CLIMATOLOGY AND THE ENVIRONMENTAL SCIENCES

Inaugural Lecture
delivered at the College
on February 28, 1967

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GEOGRAPHY has assembled under its spatial umbrella a variety of specialisms which are concerned with the characterization and interpretation of the diverse natural and human phenomena of the earth's surface. One such separately identifiable field is Climatology. It is my purpose tonight to examine the content and aims of Climatology and its relationship with Geography and other disciplines. From this analysis I wish also to indicate the aspects of Climatology which I consider most appropriately the subject for instruction and research within a Department of Geography.

Geography in the last two centuries or so has gone through several phases of definition and redefinition. Its field of study—the earth's surface—is both unique and wide-embracing. This breadth of interests has been attractive to students but has also presented exacting challenges. As specialization and the contraction in the range of individual scholar's interests have increasingly affected the organization of academic thought, so broadly based disciplines, such as Geography, have been faced with major philosophical problems.

Many branches of knowledge with some form of causal relationship with the surface features of the earth could, at first, be associated, without too much heart searching, within Geography. An increasing body of knowledge, and growing demands for precise and rigorous definitions of specific fields of study, have produced more narrowly based disciplines, formerly included within Geography, but subsequently recognised as having separate identities. The study of the nature and effects of atmospheric behaviour at the earth's surface permitted Climatology to remain happily within the framework of Geography, so long as it was concerned with descriptive statements of climatic qualities in different areas, and so long as its excursions into the investigation of processes had to be limited, through lack of knowledge, to interpretations based upon surface contrasts. Climatology has not remained in this state however. The changes in its emphasis and approach illustrate some of the problems of Geography in relation to systematic and to environmental sciences.

As a starting point Geography was involved with the collection of the material details of conditions over the earth. Description was a beginning. In the early stages of geographical description there arose a concern with a framework and technique for dealing with the collected information. Areas defined by selected natural criteria, political units or abstract concepts of regional systems provided, with varying success, divisions into which data, climatic included, could be placed. This could be no more than a beginning. Geography progressed beyond the descriptive and factual collection stage to comparison and interpretation. The subject became increasingly involved with processes and the investigation of their effects when combined over the earth's surface in an interacting system of cause and effect.

In the second half of the nineteenth century, Geographers seeking the explanation of both natural and human conditions over the earth were involved with the problems of environmentalism. For many this became a direct attempt to interpret human actions in terms of the natural or physical factors—the form and arrangement of land surfaces, plant cover, soil, climate and water. The defects of such a mechanistic and monistic approach were such that this determining environmentalism—a human society guided and controlled by its physical setting—became increasingly unacceptable to Geographers, particularly by the late 1920s.

So a new approach was sought. Some Geographers concentrated their efforts upon the search for homogeneous regions. The coincidence of different patterns was often accepted as implying interconnection and even providing explanation. Others, recognising that physical

factors could not explain all, broadened the meaning of the environment to include human social forces, which were both a product of, and a factor in, human group action over the earth's surface. The environment in the hands of many became a total[1] as distinct from a physical complex. This approach satisfied many but inevitably raised basic issues of the competence and justification of the Geographer making excursions into the interpretation of all forms of human behaviour, even though he might state that his concern was limited to the investigation of spatial patterns of human activity and organization. O. H. K. Spate[2] writing in 1952 expressed the view, 'I do not think, therefore, that the question of environmentalism is as yet finally closed, or is ever likely to be, except in the obvious sense that environment is not the answer to everything.' In 1951 A. F. Martin,[3] arguing on philosophical grounds for determinism, concluded that 'the geographer must assume that men are affected by environment.' If the view of environment is not limited to the natural factors then the environmental approach is, surely, still acceptable. As W. Kirk[4] wrote in 1963, 'Most geographical problems have an environmental context.'

Another development aimed at the restriction of the subject matter of Geography and at a more rigorous study of individual processes and their consequences. As A. N. Strahler[5] put it in 1954, 'Let processes be restored to the central position they deserve.' This trend was directed to specific aspects of terrestrial phenomena, such as climate, landforms, vegetation, soil, settlement types, systems of economic activity.

The emphasis on process and on specialization encouraged many Geographers, especially in their research interests, to concentrate upon a particular aspect. There was, first, a two-fold division into physical processes and the patterns they caused, and into social and economic systems viewed as the product of environmental, especially social and economic, forces. Subdivision within these two groups was the next step.

Specialization has tended to lead Geographers into systematic fields which overlap, or actually become, distinct disciplines, with well developed conceptual frameworks and techniques of their own. In such circumstances these Geographers have to determine precisely how they stand. If they start with studies of phenomena on the earth's surface but their final position is in another discipline, do they still remain Geographers ? If the co-ordinating quality of regional Geography is also neglected, the danger of subject disintegration is added to the possibilities of Geographers being waylaid by their specialist interests. It is worth noting that, in answer to the need to redress the balance of extreme specialization and the importance of bringing together what the specialist has had to take apart, there has been the discussion or the development in our universities of Departments or Schools of Environmental Sciences, such as at the Universities of Lancaster and East Anglia. A somewhat similar integration of related interests has produced groupings of a number of disciplines under the composite title of Earth Studies, whilst in the last five years or so there has been an enormous burgeoning of the interest in Economic and Social Studies. All these I view, broadly defined, as environmental studies. They appear to demonstrate a need for the integration of knowledge ; a need which Geography emphasizes, but which seems to be in danger of being neglected by some of its present practitioners.

It is in relation to what has been said so far that I want to consider the nature of Climatology. Climatology deals with the patterns of behaviour of the terrestrial atmosphere that are experienced over a period of time. It must therefore develop from scientific investigations of atmospheric processes. These processes have initially to be examined and understood through physical relationships often necessarily expressed in mathematical, particularly dynamic, terms. This initial approach is, properly, Meteorology.

The events which arise from the movements and transformations of energy and of the state of water in our atmosphere result in two scales of system. First there is an underlying relatively steady state recognizable for the atmosphere as a whole. Its main variations are seasonal, since they depend upon the relative position of the sun and the equator. This system of atmospheric circulation provides the basis for the interpretation of the global patterns of climate. The second system is that which provides an embroidery of detailed smaller scale atmospheric changes and interactions, rapidly moving and evolving pressure systems or perturbations for which the identifiable life span is much shorter, often no more than three or four days. They affect relatively limited parts of the atmosphere and of the earth's surface. Such smaller scale events make up the sequence of weather. Whilst there is a degree of orderliness in their behaviour, and whilst they are all interacting phenomena within a single atmosphere, anticipatory statements of where, when and how they will occur are extremely difficult to make with absolute accuracy.

The analysis of both these sytems has to be founded on mathematical physics. The ideal Climatologist should be thoroughly versed in Meterology, which in its turn should be founded on a competent manipulation of the knowledge and methods of physical science. In practical terms it may be necessary to settle for something less than the optimum. Meteorology has developed as the senior partner and Climatology, in a somewhat Cinderella-like relationship, has developed less actively. This has been true both in the applications of meteorological studies to the making of a better synthesis of world climates and even more so in sharpening the awareness of climate as an environmental element. F. K. Hare[6] has indicated the situation of Climatology, ' The forecaster absorbed into Meteorology all those portions of Climatology which he found useful, and reserved the name Climatology for those portions of the science which presented weather information in a form unsuited to his purpose' ; and also,[7] 'Not long ago to be posted to the climatological branch of a national weather service was like being made an intelligence officer, or a lighthouse keeper : it was a terminal appointment.'

Meteorologists, in the earlier development of their science, had little interest in spatial variations and an incomplete appreciation of the fundamental global interconnection of atmospheric circulation systems. Thus they saw little of help to them in much of the information being accumulated about climatic patterns over the earth's surface. Admittedly meteorologists were interested in many atmospheric processes in which the earth's surface played a limited part. In terms of both interest and training a separation of Meteorology and Geography was an early development. The initial association of meteorological studies with Geography is still apparent, however, in the fact that, apart from Imperial College, London, Edinburgh, and now Reading, much of the limited university teaching of any form of Meteorology usually takes place in Departments of Geography. That it continues there reflects, however, the recognition by the Geographer of the importance of the meteorological basis of Climatology.

Climatology was less quick to define its position as a separate branch of knowledge or to depart from its earlier concern with climatic conditions which influenced geographical distributions. Statements of climate—an abstract concept in itself—provided a useful method of organizing the heterogeneous expressions of meteorological events into a comprehensible scheme. These syntheses of regional climates could then be employed to evaluate the relationship between climate and other variables on the earth's surface. Climatology in this form was felt as very marginal to the interest of the Meteorologist, but much more part of Geography especially at the time when it was emphasizing the control of the physical environment. In the early part of this century one could read such views as those of Ellen Churchill Semple,[8] 'The greatest

events of universal history and especially the greatest historical developments belong to the North Temperate Zone. . . . Everywhere in the Tropics the enervating effect of heat, moisture and abundance make not only the natives averse to steady work but start the energetic European immigrant down the same early descent to Avernus.' In 1915 Ellsworth Huntington[9] was writing in his *Civilization and Climate* 'Many of the great nations of antiquity appear to have risen or fallen in harmony with favourable or unfavourable conditions of climate.' These were comfortable, but unproven, views to hold when seeking reasons for the nineteenth and early twentieth century material pre-eminence of Western Europe and the developed parts of North America. In this frame of mind one might ponder on the significance, perhaps with regard to our entry into the Common Market, of the words of H. H. Lamb[10] of the Meteorological Office, 'Much evidence suggests that the south-eastern half of Britain belongs at least to the fringe of the same meteorological region as central Europe.' Speculative links between climate and man are intriguing but hardly sufficient foundation for further scientific progress.

At this point I should like to deal briefly with different aspects of Climatology[11] and to indicate their relationship to the studies of the Geographer. Descriptive Climatology concerns itself with the specification of the nature and distribution of the individual climatic elements. Great strides have been made in the development of a network of recording stations over the earth's surface and in sounding the lower parts of our atmosphere. Considering the need for adequate quantitative data for satisfactory statistical analysis, the gaps, notably over the oceans or over inhospitable desert, mountain or ice-cap areas, are still far too frequent. With only some 700 radio-sonde stations providing regular upper-air information, we are more sparsely supplied with details of the vast volume of the atmosphere. Even in apparently well-instrumented areas there are unexpected deficiencies. In Wales, for instance, only three climatological stations, the highest Bwlchgwyn (Denbighshire) at 1267 feet, at present report on areas over 1000 feet (27 per cent of Wales) above sea-level. Apart from reservoir catchment areas, there are considerable areas over 1500 feet for which precipitation data are sparse (Fig. 1). Yet much of the weather of southern Britain moves in from the Atlantic, and from the viewpoint of assessing the nature of the upland environment, we must still depend upon guesswork about many of the climatic conditions. There is still a need for much more comprehensive information to be gathered. Except in special research situations, this cannot be a major task for the Geographer-Climatologist. It must be provided, rather, by extensions of the recording network of official meteorological services.

Physical Climatology investigates the behaviour of the individual elements or processes in the atmosphere, in terms of physical principles. This affords a static picture of the climate but, as progress was made in understanding the three-dimensional features of our atmosphere, it became desirable to relate the observed data to satisfactory models of the atmospheric circulation. We now move into the field of Dynamic Climatology. Basically the atmospheric heat engine derives its power from the fact that there is a surplus of energy from the sun over outgoing losses in latitudes up to about 38° and a deficiency in higher latitudes. Thus we are provided with a heat source in the lower latitudes and a heat sink in the higher latitudes. The initial development of atmospheric motion represents a balancing process which re-distributes the available heat, either as sensible or latent heat. Since the earth is a rotating body a simple convectional cell between the equator and the pole of each hemisphere does not develop. Air motion occurs relative to this rotating system. This produces what is known as the 'Coriolis effect' which results in a wind trajectory deflected to the right in the northern hemisphere, and to the left in the southern hemisphere. Air does not, therefore, flow direct

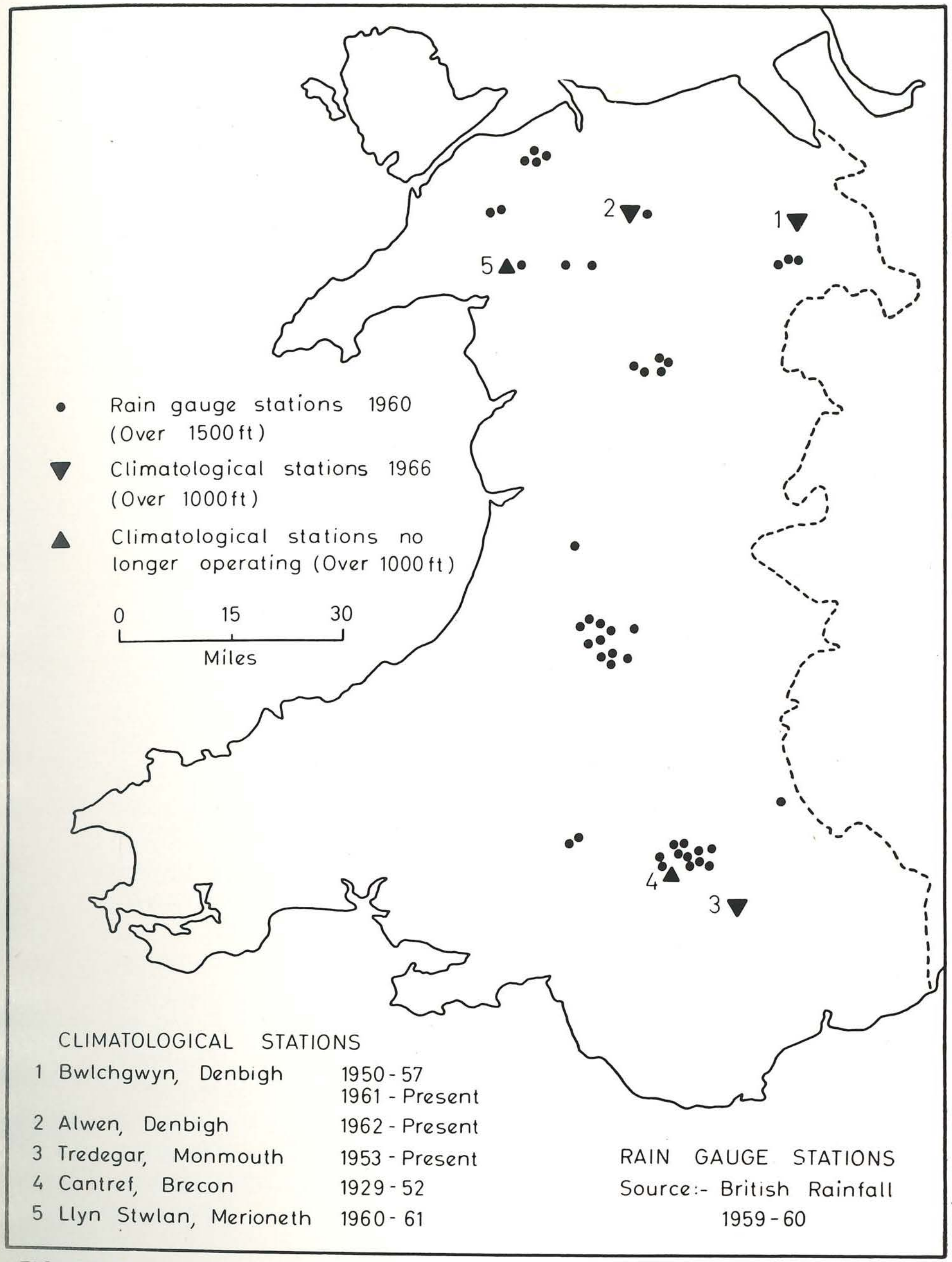

FIGURE 1. UPLAND RAINFALL AND CLIMATIC DATA AVAILABLE FOR WALES

from low to high latitudes or vice-versa. The eventual picture of the primary circulation pattern of the atmosphere is more complex. Amongst other things, it incorporates climatologically important features such as the meandering concentrations of high velocity upper troposphere winds known as jet streams, and the long wave motions or Rossby waves in the westerly winds above the surface which arise from the conservation of absolute vorticity. As well as the transfer of heat energy, in the atmospheric circulation system where air movement with both easterly and westerly components exist together, there must be a balance of angular momentum, achieved by a transfer from the easterly winds of the tropics to the westerly wind zone of mid-latitudes. If this were not so, the present circulation could not be maintained in the spinning earth/atmosphere system.

Writing in 1961 G. B. Tucker[12] commented, ' It is the emergence of dynamical climatology, the appreciation of and investigation into the dynamics of climate that has been the major development in climatology during the last decade.' The modifying effects of land and sea distribution, of extensive ice areas or high mountain-ranges complicate the circulation system referred to, but while ' Many climatic phenomena are undoubtedly the indirect result of surface physical features . . . it is the atmospheric processes that are mainly responsible for climate.' The American Geographer G. T. Trewartha[13] has shown in his discussion of *The Earth's Problem Climates*, that there are anomalous climatic features associated with particular areas. Some of the answers are to be found aloft in departures from the simpler models of atmospheric circulation but other explanations are related to earth-bound causes. The fascinating evidence from satellite cloud photographs[14] has demonstrated not only the complexity of detail superimposed upon the primary zonal, meridional, and wave motions of the atmosphere but has also shown details which are intimately tied to the configuration or character of the surface. Nevertheless, both because dynamic Climatology has greatly weakened the link between the earth's surface and major climatic differences, and because the Geographer rarely has the competence to research in the field of hydrodynamics, dynamic Climatology cannot be viewed as an integral part of Geography. Whilst saying this I must emphasize that the Geographer can neglect the basic findings of dynamic Climatology only at his peril, and faced with this challenge F. K. Hare's[15] comment, '. . . there is no half-way house except mediocrity,' cannot be ignored.

Synoptic Climatology is closely allied to dynamic Climatology. In this a synthesis of the climatic experiences at a particular place or over a limited area is made in terms of the occurrence of patterns of air-flow or regional circulation types, or the frequency of air-masses, or of pressure-field types—predominantly anticyclones and depressions in temperate latitudes. Such weather patterns can be correlated with surface weather data and the effects of surface factors. Viewed in this way they can be studied in the same manner as one can analyse individual climatic or weather records, and with these they can contribute to a fuller statement of regional climatic experiences. They would form then an appropriate part of a geographical investigation. Examined analytically in terms of cause and process, the enquiry moves into the province of physical Meteorology or dynamic Climatology and away from Geography.

Caution must be shown, however, if Geographers are to avoid the dangers of naive, over-simplified or over-generalized explanations based on surface effects, which may well lead to a misinterpretation of environmental consequences. For example, the traditional picture of rainfall in the wet season in the humid tropics has been tied to intense solar heating of the surface, rising air and cumulus cloud build-up from which, with well disciplined regularity, intense rain falls in the late afternoon to the accompaniment of thunder and lightning. Subjective impressions from some tropical stations appeared to confirm this, but the text-book pattern was sometimes departed from. Detailed studies of their times of occurrence have revealed instances when the majority of the rain-storms occurred in the night hours.[16] Moreover, not all cumulus clouds developed into rain-producers, though at the surface it was difficult to find much distinction between the conditions for those that did or did not give rain. Many such rainstorms appeared to be irregularly and haphazardly distributed, but organized belts of cumulo-nimbus clouds also occurred. Variations in surface heating or contrasts in relief did not explain all the anomalies. Balloon soundings of the upper-air have since revealed a link with upper air perturbations or disturbances moving within the larger scale circulation system. Whilst Geography Departments usually run weather stations, the upper air is outside the realm of their observational experience. This is no justification however, for failing to recognise that the atmosphere is three-dimensional even though the Geographer may be primarily interested in a result which is two-dimensional.

Another aspect has a bearing on whether explanatory studies of climate are more appropriate to climatological work in Geography or in Meteorology. This is the matter of scale. On the level of global or macro-climatic investigations, the basic approach must be through the major features of atmospheric circulation. While the physical processes of heat and moisture exchange and transformation apply in smaller scale climatic studies, what are termed meso-, local or micro climatic investigations, there is a changed emphasis on the relative importance of the different mechanisms. Near the surface molecular diffusion of water-vapour, conduction of heat or the frictional drag of the surface play a much more effective part. The active surface of the ground becomes increasingly dominant, and the depth of the atmosphere which is immediately relevant is considerably contracted. Both the nature of such smaller scale variations and their strong

connections with surface variations link them closely with Geography. One moves again away from Geography, both in terms of physical interpretation and because of the increasing concern with instrumentation techniques, when one deals with the minutest scales of microclimatology. It is of no surprise that Geographers find much of interest to them in the demonstrations of the roles of surface slope and aspect, plant cover, soil colour and soil moisture, snow cover etc. in local and micro climates presented in R. Geiger's[17] book *The Climate near the Ground*.

Whilst the Meteorologist is deeply interested in the large scale features of dynamic Climatology, he is less attracted towards the local variants upon the broader pattern. The special qualities of the local weather are often left to take care of themselves in the training of a synoptic meteorologist on the assumption that they can quickly and adequately be acquired ' on the job.' Reduction in the scale of climatic study neither minimises the scientific importance of such work nor reduces its relevance to environmental problems. Indeed some of the differences which occur over a few miles are of a magnitude which may well produce significant modifications in the agricultural or horticultural potential of areas, alter the ecological habitat or affect human comfort. It is to be expected that the Geographer will be keenly interested in these spatial climatic variations even though generalization and development of scientific laws from them may be difficult.

The topographic factor in local climates can be illustrated. In the daylight hours energy radiated from the sun is absorbed at the earth's surface. That which is available for surface heating will be the solar constant, or total available at the atmosphere's outer limits, minus that absorbed by the atmosphere or lost by back reflection to space from cloud surfaces, other atmospheric constituents or the surface of the earth itself. The total loss due to reflection, referred to as the earth's albedo, is about

35 per cent on average of the solar constant. The distribution of the radiation incident upon the surface from a beam of unit area will clearly be a function of the height of the zenithal sun, the time of day, and the gradient of the slope. On a horizontal surface day length is dependent on latitude and season. In areas of varying relief shadow zones can reduce the direct solar radiation considerably, though this will be somewhat less true in the case of diffuse radiation. Shadow areas will depend on the slope angle and the orientation of the crest line. The diagram (Fig. 2) indicates for a latitude of 50°N[18] the significance of slope and aspect. One may compare the highest annual radiation totals on the most favoured parts of the southern slope (140 to 160K cal./cm²) with a value of 160 to 180K cal./cm² on the southern margins of the western Sahara.[19] Such slope contrasts are best developed in clear, still, sunny weather, and radiatively determined local climates lose much of their distinctiveness in cloudy, windy weather.

Other forms of topographic control operate. Complex wind-field patterns are associated with areas which have a marked variety of relief. One of the best appreciated, and often practically most significant phenomenon occurs with nocturnal down-slope drainage of cold air. When the weather is conducive to strong out-going radiation, the air cooled on the higher areas may accumulate in the valleys and other depressions. In such circumstances valleys can suffer such disadvantages as increased frosts or more severe night-time minimum temperatures, mists, and the accumulation of polluted atmosphere in stagnant cold air pockets in the lowest areas. For instance,[20] the narrow Cwm-du valley, an eastern tributary of the upper Senny river in south Brecknockshire, has entrenched itself some 800 feet below the plateau. In two successive years the valley floor was colder than the exposed upland for varying periods on 140 and 145 days respectively, with the greatest diurnal difference amounting on one occasion to 10.6° Celsius. A large height difference, however, is

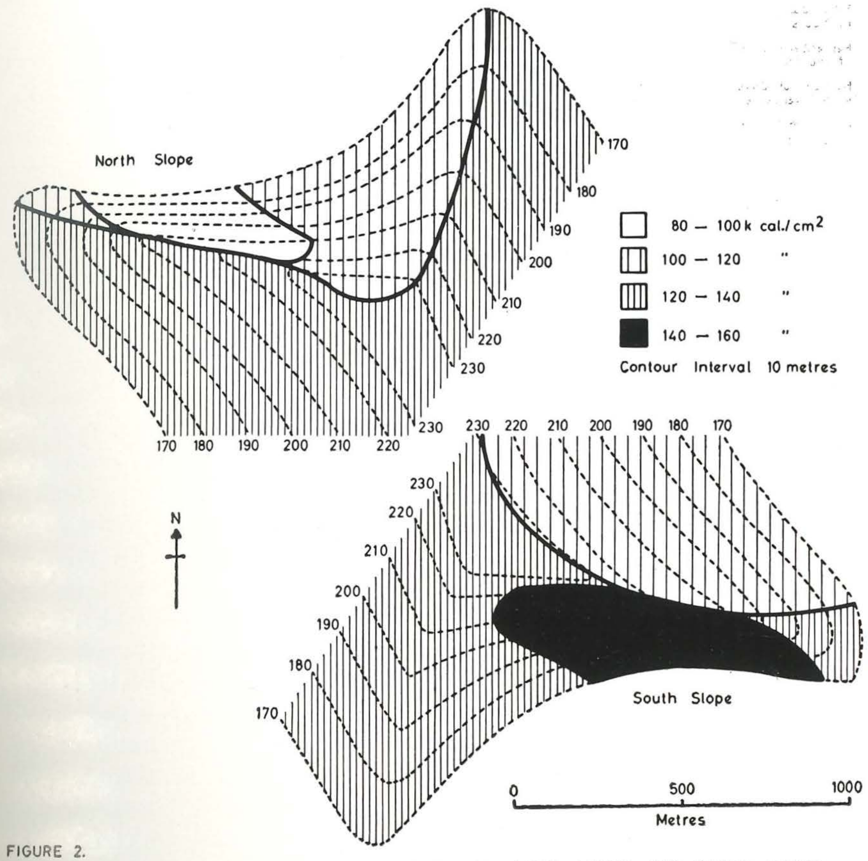

FIGURE 2.
ANNUAL VALUES OF POSSIBLE MAXIMUM RADIATION ON STEEP NORTH AND SOUTH SLOPES
(After Knoch 1963)

TABLE 1.
INVERSIONS OF TEMPERATURE
LOWER SWANSEA VALLEY
LLANSAMLET AND BON-Y-MAEN

	1964								1965				
Inversions	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total for year
Total duration in hours	59	56	175	244	180	229	263	197	209	135	115	139	2001
Percentage duration of month	12·3	7·7	23·5	32·7	25·0	30·8	36·6	26·5	28·1	20·1	15·5	19·3	22·8 of year
Number of days with inversions	16	12	20	24	24	26	25	23	20	14	15	20	239
Maximum temperature difference °C	4·1	2·1	1·8	4·6	3·8	3·2	5·6	3·7	3·1	2·3	5·8	4·2	—

not necessary to produce such temperature inversions. In the Swansea Valley,[21] well ventilated since the prevailing west-south-west winds tend to be canalized along the axis of the valley, a site close to the valley floor at Llansamlet compared with a site 220 feet higher up on the eastern slope experienced 239 days with inversions during a period of one year during 1964/65 (Table 1). 23 per cent of the total duration of the year was colder on the valley floor. Making a conventional correction to temperature for increase in height, we would anticipate that the upper station would be on average 0.5° Celsius cooler. Here are local climatic conditions which merit consideration in planning the use of such areas.

Circumstances such as those just referred to interest a Geographer because of their spatial associations, but even more they appeal because of their relevance to the last branch of climatology to which I now want to turn—Applied Climatology.[22] It is in this field that Climatology and the Environmental Sciences are most closely related. Its aim is to examine the ways in which climatic factors contribute to the development of other earth surface phenomena, natural or human. Applied Climatology can be investigated under a number of specific headings such as agricultural climatology, bio-climatology, physiological climatology,[23] urban climatology, building climatology and so on. Progress in these has varied. The climatic environment of agriculture and horticulture has long been studied ; much has been learnt but much too awaits

clarification or recognition. Rather surprisingly field investigations of the largely unfavourable qualities of urban climates have received limited attention. The thermal effect of towns—the urban heat island—has been well demonstrated for London by T. J. Chandler.[24] The deterioration of our atmospheric environment through the emission of urban and industrial waste materials into the air is now fully realized, though meteorological considerations are still too often considered of secondary importance. Relatively little discussion of weather factors appears in A. R. Meetham's work on *Atmospheric Pollution*.[25]

The climates that occur in and around buildings, and which may be highly relevant to our living comfort, have too frequently been ignored. One is often wise after the event in dealing with them. The site of this College and the complex series of buildings of varying height, shape and orientation built upon it have not been investigated climatologically. Buildings greatly modify the pattern of wind eddies between and over them. In turn these changes affect a variety of problems connected with heating and ventilation, the removal of fumes, the drifting of rain and the not unimportant matter of comfort when moving out-of-doors between different blocks. The shadows cast by tall buildings in a closely built-up site affect the internal heating and lighting of other buildings. Man is a factor in the causation of local climates as well as being affected by them. The climatic element of the built environment usually comes very low on the list of considerations thought to be relevant to site or urban planning. Should this be so ? It is impossible to be sure of the precise nature of the problems or of the importance of their consequences until the site climate and the disturbing effect of site development have been thoroughly investigated. As J. Leighly[26] put it, 'The test of the utility of climatologic data in practical affairs is the establishment of quantitative relations between these data and contemplated actions.' Until one can reduce the number of assumptions which have to be made, the

TABLE 2.

RAINFALL OF SWANSEA

AVERAGES FOR THE PERIOD 1916 — 1950

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year Total	
Monthly mean rainfall	4·73	3·22	2·49	2·41	2·62	2·41	3·48	3·87	3·83	4·69	4·73	4·51	42·99	Inches
Number of days with over ·01 inches	21	16	15	16	15	13	17	17	17	19	19	20	205	Days
Heaviest rainfall in one day	2·02	1·21	1·24	1·58	1·58	1·29	1·65	2·20	1·83	2·38	2·62	1·80	—	Inches
Wettest month (1931 - 1960)	8·64	7·20	8·44	5·98	6·21	5·36	8·07	7·47	9·08	9·44	10·42	11·00	—	Inches

margin of error in any cost/benefit analysis nullifies its value.

I frequently find myself walking from one end of the College site to the other, particularly since parking problems preclude the lazy man's solution of driving. With a mobile community the size of this College concentrated on a small area, would the expense of covered ways be justified ? The answer must be arrived at by defining potential climatic nuisance conditions, determining their frequency and severity, and calculating the cost and rewards of protective measures. What do we know about rainfall in Swansea ? (Table 2). We can start with statistics such as an annual mean value of 42.99 inches of precipitation falling on 205 days with .01 inches or more. This information, interesting though it may be, is insufficient. No-one has investigated the precise pattern of daily rainfall in Swansea. Do we suffer more rainfall in the daylight, or working hours, than at night ? What is the most frequent duration of periods of rain, and what is the most characteristic intensity ? What, for that matter, is the most discomforting type of rainfall—that falling with tropical intensity more or less vertically with relatively calm conditions or that of medium intensity driven by a 20 knot wind ? How do different intensities and spells of rain correlate with wind strength and direction—a vital matter if we can take advantage out-doors of the shelter of buildings ? I am sure that all here to-night will have impressions to put to these questions but valid answers must be based on precise statistics.

Climatically determined circumstances, even in the most technically advanced communities, still upset our calculations. The devastation caused by weather accidents can be documented and costed, but it is often with a resigned shrug that such events are accepted as unavoidable catastrophes. Prevention rather than cure is the need. Are these circumstances abnormal ? Studies of causation, statements on patterns of behaviour and probabilities and then investigation into the feasibility of preventive measures are what one needs.

The recent flood damage in eastern Brazil this January and February shows an underestimate of the possibility of such intense rainfall within the time scale of human experience. We clearly want to arrive at some statistical estimate of the degree of abnormality involved so we can plan our activities reasonably. The monsoon rains of India are notorious for their misbehaviour. Retrospective assessments of the achievements of the Five Year Development Plans for India up to 1966 make frequent reference to the failures in achieving agricultural targets because of excess or deficiency of rainfall. Such disappointments in agricultural production can have a magnitude greater than miscalculations of a purely economic origin. The present tragic situation in eastern Uttar Pradesh, Bihar and adjacent parts of north-east India has caused food shortages, acute in some areas, which may affect the lives of perhaps 70 million people. The immediate cause is climatic. Even some of the recent election misfortunes of the Congress Party may be attributable in part to the inadequacy of the rainfall. Another instance from the East Pakistan lands bordering the Bay of Bengal can illustrate the magnitude of climatically produced disasters, the scale of which we are fortunately spared in Britain. Tropical storms originating over the Bay of Bengal sweep inland and cause enormous loss of life and property. The estimated death roll of 15,000 due to the storm of May 1963 or the 17,000 killed in May 1965 (a year with another devastating storm in December) would justify a heavily financed investigation into the climatology and the meteorology of such storms.

The understanding of the mechanism of tropical storms is still imperfect. The West Indian area is another region which is subjected to them under the name of hurricanes. The energy involved in such a storm greatly exceeds that generated by a large atomic explosion. Most hurricanes originate in the western tropical Atlantic, move west and then, under the influence of the earth's rotation, curve parabolically north and north-east. Any that track across the Atlantic towards western Europe have lost their initial vigour by the time they reach our shores. Their behaviour is erratic, however, so that hurricane warning services can be caught out. In October 1961[27] Hurricane Hattie unusually tracked westwards across British Honduras into the Pacific. It caused severe local damage, but of more fundamental interest is why such anomalies of movement or instances of the re-invigoration of apparently declining storms should occur. The practical implications of an increase in the number of hurricanes recorded in the West Indies[28] from 50 in the decade 1911—1920 to 100 in the decade 1951—1960 are obvious. Over the period 1955-64 hurricanes in the U.S.A. have caused an estimated damage of £3,500 million. It is clearly desirable to try to find out whether a temporary change or secular trend in the basic features of the atmosphere is involved. More information both on the general qualities and possible extremes of the climatic environment is still essential.

The possibilities of weather control have progressed beyond the level of mere fantasy but the extent to which the climatic environment can be regularly or permanently modified is still limited, except on the local or micro-climatic scales. The seeding of clouds, by a variety of methods, can cause cloud droplets to grow rapidly to the size of raindrops, provided the physical condition of the atmosphere is close to producing rainfall anyway. If the atmosphere is in a stable state, and cloud build-up

unlikely, no rainfall can be induced. There is the possibility that the latent energy of hurricanes can be dissipated by cloud seeding before the storm can devastate the land on its route.[29] Other forms of weather management include fog dispersal or measures to reduce frost or hail destruction of more sensitive crops. Not all the problems are connected with physical processes. There are some intriguing legal aspects to rain-making, when rain clouds activated over one area produce floods or heavy rain showers downwind where they are not wanted. More extravagant schemes of climatic modification have been discussed. For instance, by covering the polar ice by a surface dusting of black powder its heat absorption capacity would be increased and melting accelerated. Not only would the extensive melting of the ice-caps raise sea-level by anything up to 200 feet, but also the high latitude heat balance would be altered, and this in turn would lead to atmospheric circulation changes. It would be extremely difficult to forecast where the chain re-action of atmospheric adjustments would lead. We have yet to determine the realistic limits of man's control of weather and climate.

The record of palaeo-climates[30] indicates that the natural climatic environment is not stable. Global climatic contrasts over much of geological time have been generally more subdued than those of to-day. At long separated intervals, however, latitudinal climatic differences have been sharpened by the growth of extensive ice-sheets in middle or high latitudes. The record of surface relief forms, glacial deposits and the evidence of soils, flora, and fauna developed under different environmental conditions bear clear testimony to the presence of ice up to as late as 25,000 years ago or less over many parts of Europe, North America, and elsewhere. Compared with just over 10 per cent of the land area of the earth now under ice, as much as 32 per cent may have been covered at the maximum of the Pleistocene. In such areas landscape, soils, and the ecological development of plants and animals are geologically youthful. What we observe to-day is a response to a changing and composite climatic environment.

After the first fluctuating melting of the Pleistocene ice the momentum of warming increased. Once the seas around our islands became ice-free, it is possible to put limits to the probable range of temperature extremes which the prevailing patterns of land and sea and the basic wave motions in the westerly winds may permit. The warming trend continued until it attained a peak in the world-wide Climatic Optimum about 7000 to 5500 years ago.[31] The decline which took place thereafter is limited within the general climatic framework. The climatic changes over the last 5000 years in the British Isles have not been spectacular, but they have been important enough to modify the ecological habitat and the natural environment of man. Climatic boundaries have been shifted over the transitional zones between more persistent climatic type areas. It is often in the marginal areas at the latitudinal or altitudinal extremes of a favourable environment that the most sensitive indications of climatic change are found.

More information must be acquired before one can make adequate assessments of the environmental significance in Britain of the dry, warm phase over the eleventh to thirteenth centures A.D. or[32] the most severe cold of the Little Ice Age between 1550 and 1700 A.D.[33] So much of the evidence about the climate of the historical period is qualitative. The answer, however, to many of the questions of economic, or indeed of related social history, can only be put into their correct perspective when the reality and impact of climatic fluctuations can be determined. Were vines widely grown in favourable parts of southern England before 1300 ?[34] If so, was this due to a shift of a few degrees of latitude in the northern boundary of economic vine cultivation because of a more favourable spring and summer climate, or were the factors purely economic and social ? It would be unrealistic to insist on

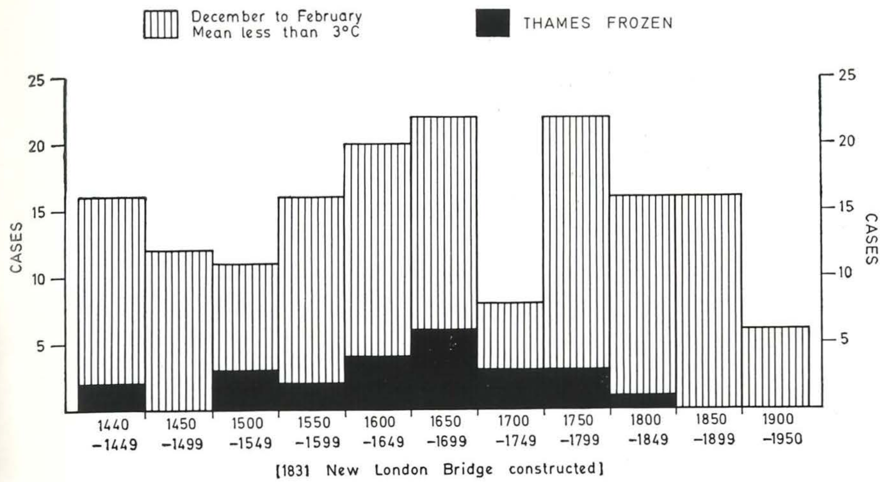

FIG. 3. WINTERS IN CENTRAL ENGLAND WITH ESTIMATED MEAN DECEMBER TO FEBRUARY TEMPERATURES BELOW 3°C WITH OCCASIONS WHEN RIVER. THAMES WAS FROZEN

climatic determinism, but I suggest that the analysis would be imperfect without allowing due weight to possible, or actual, changes in the natural environment.

An equally fascinating query is whether the lost villages, the sites of which are identifiable on aerial photographs or even on the ground in many parts of England, partly result from the stresses of a fourteenth century climatic deterioration to wetter and stormier conditions.[35] There may have been either direct effects on the rural economy of the time or the unfavourable climate may have facilitated the spread and exacerbated the effects of the Black Death and thus indirectly contributed to the denuding of the countryside of labour.

Studies of population trends in Sweden by the economic historian Gustaf Utterström[36,37] led him to conclude that the prevailing climate and the effects of climatic fluctuations were of decisive importance in explaining the demographic picture. Swedish population declined over the period 1590 to 1620. This was a period of poor harvests in southern Europe and England, and dearth in

Scotland. Not only was there exceptional climatic severity in Sweden between 1596 and 1603, but Alpine glaciers were strongly advancing between 1595 and 1610. Some of the furthest down-valley locations of moraines in front of Alpine glaciers have been dated as 1602.[38] Coincidence in time does not necessarily prove a causal relationship, however.

Climatic change means a dynamic environment. In nature ecological adjustments occur at different rates to environments which are also changing. The resultant picture of these varying rates of effect and response is a complex one which it is fascinating to study. We must admit it is difficult as yet to discern clearly all the consequences of climatic change. We must recognize too that the evidence on the climatic history is both far ranging and variable in quality. The intimate interconnection between landforms, flora, fauna, and soils, or even the climatically modified aspects of human activity, which we want to examine in climatic terms, are also the sources of evidence for climatic reconstructions. The evidence of pollen grains, the stratigraphical variations in peat bogs, the nature of surface sediments, the chemical qualities of soils or of lake waters at different depths, to mention only some of the available indicators, is not unequivocal. The use of the evidence of human settlement sites, of migrations and of the levels of material or technical civilization may prejudice some of the very issues which, having ascertained the character of the climatic environment, we wish to evaluate.

The scientist is much happier with quantitative data which he can assess as objectively as possible by appropriate statistical methods to express a mean or most common mode of behaviour, variability, trends or cyclical variations if these exist. He wants to be able to set limits to the extremes which may occur, or to indicate the probabilities of specified conditions. To attain these aims homogeneous and reliable measurements are required. Even allowing a liberal specification for our data, there is

little really acceptable information over a century old. Quantitative information of any form or quality covers only some three centuries in Europe. The earliest simultaneous records were those kept between 1649 and 1651 at Paris, Clermont Ferrand and Stockholm. G. Manley,[39,40,41] by skilfully overlapping and correcting several different records, has provided a composite picture of monthly mean temperatures representative of Central England since 1670. Over the last two and a half centuries in Britain the lowest monthly mean temperature has been —4.2° Celsius in January 1814 at Perth and the highest mean 20.1° Celsius, July 1932 at Reading. This may provide a reasonable guide to the probable extreme range experienced over the last two or three thousand years, and the magnitude of the variation for which causes have to be sought. A climatic fluctuation occurs, and can have important consequences, when departures from the normal become more frequent and persistent.

Though the earliest English rainfall records were those started in 1677 by Squire Towneley of Burnley, subsequent gaps and the difficulty of overlapping rainfall records in the same way as those for temperature, have meant that the pattern of rainfall in England and Wales becomes available only from 1727 onwards.[42]

From 1880 until 1940 a limited, but in some areas significant warming of the world, has been identified in a wide variety of environmental responses[43,44] as well as from instrumental evidence. In many parts of the world glaciers have contracted but, indicating the complexity of evidence, we find retreating and advancing glaciers sometimes side by side in the same area. I cannot expand on this recent climatic fluctuation. Perhaps H. H. Lamb's view,[45] 'I have always thought it a misfortune that the general introduction of plumbing into British houses coincided with the quite unusual run of mild winters between 1896 and 1936,' provides adequate comment. In failing to put water pipes deep enough or insulate them properly we have been gambling on avoiding winters of the severity of 1962/63.

The analysis of climatic change is particularly appropriate for the Geographer interested in climatology. In one direction the investigation of the pattern, degree and possibilities of change is a matter of dynamic climatology. To fully assess the environmental consequences of a climatic change we wish to know how it has been caused. From a practical viewpoint the reconstruction of the features of past conditions of air-circulation, water drift and ice-dispersal is the starting point for long-range weather forecasting. In this work analogue methods seem likely to remain the most fruitful approach as compared with the analysis of fundamental equations for long-term atmospheric processes for which knowledge, other than empirical, is as yet too limited.

Dr. B. J. Mason,[46] the Director-General of the Meteorological Office, has recently made a tentative costing of some of the benefits which can be derived from the application of weather and climatic knowledge. The return on the expenditure, or the nature of the most appropriate form of information, depends strongly on the appreciation of the environment. The estimate of the overall benefit/cost ratio was put at 20 : 1, whilst within this overall figure there were much greater benefits, for agriculture and horticulture for instance. Does the fact that while in Britain we spend each year on our weather services 2/6d. per head, the Australians spend 6s., the Canadians 10s. and the United States 21s. indicate that we fatalistically accept or even ignore our climatic environment ?

The strong emphasis on economic analysis and costing of human activity in terms of returns in their widest and not purely monetary sense is sensible. This implies both the avoidance of special pleading and also consideration of all the possible relevant circumstances.[47] Dr. Mason stressed the need for better meteorological guidance so that, ' the great number of weather sensitive decisions

arising daily in all walks of life can be made in the best interests of the economic and social welfare of the country. . . . Although there may be no immediate prospect of controlling or significantly modifying the weather, its favourable aspects may be better exploited and its worst effects alleviated or avoided by acting upon meteorological advice.'

Whether involved in the interpretation of the natural environment of plants and animals, or the factors in landform and soil development, or the whole complex of conditions within which human society operates, special pleading is not needed to make a case for the study of climatology. F. K. Hare[48] has noted that ' environmentalism is still an attractive idea to many outside the geographical profession.' In a recent address in April 1966 he expressed the view that ' we need to re-interest our physical geographer's in the natural environment.' He then went on to express an opinion particularly appropriate to my theme. ' Physical geography has increasingly fallen into specialist categories. We need a few men who will interest themselves in the field's many common qualities. I have made it clear that the concept of climate, considered as environment, seems to me to be a central and cementing idea about which these common qualities can be grouped and that this same cementing quality extends far outside geography itself.' I would wish to clarify one point. I am interpreting environment as an amalgam of physical, biotic and human forces and I do not limit environmental relationships to those affecting man only. R. Hartshorne's[49] comment is relevant : ' "Climate" is the sum of certain characteristics of the atmosphere which vary areally in significant relation to some other phenomena, that is, the term implies environment, though not necessarily in reference to man.'

The term geographical climatologist need not be derogatory, if it implies, as should other branches of Geography, a desire to reach a better appreciation of the earth on which we live and the results of our living on that earth. In this sense Climatology as part of the natural environment is not a peripheral specialism misplaced within Geography, nor is Geography other than an environmental science.

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