies from fine (e.g., about 38 km for the Climate Forecast System reanalysis) to coarse (e.g., 2.5° latitude × 2.5° longitude for the NCEP/NCAR reanalysis). Reanalysis fields are affected by biases associated with the operational weather forecast model and from the number and type of available climate observations; thus, they can deviate from observations especially in data-poor regions.

Archives of simulations from global and regional climate models are another important resource for climatological analysis. These simulations are useful for numerous applications, particularly for assessments of climate change impacts and adaptation. Simulations of historical and future climates obtained from global climate models developed by more than twenty modeling groups from different countries are available from the Coupled Model Intercomparison Project, phase 5 (CMIP5). Archives of finer-resolution simulations from regional climate models are also available. For example, the ENSEMBLES project distributes climate simulations for Europe for the period 1950–2100, that were obtained from regional climate models driven by reanalysis fields and multiple global climate models. For North America, multiple regional climate model simulations for two time slices (1960–1990 and 2040–2070) are available as part of the North American Regional Climate Change Assessment Program (NARCCAP).

Research methods in climatology

Climatologists employ a plethora of research methods, ranging from the simple to the complex, that are constrained only by the researcher's innovation. Statistical techniques and numerical modeling are, in particular, widely employed in climatological research and applications.

Statistical techniques

Statistical techniques are used for the extraction, quality control, and synthesis of climate information, and for establishing associations between variables. The calculation of long-term averages and the use of composite mapping are some of the first, albeit relatively simple, usages of statistical methods in climatology. For example, climate standard normals of temperature and precipitation, introduced by the World Meteorological Organization in the 1930s, are defined as 30-year averages, updated every decade, for individual stations. Composite maps, on the other hand, display the ensemble average of spatial fields of climate variables, and have frequently been used to identify the typical circulation patterns associated with a particular weather phenomenon, such as severe weather, or the typical temperature and precipitation patterns under different atmospheric teleconnections. Other early introductions of statistical methods to climatology include the use of parametric probability distributions to estimate the magnitude and return frequency of climate extremes. A classic example, dating to the 1960s, is the *Rainfall Frequency Atlas of the United States* authored by hydrologist David Hershfield, which provided extreme precipitation estimates for hydrologic design. Time series analysis also has been a cornerstone of climatological analysis. Linear and nonlinear regression methods have been, and continue to be, used to estimate temporal trends in climate variables, and techniques such as harmonic, spectral, and wavelet analysis are helpful for detecting interannual and interdecadal climate variability.

Climate classification also employs statistical techniques. The goal of any classification is to minimize intraclass variation while maximizing interclass variation. Classification has been used within climatology to summarize the spatial variations of climate and to identify frequently-occurring atmospheric circulation patterns. Early classifications were developed subjectively, such as the aforementioned Köppen classification scheme, which grouped locations based on average temperature and the amount and seasonality of precipitation, and the well-known catalog of circulation types for the British Isles developed by climatologist Hubert Lamb in the early 1970s. Over the past several decades, subjective classification methods have, for the most part, been replaced by computer-assisted approaches based on multivariate statistics. In particular, cluster analysis is frequently used to identify climate regions. Statistical approaches for identifying circulation types include correlation analysis, empirical orthogonal functions (i.e., principal components analysis), and self-organizing maps. A classic example is the use of empirical orthogonal functions by meteorologists John Wallace and David Gutzler in the early 1980s to identify wintertime teleconnection patterns for North America.

Statistical techniques are also used in climatology to downscale simulations from global and regional climate models to finer spatial and temporal resolutions, and to adjust for biases in the model simulations. An extensive literature exists that evaluates the efficacy of a range of techniques for this purpose, including regression procedures, canonical correlation analysis, artificial neural networks, support vector machine algorithms, and weather generators (Winkler *et al.* 2011 provides a review). The resulting empirically-downscaled and bias-corrected climate projections are frequently used in climate change assessments. Other uses of statistical techniques within climatology include the development of transfer functions to estimate climate parameters from proxy records of climate-dependent phenomena, such as the growth rings of a tree, quality control of observational data including tests for heterogeneities, and the spatial and temporal interpolation of atmospheric observations.

Numerical modeling

Numerical models are physically-based models developed using the principles of conservation, the first law of thermodynamics, and the laws of motion. Models are an important tool for improving the scientific understanding of the processes and internal dynamics of the climate system, evaluating responses of the system to perturbations, projecting future climate conditions, understanding the processes contributing to paleoclimates, and translating climate processes into useful information for applications and policy. Climatologists employ a variety of numerical models that differ in terms of their dimensionality and resolution, and by the number and types of the components of the climate system that are included in the model. The choice of model depends on the questions to be addressed or the applications for which the simulations are intended.

Examples of 1-D models include energy balance models, which are typically used to investigate latitudinal variations in surface temperature as a function of the Earth's energy balance, and radiative-convective models, which are single column models focusing on vertical variations but ignoring horizontal variations. Early 3-D climate models were atmosphere-only general circulation models. Although a coupled atmosphere–ocean model was first introduced in the 1960s, it was not until the late 1980s that atmosphere–ocean general circulation models (AOGCMs) were widely used. AOGCMs simulate the dynamics of the climate system, rather than only the atmosphere, and incorporate feedbacks between the atmosphere, ocean, and land and sea ice, allowing for more realistic modeling of interannual and longer-term variability of the coupled system. Earth system models (ESMs) expand on AOGCMs to include additional components of the climate system (e.g., the carbon cycle) and represent the current state-of-the-art in 3-D climate modeling. ESM simulations are routinely run for periods of a century or longer. In addition to ESMs, Earth system models of intermediate complexity (EMICs), are available. These models have more idealized representations of the climate system components, and are particularly useful for long (i.e., millennial) model integrations. As climate models became more complex, the acronym "GCM" evolved from its original meaning of "general circulation model" to the more general term "global climate model" that broadly refers to 3-D models of the global climate system. In addition to GCMs, limited-area 3-D climate models are also available. Referred to as regional climate models (RCMs), as they only examine a portion of the Earth's surface, RCMs typically have a higher spatial resolution than GCMs and can simulate sub-GCM-scale processes and distributions of climate variables. Lateral boundary conditions to drive a RCM are obtained from reanalysis fields or from GCM simulations.

The immense effort expended by climatologists to develop, evaluate, and apply climate models cannot be overstated. Through the efforts of climatologists and others, these models continue to increase in skill and scope. Furthermore, extensive effort has gone into producing the inputs needed for the initial and boundary conditions of climate models and the long-term, spatially-extensive datasets used for diagnostic evaluations. Maintenance of archives of multimodel simulations is another hugely cost and labor intensive effort, but archives such as

CMIP5 are essential for assessing model differences and uncertainty. In addition, climatologists have written extensively on the challenges of interpreting multimodel ensembles, which in effect are "ensembles of opportunity" with interdependent rather than independent members (Knutti 2010). Much effort also has been expended in developing procedures for downscaling climate simulations to scales appropriate for applications and for accounting for biases in simulations. A glimpse of the potential use of model simulations for climate assessments and decision-making was provided by geographer Linda Mearns and her colleagues who summarized the diverse applications of the RCM simulations from the NARCCAP archive (Mearns, Lettenmaier, and McGinnis 2015). Climate models are also a primary tool for evaluating the influence of land use/land cover change on local, regional and global climate. Thus, it is not difficult to understand why Schmidt and Sherwood (2015) refer to numerical simulation as the "new pillar of inquiry" in climatology.

Subfields of climatology

Climatology is routinely divided into subfields. Many different subfields have been proposed, representing differences in scale (e.g., microclimatology), techniques (e.g., statistical climatology), and thematic focus (e.g., building climatology), although there is usually considerable overlap between an individual subfield and other subfields. The subfields also differ considerably in the number of adherents, and the popularity of different subfields has waxed and waned with time. For this entry, subfields within climatology are grouped by whether they represent a different perspective on climatological research or whether they are primarily distinguished by a thematic focus.

Subfields as analytical perspectives

Several subfields of climatology reflect different perspectives to climatological inquiry; namely, physical climatology, dynamic climatology, synoptic climatology, and paleoclimatology. Physical climatology is primarily concerned with the interactions between the Earth's surface and the atmosphere, including the spatial and temporal distributions of energy, moisture, and momentum exchanges. One focus area of current significance is the role of surface cover types on climate. Physical climatologists are interested in energy and mass exchanges from the micro to the global scales. Physical geography is characterized by the extensive use of numerical models, ranging from simple to complex, although other analytical procedures including statistical techniques are also employed.

Dynamic climatology and synoptic climatology are closely related. In general, dynamic climatology refers to the climatology of atmospheric dynamics and thermodynamics. Dynamic climatologists often, but not exclusively, focus on atmospheric circulation at the global scale and are concerned with climate variability at longer (i.e., interannual) time scales. Synoptic climatology, on the other hand, is concerned with the relationship between the atmospheric circulation and local or regional climate. Synoptic climatology takes the viewpoint that climates differ because their component weather types and the frequencies of these weather types differ, which in turn are affected by atmospheric circulation at a range of scales from planetary to regional. Historically, dynamic climatology has emphasized the use of numerical modeling, whereas empirical methods, particularly classification methods, were widely used in synoptic climatology. This distinction has blurred, however, with statistical techniques (e.g., empirical orthogonal functions) frequently used in dynamic climatology and with numerical models (e.g., GCMs, RCMs) now an essential tool in synoptic climatology.

The historical perspective on climatology is provided by paleoclimatology. Here the focus is on reconstructing past climates (usually before the start of the instrumental record) and linking these proxy records to atmospheric circulation. Climate reconstructions make use of pollen analysis, tree-ring dendrochronologies, lake and river sediments, stratigraphic variations in the chemical and dust content of cores obtained from ice caps, and other proxy measures. Statistical techniques are used to develop the transfer functions between the proxy measures and other time series of climate variables (e.g., temperature and precipitation), and climate models are used to simulate past climates in order to understand the mechanisms for past climate changes and to extrapolate between the local and global scales of paleoclimates.

Thematic subfields

Innumerable thematic subfields of climatology can be defined. Of these, urban climatology, hydroclimatology, bioclimatology, and agricultural climatology are particularly active areas of climatological inquiry.

Urban climatology originated in the late 1800s and initially was descriptive in nature, primarily focusing on observational studies and the characterization of the urban heat island (i.e., the elevated temperatures of urban areas compared to surrounding rural environments). With the development of numerical models, the focus of urban climatology shifted to energy and momentum exchanges in the urban environment at all spatial scales, although micro- and mesoscale environments such as urban canyons have been of particular interest. Other areas of active research in urban climatology include air quality, urban forestry, biogeochemical cycles, water movement and storage, and the potential impacts of climate change on the urban environment.

Hydroclimatology, often described as the study of the influence of climate on hydrologic events, emphasizes the interface between the atmosphere and terrestrial water. All aspects of the hydrologic cycle, including precipitation variability, floods and droughts, snowfall and snow cover, river discharge, and groundwater recharge, are investigated, using a range of methods from descriptive summaries to numerical simulations.

Bioclimatology focuses on the interactions between the atmosphere and living organisms. Interest in the influence of climate on biota dates to Hippocrates; thus, bioclimatology is one of the oldest subfields of climatology. Bioclimatolgy is a diverse subfield, with research ranging from changes in plant development, including trends and interannual variability in the timing of the spring immergence of plants, to the influence of extreme heat events on human mortality. The analytical approaches used in bioclimatology are as diverse as the topics studied. Although agricultural climatology can be considered a part of bioclimatology, it is often singled out as a separate subfield because of the extensive work in this area and its economic significance. Research within agricultural climatology ranges from climate-crop interactions at the field and subfield scales to climate influences on global food security.

The "new" applied climatology

Applied climatology is often considered to be a subfield of climatology. In his classic textbook *General Climatology*, which was published in 1960, geographer Howard Critchfield claimed that applied climatology is one of three major subdivisions of climatology, along with physical climatology and regional climatology. Since then, few textbooks and other references have been published without specific mention of applied climatology. However, this distinction as a subfield masks that applied climatology, or at least modern-day applied climatology, draws on, and incorporates, any of the analytical perspectives of climatology and, moreover, can be situated in any of the thematic subfields of climatology. In other words, applied climatology crosses all the subfields (analytical and thematic) of climatology and even extends into the social and policy sciences.

British geographers John Thornes and Samuel Randalls argue that, in spite of considerable interest in applied climatology in the mid-twentieth century, and even calls by prominent climatologists such as Werner Terjung and Stanley Changnon for climatology to address real-world problems, it was not until the late 1990s, with rising concern about climate change, that applied climatology became an interdisciplinary endeavor involving both natural and social scientists (Thornes and Randalls 2014). Prior to this, climate had primarily been treated as a hazard or risk, and applied climatology involved mostly natural scientists. Geographer Marc Tadaki and his colleagues explain that the aim of applied climatology in the 1960s and 1970s was "not to explain social life, but the far more pragmatic one of optimizing economic returns and biophysical indicators" (Tadaki, Salmond, and Le Heron 2014, 397). They contrast this with the current status of applied climatology, arguing that "climate applications have never been more embedded into human organizations than at present" (Tadaki, Salmond, and Le Heron 2014, 399).

Much of the early work in applied climatology could also be thought of as applied in potential but not necessarily in practice, with the choice of problem often selected by the climatologist and findings simply handed off to potential users. Recognition of the limitations of this top-down approach is leading to greater calls for the coproduction of knowledge by climatologists, stakeholders, and representatives from other relevant disciplines, who work together to outline concerns and goals, jointly identify options for mitigation and adaptation, and then evaluate the potential co-benefits and negative externalities of different options. This strategy is much more time consuming than top-down approaches but offers an exciting new direction for applied climatology and increased potential for more informed decision-making.

The future of climatology

Over the last few decades, the study of climate has expanded dramatically. Geographer Andrew Carleton contends that "climatology has become a subject of active research in disciplines that formerly either eschewed it (e.g., meteorology and atmospheric sciences) or had little need for such studies (e.g., geology)" (Carleton 1999, 714). Moreover, climatologist Hervé Le Treut and his colleagues note that, in addition to greater interest in climatology, the scope of climatology also has expanded and is "now far more wide-ranging and physically comprehensive than was the case only a few decades ago" (Le Treut *et al.* 2007, 98).

Much of this expansion can be attributed to increased interest in, and concern with, natural and anthropogenic climate change. Environmental scientists Michael Grieneisen and Minghua Zhang recently queried the Web of Science database to identify publications related to climate change during the period 1997–2009 and found that the number of publications had increased exponentially with over 100 000 publications reporting climate change-related research during this period (Grieneisen and Zhang 2011). They point out that this total is equivalent to the research output of major scientific disciplines. Climate is now studied across a range of disciplines, although Grienseien and Zhang found that, with the exception of economics, the social sciences remain underrepresented compared to the natural sciences. Furthermore, Andy Reisinger argues that, in spite of cross-disciplinary interest, climate-related research has been slow to integrate the insights and contributions of different disciplines within an individual research program but, instead, remains primarily "multidisciplinary" rather than fully "interdisciplinary" in character (Reisenger 2011).

Even though the future for the study of climate is bright, the future of the term "climatology" is in question. More and more, the study of climate is referred to as "climate science" rather than "climatology," with the meaning of "climatology" instead constrained to the description, often using statistical methods, of the spatial and temporal characteristics of climate. This change mirrors nomenclature changes occurring in meteorology, where "meteorology" is being replaced as the umbrella term for the study of the atmosphere with "atmospheric science." Proponents of this nomenclature change argue that the "climate science" terminology is more encompassing and better portrays the increased use of numerical models, more frequent multidisciplinary participation, and greater recognition of the human dimension in the study of climate. Further evolution in the meaning and usage of "climate science" and "climatology" can be expected in the future.

SEE ALSO: Atmospheric/general circulation; Climate change, concept of; Climate and societal impacts; Climatology: history; Dendroclimatology; Earth system science; Earth's energy balance; Global climate change; Global climate models; Hydroclimatology and hydrometeorology; Paleoclimatology; Temperature; Urban climatology; Water budget

References

Carleton, Andrew M. 1999. "Methodology in Climatology." *Annals of the Association of American Geographers*, 89: 713–735.

Daly, Christopher. 2006. "Guidelines for Assessing the Suitability of Spatial Climate Data Sets." *International Journal of Climatology*, 26: 707–721.

Frisinger, H. Howard. 1966. "Rene Descartes. The Last of the Old and the First of the New Meteorologists." *Weather*, 21: 443–446.

Grieneisen, Michael L, and Minghua Zhang. 2011. "The Current Status of Climate Change Research." *Nature Climate Change*, 1: 72–73.

Heymann, Matthias. 2010: "The Evolution of Climate Ideas and Knowledge." *WIREs Climate Change*, 1: 581–597.

Hulme, Mike. 2008. "Geographical Work at the Boundaries of Climate Change." *Transactions of the Institute of British Geographers, NS* 33: 5–11.

Knutti, Reto. 2010. "The End of Model Democracy?" *Climatic Change*, 102: 395–404.

Le Treut, Hevré, Richard Somerville, Ulrich Cubasch, *et al.* 2007. "Historical Overview of Climate Change." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Susan Solomon, Dahe Qin, Martin Manning, *et al.*, 95–127. Cambridge: Cambridge University Press.

Mearns, Linda O., Dennis P. Lettenmaier, and Seth McGinnis. 2015. "Uses of Results of Regional Climate Model Experiments for Impacts and Adaptation Studies: The Example of NARCCAP." *Current Climate Change Reports*, 1: 1–9.

Miller, David. 2005. "History of Climatology." In *Encyclopedia of World Climatology*, edited by John Oliver, 283–289. Dordrecht: Springer.

Reisinger, Andy. 2011. “Interdisciplinarity: Are We There Yet? An Editorial Comment.” *Climatic Change*, 108: 23–30.

Schmidt, Gavin A., and Steven Sherwood. 2015. ‘A Practical Philosophy of Complex Climate Modeling. *European Journal for Philosophy of Science*, 5: 149–169.

Skaggs, Richard H. 2004. “Climatology in American Geography.” *Annals of the Association of American Geographers*, 94: 446–457.

Tadaki, Marc, Jennifer Salmond, and Richard Le Heron. 2014. “Applied Climatology: Doing the Relational Work of Climate.” *Progress in Physical Geography*, 38: 392–413.

Thornes, John E., and Samuel Randalls. 2014. “Applied Meteorology and Climatology.” *Progress in Physical Geography*, 38: 389–391.

Winkler, Julie A., Galina S. Guentchev, Perdinan Pang-Ning Tan, *et al*. 2011. “Climate Scenario Development and Applications for Local/Regional Climate Change Impact Assessments: An Overview for the Non-Climate Scientist. Part I: Scenario Development Using Downscaling Methods.” *Geography Compass*, 5/6: 275–300.

Further reading

Barry, Roger G., and Eileen A. Hall-McKim. 2014. *Essentials of the Earth’s Climate System*. Cambridge: Cambridge University Press.

Hidore, John J., John E. Oliver, Mary Snow, and Rich Snow. 2009. *Climatology: An Atmospheric Science*, 3rd edn. New York: Prentice Hill.

McGuffie, Kendal, and Ann Henderson-Sellers. 2014. *A Climate Modelling Primer*, 4th edn. New York: John Wiley & Sons.