CHAPTER 1
Introduction

While our understanding of life at the molecular level is rapidly expanding, we understand remarkably little of the mechanisms that determine major transitions in societies or that regulate the stability and resilience of the climate and ecosystems such as coral reefs, forests, lakes, and oceans. Human population growth and development invokes a gradual but profound global change that has many faces. Atmospheric CO_2 levels rise steadily, concentrations of nutrients and toxic chemicals in lakes and rivers increase, groundwater levels drop, harvest rates from the ocean increase, and forests become increasingly fragmented. It is usually assumed that the response to such an incremental alteration of our planet will be gradual, predictable, and reversible. However, remarkably abrupt changes are occasionally observed in nature and society. Outbreaks of pests or pathogens and semiperiodic bursts of populations of rodents and other animals occasionally jump out of the blur. On a larger scale, the Earth system has evidently gone through rapid transitions between contrasting climatic conditions in the past, and it seems unlikely that similarly dramatic climate shifts would not happen in the future. And last, social systems are notorious for periods of relative inertia with occasional rapid transitions on scales varying from locally held opinions and attitudes to massive shifts such as the collapse of states and civilizations. In this book, I argue that such remarkable shifts can often be explained as so-called *critical transitions*. Just as a ship can become unstable if too much cargo is loaded on the deck, complex systems

ranging from the climate to ecosystems and society can slowly lose resilience until even a minor perturbation can push them over a tipping point. While some critical transitions can play havoc on society, others represent escapes from undesirable situations. Understanding such transitions can open up surprising new ways of managing change. For instance, microcredit in the form of a small loan can allow a family to escape for good from the poverty trap, and a one-time intensive fishing effort can flip some lakes from a turbid condition to a stable clear state.

As an introduction to the theme of critical transitions, let us look at a few examples of surprising shifts. Although the causes of some of these shifts are quite well understood, others are still puzzling scientists.

1.1 Coral Reef Collapse

Caribbean coral reefs may be among the best-studied marine habitats. For decades, scientists of well-qualified research groups analyzed the structure and functioning of the reef communities. The reefs were thought to be resilient ecosystems. Incidentally, conspicuous changes, such as bleaching events and colonization of damaged sites by algae, were observed, but the reefs always recovered rapidly from such disturbances. Even when hurricane Allen caused extensive damage in 1980, the system recovered. There was a short-lived algal bloom, but within a few months, the algae disappeared and coral recruitment started filling up the open spaces created by the hurricane.

A few years later, however, a dramatic shift in the reefs took the research community by surprise and showed that it was time for a serious revision of the ideas about reef stability.[1] A species-specific pathogen caused mass mortality of the sea urchin *Diadema antillarum* with far-reaching consequences. The magnitude and impact of this event are well illustrated by the changes documented on Jamaican reefs (figure 1.1). Urchin densities crashed to 1% of their original level, and this triggered a complete change in the reef community. Rapidly the reefs became overgrown by brown fleshy algae that were now freed from grazing by urchins, and the entire community of the reefs changed profoundly. The apparent dependence of the system on

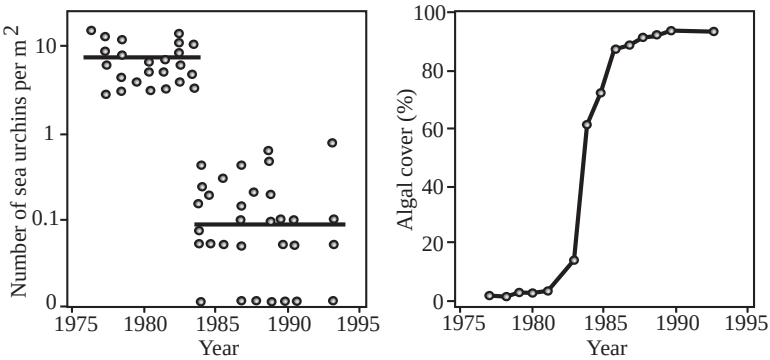

FIGURE 1.1. The Caribbean coral regime shift illustrated by changes on Jamaican reefs. (a) Collapse of populations of the sea urchin *Diadema antillarum* resulting from a pathogen outbreak. (b) Resulting increase in macro-algal cover at 7 m depth. (Modified from Hughes; see reference 1.)

a single species and the suddenness of the massive shift in the ecosystem were a surprise, but equally remarkable is the lack of recovery over most of the reefs until today.

1.2 The Birth of the Sahara Desert

A similarly striking *regime shift* seems to have happened on a very different timescale in the Sahel–Sahara region. It is difficult to imagine now that the Western Sahara has long been a relatively moist area with abundant vegetation and numerous wetlands. Yet this was the situation until about 6,000 years ago. Today, scattered bones of hippopotamus and other animals are reminders of this lush period. The dynamics of the change to the current state have been reconstructed by analyzing the amount of terrigenous dust in core samples of ocean sediments taken from the North African coast (figure 1.2). This sedimentary record suggests that for thousands of years the area was largely vegetated, until a remarkably swift transition to a desert state occurred.[2] Like the collapse of the coral reefs, this apparent desertification is a surprising deviation from what seemed to be the stable state of the system. Before this event, a mild trend existed, but certainly

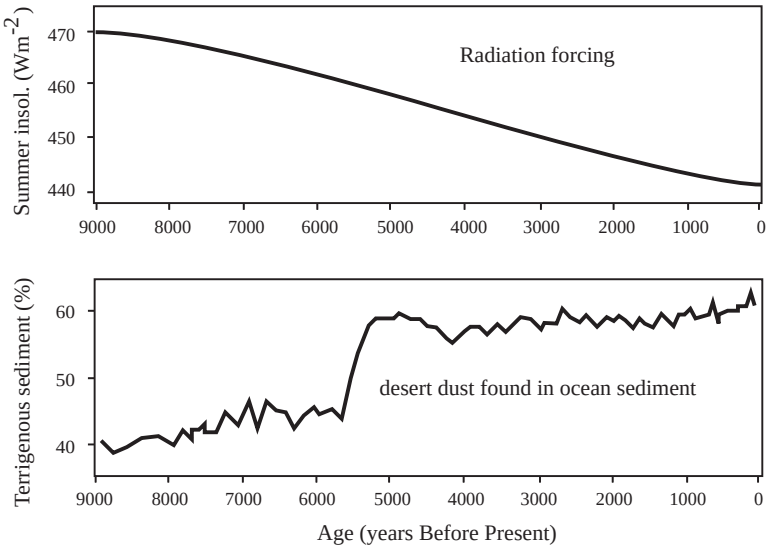

FIGURE 1.2. Over the last 9,000 years, average Northern Hemisphere summer insolation (top panel) has varied gradually because of subtle variation in the Earth's orbit. About 5,000 years ago, this change in solar radiation triggered an abrupt shift in climate and vegetation cover over the Sahara, as reflected in the contribution of terrigenous dust to oceanic sediment at a sample site near the African coast (bottom panel). (Modified from reference 2.)

extrapolating the dynamics over the millennia prior to 6,000 years ago would not suggest such a sudden and irreversible change. Imagine if we were living 6,000 years ago and had to predict the future of the region based on the information collected over the past 3,000 years. Certainly the best guess would have been a continuation of the trend that existed for thousands of years. How could we have foreseen the surprising shift? We now know that the climate change in the region is most likely related to subtle variations in the Earth's orbit, causing a gradual change in ir radiation. However, this external variable changed very smoothly compared to the observed change in the area (figure 1.2). As you will see later, this ancient event is now explained by feedback between the vegetation and the climate system. But each time we unravel the mechanism behind such a transition in the past,

the discovery immediately raises the question of whether similar events might happen again in the future and how we can predict or prevent that.

1.3 Shifts in Societies

Although this book is largely about shifts in nature, similar phenomena in human societies are too obvious to neglect. Stock market crashes are striking examples of unexpected sudden change. Also, the dynamics of public attitudes to certain problems is characterized by incidental massive shifts. Obviously, understanding such dynamics is important for politicians and anyone wanting to sell products or ideas. The book *The Tipping Point* by Malcolm Gladwell gives a persuasive account of social traps and shifts from that perspective.[3] Among the most dramatic societal shifts are collapses of nations into a state of anarchy and violence. From Rwanda and Somalia to Afghanistan and Bosnia, meltdown of governments has led to the displacement and deaths of millions of people. Having a clear image of what causes such state collapses and how they could be predicted would be invaluable. Indeed, the CIA has financed a multimillion dollar project to work on such questions.[4]

Looking further back in history, the dramatic demise of ancient cultures is one of the most persistent mysteries in the history of humankind.[5] It is puzzling that societies reaching such high levels of development disappeared so suddenly. Surely the people did not vanish altogether, but what remained was a society that left few archeological records.[6] Many explanations have been proposed for collapses of ancient societies, varying from depletion of vital resources to invasions of barbarians and catastrophes such as earthquakes, climate shifts, and floods. But this does not explain an interesting pattern that seems to underlie all of these cases. As Thor Heyerdahl put it, "The larger the pyramids and temples and statues they built in honor of their god or themselves, the harder was the fall."[7] Indeed, although adverse events may have triggered many of history's most well-known societal crashes, it appears as if complex, elaborate societies building impressive structures have been particularly prone to collapse. This

suggests that the key to explaining ancient societal collapses may be found not only in external forces but also in the gradually increasing fragility of these elaborate societies.[8]

1.4 Content of this Book

As the rest of this book will show, these examples are just the tip of an iceberg. Reconstructions of shifts such as the ones in climate and societies that happened long ago are necessarily uncertain, and some may be even be artifacts of the way traces were preserved. In contrast, recent major changes that happen before our eyes are often quite well documented. Taken together, the evidence is overwhelming that sudden shifts to a contrasting state appear to occur from time to time in a wide range of systems. The term *regime shift* is often used to describe such radical changes.[9] Regime shifts seem often triggered by a major external impact. For instance, droughts, earthquakes, and floods hit ancient societies, and a disease outbreak led the Caribbean coral reefs to shift to an algal-dominated state. However, such disturbances may not always be the complete story. A much trickier aspect is that systems may gradually become increasingly fragile to the point that even a minor perturbation can trigger a drastic change toward another state. I will call such changes *critical transitions*. This book is about understanding, predicting, and avoiding or promoting such transitions in ecosystems, the climate, and societies. You might think it a bit sensational to address such overwhelmingly large phenomena. After all, radical turnover is the exception rather than the rule in most systems. However, there are two very good reasons why a focus on big, surprising dynamics makes sense: First, radical changes may be rare, but they are undeniably of crucial importance to society. Second, as you will see in this book, big eye-catching shifts are often driven by simple, identifiable dominant mechanisms. Therefore, these shifts are not only important, but also often more easily understood than the myriad of details.

This book consists of three parts. I start with an explanation of the basics of the theory of such forms of change. Subsequently, I review examples, and then I discuss how we might use our insight into the

mechanisms of critical transitions from a practical point of view. This is what the three parts have to offer:

- **Part I** is a mini-guide to the theory of dynamical systems for people who have no affinity for math but who nonetheless enjoy a bit of abstract thinking. Dynamical systems theory is a powerful way of describing the essence of how any system, from a mix of chemicals to populations of organisms, the climate, or the solar system might behave. This theory is highly abstract, however. Rather than referring to any particular part of the world, it addresses what seems to be another world: a mathematical world of strange *attractors*, *catastrophe folds*, and *metastable states*, where *torus* destruction and *homoclinic bifurcations* are everyday events. So disparate is the language and notation in this discipline that it is difficult to imagine that it has any connection to reality as we know it. Nonetheless, underlying structures of the real world show up in the mirror world of math with a beautiful clarity that can never be seen in reality. This is not to say that the abstract models really explain anything. They simply hint at classes of mechanisms that may explain certain dynamics. Thus, dynamical systems theory goes only so far The challenge is in pursuing these hints further to obtain a true understanding of forces that drive big changes in the real world. The final sections in Part I look at ways of bridging this gap and also give an overview of more informal, intuitive theories such as the idea that systems go through adaptive cycles of change. Although I am quite passionate about dynamical systems theory, I have tried to keep this introduction to the theory as basic as possible, and have even confined all the relevant equations to the appendix. Nonetheless, if you are easily overwhelmed by abstract concepts, you can jump directly to the case studies and read pieces of the theory chapter later as background.
- **Part II** consists of case studies and is a good place to start reading if your interests are more practical. This part gives examples of major transitions and oscillations in ecosystems, evolution, the climate, and societies, explaining little pieces of theory along the way. It becomes immediately obvious here that while essentially

similar phenomena occur across this broad range of complex systems, our understanding is much better for some phenomena than for others. I start this part with lakes, not because these are the most important systems, but because they can be relatively well understood and may serve as a model for more difficult systems such as the climate, the ocean, and societies. In fact, the classic article "The Lake as a Microcosm"[10] took this perspective, although it is now considered "merely" the start of the science of ecology. Evolution, the climate system, and human societies are at the other end of the range, in the sense that their dynamics are extremely difficult to understand and predict.

- **Part III** takes the practical perspective of how we can make good use of our insights in the phenomenon of critical transitions. How can we see transitions coming? How can we prevent bad transitions or promote good ones? Why are societies having difficulties in dealing with transitions, and how could we do better?

While the scope of this book is ambitious, I believe that the time is ripe to make headway in understanding the dynamics of the vast and complex dynamical systems that we live in. We have been good at unraveling how things work at a molecular level, but that is not enough. Few would deny that major changes are to be expected in ecosystems, climate, and society over the next century. We are in charge, but we need good science to help us shape the future in the best way—science that helps in understanding and managing the dynamics not only of chemical reaction vessels, but also of oceans, forests, climate, and society. As you will see, essentially the same kinds of mechanisms govern major transitions in such systems. However, it is striking how different the approach is between the branches of science. E. O. Wilson has argued that there should really be one approach to science covering everything from the atoms to the arts, and I would consider this book worth the effort if it contributes to the construction of such "consilience."