CLIMATOLOGY: FUNDAMENTALS AND APPLICATIONS

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PREFACE

Many current textbooks in climatology provide broad surveys of the whole field or deal in depth with some limited aspect of the subject matter. It might seem that another textbook, especially at the introductory level, would hardly be necessary. This volume exists not because of the author's desire to discuss anew the basic facts of climatology in a slightly different format but rather because of the author's strong conviction that the present approach to the field of climatology at the introductory level is wrong for many of today's students.

There is no question that a sound foundation in the elements of any subject matter is absolutely essential for comprehension of that field. Many older textbooks in climatology attempt such an approach; as a result they often include "dry as dust" discussions of the nature of the basic weather elements, their distribution both in space and time, and their relation to the distribution of soils and vegetation. The approach undoubtedly has turned off many bright students and left them with the feeling that climatology is far from dynamic, less than relevant, and of little use except to those interested in static distributions and statistical displays. The result has been apathy or even rejection at a time when the field should have been rapidly developing a new role for itself in a world concerned with the interrelation of man and his environment.

This volume represents an attempt to reverse old approaches to introductory climatology and to present the field in a way that will, it is hoped, challenge a number of today's students to delve further into the field. It should, at least, encourage all students to seek new ways to live rationally within their climatic environment. The present approach seeks to provide enough discussion of the basic elements of climate and weather to provide an understanding of their nature. However, it concentrates its main thrust on the uses of the climatic information in various aspects of our lives—hydrology, agriculture, health, comfort, clothing, architecture, commerce, and industry. It is felt that if beginning students in climatology (or even those with a sound background in the basic elements of weather and climate) can be shown how knowledge of climate permits us to live and to work more comfortably and economically, many will want to pursue the field in greater depth. Today's student wants to see the need, the application, and the value of a subject before expending significant effort in its study. Applied climatology has much to offer in this respect if only we will introduce it to the student before he or she is overwhelmed by pages of descriptions about climatic distributions or the seasonal changes in conditions in remote areas of the earth.

The book requires no background in climatology, physics, or mathematics, although clearly if the student has such background he will be able to achieve a greater depth of understanding. The first chapter describes briefly the history and applications of climatology in general and provides some specific comments on types or classes of problems that require climatic information for their solution. Since heat- and water-budget approaches to climatology are emphasized, the second chapter (on basic climatic elements) devotes most of its attention to the factors of radiation, temperature, atmospheric moisture, and evapotranspiration. The third chapter describes the water-budget approach to climatology in some detail. The level of generalization shifts from the annual global balance, to the balance of the Northern Hemisphere, to the balance over North America, and ultimately to the water budget at a particular place. Chapter 4 utilizes the water-budget approach in the field of climatic classification and shows how the factors of the water budget correlate with the distribution of vegetation in North America.

The remaining seven chapters in the book describe current and past work in the field of applied climatology. The effort here is to show how climate affects nearly all aspects of our lives and how, through an understanding of climate, we can better adjust our activities to our atmospheric environment. Chapter 5 describes how the water budget relates to problems in hydrology and water resources, while Chapters 6 and 7 discuss the role of climate in agriculture. Both heat- and water-budget approaches are fundamental in agricultural relations. Chapter 8 focuses on problems of clothing and human comfort. The approach examines the heat fluxes between the body and the outside environment and the problems of maintaining a nearly constant body temperature. Chapter 9 describes our present understanding of the effect of climate on human health and includes discussions of air pollution as well as urban heat-island problems. Chapter 10 introduces the role of climate and building design, pointing out how most current developments in building have produced houses that are at odds with their environments; indoor comfort can thus be achieved only through mechanical devices at additional expense to the homeowner. Finally, Chapter 11 considers the role of climate in industrial production, commerce, business, and engineering. Just the normal day-to-day changes in weather can result in significant economic gains or losses to the businessman because of weather effects on both production schedules and purchasing habits.

Each of these last seven chapters deserves a book in its own right; at the same time many books have already been written covering just the materials in Chapters 2 and 4. Thus much has had to be eliminated or greatly condensed to keep within the bounds of a practical length. The text abounds in references to other works, and many of these should be utilized to amplify the brief discussions included in the book. If the book is used in a beginning course in climatology, Chapter 2 might be expanded by reference to other basic texts. If it is used in a more advanced course in which the students have had some background in weather or climate, Chapter 2 can be passed over rapidly and more time spent on the applications of climatic data to specific problems.

I would like to express my appreciation to all the many individuals and groups who have helped in the preparation of this book in any way. Special thanks must be extended to those who have given permission to use material from other books, journals, or reports. Some may not be acknowledged in the text, but only through oversight on my part. To these, I extend my sincere apologies, for without the help and cooperation of many, this work would not have been possible. To the staff of C. W. Thornthwaite Associates Laboratory of Climatology must go especial appreciation not only for permission to use many diagrams and other materials but also for their great help over the years in assisting in the collection of many of the basic data used here. And to Dr. F. Kenneth Hare of Environment Canada and the University of Toronto as well as to the other reviewers, my thanks for very sympathetic and helpful suggestions. Finally, to my wife must go my special appreciation for her patience and understanding through unnumbered months while this book was in preparation; and to my secretaries Mrs. S. Helen Bano, who typed the first draft, and Mrs. Marie Donaghay, who cheerfully typed later drafts and revisions, I extend my thanks for their great help.

JOHN R. MATHER

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CLIMATOLOGY— HISTORY, TOOLS, AND TECHNIQUES OF PROBLEM SOLVING 1

INTRODUCTION

Most scientific undertakings are concerned with the useful application of the results. Seldom is scientific work attempted without at least some thought as to its ultimate utility to the investigator. New and unexpected knowledge can, of course, be obtained during a scientific investigation and results emerge that are entirely unanticipated. No immediate application of the results may be visualized at the time. While some of our great scientific discoveries result in this way, it is apparent that the great bulk are the product of directed research—studies undertaken with a purpose, seeking results that can be applied to some practical problem confronting mankind.

The results of scientific work in one field are sometimes applied to problems in entirely different fields. Such investigations are often undertaken by teams of scientists from different backgrounds. By working together, they are able to focus their knowledge on a particular problem that may be influenced by factors in one or more neighboring disciplines.

Climatology, an old field of scientific investigation in its own right, has many contacts with other fields. Climate influences agricultural and industrial operations, hydrology, geology, health and disease, forestry, transportation, and many other fields of human endeavor. Because of this interdisciplinary influence, climatology becomes a prime field for (1) the application of its knowledge to problems in other fields and (2) the application of a team approach to problem solving.

It is clear that weather data are indispensable in planning many agricultural, industrial, engineering, or resource-use activities. Most of these applications of meteorological data do not necessarily involve any short-range weather forecast but rather some knowledge of past and existing weather elements in an area, including the understanding of frequencies and extremes of weather conditions. Such knowledge can be used to evaluate the likelihood of some future event, but a short-range, specific forecast of the actual occurrence of certain events is not the major aim of the applied climatologist. Rather, his goal is to use his knowledge of the influence of different weather elements on various environmental factors to provide information on how individuals can better adapt their lives and activities to the given or expected climatic conditions for more comfortable, efficient, and inexpensive living.

If weather is considered to be the instantaneous picture of various atmospheric elements such as radiation, moisture, pressure, wind, and temperature, then climate is defined by some to be the statistical summary, the averaging of the individual weather elements over a period of time. Such a definition of climate is too restricted for it emphasizes only the statistical approach and infers that it is nothing more than average weather. Weather is the condition of the atmosphere at a given moment at a given place. Climate, therefore, is the characteristic weather considered for longer periods—days, months, seasons, years—and for larger areas. Climate does refer to average conditions, but it also refers to the extremes of weather and to the probability or likelihood of different events occurring at a place or over a region. Climatology does involve statistics, but the statistics should be used only as an aid in describing the fluctuations or changing nature of climate, its long-term variability or trends, and the interrelated influence of all the weather elements.

Applied climatology can be considered to be the analysis and application of climatic data for some specific operational purpose (Landsberg and Jacobs, 1951). Table 1-1 lists just a few of the many operational purposes to which climatic data are now being applied. It suggests something of the wide range of interests facing an applied climatologist.

RECENT HISTORY

By the beginning of the nineteenth century, when climatological records were becoming more commonplace, great interest was focused on the influence of climate on particular operations or undertakings. Thomas Jefferson, Alexander von Humbolt, and others called for the collection of systematic climatological records for the express purpose of answering specific questions involving agriculture, crop introduction, health, and soil conservation. Before 1820, several orders of the Surgeon General of the United States directed that weather observations were to be taken by the Post Surgeons to provide data which could be used in answering questions about the effect of climate on the health of troops in remote outposts, on "medical topography . . . prevalent regional complaints . . . change of climate . . . cultivation of soil . . . density of population . . ." (U.S. Weather Bureau, 1955, p. 2).

In the years following, however, developments in synoptic meteorology which followed the introduction of the telegraph, in weather forecasting, and later, in aeronautical meteorology overshadowed the original interest in applied climatology. About the only phase of applied climatology that was able to develop was agricultural climatology. The Federal Weather Service had been established in the Signal Office of the U.S. Army in 1870. Recognizing the great potential value of weather and climatology to agriculture, the Weather Service was transferred from the Army to the Department of Agriculture in 1891 and became the U.S. Weather Bureau. Within the first few years of its existence the Weather Bureau published a number of important works on various phases of agricultural climatology. Those by Hilgard (1892), Whitney (1892), Mell (1893), and Abbe (1905) are classic studies well worth reading even today. These works charted lines for later, more detailed agricultural climatology studies. The Climate and Crop Weather Division was established in the Weather Bureau in the mid-1890s, and its work has continued to this day.

As the twentieth century started, the airplane became a reality and the Weather Bureau found a new and challenging field for its services—

TABLE 1-1

Applied climatology in action

COMMUNITY ACTIVITIES	HUMAN ACTIVITIES
Climatic effects on	Climatic effects on
Air pollution abatement and regulation	Physiological responses
Water supply planning	Health, morbidity, and mortality relations
City design and layout	Acclimatization
Land-use planning	Clothing requirements
Traffic hazards	House design and characteristics
Severe storm hazards	Heating and cooling requirements
Highway, bridge, culvert design	Sports activities
INDUSTRIAL AND COMMERCIAL ACTIVITIES	**AGRICULTURAL ACTIVITIES**
Climatic effects on	Climatic effects on
Plant operations, water supply, and pollution dispersion	Land-use planning
Product design and engineering	Agricultural pests, diseases, viruses
Product sales planning	Yield
Weather insurance	Freeze probabilities, frost-free periods
Transportation, storage of raw or manufactured materials	Rainfall frequencies, irrigation needs
Plant absenteeism, accidents	Crop scheduling
Utility operations	Weather insurance
Aircraft, ship, rail systems	Forest fire probabilities
	Soil tractionability
	Coastal fisheries activities

aeronautical meteorology. Less time was available for agricultural climatology. By 1926, the Weather Bureau became officially responsible for weather services to civil aviation, and by 1940, the Weather Bureau was transferred from the Department of Agriculture to the Department of Commerce. Both surface- and upper-air studies, largely for the purposes of aviation or weather modification, became increasingly significant.

Applied climatology, both agricultural and industrial, began to redevelop a role for itself after World War II. First, during the war, the need to have climatic information from many different parts of the globe and to apply these data to military operations or to the supplying and equipping of troops brought to the fore the vital role that the applied climatologist could play in an increasingly complex world. Second, the development of high-speed electronic computers that could assimilate, analyze, and present in tabular form vast quantities of climatic data made it feasible to apply some of our large store of weather data to the practical problems of weather influence. Third, the large supply of trained meteorologists, needed during the war effort but who were then being released into civilian life, provided the nucleus of skilled workers to begin the attack on problems of applied climatology.

Woodrow Jacobs (1947) published a classic monograph entitled "Wartime Developments in Applied Climatology" in which he detailed a number of different types of problems that applied climatologists faced during the war and indicated the kinds of solutions that were possible. This monograph undoubtedly had an impact on some of the meteorologists just being released from military service, and a number of them moved into the industrial applied climatology field.

The stage is now set for a redevelopment of applied climatology. While many recent developments in the industrial and consulting aspects of weather have related to weather forecasting or weather modification, there are other movements toward the development of useful applications of climatology for operational purposes. In the long run, these developments may be of as far reaching significance as the work on forecasting and weather modification.

THE TOOLS OF APPLIED CLIMATOLOGY

What are the tools with which the applied climatologist works? Quite clearly they are, in part, the meteorological data collected daily and hourly by observing stations around the world. The amount of material so available is staggering in quantity, yet the standard summaries based on these data leave much to be desired as far as the applied climatologist is concerned. Mean-value climatologies of temperature, precipitation, or other basic meteorological factors often do not provide summaries that are particularly pertinent or useful. The applied climatologist might, in a given study, need information on the occurrence of dew, the composition of precipitation, the weight of snow, the rate of snowmelt, the rate of icing on exposed surfaces, the depth of freezing of the ground, the soil moisture content, the evapotranspiration, the wind shear, the distribution of vertical winds, or on the factors of the heat balance, just to name a few possible items. Information on these and other similar factors is not generally available. Here the applied climatologist must (1) interpolate data between more distant observing points, (2) substitute some available observations for the required but not observed data, or (3) supply missing data based on past experience or known data from similar environmental situations. To be successful the applied climatologist must always be ready to bridge the gap between available and required observation.

Early Instrumental Observations in the United States

Rev. John Campanius took the first known surface weather observations in America at Swedes Fort, Delaware, in 1644–1645. The first use of the Fahrenheit thermometer to record air temperature in America probably dates back to Dr. John Lining of Charleston, South Carolina, in 1738. Dr. Lining took systematic observations under the sponsorship of the local medical society from 1738 to 1750. Weather diaries became more prevalent in the early 1800s as interest in climate and in its effect on the health and activities of man, especially in the more remote areas of the West, gave rise to the rapid collection of instrumental observations of climate. Dr. Samuel Forry attempted the first comprehensive summarization of available records in 1842 in a publication entitled "The Climate of the United States and its Endemic Influences." Lorin Blodget (1857) published the first maps of seasonal and annual precipitation of the United States in 1857. Based on data from about 400 weather stations, Blodget's map only approximates the areal distribution of precipitation as we understand it today, but his contribution to climatology and his insight into the fundamental facts of climate mark his work as one of the foremost in the field of climatology for half a century. Our own map of precipitation may indeed seem crude in comparison with later maps to be produced from more advanced sensors possibly carried over both land and water areas of the globe by satellites a few years hence.

At about the same time, J. H. Coffin (1853, and later in 1875) published comprehensive memoirs on winds over the Northern Hemisphere, while C. A. Schott (1872, 1876) prepared tables and maps of precipitation and temperature over the United States and other areas of North and South America. Blodget, Coffin, and Schott, like Dr. A. H. Guyot who authored the Smithsonian Meteorological Tables and prepared extensive instructions on meteorological instrumentation, its calibration, and its installation, all carried out their pioneering work under the direction of Joseph Henry, first Secretary of the Smithsonian Institution. High on Henry's list of research objectives was the desire to extend the network of meteorological observations for the purpose of understanding American storms. As a result, he pushed the Institution into the very forefront of American climatology, establishing observation networks, collecting, tabulating, and analyzing data, and publishing scientific memoirs and reports of highest quality.

The number of precipitation stations in the conterminous United States increased from about 400 in Blodget's time to 3,000 in 1891 when the

Weather Bureau was established, to 4,500 in 1930 and to about 10,000 by the 1940s. There has not been any great increase since that time. If all 50 of the United States as well as island possessions are considered, the observing network includes some 12,000 to 15,000 stations measuring at least precipitation on a daily basis. About 5,000 of these stations are designated as part of the permanent climatic network, taking, in addition, observations of maximum and minimum temperature each day as well as notes on frosts, thunderstorms, and other limiting weather conditions.

Upper-air observations, as valuable to the meteorologist as surface weather observations, developed only slowly. Originally only mountain stations were able to provide records of conditions at elevations much above sea level but even these stations were not truly upper air. Benjamin Franklin used kites for upper-air investigations, but it was not until 1893 that the Chief of the Weather Bureau first asked Congress to appropriate some money for upper-air kite observations. In the same year, Hargreave in Australia used a series of box kites to obtain observations to over 9,000 m (30,000 ft)!

Some observations had been made before that time by observers in manned balloon flights, but no systematic observations were possible. Pilot balloon observations (following the flight of a free balloon) to obtain winds aloft developed during World War I as did the direct measurement of upper-air pressure, temperature, and humidity by airplanes.

The first successful radiosonde ascent (a radiosonde is a lightweight meteorograph and radio transmitter attached to a small balloon, capable of sending signals of pressure, temperature, and humidity to a ground observatory) was made in 1928 by the Russian meteorologist Moltchanoff. The first United States ascent did not occur until 1935 but with it came the end of the airplane observing program, which was limited by weather conditions and expense. The number of radiosonde observing stations operated by the various United States weather services increased from 6 in 1937 to a peak of 335 in 1945 and has leveled off at about 200 in more recent years. The impact of World War II on the weather observation program of the United States cannot be overemphasized.

During the Fourth World Meteorological Congress in Geneva in 1963, the concept of a World Weather Watch was approved. Actual plans were adopted at the Fifth Congress in 1967. The purpose of the Watch was to encourage all member nations of the World Meteorological Organization (WMO) to join in the collection and analysis of meteorologic data on a worldwide basis. Such a program would provide an unprecedented opportunity for all nations to contribute to the solution of pressing observational and analytical problems as well as to derive increased benefits from the improved meteorological services such a cooperative effort would make possible. One basic aspect of the World Weather Watch was to be a Global Observing System (GOS) optimizing the density of stations for sampling purposes. Table 1-2 provides a tabulation of the number of stations in the GOS, by continent, as of the end of December 1970. Other aspects of the Watch were improved data transmission, storage and retrieval systems, as well as greatly expanded observations from the ocean areas of the globe by means of ships, buoys, and satellites.

Data Processing

Before 1940 there was essentially no centralized weather data processing facility in existence—certainly a necessary adjunct to the establishment of any large-scale climatic observing network. The British, Dutch, and Czechoslovakian meteorological organizations had used punched cards in the production of climatic summaries of marine meteorological data in the 1920s, and a WPA project established in New Orleans in 1934 had begun to explore the utility of weather data processing, but the great explosion of interest in the use of high-speed data processing waited for (1) the development of the need for a large number of weather summaries from many different places and (2) the development of equipment to do the job rapidly and accurately.

Actually, H. Hollerith, working in the U.S. Bureau of the Census in 1890, was possibly the first to employ punched cards quite similar to those now in use in the tabulation of data—in this case census data. He first had to develop equipment that could be used to read the data from the cards. Five years later, Commander C. D. Sigsbee, the Hydrographer of the United States, pointed out the value to climatology of the electrical tabulating system devised by Hollerith, but developments along these lines moved exceedingly slowly and for many years thereafter, hand-tabulated summaries of data were still the only climatic records available. With the great increase in the number of observing stations, the problem of data evaluation finally became so formidable that increased use of electrical data tabulating and processing equipment became necessary.

TABLE 1-2

Number of surface and upper air stations, Global Observing System, World Weather Watch, as of Dec. 31, 1970*

AREA	SURFACE		UPPER AIR (RADIOSONDE/RAWINSONDE)
	0000†	1200†	0000†
Africa	511	644	74/88
Asia	875	885	188/200
South America	298	315	35/32
North America	444	447	147/147
South Pacific	314	259	68/91
Europe	835	849	142/141
Antarctic	24	24	11/11
Total	3,301	3,423	665/710

* *Adapted from WMO, 1970, pp. I-11 to I-26.*

† *Observation hour.*