SCOPE 27 - Climate Impact Assessment

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2 Climatic Variability and Change

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2.1 INTRODUCTION

Climate has been a neglected factor in world affairs (Fedorov, 1979; White, 1979; Hare, 1981a; Hare and Sewell,1984). In most people's thinking climate is a vague idea, without much power to evoke reaction. As long as it performs reliably it can be ignored. Yet the 1970s showed that national economies and world trade can be shaken by extreme climates, and that our defences against such rude episodes are flimsy. The problem is to articulate the nature of climate's impact on society. And that implies an understanding of the nature of climate itself.

Climate relates to many sectors of the human economy, and to many aspects of the world's natural ecosystems. A broad concept of climate is needed for such an exercise as the World Climate Programme. This chapter seeks that broad concept, and tries to set out the facts about climate itself as an environmental factor. To assist the reader, words with a defined technical meaning have been italicized the first time they appear in the text.

Human societies are highly adapted to the ordinary *annual* rhythms of climate, which we call the seasons. Housing, clothing, health measures and recreational habits are adjusted to make good use of the seasonal changes, or to cope with their rigors. So also are most forms of technology —above all agriculture, forestry and transportation. The annual variation of the weather elements is familiar to all; it is taken for granted, and is in some ways a resource to be tapped.

Failure of the expected seasonal changes, however, often leads to dislocation, discomfort and economic loss. The bulk of what is loosely called climatic impact probably comes from disturbances of the expected annual rhythms. Strictly speaking these impacts belong to the *interannual* scale; they arise from differences between the actual and the expected, or between one year and the next. Almost all climates display these differences, which have hitherto appeared unpredictable. Wise economic strategy takes them into account essentially by built-in safety margins. But few economies do so as effectively as possible. Much of this volume has to do with this imperfect adjustment, and asks the question: can it and should it be improved?

The *decadal* scale of climate presents much the same paradox. Socioeconomic adaptation to climate is high, but implicit. On this scale there is time for significant technological change—new varieties of crop, new systems of power transmission, and many others—though here again it is the *interdecadal* changes that matter most. Climatic anomalies on such scales are usually not large, but there are noteworthy exceptions. Some decades, for example, may be marked by high variability; others may remain monotonously reliable. Climatic fluctuations lasting several decades are not uncommon, and are often strongly regional in their effects. They, too, are as yet unpredictable, and may remain so indefinitely.

At the scale of the *century* one is in the realm of sweeping technological change. Human resources with which to exploit or withstand climatic behavior can be expected to change significantly, especially in advanced industrial societies. Century-long fluctuations of climate may occur. Their impacts are long-enough enduring for societies to become partially adapted to them—and for the anomaly to be thought a permanent change.

This chapter is concerned not with the adjustments, but with the nature and behavior of climate itself. One cannot expect to learn much about the impact of climate itself remains an unexplored and undervalued idea. But what is relevant to society alters as society innovates. One must seek to understand climate in the light of what mankind can perceive, understand and adapt to.

2.2 DEFINITIONS OF CLIMATE

The word climate is often seen as ambiguous, because of confusion with related words like weather, or vague climatic conditions. In fact it is capable of fairly exact definition. In recent years, moreover, public usage seems to have moved closer to that of the professional.

In lay usage, climate usually stands for the expectation of weather on time-scales comparable with a human lifetime; it is the layman's sense of the sequence of weather he or she may expect at a given locality (see Whyte, Chapter 16). As such it governs countless daily decisions, from choice of personal clothing to the work calendar of the farmer. Habitually this expectation is taken for granted. Only when unexpected weather occurs does the ordinary citizen become acutely aware of the stresses that the atmosphere's behavior can bring—sometimes to the point where the question is asked (as it is below): `is the climate changing?' This question arises from the suspicion that recent weather lies outside normal expectation, that is, outside the present climate.

Professional usage is still erratic, but usually starts with the same idea of expectation. It is assumed

- 1. that a climate exists at any given moment; and
- 2. that the integrated experience of the recent past specifies this climate.

We tend to assume that the near future will resemble this recent past. For lack of any better guide we accept a dictum attributed to Whitehead: how the past perishes is how the future becomes. We think it highly probable that past experience will repeat itself. In effect, we assume that the climate of today will endure for an undefined period.

In <u>Figure 2.1</u> are sketched idealized time-series of a representative physical parameter, such as air temperature, or atmospheric humidity. Curves A to D illustrate modes of *variation* (i.e., change with time) typical of such series:

- 1. *Curve A* displays strictly periodic variation about a mean value, or *central tendency*, with a well-defined period of recurrence, and finite amplitude. Variation of this sort is rare in atmospheric time-series, except in association with daily and annual solar rhythms (themselves almost exact). Simple statistical analysis can, however, identify these periodic signals, if they exist, in the midst of large non-cyclical variation (i.e., noise).
- 2. Curve B shows the short-term variation typical of atmospheric time-series. Temperature, for example, varies in reality on all time-scales from fractions of a second to millennia or more. The high-frequency variation in curve B is distributed about a central tendency that changes almost impulsively in a short period to a new regime, within which quasi-periodic variation occurs. All such variation can be assigned, by means of spectral analysis, to exact periodic frequencies, but to do this is often artificial and misleading; hence the use of the adjective quasi-periodic.
- 3. *Curve C* shows a series in which a downward *trend* occurs up to the midpoint; afterwards the series is *stationary*. The short-period variations appear unchanged throughout.
- 4. Curve D displays a constant central tendency, but short-term variations appear to increase in amplitude as time progresses.

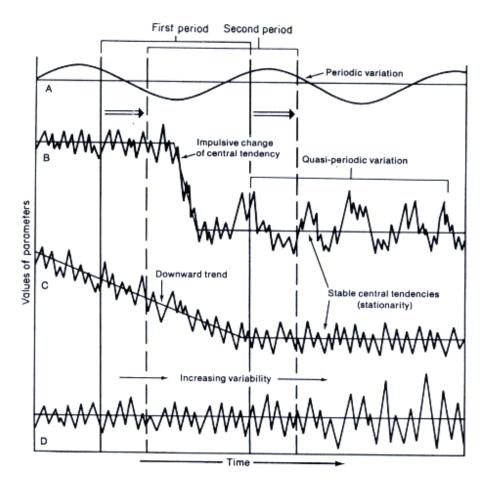


Figure 2.1 Idealized time-series (curves A to D) of a representative parameter of a climatic element that is continuous in time (such as temperature or pressure). Vertical bars indicate arbitrary averaging or integrating periods (usually 30 years) which are recalculated each decade (see dashed bars)

<u>Figure 2.1</u> implies that the parameter chosen is continuous in time, as are temperature and pressure (which are also continuous in space). In fact many climatic parameters are discrete in both realms. Rainfall is an example. Others include cloud amount and type and some aspects of atmospheric electricity. To handle such parameters climatologically we usually sum or average them over time (for example, monthly or annual rainfall) and sometimes over space as well (as with runoff); the discreteness then usually vanishes.

Formally to specify a climate, the climatologist assembles time-series of the necessary parameters (see below), and then seeks to generalize them statistically over a suitable period—the choice of which is largely arbitrary, since nature offers no clue as to correct length. Recent practice, as standardized by the World Meteorological Organization, is to use 30-year periods, which are updated every decade: 1951–80 *normals* (the misleading term in use) have recently replaced the 1941–70 set. In Figure 2.1 the vertical bars through the diagram, labelled first and second periods, indicate this procedure. In practice (though not in the hypothetical cases in Figure 2.1) the use of 30-year normals gives fairly stable values of central tendency. Differences between successive averaging periods are small.

2.3 CLIMATIC NOISE, VARIABILITY AND CHANGE

This arbitrary but necessary procedure makes possible a formal definition of the terms climatic noise, variability and change:

- 1. *Climatic noise* may be defined as that part of the variance of climate attributable to short-term weather changes. The chance location of the start and end of the averaging periods with respect to short-term variations may produce small statistical differences between successive periods. Leith (1975) confines the term climatic noise to this usage. Others use it more loosely to include, for example, anomalous weather extremes, or all short-term variation.
- 2. *Climatic variability* is best thought of as the manner of variation of the climatic parameters *within* the typical averaging period. Suitable measures of variability include such parameters as the standard deviation of continuous elements like temperature and pressure, and the frequency spectrum of the observed variations (giving such useful measures as return-period, or the probability of successive anomalous months or years). A proper statement of the climate of an averaging period should hence include, in addition to measures of central

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tendency (means, medians or totals), suitable estimates of the variability.

3. Climatic change is said to occur when the differences between successive averaging periods exceed what noise can account for, i.e., when a distinct signal exists that is visible above the noise. A common usage is to refer to short-term changes lasting only a few decades as climatic fluctuations, especially if conditions then return to the earlier state. Many authorities reserve the term change for longer-term variation extending over centuries (such as the Little Ice Age, or the mid-Holocene desiccation of much of the subtropical world). All such usage depends on the time-scale employed as standard.

Figure 2.2 shows estimated annual rainfall over England and Wales from 1766 until 1970 (after Wigley *et al.*, 1984). Clearly annual rainfall is a variable element. Within any 30-year period there are likely to be yearly totals as high as 1000 mm, or as low as 800 mm. In the 205 years of the record, rainfall exceeded 1150 mm five times and fell below 700 mm five times. The time-series shows no significant trend over the period of record, and little autocorrelation (that is, rainfall in a given year is unrelated to that of the years before and after). There is obviously high variability, and the mean value obtained for any arbitrary 30-year period is likely to differ from that derived from another choice. In the long perspective, however, the record justifies the generalization that annual mean rainfall over England and Wales, though very variable from year to year, has not changed greatly over the period.

Figure 2.3 shows a similar estimate (after Parthasarathy and Mooley, 1978) for spatially averaged rainfall over monsoon India. Again there is no significant trend over the entire period 1865–1970. If, however, one inspects the curve starting in 1900 and ending in 1960, a distinct upward trend can be seen. This was a vital climatic fluctuation that had a real bearing on India's capacity to increase food production in pace with her population explosion. The abrupt downward sag in the mid-1960s was an unwelcome surprise. The record shows a tendency for wet or dry years to follow one another, and also a small but statistically significant 2½- to 3-year periodicity. Here again, however, the most central fact is that no lasting change in mean annual rainfall can be demonstrated. It is obviously dangerous to base long-term conclusions on short-term records—or to assume that trends will continue indefinitely.

These two records illustrate another general principle. Any trends that may be present in a climatic time-series, and especially any persistent climatic changes, are usually very small by comparison with short-term variations. The latter obscure the signal corresponding to the change, just as radio noise may obscure the desired radio signal. It is not yet easy, for example, to detect the signal corresponding to the expected effects of carbon dioxide increase on the trend of air temperature (Madden and Ramanathan, 1980; Wigley and Jones, 1981), because short-term variations dominate the record.

Public recognition of these facts is very partial. A sequence of wet or dry years, as displayed in <u>Figure 2.3</u>, often raises false hopes or fears, and leads to speculation about lasting change. Institutional memory of severe extremes tends to fade quickly, but the public at large retains a recollection of events like cold winters or dry summers.

Complete uniformity of usage of the terms defined in this section is not to be expected. They are not dictated by the properties of nature, but respond to our need for a language to describe the atmosphere's steady state and modes of variation. Terms like event, episode and anomaly are used qualitatively by most workers, and do not imply precise durations or magnitudes. The three time-scales given attention in this volume —annual, decadal and century-long periods—have exact durations, but do not correspond to any special mode of climatic variation (except for the annual seasons).

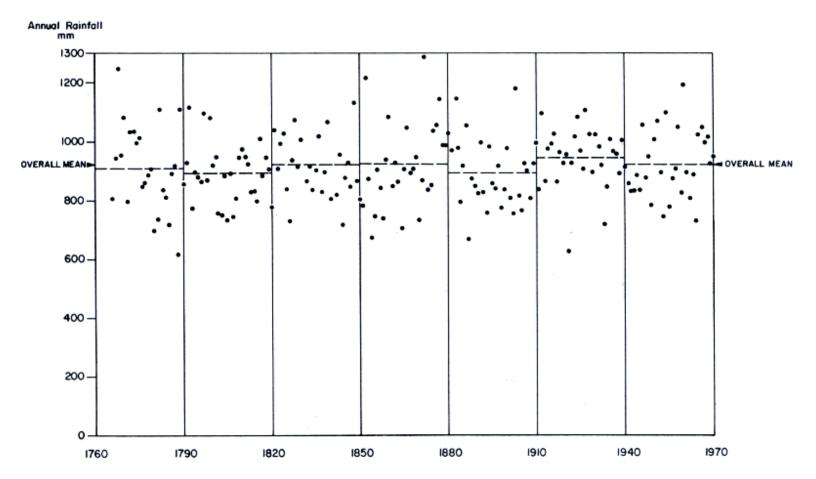


Figure 2.2 Spatially averaged and standard annual rainfall for 1766–1970 over England and Wales, showing a typical, highly variable climatic element. No significant trend or periodically is present, but very large interannual differences are common. Differences in variability between periods are also visible. (After Wigley *et al.*, 1984)

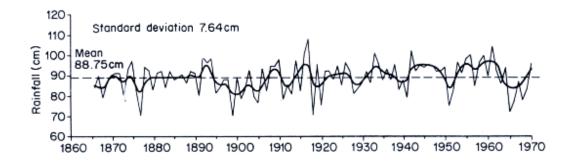


Figure 2.3 Spatially averaged and standardized summer rainfall over monsoon India. No significant trend is present, but a weak 2½- to 3-year periodicity can be detected by spectral analysis (spectral peaks at 2.72 and 2.85 years, both significant at the 90% level). (After Parthasarathy and Mooley, 1978)

2.4 THE ELEMENTS OF CLIMATE; THE CLIMATIC SYSTEM

Most published accounts of climate are based simply on measurements of rainfall and temperature, and on statistical analysis of their time-series. This is a time-honored procedure that may actually conceal certain subtle impacts of climate on the living world. Other parameters of climate are regularly observed. Still others are observed in research studies. It is hence proper to ask: what are the elements of climate that ought to be observed, if climatic impact is to be identified?

Attempts to answer this question at once raise another: what is the natural domain of climate? Is it confined to the atmosphere, or does it extend into other environmental sectors? And one must ask: is climate an entity in itself, or is it part of a larger system?

Some professional opinion (National Academy of Sciences, 1975; World Meteorological Organization, 1975, for example) heavily favors the view that the atmospheric climate is part of a larger *climatic system* that includes the domain within which there are significant exchanges of mass, momentum or energy during the typical year. In this view the upper layers of the ocean, sea ice (and to lesser extent land ice, or glaciers), the soil and the biotic cover are all parts of the system. Alternatively climate can be seen as a system that pervades these domains without actually encompassing them. In either usage the climatic system is clearly a larger concept than the more narrowly defined climate of Section 2.2 above.

In practice it is still usual to confine the idea of climate to the atmosphere and ocean (including frozen surfaces), which are closely coupled by processes of exchange and interaction. Similar parameters can be used to express the condition of both domains, and similar bodies of theory exist to explain their behavior. Meteorologists and physical oceanographers are drawn from similar backgrounds. Hence they readily understand one another, and tend to adopt similar procedures of observation and compilation.

On environmental grounds, however, the concept of climate needs to be extended to include surface hydrology, soil processes and the systems of exchange between the atmosphere and the biota. Hydrology presents few problems, since its practices are fairly close to those of the atmospheric scientists; elements such as precipitation and evapotranspiration are actually common to both scientific areas. Soil moisture, carbon and nitrogen storage, and their exchanges with the atmosphere are also vital, but are not often included in the idea of climate. The role of the biota presents the most difficulty; bioclimatology is a specialized field that has not yet yielded measures that can be systematically built into a continuous monitoring of the climatic system. Nevertheless it is highly desirable, but not operationally usual, to include suitable bioclimatic parameters in the list of measured and analyzed climatic elements. Examples might include the phenology of crops and natural vegetation, transfers of heat, moisture and carbon dioxide within crop layers, and data concerning biological productivity (which is related to water and energy incomes).

It is possible, however, to get much closer to the reality of climate—society interaction by analysis of the actual processes of linkage. One can distinguish between human physiological linkages, the field of medical climatology (Weihe, 1979; Flach, 1981) and indirect linkages involving natural vegetation, crops, surface waters, the seas and their fish populations. In all cases the linkages involve actual transfers that can, in principle, be measured. The main linkages can be simply classified:

- 1. The natural energy system, dominated by the flux of solar energy. This system includes the fluxes of solar, terrestrial and atmospheric radiation, the convective heat fluxes (latent and sensible) in the atmosphere, the fluxes of heat in the soil and ocean, and the complex conversions of energy between one form and another—including the internal transformations between potential, thermal and kinetic forms within the atmosphere and ocean. All these fluxes and transformations are in principle measurable, but few are actually monitored. Instead, the usual practice is to measure the temperature of the air, water or soil. Temperature is a parameter of heat storage, though its gradient (i.e., direction and rate of spatial variation) is a determinant of heat transfer. Preference for measurements of temperature, rather than of energy fluxes, arose two centuries ago because thermometers were cheap and easy to use—and because meteorologists and oceanographers set great store by the so-called parameters of state (temperature, pressure and density). Climatic impact nevertheless depends on modifications of the fluxes of energy, as well as on the levels of energy storage.
- 2. The hydrologic cycle, which describes the exchanges of water substance between sea, air, soil, rock, plants and animals. In this case it is usual to measure precipitation and river discharge, both of which are transfer mechanisms. Evapotranspiration is also measured, but often with too little attempt to simulate its actual behavior in nature. Again the choice of measured parameter has been influenced by cost: rain gauges, evaporation pans and stream gauging points are cheap and easy to install and operate. Storage parameters such as soil water storage have had less attention. Water is made available to crops and vegetation from stored water, for which we have fewer statistics. Here again the choice of measured element has obscured the study of climate—biota—economy interactions.
- 3. *The carbon cycle* describes the exchange of carbon between biotic, atmospheric, soil, crustal and oceanic reservoirs. Only gradually has it been realized that this cycle is of fundamental importance to climate, and is indeed part of the climatic system itself. Only one climatic element has yet been recognized—the concentration of carbon dioxide in the atmosphere, continuously monitored since 1957 at a handful of stations. Levels of carbon storage in reservoirs other than the atmosphere can only be approximated, and none of the transfer mechanisms is routinely measured. Understanding is growing, but adequate detail is still lacking (Olson, 1982; Woodwell, 1982).
- 4. The other biogeochemical cycles describe the exchange systems for nitrogen, sulfur and a few others where there are significant atmospheric storages and transfer pathways (Bolin,1979). This includes the transfer of recently added pollutants, such as the chlorofluoromethanes and other halocarbons, which may have significant climatic and health effects. Few if any of these cycles are monitored sufficiently well to include them in analyses of climatic impact. Sufficient detail is also lacking concerning the particulate and aerosol load of the atmosphere, which affects visibility and turbidity (or ability to transmit solar radiation), and may have a long-term effect on surface temperatures.

It is obvious that the analysis of climate—society interaction must currently be based on what is actually observed, and especially on those elements for which we have long records, and hence some idea of natural background levels and variability. Only in certain specific research

areas is it sometimes possible to go beyond this limitation. Gradually, as the nature of climatic impact becomes clearer, the observational habits of the climatologist will change. Meanwhile one must use what is available.

2.5 IS PRESENT-DAY CLIMATE CHANGING?

2.5.1 Public Perception

There is a widespread belief that climate is unstable, and may be undergoing change. This is not a new impression. Literary sources show that speculation about climatic change is a venerable human tradition. Yet the changes in world climate during mankind's period of literacy have been small by comparison with those of Pleistocene times (Budyko, 1977). What accounts for the persistence of what looks, in hindsight, like an exaggeration of these changes?

Public speculation about such issues has been hampered by a failure to distinguish between local and global factors in the control of climate. Major land use changes, which are highly visible, have significant impacts on local radiative balances, and to some extent on temperature. Their visibility has led to speculation that still greater changes may alter local or even global climate. Actually, however, global processes are on such a scale that they are not easily affected. It is the general circulation of the atmosphere and the planetary scale of energy exchanges that ultimately control non-seasonal temperature and humidity variations even at local sites, via the mechanism of advection. Precipitation, too, comes largely from systems controlled by global rather than local processes. Nevertheless popular apprehensions persist, perhaps with some reason, that human manipulation of the earth must lead to climatic change, perhaps of a hostile kind.

Present-day speculation seems to spring from certain recognizable sources, such as popular memory of climatic extremes, widespread media comment on the subject, gloomy statements by professional climatologists (or by other scientists), and real fluctuations of temperature during the past century. In particular, certain specific changes seem to have impressed political opinion:

- 1. The decrease in northern hemisphere surface air temperature between 1938 and 1965 (see Figure 2.4), which was of an order of 0.5 °C. This decrease has sometimes been announced by the media as the onset of a new glacial period. In actual fact the decrease has reversed since 1965, and is in any case strongly regional, affecting some areas much more than others (Van Loon and Williams, 1976–77; Kukla *et al.*, 1977; Jones *et al.*, 1982). A parallel downward trend of sea-surface temperature has been documented (Kukla *et al.*, 1977). Neither sea nor air temperature shows the same tendency in the southern hemisphere; in fact a reverse movement has been claimed.
- 2. The major west-European drought of 1975—76, which affected densely populated countries with vital agricultural areas. The drought was the most severe in more than two centuries of record in some districts, where rainfall over the crop season was as little as 40 percent of normal. The drought was short by comparison with, for example, the Sahelian drought, but exposed the vulnerability of water-supply systems and crops to rainfall anomalies.
- 3. Severe winters in eastern North America during the middle 1970s, which badly stressed the energy delivery systems of the world's most extensively industrialized region. In some areas temperatures were more than 5 °C below normal over the entire 3-month season.
- 4. Disturbances during the 1970s of the world's food system due to quite small reductions of cereal supply caused by climatic anomalies occurring at a time of increasing use of cereal as livestock feed. The crop deficiencies in the Soviet Union in 1972, 1974, 1975, 1979, 1980 and 1981 were particularly significant because they led to large Soviet grain purchases on the world market, and to dramatic fluctuations of price.
- 5. The Sahelian drought, popularly supposed to have occurred in the years 1968–73, but actually a gradual desiccation of much of north and east sub-Saharan Africa that began in 1955–60, an effect that has continued until the present. Because it imperilled many fledgling African states this desiccation achieved high visibility, leading in 1977 to the UN Conference on Desertification, the first world political conference about a climatically related stress.

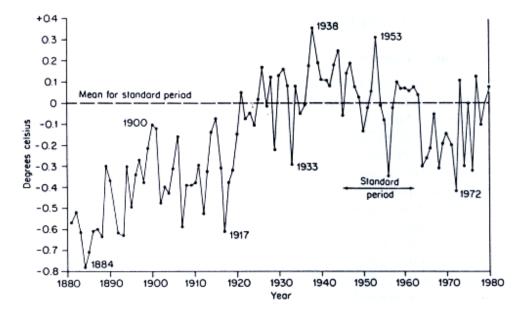


Figure 2.4 Variation of surface air temperature for northern hemisphere since 1881, to show the recent fluctuation. (After Jones et al., 1982)

2.5.2 Professional Opinion

It is a common professional view that items 2 to 5 above lie within the variability of the present climate; they ought, that is to say, to have been expected by prudent societies that kept an eye on the climatic record.

At the World Climate Conference (World Meteorological Organization, 1979) in Geneva, no evidence was brought forward from any part of the world to suggest that present climate is in the process of change, although it displays the high variability normal to its behavior. The most serious impacts on society have been brought about by short and drastic anomalies of the sort listed above. The time-series of <u>Figure 2.3</u> emphasize, for example, that in drought-prone monsoon India the rainfall anomalies are chiefly short but large departures from a basically stable régime.

The point is often made, however, that lasting climatic change, if it occurs, will mimic short fluctuations. We may not recognize the change until it has been in progress for decades. A decrease in mean rainfall, for example, will probably be accompanied by a tendency towards more frequent dry years. It will be extremely difficult to recognize climatic change in time to do anything about it.

Just as there is little evidence for significant changes of mean temperature, rainfall or most other measured elements, there is also little evidence that their variability is changing significantly. Many investigations show that variability does in fact fluctuate in magnitude and character. Thompson (1975), Haigh (1977), McQuigg (1979) and others have suggested that reduced rainfall variation in the US Midwest in the late 1950s and 1960s was responsible for part of the observed increase in corn yields in that period. Haigh's analysis does indeed demonstrate that an upward trend of mean July precipitation and a downward trend of mean August temperature (both favoring good corn yield) affected the state of Illinois between 1930 and 1976, and that variability of rainfall was markedly lower in the middle of that period. But there is no consensus that overall variability of climate has recently changed in any large region of the earth. Such variability is related in most regions to persistent anomalies of the general circulation of the atmosphere. The analysis by Van Loon and Wiliams (1976-77) cited above shows that such anomalies can have effects on temperature over 15-year averaging periods. What is lacking is any conclusive demonstration:

- 1. that variability of climate on a world scale has recently changed; and
- 2. that there is any real connection between rises or falls of mean air temperature and climatic variability, as is often claimed (Angell and Korshover, 1978; Ratcliffe *et al.*, 1978; Van Loon and Williams, 1979).

2.5.3 The Search for Predictability

Clearly the impact of climatic variability on all time-scales will depend on the ability to predict individual variations with sufficient skill to make precautionary measures possible. Unfortunately there is a professional consensus that such predictions are as yet rarely possible, even under favorable circumstances. Present day short-term numerical weather prediction models are effective only up to 4- or 5-day periods, except in areas where weather changes are slow (for example in the tropical deserts). Increases in computer capability are slowly improving this situation, but the cost of even a day's extension in reliable forecasts is very high. Moreover the nature of weather systems makes it doubtful *in principle* whether such an approach can be pushed very far. Tentative foreshadowing on the monthly or seasonal scale can be based on analogue methods,

on assumed sun-spot or orbital variations, and on assumed relationships with sea-surface temperature anomalies. Some of these attempts achieve better than chance results, but none has yet reached the point where management decisions can be firmly based on the outcome.

The search for such predictability is the major objective of the research component of the World Climate Programme. It is premature to prejudge the results of the large-scale effort now being launched, but the following generalizations appear sound:

- 1. Attempts to model future climatic variation resulting from the build-up of carbon dioxide and other infra-red absorbers yield predictions of *trend*, on the order of 0.1 °C a⁻¹ or less. Though this is not negligible, it has relevance mainly for long-range planning of such things as plant breeding, navigation in ice-infested waters, and dam construction. The models do not predict future variability with any assurance.
- 2. The best hope for seasonal or interannual prediction may well rest on two existing bodies of active research: sea-surface temperature anomaly to atmosphere relationships, and possible large-scale oscillations in atmosphere—ocean behavior. Among the latter the most promising is the so-called *southern oscillation*.

The southern oscillation has been known, though not understood, for 60 years, having served for many years as the basis for statistical forecasting of Indian monsoon rainfall. It consists of a large longitudinal quasi-periodic oscillation of atmospheric pressure, representing gigantic transfers of mass in east-west directions between the South Atlantic and South Pacific at one pole, and a broad area between the Red Sea, East Africa and Australasia at the other. Pressure is negatively correlated between these two large areas, but unfortunately the period of oscillation varies. The average period is 38 months, but individual oscillations have varied between 2 and 10 years (see Philander, 1983, for a recent review under the auspices of the Commission for the Atmospheric Sciences of the World Meteorological Organization).

The southern oscillation is highly correlated with sea temperature behavior over the equatorial Pacific. Shortly after the onset of the atmospheric event (a fall of pressure in the western Pacific, and a slackening of the southeast trades) the normal cold upwelling off the Peruvian coast is weakened, and much warmer water appears nearshore, which badly affects the highly productive marine ecosystem—the so-called *El Niño* event. In the typical case the warmest water shifts westwards along the equatorial belt of the Pacific, and within 18 months cold upwelling is reestablished off Peru. The dramatic effect of these events on fisheries has given them high visibility in recent decades. (See <u>Chapter 6</u> for further discussion of the El Niño event.)

This entire phenomenon is a vast longitudinal perturbation of atmosphere and ocean that has hitherto eluded adequate theoretical understanding. The World Climate Research Programme will give such understanding very high priority. The phenomenon seems to be meaningfully correlated with climatic variation outside the directly affected regions—for example with air pressure and temperature over North America. Unfortunately the regularities are in most cases insufficient for successful forecasting. There is first the irregular period and erratic behavior of the southern oscillation events, and second the weakness of the observed correlations. Only theoretical understanding and effective modelling can serve to reduce these uncertainties and make reliable prediction possible.

Predictability may well come in the future, for at least some of these phenomena. Meanwhile, there is abundant and conclusive evidence that variability of the main climatic elements is a normal and necessary part of nearly all climates. This variability extends to significant fluctuations over several decades. But most long climatic time-series show an underlying stability, suggesting that the variability is distributed around a fundamentally unchanging normal state. Investigations have failed to show that changes in variability tend to occur as mean temperatures rise and fall. They have also failed to confirm truly periodic anomalies. The recurrence of drought somewhere on the Great Plains of the United States in the 1890s, 1910s, 1930s, 1950s, and, to a limited degree, the 1970s, for example, is not seen as truly periodic (see, for example, Stockton and Meko, 1983). Such quasi-periodic happenings are probably misleading as to future climate, as evidenced in the unrealized expectation of widespread drought on the Great Plains in the 1970s.

2.6 IS FUTURE CLIMATIC CHANGE LIKELY?

If present and recent past climates show little sign of change, why is there so much concern about the possibility of climatic disruptions of the economy?

Two answers are clearly possible, both of which may be correct. One is that human society is becoming more vulnerable to climatic impact as population grows, as the demand for food increases, and as other pressures on the food and energy systems increase. This view is widely debated in other chapters of this volume (see <u>Chapters 9</u>, <u>10</u>). The other answer says that processes are now at work that will upset the stability of present climate. Conceivably we may be able to predict the resulting changes, so that they will not catch the world unawares.

The second view is widely held among climatologists. Since the major disruptions of the international grain trade following the crop year 1972—73, much research has been conducted to test the stability of present climate. This has consisted of one-, two- and three-dimensional modelling exercises representing the present climate as a function of present-day controls, and examination of the models' sensitivity to hypothetical changes in these controls. The sensitivities tested include the dependence of world temperature and precipitation on:

- 1. variations in solar energy input (the solar constant);
- 2. variations in atmospheric optical properties due to altered carbon dioxide concentration, the presence of pollutants such as the chlorofluoromethanes, and higher levels of particle load due to human activity or vulcanism; and
- 3. changes in air—ocean interactions, or in the extent of glaciation.

On the time-scales of importance here—interannual or interdecadal—only the second kind of disturbance seems likely to be effective. In any case these turn out to be similar to those that might follow a very small change in the solar constant (Manabe and Wetherald, 1980). There have been many attempts to establish air-sea interactions by empirical methods, and some of these have been effective (for example, Namias, 1976; Hastenrath, 1978). But these appear to relate most closely to fairly brief fluctuations of climate. Specific patterns of sea temperature anomaly are found to be connected with air temperature or precipitation anomalies elsewhere (teleconnections), occasionally with some useful time lag that may make prediction possible. As such the sensitivities of type 3 above relate more to the internal variability of existing climate than to lasting climatic change. For the latter to occur it is now fairly well agreed that changes in external forcing* are necessary.

2.6.1 Carbon Dioxide

The change in forcing seen most likely to occur is that to be expected from the build-up of carbon dioxide (CO₂) in the atmosphere (see, for example, Kellogg and Schware, 1981; Hare, 1981b). Figure 2.5 shows the observed change of CO₂ concentration in the atmosphere since serious monitoring began in 1957–58. The observational network is now worldwide, and it is clear that the build-up is a planetary process. The 1983 concentration was near 342 ppmv (parts per million by volume), equivalent to 724 x 10⁹ metric tons of elemental carbon in the atmospheric reservoir (World Climate Programme, 1981 and subsequent data in Clark, 1982). The rate of increase varies from 0.5 to 2.2 ppmv a⁻¹, averaging recently near 1.2 ppmv a⁻¹. In all, a little under 3 x 10⁹ metric tons of carbon are being added to the atmospheric reservoir each year. The source is probably chiefly fossil fuel consumption, currently a little below 6 x 10⁹ metric tons a⁻¹, which implies an atmospheric retention rate of a little over 50 percent. The balance is disappearing into some other reservoir, probably the surface and intermediate waters of the ocean. Atmospheric mixing is so efficient that both additions to and subtractions from the atmospheric store can be thought of as global processes; the CO₂ build-up is not, like acid rain, a focal or regional phenomenon.

*`Forcing' is useful jargon for an influence or factor whose behavior is external to the model itself: it `forces' the model, but is not thereby affected.

Such a rapid increase of CO_2 necessarily changes the optical properties of the atmosphere. CO_2 is largely transparent to solar radiation, but it strongly absorbs the return long-wave terrestrial radiation near 15 μ m, a wavelength at which water vapor is ineffective as an absorber. The effect of CO_2 build-up is thus to increase the resistance to the upward radiative transfer of heat in the atmosphere. To achieve the necessary global balance between incoming solar and outgoing terrestrial radiation the earth's surface must hence become a little warmer, and the stratosphere a little cooler. This is the *greenhouse effect* so extensively discussed in the popular press.

It seems clear that the build-up will continue, since its presumed causes—fossil fuel consumption, probably reinforced by the effects of forest clearance and soil impoverishment—are unlikely to abate. Estimates by Häfele (1978) and his associates at the International Institute for Applied Systems Analysis suggest for the year 2030 a total world power consumption at the rate of 18–36 x 10¹² Watt (terawatt = TW). Rotty and Marland (1980) give a similar estimate of 27 TW in 2025, a figure which allows for economic restraints to rapid expansion. If correct, this represents a growth from present consumption (8.2 TW) of only 2 percent per annum. Recent data show that between 1950 and 1973 fossil fuel consumption grew at 4.58 percent per annum; since then it has risen at only 2.25 percent (Rotty, 1983).

Rotty and Marland (1980) estimate that about three-quarters of the 2025 power demand will be met by fossil fuel burning—a level of CO_2 release almost three times the present value. Allowing for a 25 percent error on either side, they estimate a doubling of present CO_2 levels (i.e., from 342 to 684, ppmv) by 2060 at the earliest, and most probably after 2075. An expert World Climate Programme panel chaired by Bolin (World Climate Programme, 1981) concluded that in 2025 the atmospheric concentration will actually be in the range 410 to 490 ppmv, with 450 ppmv the most likely value. This is clearly far below earlier estimates, some of which visualized a doubling of present values by 2020 or 2030. Nevertheless it is vital to remember that the use of fossil fuels may proceed more rapidly than these estimates suggest, and the build-up of CO_2 with it.

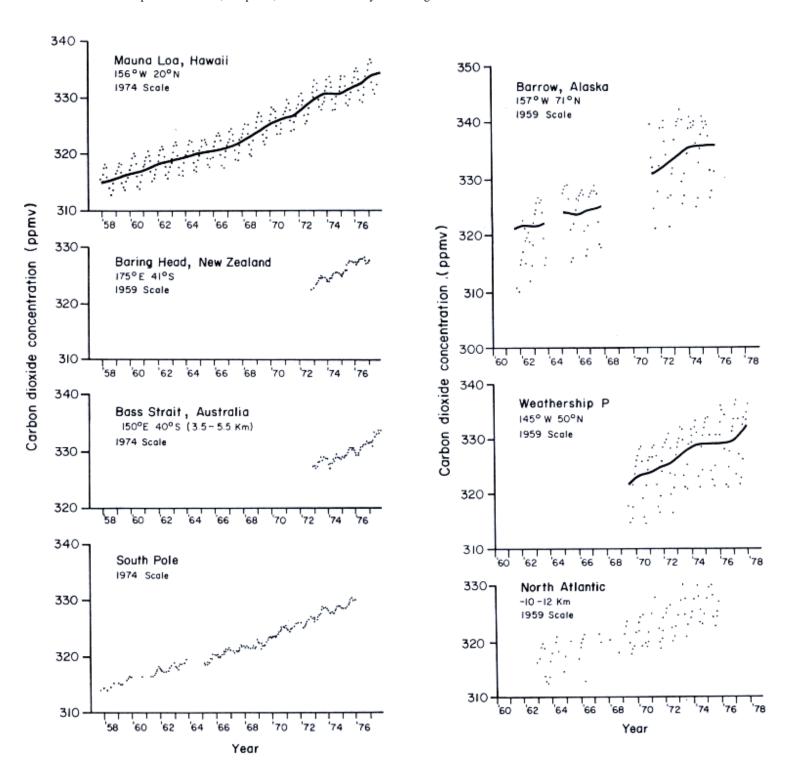


Figure 2.5 Variation of CO₂ concentration (parts per million by volume) at selected stations since 1958. Two slightly different calibration scales are used, but the upward trend is unaffected thereby. A regular seasonal variation is also visible with maximum amplitude in northern hemispheric high latitudes. (Data supplied by World Meteorological Organization)

Mathematical modelling of the potential climatic impact of such increases has been undertaken by several groups (for example, Marchuk,1979; Mason, 1979). Most expert opinion favors the use of *general atmospheric circulation models* (GCMs) (for example, Manabe and Wetherald, 1975, 1980), especially those that interact effectively with the ocean, and allow for a realistic geography (Manabe and Stouffer, 1980; Mitchell, 1983). Such models predict, for a doubling of CO_2 concentration, a rise of global mean air temperature of 2.0-3.5 °C, with slightly lower values in the tropics and much higher values in north polar latitudes (of order 5-8 °C). Much of the warming comes, in fact, from the positive feedback introduced by the water vapor added to the air as a result of the CO_2 forcing. Two syntheses (National Academy of Sciences, 1979, 1982) suggest that the best estimate is that changes in global temperatures on the order 3° \pm 1.5 °C will occur for doubled CO_2 .

If this increase—of 3 °C—does follow a doubling of CO₂, it will occur at some date after 2060, if the most rapid Rotty—Marland estimate of build-up occurs. This implies a mean global temperature increase averaging only about 0.04 °C a⁻¹, which will be so slow as to be masked by the short-term variability of the present climate. Moreover the heat capacity of the oceans may delay the expected response by some years, perhaps two decades (Cess and Goldenberg, 1981; National Academy of Sciences, 1982). We must thus face the probability that the impending change of climate will remain unidentified until it is well advanced.

In an attempt to test this possibility Madden and Ramanathan (1980) decided to test the temperature record near 60 $^{\circ}$ N, where, as indicated above, the CO_2 warming should be considerably larger than for the globe as a whole. Treating all other variations of temperature as noise, and confining themselves to summer, when noise is lowest, they showed that a 20-year average should display the CO_2 signal above the noise. In fact, however, the period 1956–75 was *not* warmer than the period 1906–25; if anything it was marginally colder. Hence they found it impossible to demonstrate that the CO_2 effect was in progress.

Wigley and Jones (1981) made a detailed study of signal-to-noise ratios by comparing their own estimates of observed temperatures with model predictions of CO₂ increase by Manabe and Stouffer (1980). Highest values of the ratio occur in summer, and in annual mean surface temperatures averaged over the northern hemisphere or over midlatitudes. The effects Of CO₂ ...'may not be detectable,' they wrote, `until around the turn of the century. By this time, atmospheric CO₂ concentration will probably have become sufficiently high ... that a climatic change significantly larger than any which has occurred in the past century could be unavoidable.' (Wigley and Jones, 1981, 208).

On the other hand, it is widely held in the Soviet Union that the signal is already visible (Budyko, 1977; Budyko and Efimova, 1981; Vinnikov and Groisman, 1981). There have also been model simulations incorporating the assumed CO₂ warming, with other influences that account quite well for climatic variation over the past century (Hansen *et al.*, 1981; Gilliland, 1982). To assess such contradictions, what is needed is agreement on the statistical tests to be applied (Epstein, 1982) and on rigorous monitoring of the actual unfolding of events in the next few decades (Weller *et al.*, 1983). Given the high importance of the outcome, major effort needs to be expended on such monitoring.

Assuming the CO_2 effect to be real, and to be roughly of the character foreshadowed in this section, we can speculate as to further climatic consequences. The major effect may be on the hydrologic cycle. There have been two complementary approaches to this question:

- Some of the GCM experiments (notably Manabe and Wetherald, 1980 and Manabe and Stouffer, 1980) show a small overall increase in world precipitation for a doubled or quadrupled CO₂ concentration. A marked decrease in available soil water is foreseen, however, for a midlatitude belt, chiefly because of increased evapotranspiration. The resolution of the models does not allow any statement as to which longitudes (i.e., actual regions) may be affected. World climate is always longitudinally differentiated.
- 2. In an attempt to provide such longitudinal detail, Kellogg and Schware (1981) compiled a world map of possible soil moisture patterns on a warmer earth. The map synthesized (a) geological experience of distant past epochs, notably the mid-Holocene Altithermal, (b) recent experience of hot and cold years in the northern hemisphere, and (c) the modeling exercises referred to above. The map showed drier conditions over interior North America, Siberia, southeastern South America, the tropical rainforest areas and the polar zones. Wetter conditions occurred in most subtropical countries and west coast temperate areas.

Such foreshadowings show the vital importance in climatic impact studies of the CO_2 effect, acting indirectly via the effect of differential atmospheric heating on the hydrologic cycle. So far the model estimates have withstood a number of objections raised against them (National Academy of Sciences, 1982).

Rising CO_2 concentrations may also have an effect on polar snow and ice distribution. Snow and ice surfaces have a high albedo. If general warming causes their equatorward limit to recede poleward, a significant increase in the absorption of solar radiation occurs, which intensifies the heating. This albedo feedback mechanism is built into the models described above, and accounts for the markedly greater effect of CO_2 heating in high northern latitudes. In the southern hemisphere the feedback is reduced by the regular seasonal break-up of the Antarctic pack-ice (Robock, 1980).

There have been many attempts to estimate the amount of heating needed to break up the permanent pack-ice of the Arctic Ocean, an enormous ice surface that has probably persisted for the past 700,000 years or more. If this ice were removed, or if it were confined to the winter and spring seasons, immense consequences would ensue. Quite apart from the obvious strategic and economic importance of the removal (Hare, 1981b) there is the fact that removal of the polar ice would imply a major reordering of world climate; the present-day pack-ice is a key controlling factor of the earth's radiative balance and general circulation of the atmosphere and oceans.

Manabe and Stouffer (1980) have estimated from their recent GCM experiments that a doubling of CO₂ would fail to remove the pack-ice in

summer, but a quadrupling of CO₂ (probable in the twenty-second century) would do so. Thereafter in the average year there would be winter ice only, as at present in Hudson's Bay and on much of the Southern Ocean's Antarctic margin. If this estimate is correct, the next century is likely to see a shrinking effect on the continental snow surfaces, and a trimming of the margins of the polar pack. There would be no clearance of the Arctic Ocean itself, though the ice would certainly become thinner. This view is opposed to that of Parkinson and Kellogg (1979) who found that a doubling of CO₂ concentration would indeed remove pack-ice in summer. Clearly there is a need to bring the assumptions and techniques of the modelers closer together.

Another point concerns the possible effect of a CO₂-induced warming on glacial ice, and hence on sea level. Contrary to public speculation a doubling of CO₂ is unlikely to produce drastic short-term effects on sea level (Barnett, 1982). The predicted temperature rises will probably reduce the extent of alpine glaciers. Sea levels have recently been rising globally at rates generally estimated in the range of 10–15 cm per century, due partly to this process, and partly to expansion of the ocean water. But the main storage of ice on land is in the great continental glaciers of Antarctica and Greenland. The ice cover of Antarctica is very old, and losses of ice are almost entirely by means of ice discharge into the sea, a process that is not very temperature-sensitive at present temperature level. Greenland loses ice half by thermally induced ablation and stream flow and half by ice discharge, mostly through a single ice stream. A considerable increase of the marginal ablation would be likely to follow the CO₂ warming. On the other hand snowfall on the upper and middle slopes of both ice sheets would probably increase, thus altering the entire mass balance. During the next two centuries it seems unlikely that a large net transfer of water to the sea will occur, though the present slow rise will probably accelerate slowly. In the longer term the threat of significant sea level change from net glacial melting remains present. On the scale of many centuries it may well become important.

It is conceivable that catastrophic changes may affect the so-called West Antarctic ice sheet (the part of the sheet north of the constriction between the Weddell and Ross Seas). Much of this ice is afloat (the Ronne and Ross ice shelves) or rests on a rock surface well below present sea level. Mercer (1978), enlarging on a speculation of Hughes (1973), suggested that the West Antarctic ice might disintegrate if a CO₂ warming becomes pronounced. Most glaciologists seem to question this opinion (World Climate Programme, 1981), but agree that should the ice disintegrate sea level would rise by about 5 m worldwide. The last stages of the disintegration might occur within a century (Thomas *et al.*, 1979). Catastrophic surges of the main East Antarctic ice sheet have also been hinted at. Hollin and Barry (1979) have pointed out that such surges are *mechanical* phenomena; only if CO₂ warming leads to increase of snowfall on the ice sheet, and if a warmer ocean trims back the margin of the ice sheet, is a climatically induced surge likely to occur. We conclude that catastrophic rises of sea level due to transfers of glacial ice to the ocean are unlikely, but not impossible. Within the next century it is improbable that major sea level changes will be a significant outcome of the warming.

2.6.2 Other Mechanisms

What other mechanisms may contribute to climatic change in the next two centuries? There is general agreement in the research community that the CO_2 effect will be the most significant influence, even though estimates of its magnitude differ widely. But several other mechanisms have been proposed, some of which may add to the CO_2 effect, and some reduce it. The list includes the effect of changes in the particle and aerosol concentration in the atmosphere, the effect of other infrared absorbing gases, and the possible effect of flip mechanisms in the atmospheric general circulation (the so-called *almost-intransitivity* effect). This last effect is treated in Section 2.7.

There has been much speculation that variable concentrations of atmospheric particles may induce changes of surface temperatures. The primary source of effective particles, chiefly sulphates in the lower stratosphere, is considered to be explosive volcanic eruptions. Distinct coolings were, for example, observed in the wake of the eruptions of Tambora (1815) and Krakatoa (1883). The 1982 eruption of El Chichón in Mexico has yet to show its effect, although the resulting stratospheric dust cloud has been widely observed.

There has been much debate as to the reality of the particle cooling. It has been argued theoretically (with some observational support) that in some circumstances—perhaps dominant—the net effect of aerosol increase may be lower tropospheric and surface warming (Budyko and Vinnikov, 1973, 1976; Chylek and Coakley, 1974; Kellogg *et al.*, 1975). Unfortunately, most of the parameters needed to settle the argument have yet to be routinely observed.

In two papers Bryson and Goodman (1980a,b) calculated atmospheric turbidity since 1880 from measured attenuation of the direct solar beam. Their results showed a prolonged period (1924–60) of low turbidity, corresponding rather closely to a reduced number of large explosive eruptions. They showed a close relationship between northern hemispheric temperature and the turbidity; a clear atmosphere favored high surface temperature. The post-1938 cooling, in this view, resulted from the resumption of more active explosive eruptions. Their model even predicted the upturn since 1965. A rather different analysis by Schneider and Mass (1975) also found that the 1920–40 upturn was explicable in terms of dust loading, but that a reduced solar constant (due to sunspot activity) since 1950 may have contributed to the downturn.

Other recent attempts to include the effect of volcanic dust on global temperature have been undertaken to identify the modifying effect of such dust on the CO₂ signal calculated from models. Hansen *et al.* (1981) estimated the volcanic effect from Lamb's (1970) dust veil index, whereas

Gilliland (1982) preferred to use the record of acidity from Greenland ice cores. When the volcanic effect was empirically weighted (in Gilliland's analysis), and variations in solar luminosity were included, a close fit between the CO₂, solar and volcanic forcings and the observed variation of northern hemisphere temperature was obtained.

A factor that appears to reinforce the CO_2 heating is the presence in the atmosphere of numerous other gases that have infrared absorption bands in the `window' region—the band between 7 and 14 μ m wavelength in which the atmosphere is largely transparent to terrestrial radiation. Carbon dioxide and ozone both reduce the transparency in this band, and hence tend to raise surface temperatures. The effects are incorporated into the various models described above, as is the effect of H_2O . But there are other active gases present in currently negligible amounts that are being increased by human activity. Wang *et al.* (1976) showed that a doubling of the concentrations of nitrous oxide (N_2O), methane (CH_4) and ammonia (NH_3) could increase surface temperatures by about 1.1 °C, which is about half the expected CO_2 warming. The extensive use of agricultural fertilizers may indeed lead to increases in the abundance of some of these gases.

More recent synthesis (Chamberlain *et al.*, 1982) has extended the list of such gases, and confirmed their importance by comparison with the effect of CO₂ acting alone. Hansen *et al.* (1981) calculated the equilibrium warming that increases in the chief absorbers may have contributed between 1970 and 1980, using a model that predicted a 3 °C rise for doubled CO₂. They found that CO₂ may have raised global surface temperature by 0.14 °C in this decade, and the other absorbers (methane, nitrous oxide and two chlorofluoromethanes) by 0.10 °C. If this were representative, and if the other absorbers were to increase at significant rates in the next century, the CO₂ effect would clearly be enlarged. Unfortunately we only speculate as to such continued increases for the other absorbers.

2.7 IS SURPRISE POSSIBLE?

The preceding sections showed that the present and future states of the climatic system are only approximately known. There are grounds for supposing, as just shown, that rising CO_2 and trace gas concentrations in the atmosphere may tend to raise global surface temperatures in the next 80 years at an average (but non-linear) rate of $0.06\,^{\circ}C$ a⁻¹, with maximum effect in high northern latitudes. It seems likely that this warming will affect precipitation and evaporation amounts. The uncertainties in the estimates have been deliberately stressed. Two questions now arise. Does such a change matter to humanity? And are surprise changes possible?

Seen in the perspective of the observed behavior of climate over the past century the above rate of change of temperature is impressive. Between 1880 and 1940 northern hemisphere temperature rose at about 0.01 °C a⁻¹, during the last two decades of the period the rate being about 0.02 °C a⁻¹. From 1938 until 1965 it fell at a comparable rate. The combined heating rate postulated for CO₂ and other infrared absorbers will eventually be much greater. These changes will all be perceived, in a highly variable climate, as changes in the incidence of extremes. A rapid change will get rapt attention, once it begins in earnest. On the other hand human societies have repeatedly absorbed even more rapid local or regional changes. Wittwer (1980) pointed out, for example, that Indiana in the United States had seen a rise of temperature of 2 °C in the past century, and that from 1915 to 1945 the increase was at the rate of 0.1 °C a⁻¹. (See Kates *et al.*, 1984, for other examples of climatic fluctuations in specific climate divisions.)

Changes of climate due to the gradual accumulation in the atmosphere of pollutants, or growth in the concentration of natural constituents like CO_2 , are likely to lead to progressive but irregular changes of the sort just described. But more impulsive changes are common in nature, and these may present greater problems for human adaptation. These impulsive changes are often visible in local or regional precipitation records. Habitually they last only a few years, but in a few cases may extend to some decades. There are theoretical grounds for supposing (Lorenz, 1968, 1975) that the general circulation of the atmosphere may flip from one quasi-stable mode of behavior to another with little change of external forcing—although the argument does not justify the conclusion that local flips are of such origin.

Remarkable instances of such flips on the regional scale have recently affected many parts of the world's desert margins, where climate has been highly perturbed in recent decades (Hare, 1977; Charney *et al.*, 1979). In the 1950s, for example, lake levels in East Africa (including Lake Chad) were low, as they had been since the beginning of the century. Early in the 1960s—1961 in the case of Victoria Nyanza, and hence the headwaters of the White Nile—there occurred an abrupt increase in rainfall over some of the plateaus. Some lake levels rose abruptly to levels not seen since the nineteenth century (Grove *et al.*, 1975; Nicholson, 1980). There was no warning of this increase. High rainfalls persisted for several years in some areas, assisting in the spread of agriculture in the East African highlands (Oguntoyinbo and Odingo, 1979). Desiccation returned after almost a decade of abundance, which misled many African statesmen into believing that a lasting change had occurred.

This East African anomaly was accompanied by a downward trend of rainfall along much of the southern margin of the Sahara. It, too, began in the early 1960s, and even earlier in some West African localities (Bunting *et al.*, 1976; Nicholson, 1980) where, however, rainfall was well above average at the outset. Between 1968 and 1973 the desiccation was of such intensity that the fluctuation became known as the Sahelian drought. In fact it was part of a two to three-decade-long fluctuation of rainfall over all equatorial Africa (Kraus, 1977; Motha *et al.*, 1980), of which the high rainfall phase of the early 1960s was a part. Fluctuations like this are probably internal to the climatic system. Such unpredicted

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variations pose a threat of major disruptions to the human economy over large parts of the world.

2.8 URBAN EFFECTS

The foregoing account has stressed general effects that are visible over the entire earth, or over extensive regions. On these large scales climate has an obvious bearing on such activities as agriculture, forestry, transportation and fisheries. One scale has been missed, however: that of the city.

Within the built-up area of the world mankind has contrived, especially within the past century and a half, considerably to influence the local climates. These effects arise from the intensive use of fuels within urban areas, which releases heat and pollutants; from the substitution of concrete, tarmac and other hard, impervious surfaces for natural vegetation and soil; and from interference with the energy and hydrologic cycles. Urban climatology has come of age, and there are now many comprehensive surveys of what has been learned (see, for example, Chandler, 1970; Oke, 1974, 1979; Landsberg, 1981).

Although the anthropogenic modification of urban climates obviously touches the lives of millions of people, the processes involved are subtle and specialized, and are beyond the scope of this chapter. Reference should be made to the reviews cited for details.

It is important to note, however, that the climate of the larger cities may already have been modified by these effects as much as the carbon dioxide build-up is likely to achieve on the global scale for at least half a century. The so-called *urban heat island*, for example, has raised mean annual temperatures in the centers of the large cities, in some cases by over 2 °C, above surrounding open areas. Substantial increases in precipitation over and downwind of cities have also been detected (see Pilgrim, Chapter 13).

2.9 CONCLUSION

What should be the strategy of a project that seeks to understand the impact of variable climate on changing society? Does any clear imperative emerge from this review of the nature of the variation?

The distinction made in the account between internal variability and climatic change is of considerable practical importance. Internal variability is distinguished by two main characteristics: it is as yet largely unpredictable, and may remain so indefinitely; but it is readily identifiable in the climatic record. In other words experience should be the guide to action. Climate was defined above as the expectation of weather. The point was also made that variability is part of the climate itself—and is in many ways the key part for the human economy. Proper measures of variability, and especially of extremes, are hence vital to the description of a climate. Above all the measures must include estimates of the probable duration and frequency of the sort of extremes that cause stress—and the need for adaptive measures—in the economic system.

As the account has shown, climate looks, in the longer perspective, like a very stable system. Since the major changes in precipitation distribution in mid-Holocene times (~ 5000 years ago), climate has been subject only to fairly small changes. If one trusts the crude analyses now available—and this may not be wise—world temperatures have fluctuated within a range less than ± 2 °C, and world rainfall by less than about ± 5 percent. Along the climatic margins—the cold and dry limits for agriculture, for example—these small changes (like the Little Ice Age) have caused considerable stress, but humanity has been well able to cope with them. In fact most professional atmospheric scientists assume that this basic stability will continue; in the absence of any contrary evidence persistence gives the best forecast.

This comfortable assumption is no longer valid if the CO₂ effect and the complementary effect of other infrared absorbers are real. A progressive rise of temperature is predicted on a world basis, with much larger increases in north polar latitudes. Adjustments of precipitation and evaporation are also predicted. These represent changes in climate, but will probably be manifest as sequences of anomalous years, at least for a short time. The eventual rate of change anticipated is much greater than those associated with the fluctuations of the past century. It may be that their effects will be reduced or compounded by other anthropogenic factors—increased particle loads, altered hydrologic cycle, and others. Adaptation of the human economy to such changes ought to be feasible, since they have been anticipated; there is time to innovate. Whether mankind can act rationally and in concert about such questions is, however, open to doubt. The rest of this volume deals with matters that bear on this question.

In brief, the search for better adaptation to climate has two components: a better use of the existing experience of climatic variability, as given by the climatological record; and a search for adaptation to the climatic changes that now seem probable. The clear imperative is to get on with the search.

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