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William James Burroughs
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1 Introduction

There is always an easy solution to every human problem – neat, plausible and wrong. H. L. Menken

The climate has always been changing. On every timescale, since the Earth was first formed, its surface conditions have fluctuated. Past changes are etched on the landscape, have influenced the evolution of all life forms, and are a subtext of our economic and social history. Current climate changes are a central part of the debate about the consequences of human activities on the global environment, while the future course of the climate may well exert powerful constraints on economic development, especially in developing countries. So, for many physical and social sciences, climate change is an underlying factor that needs to be appreciated in understanding how these disciplines fit in to the wider picture. The aim of this book is to provide a balanced view to help the reader to give the right weight to the impact of climate change on their chosen disciplines. This will involve assessing how the climate can vary of its own accord and then adding in the question of how human activities may lead to further change.

The first thing to get straight is that there is nothing simple about how the climate changes. While the central objective of the book is to make the essence of the subject accessible, it is no help to you, the reader, to duck the issues. All too often people try to reduce the debate to what they see as the essential features. In so doing, either unwittingly or deliberately, they run the risk of squeezing the evidence down too much. So, from the outset it pays to appreciate that the behaviour of the Earth's climate is governed by a wide range of factors all of which are interlinked in an intricate web of physical processes. This means identifying the factors that matter most and when they come into play. To do this we have to define the meaning of climate change, because various factors assume different significance depending on the timescales under consideration.

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1.1 Weather and climate

It is not easy to form a balanced view of the importance of climate change in our lives. We are bombarded with a continual stream of dramatic information about how the climate is becoming more extreme and threatening. This information is drawn from meteorological authorities around the world. While the process of translation is not always accurate, it sets the scene for interpreting the importance of climate change in our world. So, how are we to handle claims about the record-breaking nature of droughts, heatwaves and hurricane seasons?

The first stage in establishing how the climate varies is to discriminate between weather and climate. At the simplest level, weather is what we get, climate is what we expect. So, the weather is what is happening to the atmosphere at any given time, whereas climate is what the statistics tell us should occur at any given time of the year. Although climatic statistics concentrate on averages built up over many years, they also give an accurate picture of the incidence of extreme events, which are part of the normal for any part of the world. Here, the emphasis will be principally on the average conditions, but it is in the nature of statistics that giving proper weight to rare extreme events is difficult to handle.

Wherever possible the analysis will be in terms of well-established lengthy statistical series. These are more likely to provide reasonable evidence of change in the incidence of extremes. Where the changing frequency of extreme weather events exerts a major influence on the interpretation of changes in the climate, however, there may be some blurring of the distinction between weather and climate in considering specific events. The essential point is, in considering climate change, we are concerned about the statistics of the weather phenomena that provide evidence of longer term changes.

1.2 What do we mean by climate variability and climate change?

It follows from the definition of weather and climate, that changes in the climate constitute shifts in meteorological conditions lasting a few years or longer. These changes may involve a single parameter, such as temperature or rainfall, but usually accompany more general shifts in weather patterns that might result in a shift to, say, colder, wetter, cloudier and windier conditions. Due to the connection with global weather patterns these

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changes can result in compensating shifts in different parts of the world. More often they are, however, part of an overall warming or cooling of the global climate, but in terms of considering the implications of changes in the climate, it is the regional variations that provide the most interesting material, as long as they are properly set in the context of global change.

This leads into the question of defining the difference between climate variability and climate change. Given that we will be considering a continuum of variations across the timescale from a few years to a billion years, there is bound to be a degree of artificiality in this distinction and so it is important to spell out clearly how the two categories will be treated in this book. Figure 1.1a presents a typical set of meteorological observations; this example is a series of annual average temperatures, but it could equally well be rainfall or some other meteorological variable for which regular measurements have been made over the years. This series shows that over the period of the measurements the average value remains effectively constant (the series is said to be *stationary*) but fluctuates considerably from observation to observation. This fluctuation about the mean is a measure of *climate variability*. In Figures 1.1 b, c and d the same example of climatic variability is combined with examples of *climate change*. The combination of variability and a uniform cooling trend is shown in Figure 1.1b, whereas in curve c the variability is combined with a periodic change in the underlying climate, and in curve d the variability is combined with a sudden drop in temperature, which represents, during the period of observation, a once and for all change in the climate.

The implication of the forms of change shown in Figure 1.1 is that the level of variability remains constant while the climate changes. This need not be the case. Figure 1.2 presents the implications of variability changing as well. Curve (a) presents the combination of the amplitude of variability doubling over the period of observation, while the climate remains constant. Although this is not a likely scenario, the possibility of the variability increasing as, say, the climate cools (Fig. 1.2b) is much more likely. Similarly, the marked increase in variability following a sudden drop in temperature (Fig. 1.2c) is a possible consequence of climate change. The examples of climate variability and climate change presented on Figures 1.1 and 1.2 will be explored in this book, and so we will return to the concepts in these diagrams from time to time.

For most of these variations, a basic interpretation is that climate variability is being a matter of short-term fluctuations, while climate change is concerned about longer-term shifts. There are two reasons why this approach runs the risk of oversimplifying the issues. First, there is no reason

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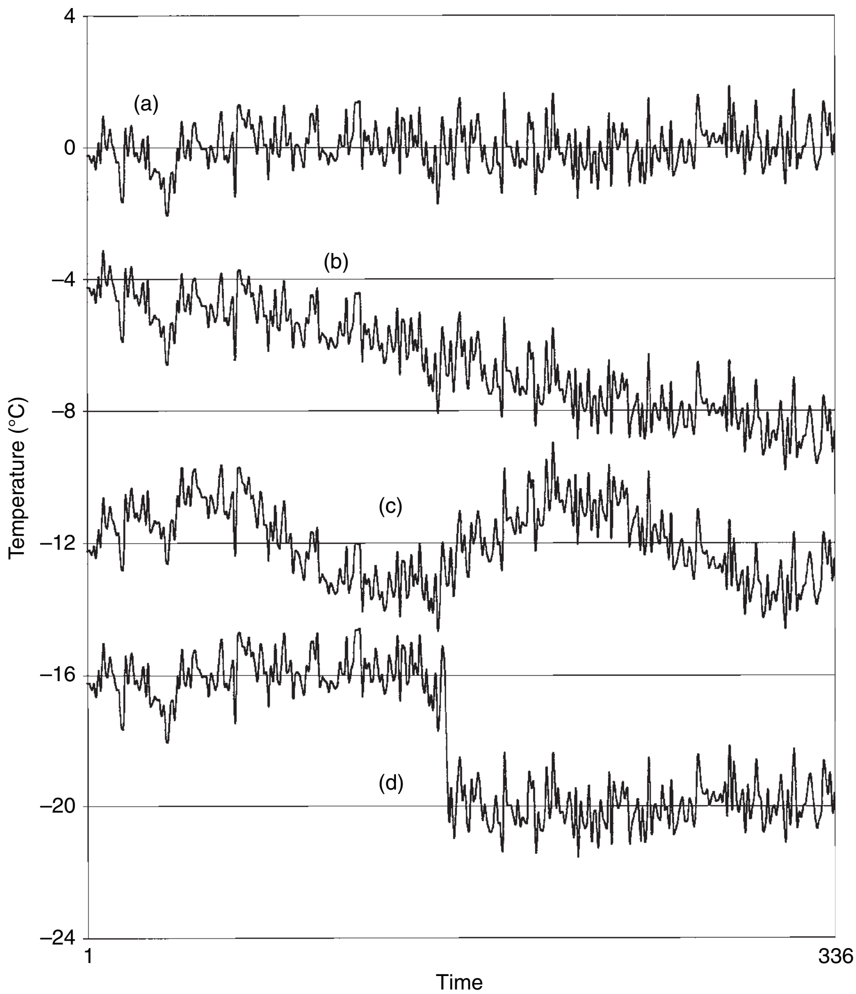

Fig. 1.1 The definition of climate variability and climate change is most easily presented by considering a typical set of temperature observations which show (a) climate variability without any underlying change in the climate, (b) the combination of the same climate variability with a linear decline in temperature of 4 °C over the period of the observations, (c) the combination of climate variability with a periodic variation in temperature of 3 °C, and (d) the combination of climate variability with a sudden drop in temperature of 4 °C during the record, with the average temperature otherwise remaining constant before and after the shift. Each record is displaced by 4 °C to enable a comparison to be made more easily. (From Burroughs, 2001, Fig.1.1.)

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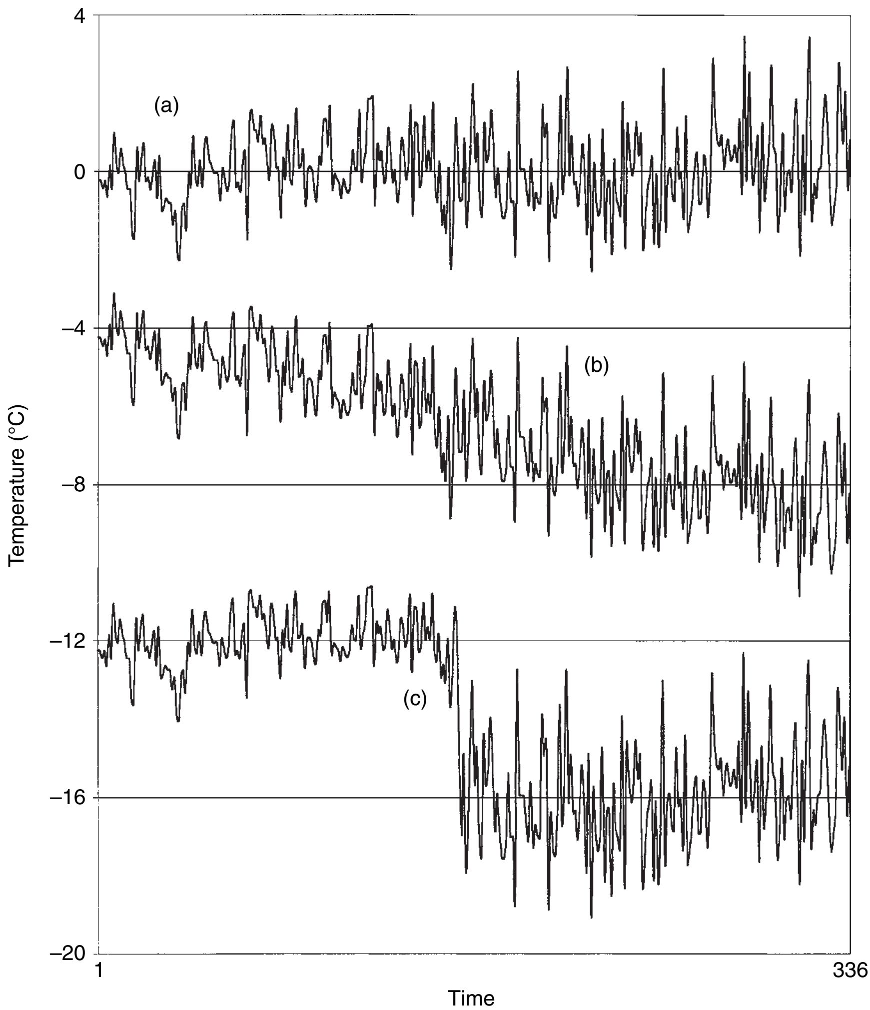

Fig. 1.2 The combination of increasing climate variability and climate change can be presented by considering a set of temperature observations similar to those in Figure 1.1 which show (a) climate variability doubling over the period of the record without any underlying change in the climate, (b) the combination of the same increasing climate variability with a linear decline in temperature of 4 °C over the period of the observations, (c) the combination of one level of climate variability before a sudden drop in temperature of 4 °C, which then doubles after the drop while with the average temperature remains constant before and after the shift. Each record is displaced by 4 °C to enable a comparison to be made more easily, and the example of periodic climate change in Figure 1.1 (curve c) is not reproduced here, as the nature of changing variability in such circumstances is likely to be more complicated. (From Burroughs, 2001, Fig.1.2.)

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why the climate should not fluctuate randomly on longer timescales, and recognising this form of variability is a major challenge in teasing out the causes of climate change. Secondly, as already discussed, climate change may occur abruptly and there is no doubt that in terms of the changes we will consider in this book this form of change has been an important factor in the Earth's climatic history.

Detecting fluctuations in the climate of the type described in Figures 1.1 and 1.2 involves measuring a range of past variations of meteorological parameters around the world over a wide variety of timescales. This poses major challenges that will be a central theme in this book. For now, the important point, is that when we talk about climate variability and climate change we are dealing with evidence from many parts of the world, which comes from a comprehensive range of sources and this varies greatly in quality. So, some past changes stand out with startling clarity, as in the case of the broad features of the last ice age, whereas others, such as the effect of solar activity on more recent changes, are shadowy and surrounded by controversy. It is this mixture of the well established and the unknown, which make the subject so hard to pin down and so fascinating.

1.3 Connections, timescales and uncertainties

From the outset the golden rule is: *do not oversimplify the workings of the climate*. In truth it is an immensely complicated subject. Part of the excitement of discovering the implications of climate change is, however, the fact it involves so many different processes linked together in an intricate web. In particular it requires us to understand the nature of *feedback processes* (see Box 1.1). The fact that a perturbation in one part of the system may produce effects elsewhere that bear no simple relation to the original stimulus provides new insights into how the world around us functions. It does require, however, a disciplined approach to the physical processes at work, otherwise the analysis is liable to be partial and misleading.

The challenge of discovering which processes matter most involves not only knowing how a given perturbation may disturb the climate but also of how different timescales affect the analysis of change. From the imperceptibly slow movement of the continents to the day-to-day flickering of the Sun, every aspect of the forces driving the Earth's climate is varying. Deciding which of these changes matters most, and when, requires evaluation of how they occur and how they are linked to one another. So while continental drift (*plate tectonics*) only comes into play when interpreting

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Box 1.1 The nature of feedback

Understanding and quantifying various *feedback processes* is a central challenge of explaining and predicting climate change. These processes arise because, when one climatic variable changes, it alters another in a way that influences the initial variable that triggered the change. If this circular response leads to a reinforcement of the impact of the original stimulus then the whole system may move dramatically in a given direction. This runaway response is known as *positive feedback* and is best illustrated by the high-pitch whistle that a microphone system can produce if it picks up some of its own signal. In the case of the climate, an example of this behaviour might be the effect of a warming leading to a reduction in snow cover in winter. This, in turn, could lead to more sunlight being absorbed at the surface and yet more warming, and so on and on.

The reverse situation is when the circular response tends to damp down the impact of the initial stimulus and produce a steady state. This is known as *negative feedback*. An example of this type of climatic response is where a warming leads to more water vapour in the atmosphere, which produces more clouds. These reflect more sunlight into space thereby reducing the amount of heating of the surface and so tends to cancel out the initial warming. Depending on the complexity of the system involved, these types of chain reaction can lead to a variety of responses to any perturbations including sudden switches between different states, and reversals where a positive stimulus can produce a negative reaction by the system as a whole. Throughout this book the appreciation of feedback mechanisms will play an essential part in understanding how the climate responds to change.

geological records over millions of years, its more immediate consequences (e.g. volcanism) can have a sudden and dramatic impact on interannual climatic variability. Similarly, fluctuations in the output of the Sun may occur on every timescale. When it comes to looking into the future, longer-term variations are bound to be the subject of speculation and, as such, are of questionable value. In the case of predictions a few days to several decades ahead, however, the potential benefits of accurate forecasts are immense. No wonder this is one of the hottest topics in climate change.

This differing perspective, depending on whether the analysis of the past is relevant to forecasting the future, will influence how climatic change is presented in this book. To use an example, the oil industry exploits the

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growing information about past climates on geological timescales to assist in the search for hydrocarbon deposits. For instance, current research includes computer models of past ocean circulation that can be used to identify regions of high marine productivity in the geologic past, where large amounts of organic matter may have been laid down, but changing knowledge about the climate on these timescales will have no influence on the industry's view on how the climate in the future will affect its plans.

By way of contrast, as production extends further offshore, the oil industry needs to know whether changes in, say, the incidence of hurricanes in the Gulf of Mexico or deep depressions in the North Atlantic will make its deep-water operations more hazardous. Such forecasts are entirely dependent on both reliable measurements of how the climate has been changing in recent decades and on whether it is possible to predict future trends. This sets more demanding criteria on what we need to know and whether it is sufficient to make useful forecasts. This applies to all areas of climate variability and climate change and so the improved understanding of the long-term climatic processes that have shaped the world around us, while central to the making of more efficient use of natural resources, can be dealt with in general terms. The more immediate issues of how the climate could change in the near future and how it will shape our plans for weather-sensitive investments requires more detailed analysis.

1.4 The big picture

One further aspect of climate change must not be overlooked. This is the fact that everything in the system is connected to everything else and so we have to be exceedingly careful in trying to explain how things fits together. Inevitably it will be necessary to look at various aspects of the climate in isolation. In so doing, however, we must not lose sight of the big picture. The connections and feedback processes described in the preceding section link every process into the system as a whole. Adopting this wider perspective helps to achieve some balance. Indeed, if you think there is a simple answer to any issue associated with climate change then you have not read enough about the subject. So, there is no point in beating about the bush; the climate is fearfully complex and while the objective of this book is to make climate change as accessible as possible, it is of no benefit to the reader to understate the complexity of the connections.

This means that any analysis depends on how changes in every aspect of the Earth's physical conditions and extraterrestrial influences combine.

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These range from the ever-changing motions of the atmosphere, through the variations in the land surface, including vegetation type, soil moisture levels and snow cover, to sea-surface temperatures, the extent of pack ice in polar regions, plus the stately motions of the deep-ocean currents, which may take over a thousand years to complete a single cycle, but which are also be capable of suddenly switching within a few years to entirely different patterns. Add to this that the prevailing climate, combined with the distribution of the continents controls the amount of nutrients washed into the oceans, which in turn affects the oceans productivity, and carbon dioxide levels in the atmosphere and you begin to get an idea of the complexity of climate change.

Some of these phenomena are predictable and some are not. For instance the features of the Earth's orbital motion, which govern the daily (diurnal) and annual cycles in the weather, can be predicted with great precision. Other gravitational effects, such as the longer-term cycles in the lunar tides, or the possible effects of the other planets in the solar system on both the Earth and the Sun, can be calculated with considerable precision, but their influence on the climate is much more speculative. The same applies to even longer-term changes in the Earth's orbital parameters, which alter the amount of sunlight falling at different latitudes throughout the year. But, as we will see later, this is the most plausible explanation of the periodic nature of the ice ages that have engulfed much of the planet during much of the last million years.

By comparison, many of the predictions of how the climate will respond to changes in various parts of the system are far less reliable. Indeed many of them expose the chaotic nature of the weather and the climate (see Box 1.1). So many aspects of climate change may well prove to be wholly unpredictable, but in studying how the various components of the climate interact with one another it may be possible to establish statistical rules about their behaviour. This might then lead to the making of useful forecasts of the probability of certain outcomes occurring as well as providing valuable insights into how the system works.

The consequence of the complexity is that from time to time we must enter the worlds of mathematics, statistics and physics. To many people studying other disciplines, which may be influenced by climate change, this may seem an unwelcome prospect but it is a necessary condition to understanding whether the issues raised by the claims of climatologists are of real consequence to your chosen discipline and so there has to be some mathematics and physics in this book. My objective will be, however, to keep the amount down to a minimum and to do my best to make it as user-friendly as possible.

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Armed with these insights, my aim will be to steer a judicious course through the essential aspects of climate variability and climate change to show how many aspects of our lives are influenced by past and present fluctuations. This will then set the scene for considering the urgent issues of the potential impact of human activities on the climate in the future and what we can do about it. The first step in this process is to consider the Earth's energy balance.

FURTHER READING

A complete reference list is available at the end of the book but the following is a selection of the best books or articles to follow up particular topics within this chapter. Full details of each reference are to be found in the Bibliography.

IPCC (1990), (1992), (1994), (1995), (2001) and (2007): In terms of obtaining a comprehensive picture of where the debate on the science of climate change has got to, these are the definitive statements of the consensus view. They are, however, both carefully balanced in their analysis, and exhaustive in their presentation of the competing arguments. As such, they are not an easy read and may appear evasive, if not confusing, until you have got a grip of the basic issues. So they are of greatest value once you have got your bearings clearly established. It follows that the greatest value will be in working with the latest review, but the earlier volumes provide an important historical perspective of the development of climate science in the last two decades.

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