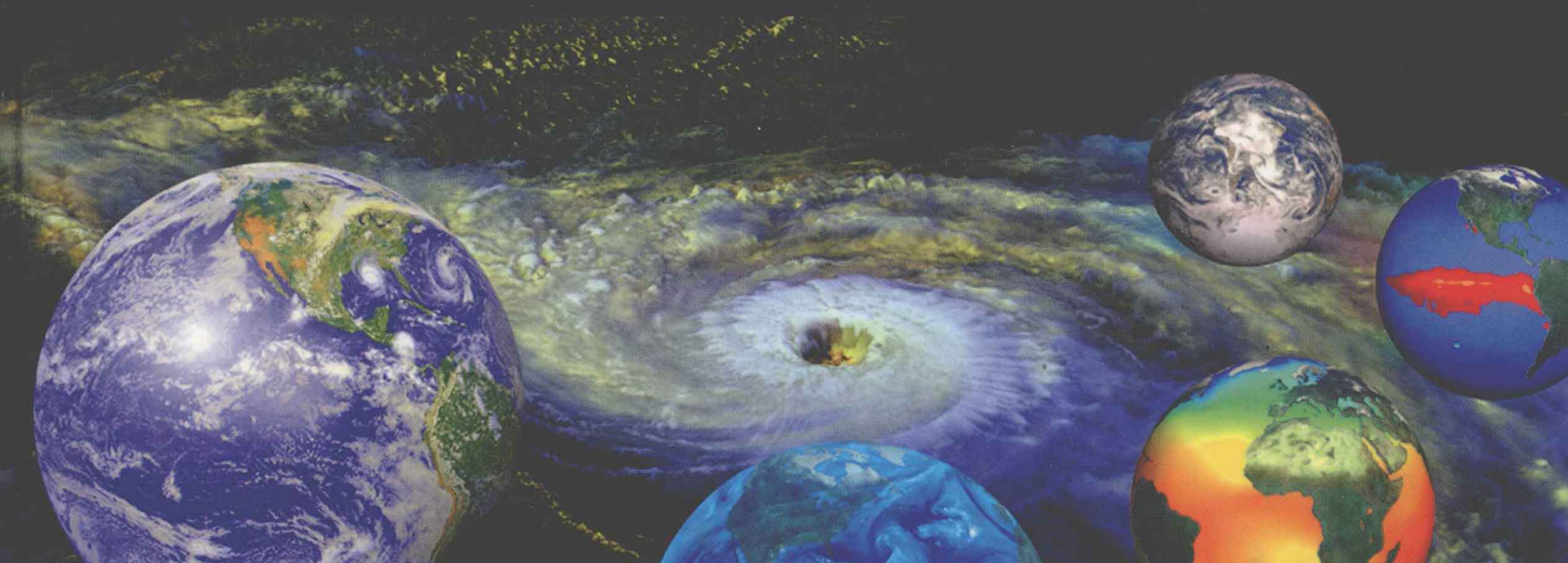
Earth Systems

PROCESSES AND ISSUES



Edited by W. G. Ernst

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Earth Systems

Earth Systems: Processes and Issues is the ideal textbook for introductory courses in Earth systems science and environmental science. Integrating the principles of the natural sciences, engineering, and economics as they pertain to the global environment, it explains the complex couplings and feedback mechanisms linking the geosphere, biosphere, hydrosphere, and atmosphere.

An impressive group of internationally respected researchers and lecturers have collaborated to produce this fully integrated environmental textbook. They bring together a vast wealth of teaching experience to cover the necessary breadth of the physical and life sciences, melded with environmental economics and legislation. This book's truly unique contribution lies in the interweaving of these topics with engineering environmental systems, regional case studies, and the economic implications of environmental policy decisions.

The textbook has been designed for the wide range of courses at the first-year university level that touch upon environmental issues: for example, Earth and atmospheric science, oceanography, biologic science, geography, civil engineering, environmental law, political science, and environmental economics. Each chapter includes a reading list of some of the most important references, and follow-on questions will encourage students to explore the subject further.

This text will favorably influence the future development of environmental studies and Earth systems science.

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W. G. Ernst is currently a professor in the Department of Geological and Environmental Sciences at Stanford University. He is the author of 6 books and research memoirs, editor of 11 research volumes, and author of more than 175 scientific papers.

Preface

This introductory text integrates principles of the physical sciences, engineering, and economics as they pertain to the global environment. The complex couplings and feedback mechanisms linking the geosphere, biosphere, hydrosphere, and atmosphere are analyzed by more than a score of authors who carry out nationally visible investigations in the fundamental disciplines, and who collaborate across field boundaries in both their research and teaching.

The subject matter has been addressed over the past five years (and is continuing) for an elementary course at Stanford entitled *Introduction to Earth Systems*. The philosophy of presentation is problem-focused, not discipline-focused. Topics have been developed by a team of lecturers who have attempted to provide a seamless integration spanning the traditional subjects of the natural sciences, engineering, and the social sciences. These lecturers include most of the contributors to this text.

This book is unusual in terms of the breadth of its physical and life sciences content; its truly unique aspects, however, lie in the interweaving of these topics with engineering environmental systems, case studies, and the economic implications of environmental public policy decisions. To achieve a relatively continuous gradation and smooth passage through the remarkably broad range of subjects, the editor and his editorial colleagues at Cambridge University Press, Catherine Flack, Tigger Posey, and Lisa Albers, have provided cross-referencing and uniformity of style and content level among the various chapters. In addition, contributors have had access to preliminary drafts of the entire manuscript for review, enabling them to cross-link subjects and areas, thereby enriching both their own contributions and those of the other authors.

The rationale for this fruitful synthesis, involving the melding of disparate disciplines, involves a nontraditional approach to the quantitative understanding of interactive global environmental phenomena and more effective Earth systems problem solving. The target audience is college/university undergraduates. *Earth Systems: Processes and Issues* is an introductory text that assumes a readership familiar with the principles of elementary chemistry and college mathematics. It attempts to provide a high-level but predominantly qualitative rather than quantitative treatment of global environmental subjects. Detailed sections and topical examples are placed in boxes so that interested students can gain in-depth understanding and the more general reader will not be deterred by the complexities. Individual chapters include an introductory box: For chapters on scientific and technologic subjects, this introduction serves as a brief preview of the societal implications; for chapters on policy issues, the introductory statement summarizes the scientific and/or technologic foundation of the problem. Short lists of pertinent references for further reading and questions posed at the end of each chapter encourage the interested reader to explore the subject in greater detail. A glossary is included at the end of the text.

What is abundantly clear from even a casual reading of this book is that the Earth's biosphere is increasingly under siege. A burgeoning human population, driven by hunger, procreativity, and an intense urge to survive, and aided by ever more invasive, efficient technologies, is altering the interconnected planetary ecosystems through a wide range of processes – both obvious and subtle. Impacts include pollution of the global atmosphere, the oceans, lakes, rivers, and groundwaters, the loss of fertile topsoils, habitats, and biodiversity. Increasing desertification and deforestation, and the exhaustion of fisheries, fossil energy deposits, and mineral resources are some of the oncoming results. In aggregate, the thirty-three chapters of *Earth Systems: Processes and Issues* constitute a worldwide wake-up call to constituencies and policy makers of all socioeconomic sectors and political persuasions. The need for conservation, human population management, and wise utilization of the environment requires action at both local and global levels. As this text demonstrates, current human practices are borrowing substantially from the future sustainable carrying capacity of the planet. The time for effective action is short, indeed – and failure to act will only exacerbate the ongoing environmental degradation. The generation for which this book is intended will decide the fate of the Earth's biosphere, one way or the other.

W. G. Ernst, editor, Stanford University, 1998

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I

INTRODUCTION

THE EARTH AS A SYSTEM

1 Why Study Earth Systems Science?

STEPHEN H. SCHNEIDER

THE GREENHOUSE EFFECT: FACT OR MEDIA HYPE?

Is the so-called greenhouse effect a fact or a controversial hypothesis? As a climatologist, I am reminded of a headline I saw in the *New York Times* in early 1989: "U.S. Data Since 1895 Fail to Show Warming Trend." I must have had fifty phone calls to my office the day after that story came out, asking, "What happened to global warming?" One week later, after a new global average set of thermometer readings were put together, the very same *New York Times* reporter wrote another front-page article, this time stating "Global Warming for 1988 Was Found to Set a Record." Taken together, these two stories caused a lot of confusion. How could there be record warmth globally when the lower forty-eight states didn't warm much? Was there a greenhouse effect or not? What was going on? In fact, the reconciliation of the two stories was quite simple. It is important to place these headlines in perspective, recognizing that the lower forty-eight states constitute only 2 percent of the Earth's surface area. There is not a very high probability of getting the correct temperature of the whole globe by looking at just 2 percent of it. In fact, if you had looked at temperatures for Alaska or for central Eurasia in that same period and tried to make a statement about global temperatures based upon those data, you would have thought that the Earth had warmed up 1.5°C in that same period. Meanwhile, the North Atlantic region cooled 0.5°C or so in the same period.

The conclusion we can draw from a comparison of timely news articles like these is that the global warming problem, to take one example, is indeed global. Often, but not always, that means that what happens in our own backyard in the time frame of our recent experience may be irrelevant to the problems of the following century. A core lesson in Earth systems science teaches that the word "global" means that the experiences we have in our neighborhood (geographic or intellectual) may be instructive about a single component of global issues, but that we can't automatically extrapolate local experience to learn how the interconnected global systems work, let alone make a credible forecast of global changes over the long term. To make such sweeping statements with any authority, we need to look across various scales and disciplines at interconnected systems. Then we need to validate our concepts of global systems, often by going back in time or to local scales to check our global ideas.

The greenhouse effect is a scientific fact. Controversy over this issue arises primarily in discussions of whether humans will make a significant impact and what to do about it. Without good science as a basis for answering important questions such as what can happen, what are the potential consequences, and how likely are these outcomes, we cannot hope to answer authoritatively or confidently the question of what to do. This book gives the student a solid introduction to several crucial scientific disciplines so that he or she may know what questions to ask of the various disciplinarians in order to find both good data and a good solution to today's complex environmental problems.

Earth systems science tries to find solutions for real, global environmental problems at the times and places that they exist. These topics cannot be addressed comprehensively by looking through the limited lens of only one of the traditional disciplines established in academia, such as biology, chemistry, engineering, or economics. We certainly can't solve most global problems without the detailed information that those disciplines provide, but the study of Earth systems science suggests that we also need to find appropriate ways to *integrate* high-quality disciplinary work from several fields. Although scholars from various disciplines may study the Earth locally – in a tax district, a volcano, a thunderstorm, a patch of forest, or a test tube – Earth systems scientists put the accent on "systems," the multiscale interactions of all these small-scale phenomena.

This introductory chapter is designed to give the reader a quick sketch of the excitement and urgency of this global-scale, systems-oriented approach to environmental science, technology, and policy problems. Our challenge is to be creative in doing something both new and necessary: to put together sets of expertise from various academic disciplines in original ways that will improve our understanding of both nature and humanity. Some will express concern over this approach, feeling that without in-depth content in each disciplinary subcomponent, our systems analyses will be shallow. Without the context of real problems, however, discipli-

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nary specialists will lack the information necessary to solve pressing issues. From the perspective of Earth systems scientists, it is not sensible to debate whether it is worse to lose *context* by approaching real problems in depth, from the narrow purview of one area, or to lose *content* by integrating information across disciplines without studying any of the interrelated subfields in adequate depth. Both context and content are necessary. We need to blend them to a considerable extent, using context to help guide the selection of appropriate content areas. Although practical considerations will, of course, prevent budding Earth systems scientists from studying all relevant fields in tremendous depth, this text gives a solid foundation in the disciplinary sciences necessary to enable the student to engage in future interdisciplinary environmental pursuits, and to choose which content areas to explore more fully in the future.

THE SCALE OF EARTH PROCESSES

At what spatial scale do you think of the Earth's atmosphere as functioning? Think about one of the famous photographs taken from space by astronauts: You can probably visualize white clouds swirling around the blue globe, with the spiral patterns of storms standing out at 1000-kilometer scales. However, if your vantage point were from an airplane during a turbulent flight, you might think of atmospheric action taking place on a scale measurable in tens of meters. A balloonist who is able to see individual rain droplets or snowflakes drift by might conclude that atmospheric action takes place at the microscale of millimeters. Of course, these observations are all "correct," but knowledge of cloud microphysics in great detail does not by itself provide the context for understanding the large-scale atmospheric dynamics visible from space. As mathematical ecologist Simon Levin once put it, the world looks very different depending on the size of the window we are looking through.

Nature has amazing richness across the range of spatial and temporal scales at which processes and their interactions occur. You know from your own experience that winds blow and oceans move, but those aren't the only natural forces that are dynamic. Our "solid" Earth is not solid, if we define "solid" to mean forever immoveable in space and time. In fact, the Earth itself moves about in response to natural forces (see Chap. 6). The drift of continents, as we'll learn later, can have a major influence on both climate and life. Except for local phenonema such as earthquakes, landslides, and mountain glaciers, the time frame for major continent-scale Earth motions is thousands to millions of years. How the "solid" Earth interacts with air, water, and life is essential for understanding the Earth as a system, as knowledge of how and why the Earth system changes over geologic time allows us to calibrate our tools needed to forecast global changes.

Studying these phenomena at all relevant scales is no small task. In order to gain a good working knowledge of the Earth and its processes, we need to understand the interaction not only between systems but also between and among the various scales of activity of the many systems. Will a change in a small-scale biological community, such as the extinction of a species of termite, have any effect upon nutrient cycling, upon emissions of greenhouse gases from the soil, and ultimately upon global-scale weather patterns? At what point will nitrogen fertilizer used in agriculture create sufficient amounts of nitrous oxide emissions to warm the climate or deplete stratospheric ozone? At a global scale, nature exists nearly in a state of balance. Parts are constantly changing, while the whole continues to function as if in near equilibrium. If humans push too many parts out of balance, what will happen to the whole? How much resilience is there in each part at various scales? These are the kinds of questions that Earth systems science must address.

LOCAL VARIABILITY AND GLOBAL CHANGE

Earth systems science focuses on an issue called "global change," a phrase invented by people who study the Earth as a system to refer to the changes on a global scale (or regional changes that are repeated around the globe) that occur to those Earth systems (which could be physical, biologic, and/or social) that are interconnected and that humans have some component in forcing. Why then, you might ask, study continental drift as part of global change if humans are not able to influence the course of continental drift? If we don't understand how drifting continents affect the gases in the atmosphere, the climate, or biologic evolution, then we're not going to have the background knowledge necessary to forecast so-called global change, even though global change is driven in part by human disturbances such as deforestation and air pollution. In this textbook we explore traditional disciplines such as geology, atmospheric science, biology, technology, chemistry, agronomy, and economics. We also explore how humans are disturbing various components of the system. In the chapters that follow, we consider a number of questions:

- How does the entire system work?
- How does it work as a coupled set of subsystems?
- How are humans disturbing the system?
- What have we learned from how the system works that can help us forecast how human disturbances might play themselves out?
- What could – or should – we do about the information we collect?

Several years ago, I traveled to the picturesque town of Argentiere in the French Alps, a trip that demonstrated the dramatic changes that can occur in a short time, geologically speaking. I went there to see a famous glacier that was located far above the town. I took photographs of the glacier, framed against a local church steeple. It is a stunning sight, made all the more impressive when compared with an 1855 etching that pictures the glacier on the very outskirts of the town, as if it were about to devour the town. The more recent photographs show the glacier at some distance from the town, quite a distance up the mountains in the background. What accounts for this dramatic retreat in the century after 1855? One hundred and fifty years ago, the global climate was colder than it is today – about 1°C colder. The warming trend over the past century and a half is correlated with a major response in that glacier. A one-degree change may sound trivial, but if it is a sustained change, then it can have an identifiable impact, particularly on sensitive indicators such as mountain glaciers – most of which have been retreating during the twentieth century.

Small changes can add up to create large ones. For example, a number of years ago a satellite photograph of Israel was taken with a near-infrared wavelength device that showed the boundary between the Israeli Negev, the Egyptian Sinai, and the Gaza Strip, an unnatural, political boundary. Why, then, does it appear in photographs as a physical boundary? The line was visible because there were animal herds grazing more heavily on one side of the border fence, and the vegetation and soils there had been deeply disturbed. That changed the reflectivity of the surface to sunlight, which, in turn, alters the amount of sunlight absorbed, which, in turn, is the primary driving force behind the weather. The climate of the Earth – the natural climate – works from a balance between the amount of absorbed solar energy and the amount of outgoing, so-called infrared radiative energy. The key is, if we can "see" a political boundary as a physical line, then the Sun can "see" it, too. If the Sun can see it, that changes the amount of solar energy absorbed. If humans can change the amount of solar energy absorbed, they can affect the climate.

These simple examples demonstrate that the repeated patterns of local and regional changes that are taking place are significant. The sum of thousands of local to regional changes in the land surface can disrupt transcontinental migration patterns of birds and might have some influence on the overall climate at a larger scale, as well. The climate changes then influence agricultural activity, water supplies, and ecosystems locally.

Another example of local landscape damage is located in the American Great Plains region. A typical aerial view of this region includes perfectly round, dark green circles that mark irrigated fields. This kind of center-pivot irrigation typically uses fossil groundwater at a much faster rate than it can be replenished in the underlying aquifers (i.e., underground natural reservoirs). It is a practice that raises socioeconomic problems – whether it is fair to future generations, for example, for today's farmer to be using up a resource at a nonrenewable rate. The relevant aspect of this example is that we're changing the water balance of the system at the same time that we're changing the brightness of the system (which can affect local rainfall); we're also changing the local habitat for migratory birds that fly between Canada and Mexico – the neotropical migrants – and for waterfowl. Those birds are used to certain kinds of wetlands and certain other forms of habitat at their nesting sites and between there and their wintering grounds. However, when human activities dramatically change habitats, some species thrive and others are endangered. This, then, can create conditions in which extinctions of sensitive species are more likely to take place.

One of the most serious problems of global change connected to Earth systems science is the combined effect of habitat fragmentation and climate change. When climate changes, individual species adjust if they can, as they have in the past. Typically, they move with changing climate; for example, when the last ice age ended some 10,000 years ago, spruce trees moved from their ice age locations in the U.S. mid-Atlantic region to their current location as the northerly Boreal forests of Canada. What would happen if climate changed comparably today and the affected plant and animal species had to move again? Could flora and fauna successfully migrate across freeways, agricultural zones, and cities? The combination of habitat fragmentation and climate change makes it much more difficult for natural communities to adjust. This, in turn, sets up a potentially enormous management problem. Do we have to set aside nature reserves in interconnected areas and not simply isolated reserves and parks? If so, whose farms or houses or fields do we take away in order to create these reserves? How do we deal with risks to wildlife from highways? Do we spend money to create bypasses or elevated sections so that migration routes can be maintained? How much is it worth to protect the survival of a species or a habitat? Although these are essentially value choices, good science is necessary to help answer how such biologic conservation practices can take place in the most economically efficient way. Global change science involves looking at these kinds of questions. To answer them, we go to the various academic disciplines to ask, "What knowledge do you have?" In particular, we ask, "What can happen?" and "What are the odds it might happen?" The Earth systems scientist tries to integrate the information from many disciplines in order to address real problems.

THE BALANCING ACT: WEIGHING LOCAL AND GLOBAL NEEDS

In this discussion about environmental protection, we begin with global-scale causes of environmental degradation. This degradation is most often ascribed to increasing numbers of people striving for higher standards of living and using technologies or practices that often pollute or fragment the landscape. However, when one abandons the global or even the national perspective and looks instead at local environmental problems, these three multiplicative macroscale causes – population times per capita affluence times technology used – may not be easily seen. Corrupt officials, unaccountable industries, poverty, lack of appropriate labor force, or simple ignorance of less environmentally deleterious alternatives stand out as prime causes of local environmental degradation. These problems intersect at large scales with the demands for increasing use of land and resources from burgeoning populations seeking to improve their living standards and willing to use the cheapest available technologies toward that goal.

There is an equity issue involved in these dilemmas: Desire for economic progress today may create environmental problems for later generations or downstream neighbors, neither of which participate in the immediate decision making. We need to find solutions that do not treat nature as a nonrenewable resource for the benefit of a few today at the expense of many later – the problem known as "intergenerational equity." Also, some nations are economically better off than others. The desire for more equality often motivates low-cost development plans (burning unclean coal, for example) that can threaten massive environmental disruptions (global warming or health-damaging smog). This sort of "environment – development" tradeoff issue will lead to major debates in the decades ahead.

On the East Coast of the United States, from Boston to New York to Washington, the amount of heat being released from all the energy uses that take place is approximately 1 percent of the incident energy from the Sun. Did you ever hear a weather forecast for Manhattan that sounded something like: "Tonight it is going to be twenty-five degrees Fahrenheit in the city, and twelve in the suburbs"? Ever wonder why it is so much warmer in the city? The answer is that there is literally a "sun" on at night, heating the city – or, at least, the energy equivalent of a winter's sunny day. The so-called urban heat island effect tells us that if we release energy comparable to a few percent or more of that which arrives from the Sun, we're going to change the climate locally. That effect is important even though, at a global scale, the total amount of heat generated by human activities is a tiny percentage of the Earth's heat budget. The key is that the combination of energy use and all other human modifications to the land, water, and air is already regionally significant – and also very inequitably distributed – and rapidly is becoming global in scope.

If we look at the Earth over the past 30,000 years, we find that up until approximately 15,000 years ago ice sheets several kilometers thick covered most of Canada, and it was only 6000 years ago that the last remnants of ice disappeared over Hudson's Bay. What happened when all that ice that was over land melted? Sea level rose by more than 100 meters, the globally averaged climate warmed up approximately 5°C, whole habitats were reconfigured, and species became extinct – all this was a natural change. Although there were regional and short-term changes that were rapid, the sustained, globally averaged rates at which nature caused ice ages to melt into the warm 10,000-year period of relatively stable climate that saw human civilization develop was on the order of 1°C per 1000 years.

If we go back approximately 150,000 years, we find a comparable cycle of temperature changes, as well as changes in concentrations of methane gas (CH_4) and carbon dioxide (CO_2) in the atmosphere. In Antarctica 125,000 years ago, that continent was approximately 2°C warmer on average than at present. Then, the temperature dropped (Fig. 1.1), fluctuated, and finally became extremely cold some 30,000 years ago. The last ice age peaked approximately 20,000 years ago. It took more than 10,000 years for the ice age to end; since then we've been in a 10,000-year so-called interglacial, the Holocene Epoch, during which temperatures have been within a degree or two of present temperatures (see Chap. 3). During this time, two gases changed their atmospheric concentrations in fairly close correlation to the temperature changes. These gases are very important climatically because they trap heat near the Earth's surface and are partly responsible for the so-called greenhouse effect. There is a strong correlation between methane gas (which is produced in nature by the anerobic decomposition of organic matter) and carbon dioxide: an approximate factor of 2 difference between the ice age and the interglacial methane, (CH_4), and a difference of approximately 30 to 40 percent CO_2 in the ice age and the interglacial. Simply put, lower concentrations of these so-called greenhouses gases occur when it is cold, and higher concentrations occur when it is warm. These fluctuations over time were all the work of nature.

Figure 1.1 shows that carbon dioxide concentrations of

Figure 1.1. Air bubbles trapped in ancient polar ice sheets can be analyzed to determine the changing composition of the atmosphere over hundreds of thousands of years. Such analyses at Vostok in Antarctica show that carbon dioxide (CO_2) concentrations were approximately 25 to 30 percent lower in glacial times than an interglacial periods over the past 160,000 years. Local temperatures (in Antarctica) at the extreme glacial times (approximately 20,000 and 150,000 years ago) were approximately 10°C (18°F) colder than at interglacial times. kyr BP = kiloyear (1000 years) before present; ppm = parts per million. (*Source*: Adapted with permission from J. M. Barnola, D. Raynaud, Y. S. Korotkevich, and C. Lorius, Vostok ice core provides 160,000-year record of atmospheric CO_2, *Nature*, Copyright © 1987.)