1. Introduction

An essay is, by definition, an initial, tentative effort, or, alternately, an analysis or weighing from a personal point of view. The thoughts expressed in this essay are just that. They began as a personal attempt to arrive at a coherent theoretical basis for climatology. After much analysis and weighing of the facts, my conclusion was that the major problem lay with the definition of climate itself. The definition that I now use, which has the character of an axiom, leads to a number of corollaries. These in turn provide a rudimentary theoretical framework, or paradigm, for climatology as a distinctive atmospheric science.

Climatology, the study of climate, is clearly a science, or at least a topic for scientific study, as attested by the fact that it is so often referred to in curricula, in scientific journals, and in the names of journals. How it relates to other sciences is less clear, for the definitions that can be found do not all agree, nor are they often supported either by reasoning or by tradition. The first part of this essay deals with how I view the general position of climatology within the constellation of sciences. I then look at how the study of climate differs from related fields.

2. The array of sciences

One way of thinking about the difference between the sciences (physical and biological), social sciences, and humanities—and, for that matter, environmental studies—is in terms of their focus. Science deals with “things” such as masses, compounds, elements, and organisms (including cells and their parts). Social studies deals with groups of organisms, particularly groups of humans, and their behavior as groups. Usually the study of groups of nonhuman organisms is regarded as part of biology. The humanities deal primarily with individuals and especially with their thoughts, their actions, and the consequences thereof.

Within the broad array of foci known as “the sciences,” one can discern a structure. This structure is diagrammed in Fig. 1. There are, in this way of visualizing the sciences, three basic sciences: physics, chemistry, and biology. Loosely put, physics deals with the structure of the universe and how it works, while chemistry deals primarily with the elements and compounds of the universe. Biology is concerned with living things, their structure, origin, and behavior.

The basic sciences may be combined in pairs, as in biophysics, physical chemistry, and biochemistry. Earth science, dealing with all the earth and what is in or on it, is a combination of all three basic sciences (Bryson 1993).

All of these broadly defined sciences are differentiated into disciplines, or subdisciplines, specialized by subject matter or methodology. For example, there are within chemistry the subdisciplines of organic chemistry and inorganic chemistry, distinguished by the compounds of interest, and other subdisciplines such as analytical chemistry, distinguished by technique or purpose. The boundaries of the subdisciplines are set as much by historical precedent as by rationale.

Earth science and environmental studies

In the case of earth science, the subdisciplines are distinguished primarily by their focus on the atmo-
FIG. 1. Schematic diagram of the basic and “interface” sciences (Bryson 1993).

sphere (meteorology), on the hydrosphere (oceanography, hydrology, physical limnology, etc.), on the cryosphere (glaciology), or on the lithosphere (geology, soil science, etc.). Ecology could be thought of as a link between biology and earth science. If the particular organism of concern is the human, then one is concerned with geography or human ecology (NAS–NRC 1965).

Earth science is similar to the basic sciences in many ways and borrows principles and techniques freely from them. However, there are several fundamental differences. First, earth science, as such, is not, per se, a laboratory science. It is primarily a field science. There is, to be sure, a role for laboratories in the earth sciences, but the primary “laboratory” is the world itself. Most laboratory work in the earth sciences is aimed at the analysis and understanding of samples from the field and the data derived therefrom rather than at doing experiments (other than computer model exercises that are called experiments). Neither the atmosphere, the seas, nor the solid earth can be put in a test tube or a cage to be observed and manipulated. No experimental method has been devised to control one variable at a time, other than statistically. Second, to borrow a truism from ecology, everything is interconnected. For example, everything that breathes or oxidizes, emits, stores, or absorbs gases from the air affects the composition of the air. In turn the composition of the air affects the organisms, the oceans, the climate, and the weathering of rocks. The atmosphere, cryosphere, hydrosphere, lithosphere, and biosphere are intimately related in behavior and history. There are a multitude of discernible interactions between the parts and the whole of the segments of the earth system. These interactions are generally known as “feedback loops.” The loops themselves are interconnected.

Fossils cannot be understood without reference to biology. The composition of the air cannot be explained without use of early earth history and biological evolution. Continental drift, now called plate tectonics, cannot be discussed without reference to the physical properties of rocks as a function of time and the physics of heat generation within the earth. Rocks and minerals cannot be understood without chemistry. Earth science is the quintessential interdisciplinary science.

This “plane” of the sciences, shown schematically in Fig. 1, may be thought of as paralleling the planes of the social studies and the humanities. Environmental studies, being the interdisciplinary study of the human–environment system, encloses a volume that includes the earth sciences and parts of the social studies and humanities planes.

3. The definition of climate

It appears that the way a segment of the world is studied depends as much on how the topic is defined relative to the expertise of the scientist and the historical precedents of the scientist’s discipline as it does on rational analysis. This may lead to definitions and biases that affect the study of the topic.

The usual definition of climate according to meteorologists is approximately that given in the Glossary of Meteorology (Huschke 1959). Here, climate is defined by reference to C. Durst, a meteorologist, as “The synthesis of the weather.” Huschke then goes on: “More rigorously, the climate of a specified area is represented by the statistical collective of its weather conditions during a specified interval of time (usually several decades).”

Geographers tend to use a similar definition: witness G. Trewartha’s, “Climate . . . refers to a more enduring regime of the atmosphere; it is an abstract concept. It represents a composite of the day-to-day weather conditions, and of the atmospheric elements, within a specified area over a long period of time” (Trewartha and Horn 1980). (How one can use facts, figures, and equations to study an “abstract concept” is more than a little puzzling.) Lamb (1972) uses a
similar definition of climate: "Climate is the sum total of the weather experienced at a place in the course of the year and over the years."

Lamb's definition of climatology, however, reveals most about his own approach to the study of climate: "Climatology, the study of climate, the long-term aspects and total effects of meteorological processes, is (like meteorology) a branch of Earth physics (geo-physics). It is concerned with the various conditions of the atmosphere that occur and with everything that, habitually or occasionally, influences the condition of the atmosphere, either locally or over great regions of the Earth. Like any other branch of physics. . . ." (Lamb 1972). Clearly Lamb's definition of climatology is at odds with that which is implicit in Fig. 1.

Viewing climate as essentially a summation of the weather has profound implications for the development of a body of climatological theory. Indeed, the preceding sentence might evoke disagreement from many "atmospheric scientists" for the common definition of climate indicates that there is no distinct body of theory separate from that of the weather, except perhaps statistical theory. With this viewpoint I disagree, based on a quite different view of the relation of climate and weather.

4. The relation of climate and weather

An experienced meteorologist can identify the atmospheric circulation pattern on a weather map immediately as to whether it represents a summer pattern or a winter pattern. Usually the identification of the season can be even closer. The reason the array of weather patterns characteristic of a season differs from the array of another season is that the climate differs from season to season. This statement, of course, does not make sense if the climate is the summation of the weather. It does make sense if the thermodynamic status of the earth—atmosphere—hydrosphere—cryosphere system determines the array of possible (and necessary) weather patterns. This status, which changes with time and season, along with the associated weather patterns, constitutes the climate. This concept logically leads to a series of definitions and axioms, if one wishes to so characterize them.

Definition: (Axiom 1) Climate—Climate (climatic status) is the thermodynamic/hydrodynamic status of the global boundary conditions that determine the concurrent array of weather patterns.

Clearly this definition includes the array of weather patterns and their consequences in temperature and precipitation, etc. within the scope of climate. It also creates a terminology problem, for in general usage "climate" is taken to mean the statistical characteristics of the weather assemblage at various places, or "typical weather." For this reason "Climate" (capitalized) will be taken to mean, in the following, that which is defined above, while "climate" (lowercase) will mean the statistical assemblage of the weather in a region or at a place. This distinction has often been hinted at, for example by Trewartha (op cit.), in discussions of climatic controls as opposed to climatic elements, the latter being such parameters as temperature and precipitation. No distinction was made, however, between climate controls and weather controls.

Meteorology, in one of its aspects, is concerned with the day-to-day evolution of weather systems. In fact, weather forecasting is usually treated as an initial value problem and the kinematic and weather element consequences thereof. As defined here, climatology deals primarily with a boundary condition problem and the patterns and climate devolving therefrom.

Some corollaries of the definition

Corollary 1.1: The initial emphasis of climate theory and associated modeling should be on the conditions of the most important boundaries. Since the most important fluxes of energy and momentum are near the surface rather than far aloft, this means at or near the surface of the earth.

Corollary 1.2: One need not model the weather day by day for many years equivalent and then sum to model the climate. The Climate (climatic status) must be modeled, and then the weather patterns and their consequences derived from the basic climate model. Of course there may be feedback loops and the usual dynamic constraints.

Corollary 1.3: Climate is multidimensional (a vector), not a single scalar datum.

Some of the implications of corollary 1.1 may be seen in the fact that a rather good simulation of a 500-mb contour pattern, for example, may be constructed by using the surface temperature distribution to estimate the 1000–500-mb thickness, adding the averaged thickness to the observed 1000-mb height and
then space averaging. Indeed that was essentially the method W. Plumley and I used in 1944 to predict the discovery, by the U.S. 20th Air Force, of the jet stream near 300 mb over Japan (Bryson 1994). The reverse calculation from 500 or 300 mb to the details at the surface is not as possible, for one cannot derive these particulars from the average.

5. Climatic variation and climatic change

Perhaps the most important principle to bear in mind in studies of the variations of climate is the ancient axiom that a null hypothesis cannot be proven. Calling the observed variations of the climate random, in the sense of “no cause,” is the statement of a null hypothesis. All that can be said, in fact, is that the variations are or are not distinguishable from what they would look like if they were indeed produced by a random process, at some level of confidence. Assuming that there is a random element in climate (other than observational error) would appear to be a very poor research strategy, for it constitutes an unprovable hypothesis. If one really believed climate to be random, then there would be no point in further study.

From the observational evidence it is abundantly clear that the earth’s history, including climatic history, may be regarded as a sequence of periods, epochs, or episodes separated by times of rapid change (Bryson 1987). This is hardly surprising for a highly nonlinear system operating on an ellipsoid. Nor are these features of climatic series characteristic of stationary time series. From these observational facts there comes the second axiom.

Axiom 2: The history of climate is a nonstationary time series.

Corollary 2.1: There are no true climatic “normals.”

This axiom does not require that there be chaotic behavior, or “strange attractors,” though such considerations may constitute an interesting way of examining climatic behavior. The episodic, step-function, character of climatic history has profound consequences for essentially any statistical analysis of climatic data. Climatic distributions are inherently non-Gaussian, often multimodal, usually skewed to some extent, and the characteristics of the distributions may change with time [e.g., see the distributions in Bryson (1966)].

The range over which the climate varies is surprisingly small, with even ice ages being only about 6°C colder than the present for the globe and the warmest periods of the past being only a few degrees warmer than now. This clearly suggests that most feedback loops in the climatic system are negative or stabilizing. It is unlikely that there would be any discussion of feedback loops at all if they were strongly positive, for we probably would not have evolved in such an unstable environment. It appears to be nonsense that “the flap of a butterfly’s wings in the Amazon might trigger a major storm in North America.” Indeed there appears to be no evidence for any triggers smaller than El Niño, and perhaps not even for events of that size.

It is not necessary that there be triggers to change the climate in a steplike fashion. The fact that hemispheric longwave numbers must be integers means that a smooth monotonic change in the boundary conditions may produce abrupt changes in the climatic pattern as the equilibrium longwave number changes (Bryson and Lahey 1958).

Axiom 3: Environment and climate change on timescales from near instantaneous to millions of years.

Corollary 3.1: There can be no perfect climatic or environmental analogs in the last million years. Conversely, reconstruction of past climates must be based on methods that do not require perfect analogs. For example, the combination of Earth–Sun orbital parameters, and thus the annual march of irradiation, has not repeated during the Holocene (Bryson 1985).

It is clear to the scholar of past climates that the climate (climatic status) and the climates have always been in a state of flux. This carries the implication that there has been a reason or reasons for continuing change and that climatic change is not primarily the result of singular events. An example of the application of this observational fact is that if one is to attribute the global warming of the past century to an anthropogenic increase of atmospheric carbon dioxide (a singular event), then one must show that this particular warming could not be due, instead, to the causes that produced similar previous warmings (and coolings).

Furthermore, an adequate climatic simulation must be able to simulate the interannual variability. It simply is not scientifically acceptable to pass off the short-term variability that is not simulated as being
the result of "natural variability." It is the natural variability that scientists are supposed to explain, especially since there is no evidence that the variability is not explicable.

This same variability on many timescales provides the opportunity to test climate forecast models, for one can always go back to some previous starting point and make a forecast into the region of the record where the correct value is known. Only in this way can the probable error of the forecast be known a priori.

6. Proxies and the reconstruction of past climates

For testing hypotheses about the longer-term climatic variations, say with lead times of many decades to centuries, it is necessary to extend the length of the climatic record beyond the period of instrumental observations. This can be done with the use of climatic proxies, if they can be found for the region and time of interest. Proxy data records are quantitative time series of some variable that covaries with climate, such as tree-ring thickness records.

The work of the climatologist is eased greatly by the fact that nature has recorded, in many places, its own history. It is then necessary for the scholar of past environments to learn how to read the record or translate the language of nature into humanly understandable terms—quantitatively if possible. This has proven possible in some cases, especially for the interpretation of pollen profiles [see Webb and Bryson (1972) for the first reasonably accurate quantitative method for translating pollen spectra into climatic spectra].

Examples of proxies range from tree rings to pollen rain to oxygen isotope ratios in seafloor sediments. Trees are not thermometers or rain gauges, however; nor is the array of pollen taxa that falls at a place. Trees tend to trade off the effects of temperature and rainfall in terms of radial growth increment. Colder is like wetter and warm is like dry, and vice versa. Extracting the variables that we like to use from the tree-ring records is conceptually quite simple. We must develop as many ring thickness versus climate equations as there are unknowns. Most tree-ring records that are published, however, have the interspecific and intersite variance removed, so that development of the requisite number of equations is precluded.

Oxygen isotope ratios in fossils on the deep-seafloor do not record climate at all, but rather the integral of the climatic variable "snowfall minus wastage rate" on the land, that is, the continental glacier mass. Still it is possible to extract data useful for paleoclimatic interpretation from such records.

Pollen arrays extracted from stratified sediments often have the right number of pollen variables to allow the calculation of a number of climatic variables to describe the climate (see corollary 1.3). There are pitfalls in the translation of the pollen record to a climatic record, but rather unequivocal answers seem to be possible. An example from southeastern Minnesota is shown in Fig. 2. Note that even without removing the lag of the vegetation after the climate, the tempera-

![Fig. 2. (a) A history of July temperature and annual sunshine hours at Kirchner Marsh, MN, derived from the pollen array at each level. (b) A history of snowfall, length of the growing season, and rainfall during the growing season at Kirchner Marsh, MN. Pollen data are from Wright et al. (1963).](image-url)
ture rise at the beginning of the Holocene, at circa 10 000 yr B.P., is very fast.

By far the most satisfactory source of past environmental data for a specific locale is a good proxy data record for that local area. For example, Baerreis and Bryson (1967) were able to reconstruct, from pollen and bones, the environment of the Mill Creek people in northwestern Iowa (ca. 900–1400 A.D.). In this case the data were obtained from the village areas themselves. That is not always possible, especially in areas of alkaline soil where pollen is not well preserved. Nor does the proxy data answer why the environment was what it was or why it changed.

There is a caveat, however, that controls the use of very local data, for the macroclimate is the mean microclimate of a region.

**Axiom 4:** There are various microclimates that depart more or less from the macroclimate in each terrestrial region.

**Corollary 4.1:** It follows that proxy data that are very local, that is, dependent on the local microclimate, may not reflect the true macroclimate.

Proxy data of various kinds are in accord that the global warming of the past century is not unique in any way. There were past times of warming and cooling of quite comparable magnitude. If a theory of climatic change is to be acceptable, it must explain these past warmings and coolings as well as that of the last century.

**7. Summary**

This essay has suggested that Climate (climatic status) is the array of boundary conditions affecting the state of the atmosphere and that the climatic state determines the array of weather patterns compatible with this state. This is not incompatible with the idea that one weather pattern evolves primarily from the previous patterns, but simply puts bounds on the probable evolution to keep it within the season’s allowable array.

The major points of the essay were presented as a set of axioms and corollaries.

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I believe that the best test of an hypothesis or set of hypotheses is in application. A climate model based on the ideas above plus synoptic climatology has now been constructed and, apparently, has succeeded in reproducing observed past climates quite well (Bryson 1992; Bryson and Bryson 1996).

**Acknowledgments.** Several starts were made on this paper in the past few decades, but the impetus to finish it was provided by my longtime friend and distinguished colleague, the late Prof. Verner E. Suomi, who pointed out that there was no extant statement of the basis of climatology as a distinct science. I sincerely appreciated his confidence in my ability to make a meaningful statement on the topic.

**References**

Educators, students, and weather enthusiasts! A glossary of over 3000 terms on weather and climate is now available for a general audience! Produced under the Project ATMOSPHERE initiative, the development of The Glossary of Weather and Climate was inspired by increasing contemporary interest in the atmosphere and global change and by the absence of a timely and reasonable comprehensive glossary for the public. The objective of the glossary is to provide a readily understandable, up-to-date reference for terms that are frequently used in discussions or descriptions of meteorological and climatological phenomena. In addition, the glossary includes definitions of related oceanic and hydrologic terms.

Edited by
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