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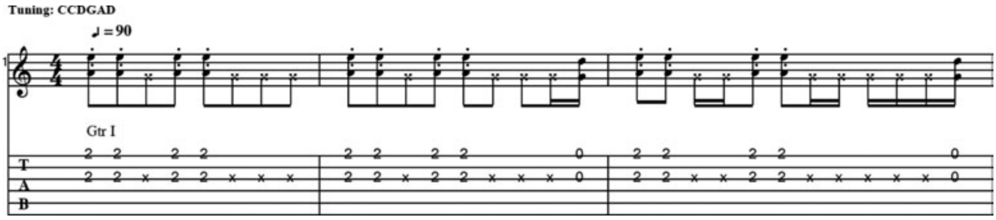
Climate Variability



Complex motions on the sphere.
CCDGAD, Aerial Boundaries, Michael Hedges

Human life is possible because of the specific conditions of the fluid envelopes surrounding the Earth. These fluid envelopes and the processes affecting their behavior are usually grouped into one system: the climate system. Quantities in the climate system, such as temperature and precipitation, vary on many time scales, and these variations are highly relevant for many aspects of human life, such as food production and safety.

There are many very good textbooks containing a description of the components of the climate system (Peixoto and Oort, 1992; Ruddiman, 2001), the relevant processes (Hartmann, 1994) and the modelling of the development of this system (McGuffie and Henderson-Sellers, 2006; Neelin, 2011). Many of these books first introduce the radiation balance with all the physical, chemical and biological processes affecting it. Next, the large-scale atmospheric circulation and ocean circulation are considered, followed by the smaller-scale processes in these components of the climate system. Finally, the role of the biosphere and cryosphere is discussed.

This is a book in which variability in the climate system is viewed from a stochastic dynamical systems framework. After an introduction into the observational database

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in Section 1.1, typical phenomena of climate variability are presented in Section 1.2. In Section 1.3, we focus on the dynamical organization of the climate system, which is followed by an introduction into the stochastic dynamical systems framework in Section 1.4. An overview of the contents of the book is given in Section 1.5, together with specific reading paths.

1.1 The observational database

Climate research is a data-poor science considering the questions it attempts to answer (Wunsch, 2010). There are two sources of data: the instrumental record and the palaeorecord. The instrumental record teaches us about the transient behavior of the climate system under a changing forcing (solar, greenhouse gases) since the early 1860s. It consists of the following different databases:

- Local routine measurements at certain stations. Examples are radiosonde observations, tide gauge data and data from ocean weather ships. The length of the time series varies enormously from location to location, and the spatial coverage is usually poor (e.g., only a few locations in the Southern Ocean region).
- Databases from different international monitoring programs. In several of these programs, such as the World Ocean Circulation Experiment (WOCE), a global (but coarse) coverage was achieved.
- Remotely sensed data. Satellite data have been collected since the early 1980s, providing near global coverage of the Earth.
- Data from drifting platforms. Since the early 2000s, floats have been released in the oceans, which monitor quantities such as temperature and salinity as they move with the currents.

Much of our knowledge on climate variability is based on observations of which data are stored in several databases around the world. These databases are continuously updated with new observational records from in situ (atmospheric, oceanic) measurements and with satellite data. The observational data sets are composed of time series of particular so-called climate indices and of three-dimensional (longitude, latitude, time) or four-dimensional (longitude, latitude, height/depth, time) fields of many quantities, such as temperature and precipitation. Most of the instrumental climate data are available through the Royal Netherlands Meteorological Institute's Climate Explorer (http://climexp.knmi.nl), where they can also be easily visualised and analysed. An important example is the time series of the sea surface temperature anomaly in the eastern Pacific, the so-called NINO3 time series (Fig. 1.1a).

In addition to the instrumental record, there is also the palaeorecord, containing (mainly) data that are not direct measurements of climate variables but of a quantity

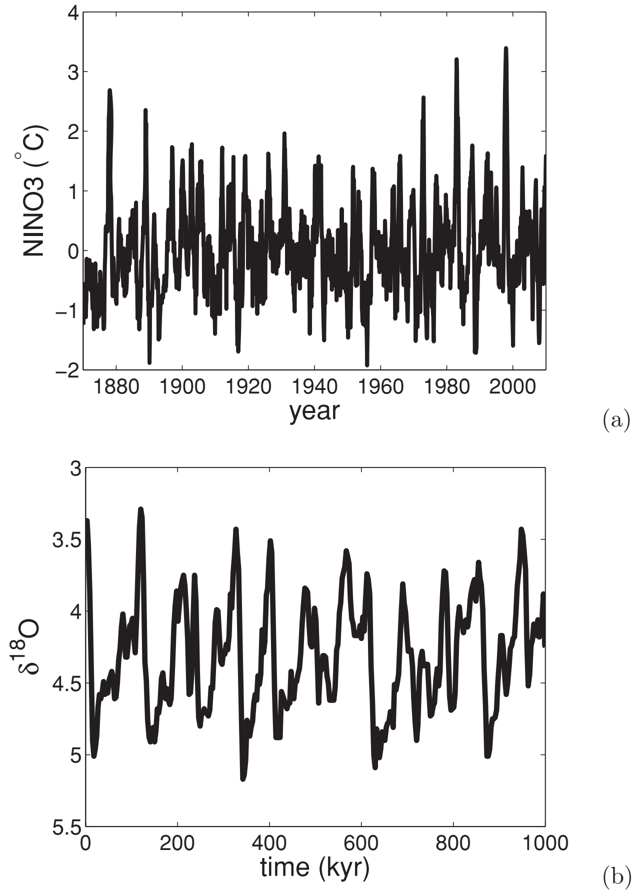

Figure 1.1 (a) Time series over the period 1870–2010 of the sea surface temperature anomalies (with respect to the mean seasonal cycle) in the Eastern equatorial Pacific averaged of the domain [150°W-90°W] × [5°S-5°N], the so-called NINO3 box, as provided in the HadISST1 data set (Rayner et al., 2003). The time series is low-pass filtered with a cut-off value of 24 months. (b) Time series of δ^{18}O at Ocean Drilling Program Site 677 (1°N, 83°W) at a depth of about 3 km over the last one million years providing an indirect measure of temperature fluctuations in the deep ocean (a high [low] value of δ^{18}O indicates a low [high] temperature).

(a proxy) that can be related to a climate variable. An example is the oxygen isotope ratio δ^{18}O determined from water molecules in ice cores, which can be related to the temperature at the time of deposition of the snow. Also δ^{18}O derived from carbonate containing marine organisms provides information on the changes in the deep ocean temperature (Fig. 1.1b). Most of the palaeodata are available through the palaeoclimate Web site at the National Oceanic and Atmospheric Administration (NOAA) http://www.ncdc.noaa.gov/paleo/paleo.html.

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1.2 Phenomena: temporal and spatial scales

An artist's view of climate variability on 'all' time scales is provided in Fig. 1.2. The first version of this figure was produced by Mitchell (1976), and many versions thereof have circulated since. The figure is meant to summarize our knowledge of the spectral power $S = S(\omega)$, that is, the amount of variability in a given frequency band, between ω and $\omega + \Delta\omega$; here the frequency ω is the inverse of the period of oscillation, and $\Delta\omega$ indicates a small increment. This power spectrum is not computed directly by spectral analysis from a time series of a given climatic quantity, such as (local or global) temperature. There is no single time series that is 10^7 years long and has a sampling interval of hours, as the figure suggests. Instead, Fig. 1.2 includes information obtained by analysing the spectral content of many different time series, for example, those in Fig. 1.1.

Between the two sharp lines at one day and one year lies the synoptic variability of mid-latitude weather systems, concentrated at 3–7 days, as well as intraseasonal variability, that is, variability that occurs on the time scale of 1–3 months. The latter is also called low-frequency atmospheric variability, a name that refers to the fact that this variability has lower frequency, or longer periods, than the life cycle of weather systems. Intraseasonal variability comprises phenomena such as the Madden–Julian oscillation of winds and cloudiness in the tropics or the alternation between episodes of zonal and blocked flow in mid-latitudes.

Immediately to the left of the seasonal cycle in Fig. 1.2 lies interannual (i.e., year-to-year) variability. An important component of this variability is the El Niño phenomenon in the Tropical Pacific: once about every four years, the sea-surface temperatures (SSTs) in the Eastern Tropical Pacific increase by a few degrees over a period of about one year. This SST variation is associated with changes in the trade winds over the tropical Pacific and in sea-level pressures (Philander, 1990); an east–west seesaw in the latter is called the Southern Oscillation. The combined El Niño/Southern Oscillation (ENSO) phenomenon arises through large-scale interactions between the equatorial Pacific and the atmosphere above. Equatorial wave dynamics in the ocean play a key role in setting ENSO's time scale. The time series of the NINO3 index as shown in Fig. 1.1a is a measure for the variability in the SST in the eastern Pacific.

On slightly larger time scales, decadal-to-multidecadal variability appears, which is particularly prominent in the North Atlantic because of a phenomenon called the Atlantic Multidecadal Oscillation (AMO). The AMO is associated with basin-wide changes in sea surface temperatures on a 20- to 70-year time scale, with most of the action occurring in the northern North Atlantic. Multidecadal variability was also found in the 335-year-long record of the Central England temperature time series (Ghil and Vautard, 1991).

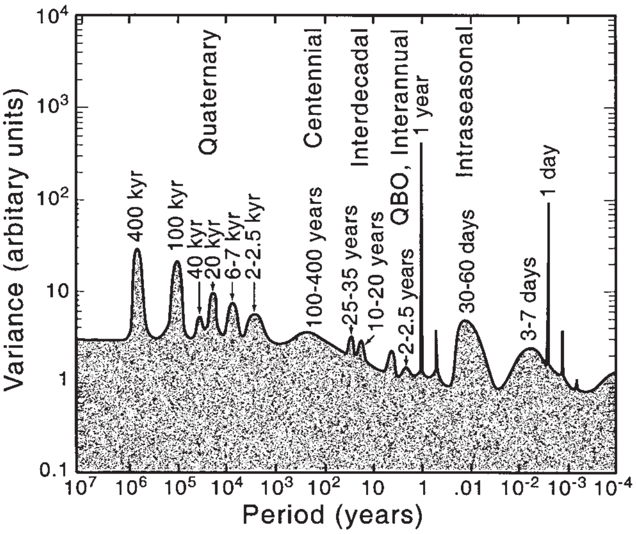

Figure 1.2 An artists' view on climate variability (Mitchell, 1976) displaying a 'hypothetical' spectrum based on information of different time series such as shown in Fig. 1.1 (from Dijkstra and Ghil, 2005).

The leftmost part of Fig. 1.2 represents palaeoclimatic variability. The information summarized here comes exclusively from proxy indicators of climate variables (Imbrie and Imbrie, 1986). These include coral records and tree rings for the historic past, as well as marine-sediment and ice-core records for the last two million years of Earth history, the Quaternary. Glaciation cycles, an alternation of warmer and colder climatic episodes, dominated the Quaternary era. The cyclicity is manifest in the broad peaks present in Fig. 1.2 between roughly 1 kyr and 1 Myr and can be seen in Fig. 1.1b. The two peaks at about 20 kyr and 40 kyr reflect variations in Earth's orbit, whereas the dominant peak at 100 kyr remains to be convincingly explained.

Within these glaciation cycles, there are higher-frequency oscillations prominent in the North Atlantic palaeoclimatic records, in particular in Greenland ice core records. These are the Heinrich events, with a near-periodicity of 6–7 kyr, and the Dansgaard-Oeschger cycles, which provide the peak at around 1–2.5 kyr in Fig. 1.2. Rapid changes in temperature, of up to one half of the amplitude of a typical glacial–interglacial temperature difference, occurred during Heinrich events, and somewhat smaller ones occurred over a Dansgaard-Oeschger cycle. None of these higher-frequency oscillations can be directly connected to orbital or other external forcings.

In summary, climate variations range from the large-amplitude climate excursions of the past millennia to smaller-amplitude fluctuations on shorter time scales. Fig. 1.2 reflects three types of variability: (i) sharp lines that correspond to periodically forced variations, at one day and one year; (ii) broader peaks such as that associated with

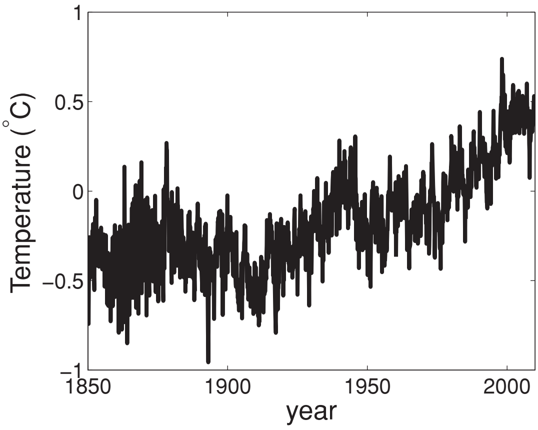

Figure 1.3 The global mean surface temperature anomaly with respect to the period 1961–1990 from the HadCRUT3 data set (http://www.cru.uea.ac.uk/cru/data/temperature/).

ENSO in the interannual frequency band; and (iii) a continuous background with a higher power in the lower frequencies. The understanding of these spectral properties of climate variability is crucial to interpret the time series of the global mean surface temperature from the instrumental record, as plotted in Fig. 1.3, and to assess its predictability.

1.3 The climate system

Although climate scientists' views on the climate system probably greatly differ, most would admit that it is a system displaying very complex spatio-temporal variability in many of its components, such as the atmosphere, the hydrosphere (including the oceans), the cryosphere, the biosphere and the lithosphere.

In a report to the NASA Advisory Council, Bretherton (1988) presented a sketch of the Earth System components and their interactions. The original figure (Bretherton, 1988), sometimes referred to as the 'horrendogram' of the climate system, and its simplification shown in Fig. 1.4 are certainly useful in recognizing many of the subcomponents of the climate system and identifying the important processes. The figure also provides a basis for understanding the transfer of properties (e.g., energy and mass) that are exchanged between these different subsystems. Examples of such interactions and associated fluxes are usually referred to as the energy cycle, the hydrological cycle and several biogeochemical cycles (e.g., the carbon, the sulphur and the nitrogen cycles).

To understand climate variability, it is important to realize that different characteristic time scales are introduced into the climate system by the different processes in the subsystems. One way of looking at these time scales is to perturb the specific subsystem out of an equilibrium and then monitor how long it takes for it to reach

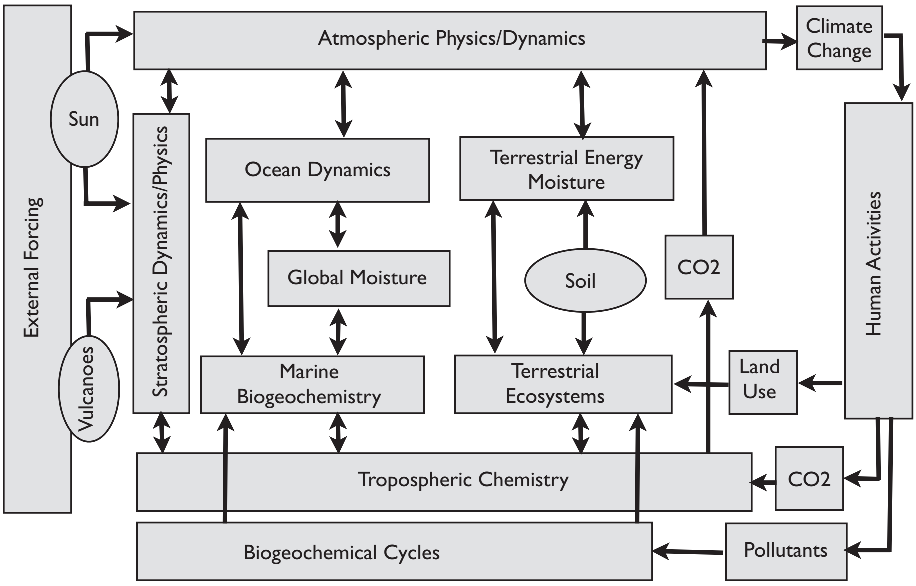

Figure 1.4 A schematic of the organization of the climate system, showing the different components and their connections (simplified from Bretherton [1988]).

equilibrium again. Such characteristic (or response) time scales of atmospheric processes range from a few seconds (e.g., formation of cloud droplets) to a few days (e.g., dissipation of midlatitude weather systems). For the ocean, these scales range from a few months (e.g., upper layer ocean mixing) to thousands of years (e.g., deep ocean circulation adjustment). The cryosphere has an even larger range because sea ice processes are much faster than those of ice on land. The time scales of the biosphere also have a very wide range, and those of the lithosphere (e.g., motion of continents) are up to millions of years.

In addition, feedbacks between the different components may also introduce new time scales of variability. One of the most important examples is the coupling between the equatorial ocean and the global atmosphere, which introduces the interannual time scale of variability associated with the ENSO (Fig. 1.1b). For feedbacks to occur, it is important to know the relevant strengths of the couplings between the different subsystems. The organizational structure of the climate system, as sketched in Fig. 1.4, together with the different response time scales and relatively coupling strength of the subsystems provides the basis for the stochastic dynamical systems framework, which is introduced in the next subsection.

1.4 The stochastic dynamical systems framework

To determine how the Earth system develops as a whole, humans included, appears an impossible task. Although there are basic mathematical equations available for the

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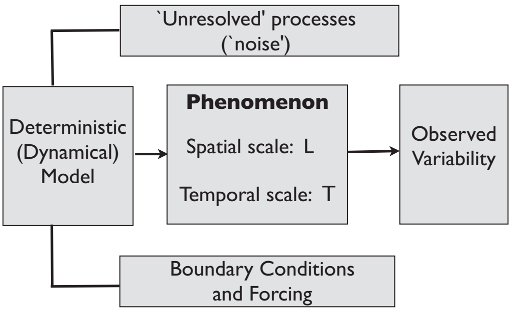

Figure 1.5 A schematic of the stochastic dynamical systems framework of climate variability. A deterministic dynamical system represents the particular phenomenon on a dominant spatial scale L and a temporal scale T. Smaller and faster scale processes (labelled here as ‘unresolved’ by the deterministic system) are represented as ‘noise’, whereas slower processes are fixed into the boundary conditions.

physical components of the system (i.e., conservation principles), such equations are (still) lacking for many other components, such as for the development of ecosystems. Missing such equations on highly relevant components and facing the problem of many spatial and temporal scales of the system, we necessarily must turn to more modest approaches.

The issue of trying to determine the development of the Earth System is closely related to the question one asks. Is the question related to the development of the El Niño over the next few months, is it to predict when the next ice age will occur, or is it about the changes of the temperature in Western Europe over the next 50 years due to the increase in atmospheric greenhouse gases? Once the question has been fixed, we can immediately take advantage of the fact that processes can be differentiated according to the spatial and temporal scales, and hence one can make adequate approximations. For example, we can make a very good approximation by assuming that the continents are at fixed positions when studying the development of the weather over the next few days.

Let us focus on a phenomenon with a characteristic time scale T occurring predominantly over a spatial scale L (Fig. 1.5). As an example, we can think of the interannual associated with the present-day El Niño with spatial patterns extending over a large part of the Pacific basin, that is, $T \approx 5$ years and $L \approx 10^7$ km. In a stochastic dynamical systems view of this phenomenon, all processes on time scales $\tau \gg T$ can be assumed to be fixed in time. For example, for present-day El Niño prediction, the ocean bathymetry can be fixed to present-day values, and orbital variations in insolation can be neglected.

How do we handle in this case the processes occurring on much smaller time and spatial scales, such as wind waves on the surface of the Pacific Ocean? This is in general a tricky issue, as collective behavior due to small-scale processes certainly can influence the large-scale behavior. Hence there is no general theory to cope with the

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small-scale processes apart from explicitly modelling them. When this is impossible, one can resort to several options, usually referred to as parameterisation of the small scales into large-scale descriptions. Parameterisations may be deterministic (i.e., given by explicit relationship between variables), or they may be stochastic (Majda and Wang, 2006). In the latter case, a stochastic model of the small scales has to be proposed. Both this stochastic model and the deterministic parameterisations are in most cases (at least partially) based on observations.

What results from this stochastic dynamical systems framework (Fig. 1.5) is a set of mathematical (in general, stochastic partial differential) equations for the description of the phenomena at the scales T and L. The equations for these large scales contain parameterisations in which the effects of the small scales are represented. Boundary conditions are formulated at areas where development of the system is much slower. Because of the cyclic nature of the insolation entering the climate system, the set of equations may contain a periodic forcing component. The response of this (in general, nonlinear) periodically forced stochastic dynamical system can then be compared with data sets from the instrumental record and from proxy records.

1.5 Overview of the book

The use of a stochastic dynamical systems framework for addressing problems in climate variability logically structures the book into three parts: a methods part (Chapters 2–5), a climate dynamics part (Chapters 6–11) and a climate predictability part (Chapter 12).

In Chapter 2, an introduction to the theory of deterministic dynamical systems is given. It is relatively short on bifurcation theory compared with material presented in Dijkstra (2005), but it provides more details on transient phenomena such as non-normal growth. In Chapter 3, methods of stochastic calculus are described starting from the very basics. The main aim of this chapter is to give a ‘mild’ mathematical description of stochastic methods as applied to climate dynamics. The general solution of the linear scalar stochastic differential equation and the basics of the Fokker-Planck equation are described. In Chapter 4, a short exposition of bifurcation theory in random dynamical systems is given. Chapter 5 focuses on data (either from models or observations) analysis techniques. We also start from the basis, discuss the traditional linear stationary statistical methodology (univariate and multivariate) and extend it slightly with modern nonstationary (e.g., wavelets) and nonlinear time series analysis (e.g., attractor embedding) techniques.

The climate dynamics part of the book starts with Chapter 6, where an introduction is given into the hierarchy of climate models that are used in subsequent chapters. In each of Chapters 7–11, an important problem of climate variability is discussed using the stochastic dynamical systems framework, that is, the North Atlantic Oscillation (Chapter 7), the El Niño/Southern Oscillation (Chapter 8), the Atlantic Multidecadal

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Oscillation (Chapter 9), the Dansgaard-Oeschger events (Chapter 10) and the Pleistocene Ice Ages (Chapter 11). The choice of these problems is motivated by the following:

- The phenomena all occur on different time scales, and hence different processes affect the dynamics of each of the climate subsystems. Also the ‘noise’ has a different interpretation in each of the problems.
- For each of the phenomena, a reasonable amount of data (either from the instrumental record or from proxy archives) are available to provide model-data comparisons.
- The techniques from stochastic dynamical systems theory, as presented in Chapters 2–5, have been applied to these problems, so there is an extensive set of results from the literature.
- In each of the problems there are different stages of understanding of the phenomena based on the use of different levels of models (in the model hierarchy presented in Chapter 6).

The book concludes with Chapter 12, in which the application of stochastic dynamical systems techniques on predictability problems associated with present-day climate change is presented.

This book has been written with two types of readers in mind. Reader type A likes an introduction into the modern theory of stochastic dynamical systems using a less formal mathematical description than is given in most mathematics textbooks. Someone wanting to learn only about the methodology of random dynamical systems would focus on Chapters 3 and 4. Reader type B is curious about what the stochastic dynamical systems framework provides to the understanding of his/her topic of interest described in Chapters 7–11 or how these concepts are applied in climate predictability (Chapter 12). For example, someone interested in the Dansgaard-Oeschger events can turn directly to Chapter 10 and read background material from Chapters 2–6 when required. The material in each chapter is largely self-contained, although obviously in Chapters 7–11, extensive reference is made to material in Chapters 2–6.