CLIMATE
Present, Past and Future

H. H. LAMB

Volume 1

Fundamentals and Climate Now

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The study of climate necessarily involves the collection and processing of large amounts of data gathered from all parts of the globe, but for many years meteorologists could do little more than to identify and describe the main climatic zones of the Earth. We are still a long way from a complete dynamical and physical explanation of climatic features, but it is now recognized that a proper examination of the long-term and large-area aspects of atmospheric variations must be as deeply rooted in physics as is the study of transient weather systems. The author of this work is a professional meteorologist who has spent his life among mathematicians and physicists, and it is natural that his account of climate begins with its fundamental physical aspects. But climatology is more than a branch of physics and it is in the wider aspects of its study that the unique nature of this book lies.

The climatologist has to consider not only what is happening today, as revealed by the vast amount of information collected every day by the national weather services, but also what happened long before man invented instruments to measure and record the atmospheric elements. He has to call on many fields of knowledge for his facts—on history, geography, archaeology and geophysics, to name but a few. The essential clues to past variations of climate may have to be sought in the story of the wanderings of primitive peoples in search of food, or equally, by the analysis of ice deposited centuries ago in Greenland.

Mr Lamb is recognized, not only in Great Britain, but in all countries of the world as a leader (if not the leader) in this work. He is a man of wide learning and boundless energy who has devoted his life to the study of climate by all possible means. His eminence in this work was recognized some years ago when he was awarded a Special Merit Promotion in the Meteorological Office to enable him to engage in his researches without the trammels of routine duties. He is now to enter academic life as the Head of the newly formed Climatic Research Unit of the University of East Anglia.

This is the book that I always hoped Mr Lamb would write. It is a treasure house of information gathered in a lifetime of dedicated work. I know of no other work in this field that approaches it in scope and reliability. I have no doubt that what I have been reading are the proofsheets of a classic of meteorology, and that here, if anywhere, climatology really enters into its own.

Sir Graham Sutton,
C.B.E., D.SC., F.R.S.,
formerly Director-General of the Meteorological Office

Introduction

This book is a study of the development and history of climate. It is intended to meet a variety of needs. Students of meteorology and climatology and workers in other disciplines concerned with the impact of climate upon human affairs, upon the animal and plant kingdoms and upon the surface of the Earth itself, will find in it an account of what makes climates what they are, and of how they vary and have varied. Practical men – farmers, engineers, industrialists and especially those concerned with long-term economic development and planning – may gain from it a new appreciation of things to be allowed for where climate affects, or might come to affect, their schemes.

The question of whether climate is effectively constant is one on which prevalent opinion – even expert opinion – has changed several times. It was alarm about 'the sudden variations in the behaviour of the seasons', to which the climate of Europe seemed in the late eighteenth and early nineteenth centuries to have become 'more and more subject', that apparently led to the institution of the first country-wide networks of weather observation posts where temperature, barometric pressure, rainfall and so on were to be recorded daily. This was attempted by the government of France in 1775 and done by Prussia in 1817, and instruments were supplied for the purpose. An international network of observation points scattered between Greenland and eastern Europe was arranged in 1781 by the first meteorological society, in the Palatinate of the Rhine, the *Societas Meteorologica Palatina*, which owed much to the interest of the ruling prince. By the end of the nineteenth century, however, leading climatologists, including HANN in Vienna and MOSSMAN in Edinburgh, who had studied the accumulating observation records, were of the opinion that climate was so nearly constant that one had only to average the figures over a long enough period of time to acquire results of lasting validity, mean values to which the climate would always return. Climate was commonly defined just as 'average weather' and climatology as the statistical (and, it was thought, dullest) branch of meteorology.

It was admitted, to be sure, that there had been changes of climate in the geological past. It was known that many thousands of years ago there had been ice ages[1] and also eras of

1. As far back as the eighteenth century Swiss country-folk familiar with the scored and glacier-smoothed rock-faces and boulders to be found far down the valleys and in the forests were aware that the Alpine glaciers had had a far greater extent in some former time. The evidence was put before the *Societas Helvetica* in Luzern

tropical warmth[1] in England, continental Europe and North America, but the general belief was that for at least the last two thousand years the climate had ceased to undergo any important change. Two things may have contributed a good deal to this attitude. Firstly, Classical studies revealed that there was much, if not quite perfect, similarity between the climate of the Mediterranean two thousand years ago and in modern times. (We shall come later in this work to regard the similarity of these two epochs two thousand years apart as to some degree fortuitous. And the fact that Britain impressed Tacitus and other Italians in various centuries as a misty isle with a mild climate only means that *relative to Italy or other parts of the continent* Britain's climate has maintained the same sort of differences of frequency of fogs and of extreme temperatures: it does not necessarily imply that the frequencies in either place have stayed constant – they could have undergone more or less parallel variations. Indeed, we shall come across many indications that something like this happened.) Secondly, it did happen that the European climate in the 1880s and 1890s had reverted to figures close to those ruling between 1760 and 1820.

One must probably also make some allowance for people becoming mesmerized with the importance of averages taken over long periods of time in an era when averages were the only statistic that it was practicable to compute – and even they represented a fearful labour.[2]

Modern computing equipment and statistical methods have made it possible to compute a variety of statistics that tell one much more about a series of observations than mere averages can do. Moreover, from 1900 onwards for thirty to fifty years climates in almost all parts of the world underwent an unmistakable warming, significant in many of its aspects, both in the statistical sense and as regards effects upon the natural environment, agriculture and the human economy. And latterly there have been signs of reversion and renewed instability of climate that have produced in England since 1950 several of the wettest summers in a 200-year-long record, and in the winters an increased incidence of snow, as well as two that were respectively the coldest (1962–3) and the driest (1963–4) winters for over two hundred years. Few people nowadays therefore – and certainly no

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by I. Venetz in 1821 and published in 1833. A similar conclusion about the glaciers in Norway was published by J. Esmark in Christiania in 1824. The concept of a general ice age, with a great ice sheet over all northern Europe, made widely known by J. L. R. Agassiz between 1837 and 1847, seems to have been first put forward by R. Bernhardi in 1832. (See R. F. Flint 1957 and M. Schwarzbach 1961 for further history of the development of the idea.)

1. Deduced in 1686 by Robert Hooke, F.R.S., from fossil ammonite and turtle shells found at Portland on the south coast of England.

2. Arago, writing in 1858 about a series of daily observations made in Florence in the 1650s and 1660s with some of the earliest thermometers, the calibration of which had been determined by Libri twenty-six years earlier in 1832, was able to quote the extreme values of warmth and cold represented by the Florentine series but had to remark that a better comparison with contemporary experience would be possible when the averages had been worked out: at that date they were still not ready. Comparison of extremes and ranges was common practice even till the early part of the present century, because averages took so long to compute.

informed person – would still place much reliance on the easy assumption of climatic constancy so prevalent at the beginning of the century. But it is high time to get away from these repeated changes in the fashion of thought and take stock of the situation,

(*a*) to see the problem in that perspective which can only be gained from careful numerical assessments and comparisons extending over the longest possible period of time and over a world-wide survey; and
(*b*) to seek to understand the matter in terms of the processes going on in the atmosphere and oceans which must produce climatic changes; and to take note of any changes that may be relevant in the terrestrial and extraterrestrial environment.

These are the things this book is about. Only so can the erratic course of opinion be checked and substituted by the sure foundation of knowledge. Moreover, in recent years climatology, developing as a branch of physical and dynamical meteorology, and statistics, have both become a great deal livelier subjects.

The author is a meteorologist, and the book sets out to present the meteorology of climate and its changes. It contains the results of the first strictly meteorological investigation of the climatic sequence of the last thousand years besides giving a digest of the known facts, recent investigations and tentative conclusions regarding the climatic history of much longer periods of time, involving evidence contributed from many other branches of learning. In the nature of the case, these other fields, such as botany and geology, from which so far most of our knowledge of ancient climates has come, receive very cursory treatment. The author is conscious of the long years, indeed generations, of patient research that have gone to produce these results, and is very appreciative of the help and guidance he has received from original workers too numerous to mention save where their published works are cited. He has tried to do justice to all, while showing how the sum total of their evidence at present appears to the meteorologist; yet some unintended changes of emphasis or representation of evidence in fields that are far from meteorology are likely to have arisen. Those readers requiring deeper knowledge in fields other than meteorology should supplement this book by consulting the works cited.

Meteorology must, however, in the end provide the central viewpoint and unified vision of what is essentially a meteorological phenomenon. It sees the variations in different aspects of the weather in different parts of the world as manifestations of deviations in a single chain of events – the supply of heat from the sun, which, despite much that is wasted, warms the Earth and drives the winds that redistribute the heat to all parts of the world. Only some of the heat is conveyed by the winds; much is stored in the ocean and carried along with the ocean currents that the winds drive and which release heat to the winds in high latitudes. In the great circulation of winds and oceans, moisture is put into the air from the sea surface and transported to every part of the globe and to great heights in the atmosphere. The moisture produces what we call weather; its condensation produces clouds, rain and snow and in the process converts large amounts of latent heat into sensible heat (i.e. into warmth that can be felt) in places thousands of miles away from the tropical oceans where most of the evaporation occurs.

This way of looking at climate presents it as an organic whole, in which the different elements are intelligibly related to one another and combine to tell the same story. It becomes possible to use quite diverse fragments of information about the climates of any age to confirm and fit together like the pieces of a jig-saw puzzle, indicating the outlines of a connected picture – a global pattern – and finally to glimpse the sequence of global climatic patterns. This overall view is needed if we are to see the development, variations and changes of climate as an intelligible physical process.

This presentation is likely also to be of use to research in the disciplines other than meteorology that encounter evidence of the course of the world's climatic history. Practically every branch of learning is potentially involved, since the behaviour of climate touches all aspects of our Earthly environment. Hints are not lacking that astronomical factors are also involved, at least in the longest-term changes, and that semi-regular variations of solar behaviour may play a part in some of the variations from year to year and century to century. The record of former hot climates and deserts, of ancient floods and masses of ice, is registered – not always clearly and unambiguously – in the rocks and soils. The present and past distribution of plant and animal species is ultimately a response to climate and the environment that climate conditions, or has conditioned. The fate of human populations living near the climatic limit, whether of cold as in Greenland and Iceland, or of drought as in central Asia and parts of Africa, America and Australia, may be determined – and has been determined – by climate. So geologists, biologists, medical men, historians, archaeologists, oceanographers and others may all find something here that concerns them. It seems a reasonable hope, moreover, that the meteorological treatment and arrangement of the book may make clearer the significance of some of the evidence turned up in other fields of study. This could lead to the advancement of knowledge, by encouraging the unearthing of further evidence.

The aim of this work is to base understanding as closely as possible upon observed facts and known physical or mechanical processes rather than to present elaborate theoretical ideas that have little sure foundation. Over much of the field of past climates, particularly in regard to the ice ages, there has long been, and still is, a surfeit of rival, and often unrelated, theories. One reason for this is certainly that the greatest overall changes of world climate can only be brought about by the working together of many contributory influences, in some cases including things of very diverse natures. In a word, the big changes are polycausal. The chapters in Part I attempt to identify the most important influences in the genesis of climate and climatic variations and to isolate the characteristic effects of each. In some cases quantitative estimates of the magnitudes of the effects can be given. But this is by no means always possible as yet, particularly when several factors operate simultaneously. Whenever the causation of a given climatic shift remains unresolved, or presents difficulties despite fairly confident identification of the major influences at work, this is admitted. The search for fuller understanding is most likely to be helped in this way.

In the pooling of knowledge of past climates we see that all learning is really one, and that any rigid separation of science and humane studies can only hinder our quest. There is need for common sense and the systematic methods of science in sorting out the significance and trustworthiness of evidence. Many would-be interpreters of climatic history have gone astray through uncritical acceptance of travellers' tales. To the visitor from Rome or Greece, Britain has always seemed remarkably mild (though misty) for its latitude and Russia has always appeared to have dreadful winters. We also need the verdict of some immortal 'traveller through time' who knew these countries two thousand years ago, visited them again two hundred or even fifty years back and came again today. In some respects he could notice differences. The quest to find out the facts of past climates – let alone the agencies and processes responsible for different climatic behaviour – is one of the most fascinating in all science. It is a never-ending detective story, though like all detective stories it requires disciplined thought and testing of conclusions at every stage. Advance in knowledge of climatic history is bound to be a co-operative effort.

In a subject of such diversity one book cannot go into all details. Nor do we attempt here to follow equally far along every line of inquiry. This book seeks to provide the essential framework of knowledge on which further studies aimed at fuller, or more detailed, understanding must be built. Essentially, what has to be done is to lay the foundations of a hitherto neglected subject, physical and dynamical climatology, which embraces the long-range processes of meteorology and other physical aspects of the Earth's environment. To further this aim an extensive bibliography is given. Another aim, however, has been to give within this and the forthcoming volume more of the known or ascertained facts of climatic history than have hitherto been available in a single work as well as adequate reference data on present-day climate.

Meteorology was in no position to help very much in the interpretation of past climates and climatic relationships until quite recent years. There was no sufficient understanding of the general circulation of the atmosphere. Such understanding could not be expected before what has turned out to be the mainstream of the wind circulation, the powerful flow of the wind in the upper troposphere, was within our means of observation and so had been recognized for what it is and submitted to continual, day-by-day survey of its behaviour. It was the daily sending up of radio-sonde balloons and radar directed at them to follow the upper winds, at a world-wide network of places developed between about 1940 and 1955, that first made this possible. By now, theory, though still incomplete, has provided a far-reaching understanding of atmospheric flow that has been applied to the improvement of daily weather forecasting, to the introduction of dynamical methods of numerical prediction of the weather map up to three to five days ahead, to the introduction of longer-range weather forecasting and to a new view of climatic variations and vicissitudes.

Before one can produce a reasonable interpretation or classification of climates, describe climatic regions and define their boundaries – let alone the shifts of these boundaries from one decade, or one epoch, to another – one must be acquainted with the fundamental processes: the manner of the heat supply, the budget of gain and loss, the winds and ocean currents, and the moisture cycle. These will be considered in the opening chapters. A genetic interpretation of climate leads directly to understanding of the geographical distribution of climates and their boundaries. Such a genetic basis must be part of any simple classification of climates that aids the memory and makes the details 'fall into place'. We can then begin also to grasp the vagaries of climate as physical phenomena – i.e. to recognize some of the processes at work in them too. We are no longer forced to treat them only as haphazard events or at best as the systematic, but still obscure, element that emerges from statistical analysis of a time series of observations.

This first volume of the book is devoted to explaining the present-day world distribution of climates and providing a skeleton reference of facts and figures for comparison. Fuller details can be found in the climatic atlases of different countries and regions, in climatic tables and in the year-books of official weather services. This understanding of the present day provides a basis from which one can proceed to examine and discuss the differences that are found to have characterized other climatic epochs. There will follow in volume two a general survey of the multifarious evidence of climatic differences in the recent and more remote past. The magnitudes of the differences and the probable maximum rates of change should both engage attention. Information under these headings relating to quite recent years throws new light on the proper and judicious use of climatic statistics in planning for the future. Any climatic table records what happened during some period (that should always be specified) in the past. Yet most users of such tables are concerned only with the future. A climatic table can never be a substitute for a forecast, and to use one as a forecast involves the – usually unwitting – assumption of climatic constancy. Nevertheless climatic forecasting must wait until the proper scientific foundation, a knowledge of the physical factors and processes entailed, exists.

In the meantime, however, practical decisions involving the future have to be made. The available climatic statistics of the past have to be used for as much as they are worth; meteorological services and individual users have, moreover, to choose the most appropriate range of past years to include in a climatic table. This may differ according to the purpose the user has in mind. The most relevant past period is not necessarily the most recent thirty to fifty years, though it should probably always include the last ten years and beyond that such decades as seem, on grounds of similar environment in terms of ocean temperatures and extent of ice, and similarity of prevailing wind circulation patterns and strength, to show the best analogy. When concerned with *long* periods in the future, it becomes important to survey (if possible) a very much longer period of the past.

The title of this book should not be taken to mean that it provides a forecast of the climatic trend over future ages. For this, no adequate scientific basis exists as yet. The investigations described do, however, point to certain indicators and symptoms of variation or change (particularly in the sun, the atmosphere and the oceans) which should be watched and appear likely to prove valuable. In so far as a genuine insight is gained into the physical processes at work in climatic changes, these indicators may constitute part of the framework on which a scientific system of climatic forecasting can be built. And in these ways the reader will be made aware of the problems involved in thinking of future climates and can make his plans accordingly.

Until climatic forecasting becomes possible – including prediction of the magnitudes and distribution of effects of various external influences, whether solar, terrestrial or induced by man – any large-scale attempt to manipulate or modify world climates would be extremely hazardous and foolhardy. It could lead to disaster for wide regions.

Volume two will summarize much of what is so far known of past climates era by era either in the form of regional climatic histories, partly tabulated, or under the different categories of evidence – in some cases, both. The meteorological treatment in the present volume reveals at least some of the physical and dynamical processes at work in the climatic variations of the recent past; these may be of use in seasonal weather forecasting and in a first approach to prediction of the climatic trend for a few years or decades ahead. It will be seen, however, that any such forecast that could be developed in the foreseeable future could only be an estimate of the 'natural' or 'undisturbed' trend, 'other things being equal'. In addition to its probably wide margin of error due to incompleteness of the scientific basis, the success of such a forecast would be threatened by the supervention of influences of a manifestly unpredictable nature – great eruptions of volcanic dust and other natural events or changes due to the works of man, intended or unintended.

Some of the possible external events that might supervene to change the course of climatic history could have effects of disastrous magnitude. Such would be the case, for example, if increasing carbon dioxide in the atmosphere were to warm the climates as much as some estimates predict, and therefore raise world sea level by melting the Antarctic ice sheet, or if certain other events were to induce significant cooling. Generally some regions would gain and others would lose by any changes. Further research and stock-taking of the quantities involved is urgently called for, if we are to be able to face these questions. The book provides an introductory guide to such problems.

For the present, the problem of planning comes down to estimating the prudent margins of error for variability of climate that should be allowed in connexion with any project. Exploitation of every favourable turn of the climate may be gainful only if it is done with awareness of the threat of climatic reverse that hangs over such ventures and that will affect first the exotic crop and the marginal land, and enterprise.

Contents

		page
	Tables	vii
	Figures	ix
	Acknowledgments	xxi
	Foreword by Sir Graham Sutton	xxiii
	Introduction	xxv
Part I	**Fundamentals**	
1	Concepts and definitions: the weather, the atmosphere and the sun	3
2	Radiation and the Earth's heat supply	14
3	The atmosphere in motion	68
4	Seasonal changes	138
5	The stratosphere	187
6	Cyclic and quasi-periodic phenomena	212
7	Anomalous patterns of atmospheric circulation, weather and climate	254
8	The oceans	307
9	The water cycle	346
10	Some observed causes of climatic variation	385
	APPENDIXES TO PART I	
	I Supplementary tables	467
	II The production and decay of radioactive carbon in the atmosphere	491
	III Orbit data	492
	IV Departures from the long-term average of monthly mean pressure at sea level associated with different phases of the sunspot cycle	496

Part II Climate now

11 Observational reference data and classification of climates 501
World maps 501
World-wide classification of climates 509
World climatic table 514

References 555

Geographical index 597

Subject index 602

Tables

Part I

		page
2.1	Constituents of the atmosphere and their absorption bands	43
2.2	Albedos of different surfaces	51
2.3	Albedo of clouds	52
2.4	Summary of the Earth's radiation budget	54
2.5	Heat balance of the northern hemisphere	63
4.1	Radiation reaching a horizontal surface under average cloud cover	147
4.2	Upper flow over Asia in strong and weak monsoon summers	167
4.3	Singularities in the weather of central Europe	174
4.4	Natural seasons in the British Isles	183
5.1	Alternate year rhythms in surface weather	209
6.1	Radiocarbon dates of glacial stages in North America	217
6.2	Periodicities most frequently and prominently indicated in meteorological and related data	242
7.1	Temperatures of the warmest and coldest Julys and Decembers at Archangel and Verkhoyansk	279
7.2	Russian natural synoptic seasons and forerunners	297
8.1	Density of water of different salinities at different temperatures	312
8.2	List of the world's main ocean currents	322
8.3	Dimensions of the West Wind Drift in the Southern Ocean	325
8.4	Saturation vapour pressure in air over water of 35‰ salinity	329
9.1	Saturation vapour pressure	347
9.2	Apparent changes in the amount of water evaporated from the tropical oceans in different climatic eras	348
9.3	World distribution of evaporation	351
9.4	Monthly evaporation measured in England	352
9.5	Probable moisture content of a vertical up-current in cloud in liquid and vapour form	357
9.6	Average sunshine on mountains and neighbouring lowlands	359
9.7	Average sunshine at coasts and inland	360
9.8	Examples of föhn effect	383