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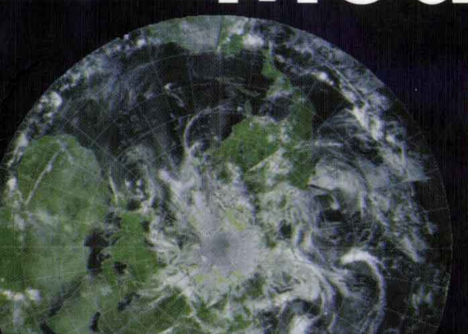
Environmental Modelling and Prediction



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Preface

The environment is the aggregate of the physical, geographical and biochemical conditions under which we live. It significantly influences all aspects of human society, including agriculture, industry, human health, resources, etc. In recent history, we have been challenged not only by the impact of natural environmental variability, but also by human induced environmental changes, such as deforestation, destruction of the ozone layer, increased emission of greenhouse gases and pollution of air, water and soil. It is now increasingly understood that to better protect the environment is an essential task of human society. Environmental modelling and prediction, i.e., the modelling of environmental processes and the prediction of environmental changes, form a critical component of this task.

The environment is a complex interactive system comprising five major components and numerous sub-components. The major components are the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere. Environmental modelling and prediction is concerned with both the behaviour of the individual components and their interactions, through the mathematical and numerical representation of the the physical, chemical and biological processes taking place within the environmental system. It is also concerned with the variability, stability and predictability of the environment as a dynamic system on a wide range of temporal and spatial scales.

There is an increasing requirement throughout the world for a better understanding of environmental processes and an enhanced capability for predicting environmental changes resulting from natural variations or human interferences. Numerous studies dealing with the modelling and prediction of individual components have been carried out in the past with considerable success. In recent years, environmental research is more focused on integrated approaches in which the environment is treated as a cohesive dynamic system. However, so far there have been very few books dealing exclusively with the latter subject. Our aim in this book is to bring together the collective efforts of scientists from several disciplines, to summarize recent developments in theories, methodologies and applications of integrated environmental modelling and prediction. Our effort in achieving this aim is reflected in Chaps. 1, 2 and 11. In Chap. 1, the subject area is explored and the scope of the book is defined. In Chap. 2, we have attempted to establish a theoretical framework for modelling and predicting the environment as a dynamic system, while in Chap. 11, examples of integrated environmental modelling and prediction are presented.

For environmental modelling and prediction, the modelling and prediction of the weather and climate components are of great importance for two main reasons. First, the atmosphere is the most active part of the environmental system on short time scales (up to a year). Second, the methods used in atmospheric modelling and prediction are arguably the most highly developed and also have the most complete data sets for verification. Chap. 3 of this book is devoted to the modelling and prediction of the atmosphere on a wide range of time and space scales. The next most important component of the environment is the ocean which dominates the behaviour of the environment on time scales from annual to decadal and beyond. Recent developments in ocean modelling and prediction are presented in Chap. 4.

A detailed treatment of the other environmental components is also presented because, although they interact with the atmosphere and the ocean, they have their own distinct dynamic features. It is important for success in environmental modelling and prediction that these individual components and their interactions are also well understood. We summarize the theories, methodologies and achievements in the modelling and prediction of the land-surface, the continental hydrosphere, the cryosphere and the continental biosphere (Chaps. 5, 6, 7 and 8, respectively). The interactions between the atmosphere, the ocean and these environmental components are also discussed. Some aspects of biological modelling and air quality modelling are discussed in Chaps. 9 and 10.

The book also explores recent developments in the theory and applications of environmental prediction, including systems analysis, information theory and natural cybernetics. The further development and application of these theories are very important for environmental modelling and prediction.

This book is a collective effort of many people. In particular, we wish to thank Drs. R. Morison, M. England, P. Oke, P. Irannejad, S. Liu, C. Ciret, Y. Tan, H. Duc, S. Zhao, M. Speer and L. Qi for their contributions to the various chapters. The assistance of Dr. S. Xia in the preparation of the manuscript and graphs is gratefully acknowledged.

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1. Environmental Science

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1.1 The Environment and Environmental Challenges

It is difficult to define precisely the environment , but in general, it embraces the social, geographical, physical and biochemical conditions under which we live. Conceptually, it can be divided into the social and the natural environment. The former is created by human activities, including industrial complexes, cities, villages etc., while the latter is a system comprising the atmosphere, hydrosphere, lithosphere, cryosphere and biosphere. The components of the natural environment undergo changes on a range of temporal and spatial scales, which impact upon the social and economic activities of human society. Figure 1.1 is a schematic illustration of the environmental components and the interactions between them.

The content of this book is comprised mainly with the study of the natural environment, which we refer to simply as the environment. Environmental science is concerned with the scientific laws governing the evolution of the environment and its impact on the human society. Further, it focuses on environmental assessment, prediction, management and control. It is a multidisciplinary subject, embracing physics, chemistry, mathematics, biology, ecology, geography, hydrology, computational science and astronomy, among many others. One of the cornerstones of environmental science is environmental modelling and prediction.

A profound feature of the environment is that its processes take place over a wide range of time scales, from micro-seconds to millions of years, and even billions of years if geological processes are also considered. The spatial domain of the environment depends upon the time scales we are interested in. In general, it extends from the upper levels of the stratosphere, about 50 km from the Earth's surface, to the upper level of the lithosphere, about 5 to 6 km over land in average and 4 km over the bottom of ocean. According to this definition, the time scales of the environmental processes, including some geological processes, extend over millions of years. The most obvious and intensive interactions between the environment and human society take place on time scales less than several hundred years. From this perspective,

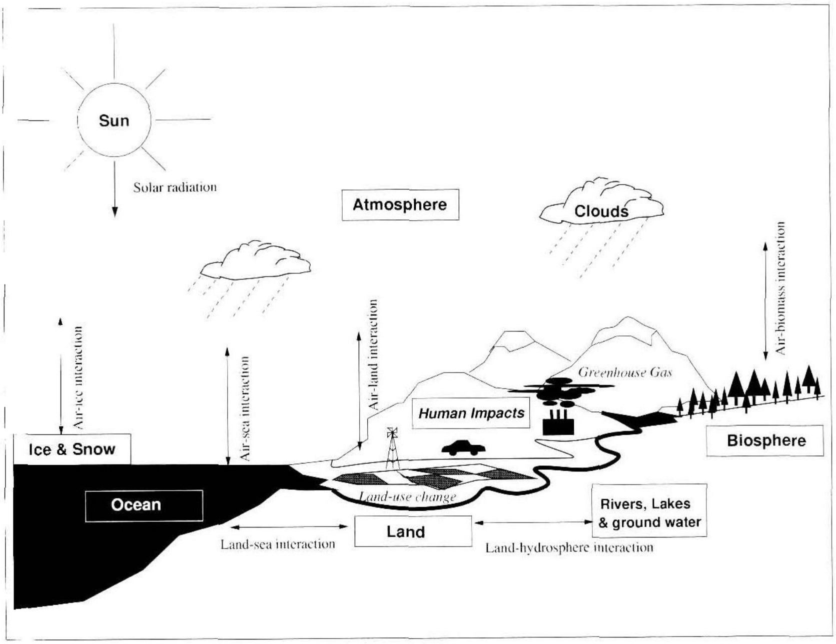

Fig. 1.1. A schematic illustration of the environmental components and the interactions among them (modified from Trenberth et al., 1996).

the deep lithosphere can be excluded from consideration. In this book, the environment is defined to comprise the upper stratosphere down to the top part of the lithosphere, about several hundred meters deep. The geological processes taking place in the deep lithosphere are not considered. While these processes are not unimportant, they can be considered to be either stationary or sporadic (e.g. volcanic eruptions and earthquakes) on the time scales of concern to this book.

In the new millennium, human society faces unprecedented challenges arising from environmental changes, brought about by both natural and human-induced processes. Some of the major challenges are described below.

Population. The world population has been rising rapidly from 2.5 billion in 1950, 4 billion in 1975 to over 6 billion in 2000 and will rise further to about 9 billion in 2050. The present rate of population growth is about 80 million per year. Over the next 50 years, global economic productivity will be several times its current level. These increases will exert serious pressures of global dimensions on natural resources. Every year about 5 to 7 million hectares of agricultural land is lost, giving a total of over 2 billion hectares (or 20 million sq kilometres) since records became available. There is now a serious shortage of cultivated land due to the combined effects of land degradation and urbanization. The forested areas of the world have also been falling sharply. At the beginning of the 18th century, they occupied 34% of the total land surface, in contrast to 24% at the end of the 20th century (Qu, 1987; Zhang, 1999). Presently, they are shrinking at a rate of about 11 million hectares per year. Because forests play an important role in the cycles of energy, water, CO_2 and aerosols, their destruction disturbs the balance between the different components of the environment, influencing atmospheric temperature and precipitation, and resulting in the degeneration of the entire ecosystem.

Global Warming. The burning of fossil fuels, industrial activities and deforestation significantly affect the atmospheric composition. Increases in CO_2 and other trace gases have led to global warming. The global surface temperature has increased by 0.3–0.6°C since the late 19th century, with the greatest warming over the region between 40 and 70°N. The most rapid increase appears to have occurred during the period 1955–1994 (Fig. 1.2). The global surface temperature appears to have been higher in the late 20th century than any other similar period in the past 600 years. In some regions, the 20th century has been the warmest for some thousands of years (Nicholls et al., 1996). The 1990s have been the hottest period on record. In 1998, the global mean surface temperature reached 16.86°C, which is higher than the mean value for 1931–1990 by 0.56°C. The high temperatures in 1998 caused many serious environmental problems. Corresponding increases in ocean and soil temperatures have been observed. Closely related to global warming of the atmosphere and oceans is rising sea-levels. In the 20th century, the global mean sea-level has risen about 10 to 20 cm, at a rate of 2.35 mm per year (Zhang, 1999), associated with an estimated ocean temperature increase of more then 0.1 °C.

Desertification. Desertification is one of the most serious environmental challenges. The drought affected areas on Earth total almost 48.8 million km^2 (about 1/3 of the total land surface) and 3/4 of this area is experiencing desertification, affecting about 1 billion people. The land surfaces in these areas are often subject to severe wind and water erosion. About 21 million hectares of farmland are affected each year by erosion activities. For example, dust storms frequently occurred in northern China in the 20 century. During the 1990s, dust storms occurred almost every year and were most severe in 1998 and 2000. Figure 1.3 shows the dust clouds associated with an intense wind erosion episode in the Takla Makan desert. The desert areas in northwestern China have been rising sharply, extending by 1560 km^2 per year in the 1970s, 2100 km^2 in the 1980s to 2400 km^2 in the 1990s (Chen, 1998).

Water Resources. Water covers about 71% of the Earth's surface, but water resources in many regions of the world are limited. Fresh water from lakes and rivers suitable for drinking constitutes less than 1% of the total amount of water. According to the Food and Agriculture Organization of the United Nations, by 2000, 51% of the available water will be consumed by agricultural