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CURRENT PROBLEMS IN RESEARCH

Trends in Climatology

The investigation of climates is moving from a descriptive science to a science grounded in physics.

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The aim of climatology is to abstract from the varied and rapidly changing weather phenomena the underlying patterns that characterize the atmospheric environment for regions of the earth and for the earth as a whole. In recent decades climatology has gradually evolved from a purely descriptive science to a science that is grounded in physics. But climatology is not confined to the study of large-scale climatic events alone; it is also, for example, concerned with microclimates and with the influence of climatic factors on the life processes of plants and animals. The field is so broad that it is impossible to treat more than a limited number of topics in a single article; accordingly, I have selected certain topics for discussion but at the same time have tried to present a general view of climatology.

History

The problems in this field are difficult because of the many different ingredients—in complex spatial and temporal interrelations—which make up a climate. The major factors affecting climate are the sun (the primary source of energy), the position of the earth in the solar system, and the inclination of the earth's axis with respect to its orbit. That these are the most important factors in causing differences in climate was recognized even by some early Greek scientists, probably first by Eratosthenes. The Greeks defined climate according to the mean inclination of the sun's rays with respect to the terrestrial horizontal. Thus temperature zones according to latitude were distinguished. This gave rise to an organization of climatic facts into a causally related scheme of *torrid, temperate,* and *frigid* zones, albeit somewhat anthropocentric in scope.

Little was added to this concept for over 1800 years. But then, one by one, the complicating factors and their influence became obvious. On a large scale, these were the distribution of land and ocean on earth and the existence of larger and smaller mountains. The local influences of lakes, forests, and vegetation-covered and bare soil also became recognized. In the atmosphere itself one of the controlling factors is that *bête-noire* of the meteorologist, the water. Its presence in all states of aggregation—vapor, liquid, solid—often the three of them simultaneously, and quickly changing from one to another, complicates matters immensely. Through evaporation and condensation, cloudiness and precipitation, it governs much of the climate, as is discussed more specifically later.

Historically, significant advances in the study of climates were made after systematic measurements of atmospheric parameters began. Although such measurements started in some places in Europe in the 17th century, it was during the high surge of science in the second half of the 18th century that many learned men the world over became interested in the atmospheric environment. Physicians, astronomers, natural philosophers, and clergymen recorded the temperature, pressure, wind, precipitation, and weather conditions faithfully. There was considerable appreciation that knowledge about climate might be useful and broad speculation that climate had a notable influence on health. This last was a notion which had an early antecedent in Greece, in the theories of Hippocrates. Equipment and procedures, though primitive in the beginning, became gradually standardized.

The problem of standardization has remained with us for nearly two centuries because only with standardization can comparisons between simultaneous records at various localities or between earlier data and later readings become meaningful. Only in recent years has the World Meteorological Organization, one of the specialized agencies of the United Nations, shown a modicum of success in establishing uniform observation practices in all countries.

The interest in the atmospheric environment in the outgoing 18th century was quite universal among the well-educated. Thomas Jefferson (*1*) considered climatic observations important to "increase the progress of human knowledge." From data collected at Williamsburg, Virginia, in the years 1772 to 1777, he prepared one of the first climatic summaries for North America (Fig. 1). A cooperative venture of sizable proportions was initiated by the Societas Meteorologica Palatina with the Prince Elector Karl Theodor of the Palatinate as sponsor. Uniformly calibrated instruments and observing instructions were distributed to 35 academies and learned societies in the then readily accessible parts of the world. Data were collected and published in detail (*2*). These data became the raw material for the first comparative climatological studies. Twelve annual volumes appeared before this pioneering survey ceased in the turmoil of revolu-

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	Fall of rain, &c. in inches	Least and greatest daily heat by Farenheit's thermometer.		WINDS.								
				N.	N.E.	E.	S.E.	S.	SW.	W.	NW.	Total.
January.	3.192	38½ to 44		73	47	32	10	11	78	40	46	337
Feb.	2.049	41	47½	61	52	24	11	4	63	30	31	276
March.	3.95	48	54½	49	44	38	28	14	83	29	33	318
April.	3.68	56	62½	35	44	54	19	9	58	18	20	257
May.	2.871	63	70½	27	36	62	23	7	74	32	20	281
June.	3.751	71½	78¼	22	34	43	24	13	81	25	25	267
July.	4.497	77	82½	41	44	75	15	7	95	32	19	328
August.	9.153	76¼	81	43	52	40	30	9	103	27	30	334
Sept.	4.761	69½	74¼	70	60	51	18	10	81	18	37	345
Oct.	3.633	61¼	66½	52	77	64	15	6	56	23	34	327
Nov.	2.617	47¾	53½	74	21	20	14	9	63	35	58	294
Dec.	2.877	43	48¾	64	37	18	16	10	91	42	56	334
Total.	47.038	8 A. M.	4 P. M	611	548	521	223	109	926	351	409	3698

Fig. 1. Climatic table for Williamsburg, Va.; from Thomas Jefferson (*1*).

tions and wars of the outgoing 18th century.

However, the pattern was set. From a few score stations, climatological networks have been expanding. Including rainfall stations, there are presently probably about 150,000 land locations from which some climatological information is available. The rapid rise in stations is well marked in the United States (Fig. 2). The desirable end is not in sight because station density goes hand in hand with population density and many areas are void of settlements. Only since the start of the International Geophysical Year have we had systematic climatological information, for example, from the South Pole area. The uneven coverage of the land areas with observing posts is a handicap to climatological research. It is even worse over the oceans. There regular observations started in the 1850's. One of the principal movers to obtain weather data from the seas was the U.S. naval lieutenant Matthew F. Maury. Millions of individual readings have been gathered in the weather archives since, but they are bunched on the shipping lanes. There are vast ocean areas which are hardly ever crossed by a ship. From the Arctic sea, ice data are also scarce. We have no systematic measurement of rainfall over the ocean. Some data are accumulating from Texas Towers offshore, but a climatological survey of the oceans, perhaps by regularly spaced, anchored, automatic weather floats, is still a dream for the future (*3*).

Thus the climatologist is still struggling with the question, "What is there?" For this reason the answers to the usual second question in science—Why is it so?—are woefully incomplete.

Climatic Energetics

At the basis of all quantitative considerations in climatology are the questions of energy balance. Presently this starts with the assumption that income from solar radiation and loss of heat by the earth are equal. The income from the sun (the so-called solar constant) is known to be about 2 calories per square centimeter per minute at the boundary of the atmosphere, at the mean distance between earth and sun, normal to the incident rays. This over-all value is probably valid within 1 percent. However, in various spectral regions, especially in the short wavelengths, considerable fluctuations in intensity can occur. The total energy income and its spectral distribution are now amenable to direct measurements from satellites. This will be one of the most valuable contributions of these vehicles to climatology. Equally important will be essentially extra-atmospheric measurements of the earth's albedo, that is, the portion of the incoming energy directly lost to space by the planet through reflection from clouds, snow and ice surfaces (as primary contributors to the loss), and from land and ocean surfaces (as secondary reflectors). The over-all albedo of the earth has been estimated at 35 percent, but this value might be off by several percent either way. There are certainly considerable seasonal variations and, possibly, changes from year to year. Equally important for areal climates are the local values of albedo and the variations in different landscapes and seasons. These values govern how much heat is absorbed and becomes available for atmospheric energy transformations.

Quite unknown are the storage factors. There is certainly the possibility that heat energy beyond the yearly cycle is stored in the ocean. It may then be released again over a longer period of time, rather than be used immediately for driving the general circulation of the atmosphere. Even though this question of heat storage is open, attempts have been made to estimate the heat balance of the earth and of smaller portions of its surface. Various approaches have been used, most of them indirect. Among the direct approaches are the measurements of incoming and outgoing radiation to establish locally the radiation balance. This has been done at too few places as yet to furnish significant information for the global picture. However, net-radiometers which measure and integrate the radiation balance from day to day are becoming more common equipment at observing stations. The other components of the total heat budget—condensation-evaporation and advection—are difficult to observe directly. They are generally deduced from other climatic elements. The most comprehensive study in this connection has been carried on by Russian investigators (*4*). For the earth as a whole, and on an annual basis, they obtained the following figures (all in kilocalories per square centimeter per year): total radiation received, 129;

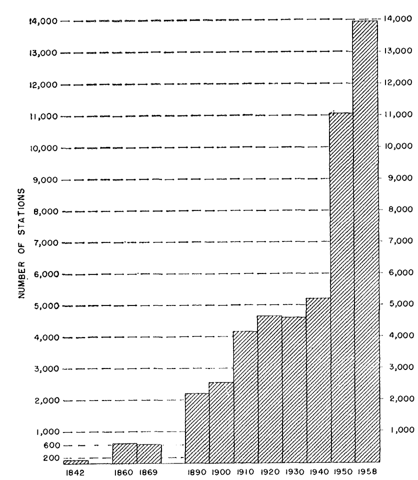

Fig. 2. Number of climatic observing stations in the United States and possessions, 1842–1958.

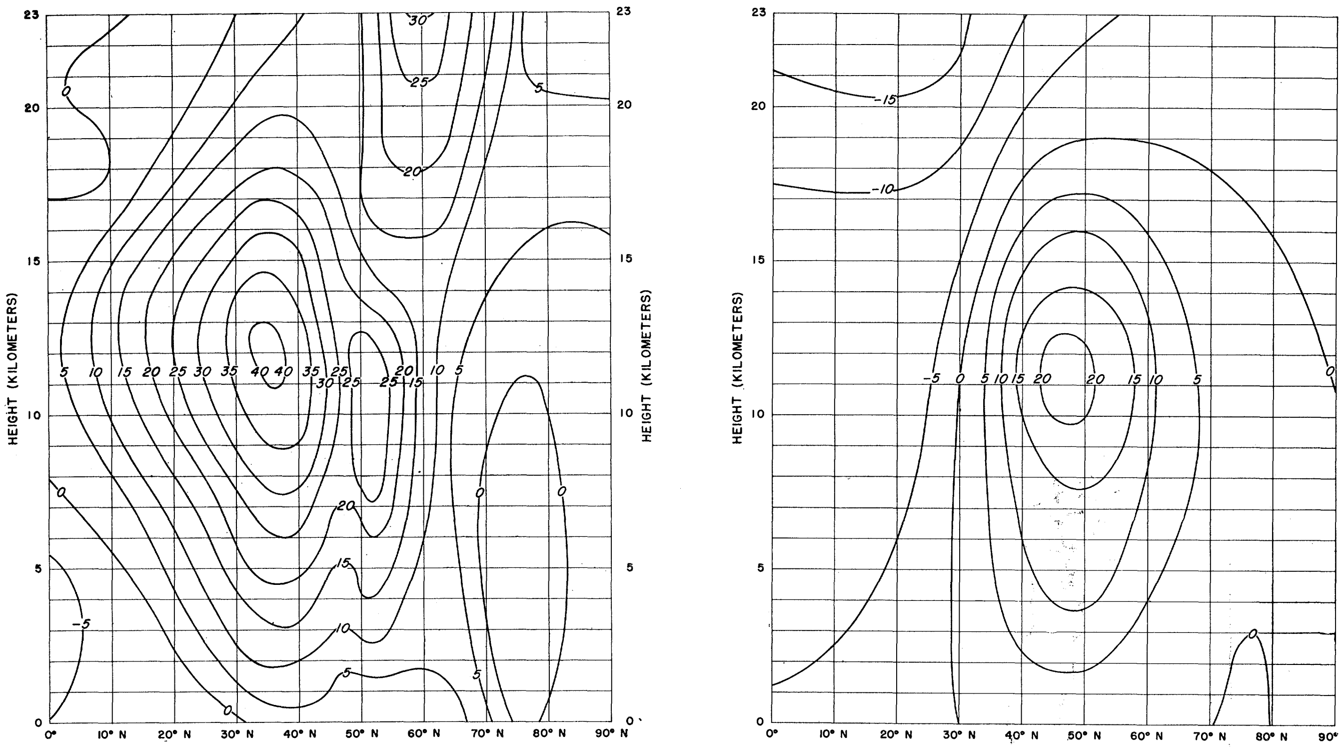

Fig. 3. Mean westerly component of the wind in meters per second in vertical section through the atmosphere along the 80th meridian west, based on ten years of observations (*38*). Negative values indicate prevailing easterly winds. Left section shows values for January, right section for July.

heat available for atmospheric transactions and motions after reflection and other direct losses, 68; lost by use in evaporation, 56; lost by turbulent transport, 12. The values for continents and oceans by individual latitudes are, of course, quite different from these means. The differences between the larger subdivisions of the globe are the cause of the general atmospheric circulation and its local manifestations. They cause the trade winds, the westerlies, the monsoons, and all the embedded eddies, such as ordinary cyclones and tropical storms. All of these currents, including the now famous atmospheric jet streams, are part of the energy-dissipating mechanism.

As already stated, the role of water in the atmosphere is of fundamental importance. It enters actively into all heat balance considerations. In a limited way this is due to the infrared absorption spectrum of water vapor. But the primary contribution comes about by evaporation (consuming heat) and condensation or freezing (liberating heat). The vapor phase is a means of transporting latent heat from one place to another. Last but not least, water plays a passive role in heat transactions because, as clouds and surface snow or ice, it reflects large amounts of incoming shortwave radiation from the sun. Next to air temperature, it is also the element which has the greatest influence on plants, animals, and human activities. In the form of rain or snow it governs water supplies; in the form of hail it causes crop damage. Its lack spells desert conditions or temporary drought for afflicted areas. Even as fine droplets in clouds or fog it affects life processes and recreation or traffic on land, sea, and in the air.

The water cycle from the ocean through the air to rivers, streams, and underground storage in its relation to the general atmospheric circulation has become fairly well known in broad outline and is reflected on the climatic charts. But as a process of atmospheric energetics, understanding has barely begun. Considerable effort has been expended on the problem of evapotranspiration (*5*). This concerns the water losses from land surfaces. Evaporation from open water surfaces in terms of the atmospheric environment has at least yielded to empirical approaches, but the water losses from bare and plant-covered soil can as yet be ascertained only in rough approximation. Locally it can be calculated as a function of the heat flux and the turbulent transfer of mass. Such losses, together with the gains by rainfall, can be entered into a bookkeeping system which indicates an approximation of available soil moisture. This factor is important in farm management and irrigation planning. The climatology of the moisture balance has become one of the most important factors in agricultural land utilization. It is likely to stay in the foreground of interest because of the world food problems engendered by population pressures.

It is fortunate that theoretical schemes which underlie much of present-day procedures for ascertaining the water cycle can now be supplemented by tracer techniques. These make use of isotope determinations. Both deuterium and tritium have recently been employed for this purpose (*6*). Interesting new facts have been added to our knowledge by these procedures. For example, the storage time of water in vapor form in the air ranges, on an average, from 3 to 10 days. In the central United States it also appears that the storage time of water lost to the soil by percolation is of an order of magnitude of several years. More work needs to be done with these techniques. Also, a wide geographical coverage is desirable. This new avenue of research will certainly supply quantitative answers to many of the questions related to atmospheric water transport.

The foregoing problem is one among many that make it clear that solutions in climatology can no longer be looked for or found by reference to surface observations alone. Great strides have been made in the collection and summarization of upper air data. These have found practical application in the planning for air routes and as basic design information for rockets. They have been used as guidelines for estimating radioactive fallout from various levels (*7*). They also give us better insight into the three-dimensional flow patterns of global air currents. Among them are the swift, meandering jet streams. The jet streams are a dynamic consequence of momentum transport into narrow zones of confluence of various air currents produced by the general circulation. The primary seat of these fast flows is in the upper troposphere, where they not infrequently exceed speeds of 200 miles per hour. The strongest jet streams are in the middle latitudes, but there are less pronounced and less steady currents of this type in the tropics and polar regions. It even appears that stratospheric jets are in existence. The main jet stream is quite noticeable even in atmospheric cross sections reflecting mean conditions (Fig. 3). The mean flow patterns are now reasonably well known for the Northern Hemisphere, but in the Southern Hemisphere data are still too sparse for more than local climatological analysis (*8*). Also, the fluctuations of the jet streams in time and space are still targets of exploration. As there are close associations between the jet stream and rainfall, studies of the more comprehensive data to be expected in the future will give better insight into the broad dynamics of global precipitation (*9*).

Climatic Classification

For several decades the problem of climatic classification has created lively discussions. More than a score of schemes for classifying climates have been proposed (*10*). None of them satisfies all the requirements. The basic difficulty is inherent in the fact that there exist hardly any sharp boundaries between climatic zones. Except at the crests of high mountains (Fig. 4) and at the coast lines, various climatic regimes gradually fade into each other. Also, the shifts of the general circulation of the atmosphere from season to season and year to year bring fixed localities on the surface of the earth sometimes into one climatic zone and then into another. Hence a strict taxonomy which separates natural entities is not possible. All dividing lines are essentially arbitrary. This is the more the case when, as in most climatic classifications, the class criteria are based on mean values of climatic elements. A climatological mean value is often only a very poor representation of conditions. The width of variation of atmospheric elements harbors often decisive factors. In addition, the choice of combination

Fig. 4. Major mountains act as great climatic divides. Usually their windward and lee slopes have radically different climatic conditions. Orographic cloud formations such as those shown are frequently very spectacular. They offer a primary hope of increasing precipitation by suitable seeding techniques. [U.S. Weather Bureau, by F. Ellerman]

of elements represented in the classification is usually dictated by a specific application rather than by inherent properties of the climate itself.

For geographical purposes, climatic classifications often have the boundaries of types essentially governed by other entities, such as plant cover associated with (or perhaps caused by) a specific combination of climatic conditions. Even that will not yield an unambiguous answer, because several combinations of climatic factors may have the same end result. The classical climatic classification schemes, which essentially arranged their limits to coincide with the major plant provinces on earth, have didactic value. They help in visualizing the global distribution within a readily comprehensible framework.

In many climatic classifications only temperature and precipitation are considered as climatic elements. Admittedly, these are most widely observed. They also generally affect human activities, particularly agriculture. However, there can be as many classifications with various combinations of elements as there are practical purposes. For air conditioning, one would choose suitable combinations of temperature, humidity, and air motion as classification elements. In that case the class limits would be comfort sensations. To classify airports or air routes in a climatic sense one has to consider the flying weather. The class limits are then determined by cloud ceilings, visibilities, turbulence, wind directions and speeds, and their respective joint frequencies. Essentially, one can arrive at a classification for every activity influenced by climate. To illustrate this point further: Very recently a classification has been devised for refractivity of the atmosphere as it affects radio wave transmission (*11*). This incorporates the pertinent elements of pressure, temperature, and humidity and their

Fig. 5. Climatic changes through the millenia are particularly notable in the arid and semiarid regions of the southwestern United States. At one time heavy rainfall and run-off helped in modeling outstanding features of the landscape such as those shown in the Grand Canyon of the Colorado. [U.S. Weather Bureau, by Madison Gilbert]

Table 1. Notation for climatic typing. Mixtures of two types are indicated in parentheses, as (*CA*), (*AE*). A further symbol employed is the subscript *e* to designate extreme conditions.

Feature	Symbol
Major circulation patterns (primary controls)	
Migrating cyclones	*C*
Quasi-stationary anticyclones	*A*
Equatorial convergence	*E*
Secondary or seasonal circulation features	
Typical monsoons	*S*
Predominant trade winds	*T*
Major surface influences	
Continental	*c*
Oceanic	*o*
Mountain	*m*
windward slope	*mw*
lee slope	*ml*
Glaciated	*g*

normal vertical and seasonal variations.

A purely qualitative scheme of climatic classification can be designed to avoid the multiplicity and the difficulty of fixed, yet arbitrary, numerical values. This classification stems from the broad meteorological aspects of climate and the basic factors of the general circulation. It is in line with attempts in recent years to get away from the static concept represented by mean values of climatic elements (*12*). After all, there is nothing fixed in the atmosphere, and even such abstractions from its unending motions as the climate should reflect the dynamics of the system. The classification procedure then is nothing but a descriptive symbolism or shorthand notation of major types. Table 1 shows such a notation system. In this notation the climate of western New York State would be designated as *Cc,* that of Ireland as *Co,* and that of North Dakota as Cc_e. The coast of California would be (*CA*)*o*; the Sahara, Ac_e; Bermuda, *Ao*; and Oahu, *ATo*. The central Amazon valley would be labeled *Ec* and the Gilbert Islands *Eo*. Among the mountain climates, the Cascades have *Cm,* the Australian Great Dividing Range has *Am,* and the Mount Kenya area, *Em*. The various combinations of symbols cover all macroclimates. However, they do not reflect the local influences, usually labeled meso- or microclimates, such as lake breezes, slope exposures, and vegetation conditions.

Climatic Changes

Another reason why classification, in fixed terms, is an ad hoc procedure, is inherent in the fluctuations of climate with respect to time. These climatic changes are among the most fascinating problems in climatology. Changes occur both in short and long intervals of time. The long intervals comprise geological epochs; the short ones, centuries and millenia (Fig. 5). There is little point in talking about *climatic* changes or fluctuations when only a few years or decades are under consideration. Usually the fluctuations in such limited intervals are difficult to distinguish from random variations, if indeed they are not such variations. Any cyclical—or better rhythmical—elements in the same decadal intervals, if any, are masked by "noise." There is some evidence of weak components of one half, one, two, and perhaps other multiples of the sunspot cycle in some series of climatic data, but their amplitude is small. Other rhythmical elements appear and then vanish again from climatic times series.

For a great many practical purposes the values in a climatic time series can be treated on probability premises as if they had occurred by chance. This makes it possible to use climatic data from the past with considerable confidence for purposes of future planning. Various risks can be assessed for engineering construction and design as well as agricultural use. The list of such applications is large and steadily growing. A few examples will suffice as illustration. Many structures have to be built with knowledge of extreme weather events to insure adequate safety: the maximum wind for a tower, hangar, or bridge; the highest snow load for a roof; the heaviest rain intensities for culvert design. The probabilities of various limits can be estimated from the observations by use of various extreme-value distributions (*13*). For heating or air conditioning plant capacity, the knowledge of normal and extreme loads is also essential. These, too, can be efficiently estimated from the statistical properties of the past climatic record. Statistical functions, such as the incomplete gamma distribution, have been successfully applied to weekly or monthly rainfall values. This approach yielded valuable planning information for agricultural purposes (*14*). Similar analyses for freeze dates have been of considerable practical value for crop practices.

Even if we can safely assume that for plans not exceeding a few decades the past climatic record can be taken as a guide to the future, this does not imply the absence of trends. As more data accumulate the evidence for measurable climatic changes multiplies. For nearly half a century a gradual warming of the Northern Hemisphere has been noted. Were we to rely on temperature readings alone, the data for many areas could be challenged. To be sure, a rise of several degrees Fahrenheit can be noted in many temperature series since 1900. Unfortunately, numerous weather observing stations have been shifted around, and their records are far from homogeneous. Moreover, many are in or near growing cities. Part of the rise of temperature

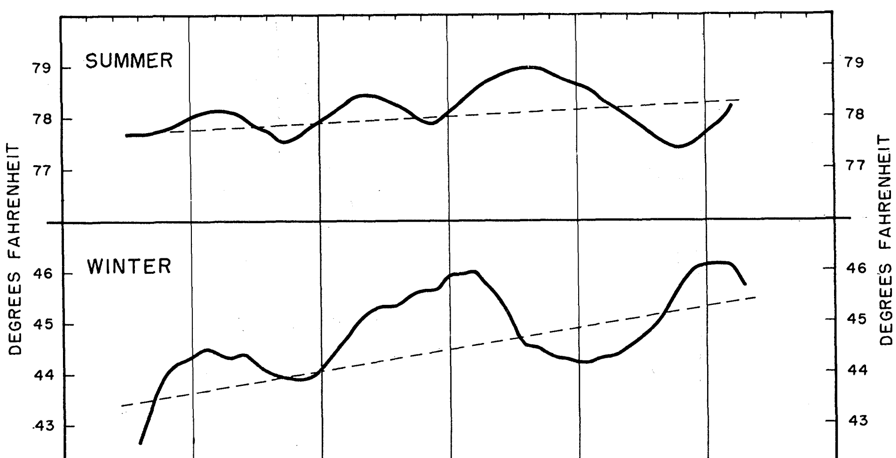

Fig. 6. Time series of seasonal mean temperatures at Winthrop College, South Carolina, one of the climatic reference stations (lat. 34°57′N, long. 81°03′W, elevation 690 ft). Summer comprises the months June-August, 1900–57; winter, December-February, 1900–58. Data have been smoothed by a normal-curve smoothing function of length $2\sigma = 5$ years. Values are plotted at the midpoint of the smoothing interval (*39*). Dashed lines show the general temperature trend of the region.

must be attributed to the large number of heat-producing factors of modern industrial communities. These factors, together with air pollution, have created a new man-made climate which has developed in parallel with any natural climatic changes over the same time period. It is hard to apportion what part of the temperature rise has been artificial and what portion natural. This difficulty will be minimized in the future by establishment and maintenance of climatic stations in isolated areas where man-made environmental changes will remain minimal. These will be called climatic reference or "bench-mark" stations (*15*). Fortunately, there exist now enough rural data and other evidence to give us some clues. For the moderate latitudes, 30° to 50°N, in the area around the Atlantic, the natural rise can be estimated at about 2°F per century. At higher latitudes the value may be about twice that amount. The rise has been particularly pronounced in the winter season (Fig. 6).

It is interesting to revert here for a moment to Jefferson's climatic table of Williamsburg. Even though we know little about the circumstances under which the observations were made, comparison with a recent time interval shows that no *radical* change of climate has taken place. Temperatures are now slightly higher than they were at the end of the 18th century. But it should be remembered that there was a marked temperature fall between the beginning and middle of the 19th century, which was followed by the rise of the 20th. Rainfall is still about the same. The winds seem to show now a few more southerly and less northerly components than in Jefferson's day.

The indirect evidence for the most recent warming in higher latitudes is, however, quite impressive. There are positive trends of sea surface-water temperatures in the North Atlantic of the same order of magnitude as the long-term air temperature changes (*16*). Also, retreats of glaciers (*17*), upward migration of snow lines, lengthening of the freeze-free season, northward migration of animal species and plants (Fig. 7), and phenological data all point in the same direction. There is little doubt that the past two or three decades, taken over-all, have been among the warmest in centuries. The question as to what may be the causes immediately arises. First, let me state that periods of similar warmth have been noted in earlier historical times. Even warmer intervals have occurred since the last glaciation. The most widely held opinion ascribes the changes to variations in the solar radiation. Satisfactory proof for this relationship is still lacking (*18*).

For the latest temperature change, there is an important contender as cause: atmospheric carbon dioxide. There are some interpretations of historical and current observations pointing toward a gradual increase of this atmospheric constituent (*19*). The increased consumption of fossil fuels has brought very large quantities of carbon dioxide into the air. Isotope investigations attest to this fact. Carbon dioxide is an absorber of outgoing long-wave radiation, and hence has an influence similar to that of a glass cover. This phenomenon is therefore often referred to as the "greenhouse effect." Only since the start of the

Fig. 7. The recent warming of the arctic has been particularly notable at the edges of the forested regions both in North America and Eurasia. The tree line has been advancing gradually northward. In some areas which have been resurveyed, the forest has advanced 2 miles northward over the last 30 years. [U.S. Weather Bureau]

International Geophysical Year have there been sufficiently widespread and accurate observations of atmospheric carbon dioxide to enable us to gain perspective on this question. Local variations and the uncertainties in the carbon dioxide balance between ocean and atmosphere make interpretations difficult. For an answer on the role of carbon dioxide in atmospheric temperature trends, many more years of systematic observations will be necessary (*20*).

Even if one accepts the thesis that atmospheric pollutants, such as dust and carbon dioxide, or terrestrially caused changes in atmospheric water vapor content could have an influence on the decadal or perhaps century-long trends, the main question still remains: What causes the large-scale epochal changes? Much thought has been given to this problem in recent years. New techniques, such as oxygen isotope analysis of sea shells, have been applied to it (*21*). But basically no new answers have been obtained.

If anything has happened, the ingenious hypothesis of attributing major climatic changes to the periodic elements in the obliquity of the earth's axis and in the eccentricity of its path (*22*) has lost its attractiveness. These path elements of the planet seem to account for only minor changes (*23*). Some new ideas have cropped up. They link pole shifts, oceanic currents, the ice conditions of the North Polar Sea, and the land glaciations (*24*). There is, of course, a much underrated relation between the oceanic heat (or cold) reservoir and the climatic fluctuations on land. However no *quantitative* consideration has as yet demonstrated that these could account for the observed, and evidently recurring, phenomena of major ice epochs. They may perhaps be adequate to explain stages within these eras.

Sooner or later most considerations get back to the question of changes in the solar radiation. Some astrophysicists contend that there are simply none of the magnitude required for major climatic changes (*25*). Others equally stoutly maintain that nuclear refueling processes on the sun actually call for periodic substantial changes in solar energy output (*26*). A once favored idea that cosmic dust clouds might act as interceptors has not been refuted but no new supporting facts have been marshaled either.

There is no unanimity about what the effects of changes in the solar radiation would be. Some contend that an increase could lead to an ice age (*27*). The essential reasoning is that initially higher temperature and increased circulation would lead to more cloudiness and hence greater albedo values. It is, however, more logical to assume that increases in radiation cause warmer conditions, such as once prevailed in the Tertiary, and that decreases in radiation produce ice ages of the Pleistocene type. Both sides of this question are still being vigorously argued in current writings (*28*).

Climatic "Control"

Of late there has been a great deal of publicity about controlling the climate. The word *control* implies that you know what to do, and when and where to do it. Some of this talk about control can be ascribed to misinterpretation of dimensions. Most of it glosses over the fact that for *major* climatic changes one would have to modify substantially the tremendous amount of solar energy received by the earth. We might note here in passing that the energy liberated from the total probable stores of fission and fusion bombs would not equal the energy of the average thunderstorm activity on earth over a few days' time. Albedo changes can presently be envisaged only on a relatively small scale. Ocean currents are hard to divert; mountains are difficult to move. And these remain the major terrestrial climatic controls.

Conceivably one could throw enough dust into the stratosphere by nuclear explosions to intercept an appreciable amount of the solar radiation. This might, again conceivably, cause some changes of the general circulation. The effect would pass off in a few years—a short time as climatic spans go. Also, the effect would be general over the globe, with unpredictable effects as far as small land segments are concerned. It could hardly be called control.

Some talk glibly about trigger effects. This means that a small amount of energy can set off a much larger, latent energy store. But where is the "loaded gun" in the atmosphere? The nearest analogy is the latent heat of the water vapor. If condensed in spots it could add heat which could be transformed into other forms of energy. Temperatures might be raised, motions increased. Here, too, in spite of the sometimes advocated spreading of hygroscopic nuclei, little in the form of "control" can be foreseen in the near future. There are also some latent electric energies available in the atmosphere. These have hardly been explored yet.

The trigger effects, the albedo effects, even the direct addition and subtraction of energy, can now only be envisaged for local modifications of climate. The microclimate is readily manipulated and much along this line has been accomplished over the last few decades. This includes many of the horticultural practices from frost protection to shelter belts, from moisture-conserving mulching to irrigation. On a somewhat larger scale, creation of artifical lakes, changing of river courses, large-scale reforestation, and artificial suppression of evaporation have small, but measurable climatic influences. Also along this line, slight local increases of orographic rainfall by cloud seeding have been made probable (*29*). Cloud modification, if systematically carried on, by coalescence of droplets or by their dissipation, is among the potential producers of local climatic effects. There is theoretically a bare possibility of operating on the latent energies of severe storms and causing measurable effects. Experimental evidence has yet to be obtained in this respect. If practical, it will have, at best, climatic influences on a meso-scale. In all these aspects, a little more humility in the face of the overwhelming powers of nature seems to be indicated for the present.

Microclimatology and Bioclimatology

It has long been known that in the layers close to the ground, climatic conditions of wide variety can exist in close proximity (*30*). These conditions are often quite different from the general, or macro, climate of the region. Because they are often confined to small spaces they have been labeled microclimates. The term is, however, loosely used in the literature. Some authors restrict it to indicate climatic differences on the smallest scale only. This might show the comparison of the climate of a furrow compared to that of level soil, or the climate on the windward versus the lee side of a small hill or hedge. It might show the climatic difference between a forest and bare soil in the same area. Generally, however, climatic differentiation of somewhat larger scale is usually included in a discussion of microclimatology. In this broader sense the scope of this field includes the contrasts of valley, slope, and crest climates in a hilly terrain, or it pertains to the climates of a settlement, town, or city as distinct from the surroundings, undisturbed by human activity.

The microclimatic differences are often startling. They develop primarily under conditions of clear sky and little wind, but some still exist with clouds, wind, and rainfall. Human interference, as can be seen from the foregoing, is important in creating and destroying microclimates (*31*). Manipulation of microclimates is, or should be, an important adjunct to planning land utilization, agricultural management, architecture, and urban development. In this connection, it may be interesting to cite a few figures on the major climatic differences between cities and their surroundings (Table 2).

Table 2. Climatic changes produced by cities (*40*).

Element	Comparison with rural environment
Dust and pollution	10 to 25 times more
Radiation	15 to 20 percent less
Clouds	5 to 10 percent more
Precipitation	5 to 10 percent more
Temperature (average)	1 to 2°F more
Relative humidity	3 to 10 percent less
Windspeed	20 to 30 percent less

In many instances air pollution accumulations are direct consequences of microclimatic settings. Topography, source of pollution, and general climatic conditions combine in patterns which become a typical element of local climate. It is feasible to estimate the pollution hazards of an area from climatic records and the terrain features, if sources of contamination come into being.

Microclimatic principles are among the best established in climatology. The facts are usually the most readily amenable to observation. Advanced instrumentation is available (*32*). Quantitative theories that begin to explain the observed facts are in a better state than those of general climatology. Last but not least, experimentation with test plots, not too far removed from laboratory conditions, is feasible and is being carried on.

The microclimatic conditions play an important role in life processes. Some of these influences operate on the smallest scale. Bacterial, fungal, and insect life in plant cover are governed to a considerable extent by prevalent temperature and moisture conditions. Presence or absence of dew on leaves may determine infestations of plant pests. The microclimate in a high stand of grass, for example, may prevent extremes of heat and cold and thus enable survival of certain insects in otherwise lethal conditions. Intricate relations between climate, plant life, and low forms of animal life exist, but much remains to be learned about the microecological complex.

A mixture of both macro- and microclimatological influences operate on plants. These effects have been the target of a great many investigations because of their importance in crop ecology. In its simplest aspects, photosynthesis is, of course, a direct function of sunlight, and hence is subjected to the climatic variations of this element. But this is where simplicity ends in the plant-climate relation. The effect of temperature is fairly well understood, but when it comes to water use, the problems become really involved. In the higher plants, light, heat, and water interact in a nonlinear fashion. At various stages of development the requirements of the plant for optimal conditions change, and the interplay of climatic factors subtly shifts (*33*).

Although a modicum of order for the atmospheric environment can be obtained for plants growing in phytotrons, under field conditions it is hard to ascertain the role of each climatic influence. The only exceptions are singular, lethal events, such as a hard freeze or absolute drought. In their absence one has to ascertain the complex effect of *all* climatic elements on the development of the plant. The use of statistical techniques with multiple regressions is of some help. More commonly, investigators have tried to condense the complex climatic factors into single influence indices. This is helped somewhat by the fact that there exist fairly high correlations between some of the climatic elements. Thus temperature is correlated with sunshine, and water depletion is, to some extent, a function of saturation deficit and wind. These, in turn, vary not entirely independently of temperature and sunshine. Among the influence indices which have been used with some success are the (i) soil temperature at shallow depth; (ii) evaporation (from porous bodies or open water surfaces); (iii) heat sums (expressed in terms of temperature excess above a given threshold); (iv) potential evapotranspiration. The first two are directly measurable; the other two can be derived from simple climatic observations. These influence indices substitute, even if in an incomplete fashion, for radiation, soil moisture depletion, and transpiration from plants. They can be used as correlatives for various stages of phenological developments of plants (*34*).

Similarly complex are the climatic influences on the human and animal bodies (*35*). In the healthy organism we deal with problems of acclimatization. Some phases are well understood. As an example, we can cite the reactions of the human skin to ultraviolet solar radiation. Another one is the adaptation to reduced oxygen tension in the atmosphere, resulting in increased red blood corpuscles and thoracic capacity. Considerable evidence has also been advanced that the primary differentiation of races was caused by climatic conditions (*36*).

The influence of climate on pathological states is not well known. We find ourselves in a vast realm of speculation. Are there climates beneficial to older persons? Opinion leans toward an affirmative answer, specifying as optimal a "mild climate," without extremes of temperature and with a minimum of change. Are climates with low relative humidities beneficial to sufferers from sinus disease? Again, a poorly documented "yes" sums up the present level of knowledge, or better, ignorance.

Seasonal incidence of certain infectious diseases, or geographical distribution of endemic plagues, points toward a climatic causative factor. However, it is not known whether the influence is on the receptiveness of the human organism, on the pathogen, or on the various disease-carrying vectors. Equally ill-established is the role of climate in the air-borne allergies.

Outlook

Let me indulge now in speculating a little where we will go from here in climatological research. It is certain that the vast stores of accumulated climatic observations will be tapped for their concealed information by use of modern electronic methods of data processing. The phases of this work applied to various branches of engineering will flourish. Similarly, much progress can be expected in establishing the true climate of the upper air. From this will be derived dynamic parameters of the general atmospheric circulation which will define local and areal climates. Hand in hand with this will go research on energy transactions that determine climatic regimes (*37*). As a first step, a comprehensive radiation climatology of the globe is needed.

Better information on extraterrestrial fluctuations of radiation and deeper understanding of the atmosphere-ocean relations will throw new light on the problem of climatic trends. The tedious analysis of geological evidence is likely to leave the problem of ice ages in the state of working hypotheses.

The greatest advances of climatology are destined to lie in the border field of biology, provided an adequate cooperative research program is started. The interactions between the physical changes in the atmosphere and living organisms are too great a challenge to scientific curiosity to remain in a relatively unexplored state. We have already pointed to the special problems of agroclimatology, a solution to which population increase will demand. Similarly, the role of climate in gerontology and various pathological states begs for quantitative studies.

It is further certain that some experimentation with artificial alteration will take place. One can only hope that the long-range view will prevail and that the experiments will be carefully designed with a view toward physical and statistical validation. This is a large program which probably will take years and permit of few short cuts. Man may not become master of his climatic environment, but the next decades at least promise that he will be able to understand it much better than in the past.

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Pavlov and Lamarck

The great Russian scientist once reported experiments in support of Lamarck. Were his final views Lamarckian?

Gregory Razran

Recently Nathaniel Kleitman wrote me: "For quite some time I have been trying to ascertain if Pavlov ever retracted the statement made in 1923, at the International Physiological Congress at Edinburgh, and elsewhere, that successive generations of rats acquired conditioned reflexes with progressively less training. In his review of *I. P. Pavlov: Selected Works,* that appeared in *Contemporary Psychology,* Vol. II, p. 274, Gantt stated that Pavlov 'rescinded this statement about heredity when he had more critically surveyed the original experiments . . .' However, when queried by me on this subject, Gantt said: 'I have no reference to a retraction in print, although there may be one.' "

Analogous questions have been directed at me, from time to time, at meetings and in letters, by a number of American scientists, and once by a member of the State Department. Consideration of the evidence on this matter in its entirety and, for convenience, in chronological sequence, may thus be worth while, particularly since Soviet theorists have for some years been proclaiming Pavlov the true and renowned backer of scientific Lamarckianism or,

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