1 INTRODUCTION

THE PHYSICAL ENVIRONMENT THAT ORGANISMS INHABIT

The interactions between climate and ecosystems occur on different timescales—a day, a year, or longer. On short timescales, we refer to *weather,* the actual atmospheric sequence of events (storms, wind, daily temperature). *Climate* is defined as the average of these events over years and longer time periods, and is described by storm frequency and intensity, mean wind, average temperature, and so on. Ecological systems experience and respond to atmospheric events (weather) as well as change more slowly with average conditions (climate).

A DAY

Consider a single summer day in a forest. As the sun comes up and temperatures warm, trees become active and the chemistry of photosynthesis begins. Some animals begin their daily activity, while others may seek refuge. Over the course of a single day, trees transition from removing carbon from the atmosphere and growing (daytime photosynthesis), to ceasing photosynthesis (nighttime) but releasing some of the day's photosynthetic gain of carbon back to the atmosphere during continued metabolism. During photosynthesis, water evaporates from the leaves, cooling not only the leaves but also the air above the forest. While trees are growing, changes in their size are usually imperceptible over a single day.

A YEAR

Let's expand our perspective to a year. In the spring, leaves begin to grow and expand, drawing on energy stored the previous year. The plants begin to take up carbon from the atmosphere, but the ecosystem as a whole still mainly respires stored carbon back to the atmosphere. As we'll see later, the atmosphere records this annual cycle of photosynthesis and respiration, so cumulatively, these plant processes affect the entire planet. As the weather warms and the season progresses, the carbon balance shifts, and photosynthesis begins to exceed respiration, leading to net growth of the biosphere. Leaves expand, plants increase in stature, and the daily cycle, described previously, continues within this grander cycle of the seasons. As winter and cold temperatures approach, growth ceases, leaves are shed, and respiration again exceeds photosynthesis.

A DECADE

Stepping back further, let's look at the ecosystem over a decade. Within the days and years of the decade, we see the preceding cycles, but we may also see a less orderly pattern. Some years have warmer or wetter conditions, while others are cooler or drier. The vegetation follows these climate signals, with more growth one year and less another. During a particularly dry year, a fire may remove most of the plant growth present, leaving bare soil. The carbon the forest stores or loses to the fire affects the amount of carbon in the atmosphere and eventually affects the climate. We begin to see the first clues as to how climate *change* may affect ecosystems, as variations in the physical resources plants need to grow (water, sunlight, heat) cause variations in the growth of individual plants.

A CENTURY

If we observe over many decades, we may note that although rainfall varies from one year to the next, the *average* amount of rainfall is changing. Although all the trees in the forest grow more in wetter years and less in drier years, some species are affected more than others. The more drought tolerant trees grow faster, and they may come to dominate the forest, inititating a change in its *species composition*. Thus, the effects of climate on individual forest organisms begin to be translated into altered relationships among species.

Imagine a drying trend. The increasingly taller drought-tolerant trees begin to shadow the water-loving species and reduce the light available to them for growth. Even in wet years, the drought-tolerant trees now have an advantage, and the entire community of organisms (including the animals that feed on the trees, and the predators that eat those herbivores) begins to change.

Although climate initiated the change, the interactions among the forest's organisms now take hold and control some of the change. Did a water-loving tree die of drought, or did it perish from inadequate light for growth owing to shade from a taller drought-tolerant tree? Was this tree death a climate effect or an effect of plant community processes? Of course, it was both, and in this simplified tale we can begin to see the complexity of climate–ecosystem interactions. As the forest canopy grows and covers more of the landscape, it makes the land surface darker, so it absorbs more sunlight, warming the surface more, and actually begins to change the local climate. Climate affects the metabolism and behavior of individual organisms, but these biological changes affect an organism's interactions with other organisms, and both the physics and the ecology of the system.

THE GLACIAL CYCLE

Climate and ecological change over decades is difficult to perceive, and scientists are just beginning to understand it, but the climate system and life are coupled on longer timescales as well (Barnola et al. 1991). The glacial–interglacial cycles, during which the earth cools and allows the growth of huge ice sheets, and then warms, releasing the water stored in the ice back into the oceans, are familiar. Some of the biological changes that occur over millennia as the earth warms and cools are similar to those described for a century. Some species fail, while others prosper, in glacial or warm interglacial climates. On these timescales, changes to marine and terrestrial carbon cycles have significant effects on climate, acting as controllers and not just responding passively.

However, over millennia, evolutionary change also occurs. Within species, cold- or heat-dominant genes may become more or less common, and entire species may arise or become extinct. Some of these changes may occur because of direct effects of climate. For example, a species may be unable to adapt to cold conditions, and all members of that species may die or fail to reproduce. Cold may reduce the numbers of a key prey species, leading to the extinction of a predator, or another predator species may be better able to travel over snow and thus may drive a competitor species to extinction through its higher effectiveness in a snowier climate.

THE GEOLOGICAL TIMESCALE

Climate and life also change together on the longest timescales. Paradoxically, these relationships may be the most familiar, as we know, for example, that dinosaurs flourished in a warmer past epoch of the planet. On the geological timescale, species or entire phyla flourish and decline in synchrony with vast, slow changes in the climate. On these timescales, life affects the geological and geochemical Earth System, changing rates of erosion (as land plants developed, they anchored the planet's soils); weathering of minerals (by fixing carbon and releasing it in soils as acidic compounds that affect mineral chemistry); and changing the composition of the atmosphere, releasing oxygen, methane, nitrous oxide, and other chemically or climatically important gases.

THE HUMAN TIMESCALE: THE ANTHROPOCENE

Geological time periods reflect events that are recorded in the rock record, through volcanic or erosional processes and other events that leave global traces evident to geologists. Recently, scientists have discussed terming the present the Anthropocene, because the effects of human use of natural resources, construction of cities and other infrastructure, climate change, and the impact of human-caused mass extinctions on the future fossil record should be evident to far-future researchers. In trying to understand present climate–ecosystem interactions the impacts of humanity are crucial. Human activity can change the way events occur over many different timescales. Harvesting a forest can instantaneously remove most of the wood slowly accumulated over days to centuries. However, that removal resets the forest's clock and will influence its dynamics for—at least—the lifespan of those trees. Human disturbance (forestry, conversion to agriculture) tends to cause rapid change to ecosystems but triggers slow responses as systems recover biomass and species composition over decades.

Of course, living systems are responding on all these timescales simultaneously. Early efforts to understand climate and ecosystems took shortcuts and tried to identify dominant influences of one timescale or another, but now we know that all these processes interact on different timescales. Year-to-year differences in crop yield may be due to just one extreme weather event. Centennial changes can arise when a fire or drought resets the age structure of a forest. A long-term trend may drive ecosystems to a state in which they respond differently to an extreme event. In the western United States, long-term trends in forest management have changed the sensitivity of forests to drought by allowing thick stands of trees to develop in the absence of fire; when drought comes, the dense forests (which fully use all the water available in wet years) are more stressed than they would be if there were fewer trees. In marine systems, slow changes in climate may influence long-lived fish populations, again changing the vulnerability of the system to rapid changes in phytoplankton following a climate event such as El Niño. Examination of the contingent and interacting effects of events and processes on different timescales is a major theme of this book and, as we'll see, provides much of the interest, challenge, and complexity of this science.

This book discusses the role of the earth's living organisms in the Earth System (ESSC 1988), which comprises the interacting atmosphere, oceans, lithosphere (soil and rocks), cryosphere (snow and ice), and biosphere, all influenced by and, most important, ceaselessly interacting with human activities (see figure 1). The biosphere affects the other Earth System components and is, in turn, influenced by them in many ways. A few decades ago, most scientists thought that life exists within the geophysical Earth System but influences it only in minor ways. The reality is more complex and more interesting.

Ecosystems and their interactions with climate vary greatly in different physical regions of the planet. Warm

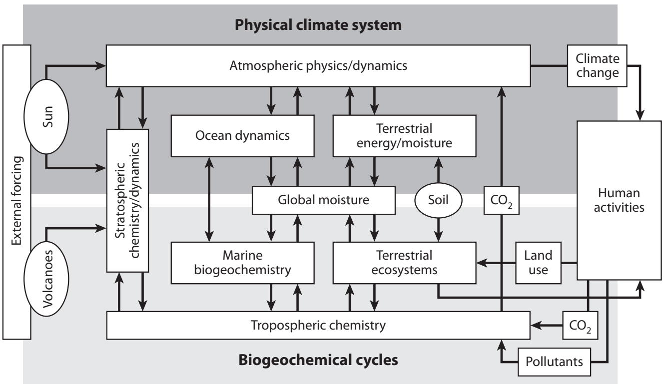

Figure 1. The Bretherton Diagram showing the key components of the biogeophysical Earth System and its human dimensions. Although the Earth System is considered a topic of interdisciplinary study, Bretherton pointed out that the Earth System, as an object, is also a subject for deep and coherent study. Many of its most important behaviors arise from the interactions among systems studied by the traditional disciplines (atmosphere–ocean, human behavior–atmospheric chemistry, etc.), requiring a new approach to research. (Source: ESSC 1988)

and wet climates have abundant growth and great diversity of organisms, and vegetation controls the flux of energy back to the atmosphere. Cold northern regions have simpler and less diverse systems but store vast amounts of carbon. The cold waters of the north have productive fisheries but lack the complexity and diversity of tropical reefs. While we observe that climate shapes life on the planet, great mysteries remain about how life responds to climate.

The living world, in turn, also shapes the physical and chemical Earth System. The composition of the atmosphere reflects the chemistry of life and is far from the chemical equilibrium that would obtain without the oxygen released by plant and microbial photosynthesis, the nitrogen converted by microorganisms into the forms that help warm our planet, and the water mined by trees from soils and released back into the atmosphere to cool the planet's surface.

The interaction of climate and life has been a scientific topic for centuries and an especially vibrant field of research for the past few decades. However, as the realization that our planet's climate is inexorably changing has dawned on humanity, understanding the effects of climate on living systems—and how life might affect the climate changes triggered by fossil fuel burning—has become more than an academic curiosity and is now needed to guide adaptation to these changes. Organisms, communities of organisms, and the great planetary biosphere itself respond to environmental change, and these changes affect the services the biosphere provides to humanity. While much is known about how the biosphere interacts with the rest of the Earth System, much remains unknown, This book focuses on how climate-triggered biological changes feed back to the physical and chemical parts of the Earth System across a wide range of timescales.

The scientific study of Earth is broken up into a number of disciplines, including atmospheric science, oceanography, ecology, geology, the natural resource disciplines of forestry and agronomy, hydrology, and—increasingly—the human studies including anthropology, history, economics, and geography. Often, subdisciplines concentrate on certain timescales as well, with paleoclimatology, paleoecology, and paleooceanography focused on the past. The human disciplines history and archaeology are distinct from studies of the present. You may be taking or teaching a course organized in one of these ways, but understanding climate and ecosystems and studying the Earth System draws on and unifies these approaches. This book is grounded in biology but draws on all these related approaches to studying our planet. The nexus of these different approaches is an emergent and coherent body of thought, sometimes called Earth System Science, and this book is written from that perspective.