Furthermore, many changes do not occur in a linear fashion, but rather, thresholds are passed and rapid, non-linear changes ensue. For example, the initial pockets of deforestation in a large tropical forest may have little or no impact on the number of species of animals and birds. However, as the forest becomes increasingly fragmented, the rate of species loss can increase sharply (Hobbs 1989; Noss 1996). Similar effects have been shown to occur in the responses of insects to changing climate. In Sweden the tick species which carries encephalitis normally requires two seasons to complete its life cycle. However, with a warming climate in the high latitudes, at a certain point in the warming trend the tick can complete its life cycle in a single season, causing an apparently unpredicted outbreak of tick populations (Lindgren 2000). The pattern of little or no change until a critical threshold followed by a sharp response is common in Earth System dynamics, and may be the rule rather than the exception, especially as global change intensifies. In addition, many effects of global change are cumulative; for example, slow addition over time to the atmosphere of seemingly innocent chemicals in the form of chlorofluorocarbons led eventually to a rapid and significant disruption of the atmospheric chemical system in the stratosphere with the production of the so-called ozone hole.

Finally, global change is being played out in contrasting ways at different locations, each with its own set of characteristics being impacted by a location-specific mix of interacting changes. The global environment and the phenomenon of global change are both heterogeneous, and the variety of human-environment relationships is vast. The potential for an almost infinite range of interactions is large. To cope with or adapt to global change requires analyses that couple the particular characteristics of a location or region with the nature of the systemic, globally connected changes to Earth's environment as they interact with other factors affecting the location or region. Any attempt at achieving sustainability at any scale requires that this is done and that human societies learn to live with global change.

1.4 Objectives and Structure of the Book

The intent of this book is to explore what has been learned about the fundamental workings of the Earth System (see Box 1.1 for a definition of the Earth System),

Box 1.1. The Earth System

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In the context of global change, the *Earth System* has come to mean the suite of interacting physical, chemical, and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes which provide the conditions necessary for life on the planet. More specifically, this definition of the Earth System has the following features:

- It deals with a materially closed system that has a primary external energy source, the sun.
- The major dynamic components of the Earth System are a suite of interlinked physical, chemical and biological processes that cycle (transport and transform) materials and energy in complex dynamic ways within the System. The forcings and feedbacks *within* the System are at least as important to the functioning of the System as are the external drivers.
- Biological/ecological processes are an integral part of the functioning of the Earth System, and not just the recipients of changes in the dynamics of a physico-chemical system. Living organisms are active participants, not simply passive respondents.
- Human beings, their societies and their activities are an integral component of the Earth System, and are not an outside force perturbing an otherwise natural system. There are many modes of natural variability and instabilities within the System as well as anthropogenically driven changes. By definition, both types of variability are part of the dynamics of the Earth System. They are often impossible to separate completely and they interact in complex and sometimes mutually reinforcing ways.
- Time scales considered in Earth System science vary according to the questions being asked. Many global environmental change issues consider time scales of decades to a century or two. However, a basic understanding of Earth System dynamics demands consideration of much longer time scales in order to capture longer-term variability of the System, to understand the fundamental dynamics of the System, and to place into context the current suite of rapid global-scale changes occurring within the System. Thus palaeo-environmental and prognostic modelling approaches are both central to Earth System science.

The term *climate system* is also used in connection with global change, and is encompassed within the Earth System. Climate usually refers to the aggregation of all components of weather – precipitation, temperature, cloudiness, for example – averaged over a long period of time, usually decades, centuries, or longer. The processes which contribute to climate comprise the climate system, and they are closely connected to biogeochemical cycles. However, there are some important differences between climate change and global change:

- Many important features of biogeochemical cycles can have significant impacts on Earth System functioning without any direct change in the climate system. Examples include the direct effects of changing atmospheric CO_2 concentration on carbonate chemistry and hence on calcification rates in the ocean and also the sharp depletion of stratospheric ozone from the injection of chlorofluorocarbons in the atmosphere.
- Many interactions between biology and chemistry can have profound impacts on ecological systems, and hence feedbacks to Earth System functioning, without any change in the climate system. Examples include the impact of nitrogen deposition on the biological diversity of terrestrial ecosystems and the effect of non-climate driven changes in terrestrial and marine biospheric emission of trace gases and hence to the chemistry of the atmosphere.
- Human societies and their activities are usually not considered to be a direct part of the climate system, although their activities certainly impact on important processes in the climate system (e.g., greenhouse gas emissions).

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