Earth Systems

PROCESSES AND ISSUES

Edited by

W. G. ERNST

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http: //www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http: //www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain

First published 2000

Printed in the United States of America

Typefaces Stone Serif 8.5/12 pt., Eurostile Demibold, and Optima *System* DeskTopPro/UX® [BV]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging-in-Publication Data
Earth systems : processes and issues / edited by W.G. Ernst.
p. cm.
ISBN 0 521 47323 3 (hardbound)
1. Earth sciences. I. Ernst, W. G. (Wallace Gary), 1931– .
QE28.E137 1999
550–dc21 98-37539
CIP

Source for title page photograph: Courtesy of United States Geological Survey.

ISBN 0 521 47323 3 hardback
ISBN 0 521 47895 2 paperback

Contents

Preface — *page* vii
List of Contributors — ix

PART I. INTRODUCTION

THE EARTH AS A SYSTEM

1 **Why Study Earth Systems Science?** — 5
STEPHEN H. SCHNEIDER

2 **Physical Geography** — 13
DONALD KENNEDY

3 **Time Scales: Geologic, Biologic, and Political** — 26
W. G. ERNST

PART II. NATURAL PROCESSES

THE GEOSPHERE

4 **The Earth's Place in the Solar System** — 45
W. G. ERNST

5 **Earth Materials, and the Internal Constitution of the Planet** — 59
W. G. ERNST

6 **Drifting Continents, Sea-floor Spreading, and Plate Tectonics** — 81
W. G. ERNST

7 **Fluvial Landforms: The Surface of the Earth** — 102
KEITH LOAGUE

8 **Chemical Weathering and Soils: Interface between the Geosphere, Hydrosphere, Atmosphere, and Biosphere** — 119
MARK J. JOHNSSON

THE HYDROSPHERE

9 **The Hydrologic Cycle** — 135
PATRICIA A. MAURICE

10 **Atmosphere–Ocean Coupling and Surface Circulation of the Ocean** — 152
JAMES C. INGLE, JR.

11 **Deep-Sea and Global Ocean Circulation** — 169
JAMES C. INGLE, JR.

12 **Chemical Oceanography** — 182
PETER G. BREWER

THE ATMOSPHERE

13 **Atmosphere Composition, Mixing, and Ozone Destruction** — 197
ROBERT CHATFIELD

14 **Atmosphere Motions and the Greenhouse Effect** — 215
ROBERT CHATFIELD

15 Can We Forecast Climate Future without Knowing Climate Past? 230
STEPHEN H. SCHNEIDER

16 Can We Predict Climate Change Accurately? 241
STEPHEN H. SCHNEIDER

THE BIOSPHERE

17 Biodiversity: Result of Speciation and Extinction 255
CAROL L. BOGGS AND JOAN ROUGHGARDEN

18 Evolution: Adaptation and Environmental Change 267
CAROL L. BOGGS AND JOAN ROUGHGARDEN

19 Global Biogeochemical Cycles: Carbon, Sulfur, and Nitrogen 278
ISAAC R. KAPLAN AND JULIE K. BARTLEY

20 Global Change and the Terrestrial Carbon Cycle: The Jasper Ridge CO_2 Experiment 297
CHRISTOPHER B. FIELD AND NONA CHIARIELLO

21 Ecology: Possible Consequences of Rapid Global Change 315
TERRY L. ROOT

PART III. SOCIETAL AND POLICY IMPLICATIONS

RESOURCE USE AND ENVIRONMENTAL TECHNOLOGY

22 Population and the Environment 329
SUSAN E. ALEXANDER AND PAUL R. EHRLICH

23 Mineral Resources: Assets and Liabilities 346
MARCO T. EINAUDI

24 Energy Resources and the Environment 373
JANE WOODWARD, CHRISTOPHER PLACE, AND KATHRYN ARBEIT

25 Natural Hazards: Prediction and Risk 402
W. G. ERNST

SOCIETY, THE ENVIRONMENT, AND PUBLIC POLICY

26 Steps from Environmental Science to Effective Policy 425
LAWRENCE H. GOULDER

27 Confronting the Prospect of Global Climate Change: Carbon Taxes and Other Domestic Policy Options 434
LAWRENCE H. GOULDER

28 Land Use: Global Effects of Local Changes 446
EDWARD A. G. SCHUUR AND PAMELA A. MATSON

29 Agriculture and Global Change 462
ROSAMOND L. NAYLOR

30 Water Allocation and Protection: A United States Case Study 476
BARTON H. THOMPSON, JR.

31 Valuing Nature 492
LAWRENCE H. GOULDER AND DONALD KENNEDY

32 The Life Support System – Toward Earth Sense 506
W. S. FYFE

PART IV. SUMMARY

33 Synthesis of Earth Systems and Global Change 519
W. G. ERNST

Glossary 533
Index 559

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-

W. G. Ernst (ed.), *Earth Systems: Processes and Issues*. Printed in the United States of America.

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 phenomena 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.

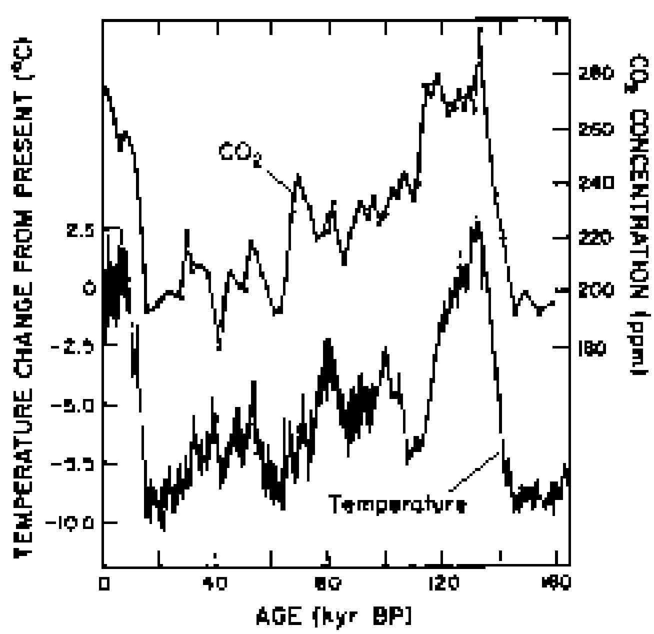
On the East Coast of the United States, from Boston to New York to Washington, the amount of heat being released from all the energy uses that take place is approximately 1 percent of the incident energy from the Sun. Did you ever hear a weather forecast for Manhattan that sounded something like: ''Tonight 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.)



approximately 280 parts per million have remained very stable for the 10,000 years of our current interglacial era. However, as of 1998 that concentration level is at least 370 parts per million, an *un*naturally high number – the result of more people on the planet, demanding higher standards of living, engaging in agriculture, using fossil fuels for energy, developing the land, and cutting down trees. The fact of this global change in atmospheric composition of carbon dioxide is not controversial; is well understood by everyone who has studied the evidence, and humans are almost certainly responsible for it. What is controversial is the consideration of questions such as ''What precisely is it going to do to the environment?'' and ''What can we do about it?''

Many components of Earth systems science are well understood. For example, we can divide the amount of incoming solar energy into percentages and track how much of it reflects from clouds or passes through to the Earth's surface. Likewise, we can track infrared radiative heat from upward emission to downward reradiation by so-called greenhouse gases such as water vapor, carbon dioxide, or methane, all in an effort to explain how the greenhouse effect works (see Chap. 14). That is not controversial, either. What is controversial is how much of the extra heat from such global changes (e.g., the 30 percent increase in carbon dioxide since the Industrial Revolution) will be available to raise surface temperatures directly versus how much will result in increased evaporation, which in turn might change cloudiness, which might reflect away extra sunlight or trap extra infrared radiation. The changes in evaporation or cloudiness, in turn, can ''feedback'' on the amount of energy retained by the climatic system and either accelerate or retard the initial warming from the global carbon dioxide change that would have occurred in the absence of such feedback.

FEEDBACK MECHANISMS AND THE HUMAN ELEMENT

Humans are what physiologists call homeostatic systems. We contain stabilizing, *negative feedback mechanisms*: If we get too hot, we sweat to cool down; if we get too cold we shiver, which is a mechanical way of generating heat. There are lots of feedback processes in the dynamic climatic system as well, some of them stabilizing, and some of them destabilizing. For example, if the Earth warms, some snow and ice will melt. Bright, white, reflective areas are then replaced by green trees, brown fields, or blue oceans, all of which are darker than the snowfields, so they absorb more sunlight. Hence, if the Earth warms and some snow melts, it absorbs more of the incoming sunlight and this feedback process accelerates the warming. That is a *positive feedback*. However, if more water evaporates and makes wider cloud cover that reflects more sunlight back to space, that is a negative feedback. In addition to the climatalogic feedback responses, we have to deal quantitatively with the biologic system. Trees absorb carbon dioxide from the air through photosynthesis – a potential negative feedback on global warming. However, soil bacteria, which decompose dead organic matter into carbon dioxide or methane gas, work faster when it is warm – a potential positive feedback on global warming. We need also to understand the history of biologic evolution in order to identify rates of speciation (forming new species) and extinction that are natural, and causes that are natural. Just as we need to understand the geologic backdrop of ice ages coming and going in order to see how the climate works and thus be able to forecast climate change credibly in the future, we need to have some sense of how biologic evolution works in order to see how land and habitat fragmentation, chemical and pesticide release, climate change, species competition, and the synergisms of all these might impact on ecosystems and how specific species will fare in the future.

Into this mix must be added human science. There are approximately 6 billion people in the world today, with 1 billion living on the margins of nutritional deprivation, and many tens of millions who die every year from preventable illnesses because they are malnourished. These people demand and deserve improved standards of living. However, how they achieve those improved standards of living is critical to the environmental future. Will they develop the way more developed countries did it, using the cheapest available means with little regard for nature until society becomes affluent? Or will currently poorer countries develop and grow economically by using better technology and better organization in less environmentally destructive ways? The answers are going to have a dramatic impact on the future nature of the environment, and on what global change portends. Development is inevitable. The open questions are: ''What kinds of development?'' ''Who pays?'' ''What is the distribution of resources and the distribution of consequences, be they economic, social, or environmental?'' To study this problem we've got to look at the human dimension, which is driven by values, feelings, history, tradition, and, power.

I recall Indonesia in the late 1970s. On a particularly steamy afternoon when I was driven around Jogjakarta by a sweating pedicab driver, I asked him what his dream was, and a one-word answer quickly came back: ''Toyota.'' On my return trip two decades later, nearly all the pedicabs I had seen earlier have now been replaced by Toyotas and the like. The tremendous increase in the number of cars worldwide has resulted in smog-choked cities and millions more tons of carbon dioxide being generated. To some – like most people in now developed nations who take their cars for granted – their proliferation is the price of progress. To others, the increase symbolizes quality of life. At present, most people are, reluctantly or enthusiastically, unwilling to trade cars for less polluting modes of transportation, regardless of the potentially beneficial consequences for the atmosphere. The inevitable consequences of population growth and development by business-as-usual technologies seem to be negative environmental side effects.

The open question isn't ''Should we protect the environment *or* encourage the economy?'' The better question is, simply, ''How can we develop in environmentally sustainable ways?" The answer is that there *are* ways to try to do both, but they are not necessarily the traditional ways of development. To convince people to accept these nontraditional ways can be a "hard sell." It takes hard economics and hard science to describe what is commonly called "environmentally sustainable development." Carbon dioxide is one of the principal greenhouse gases, and it results primarily from burning fossil fuels – coal, oil, and natural gas. Considering the total amount of emissions of carbon dioxide country by country around the world, we find the greatest emissions in the former Soviet Union, China, India, the United States, and Brazil. In India or China, data that might elicit comments such as, "We're not the problem – the over-affluent are the problem." That is because these countries focus on the per capita emissions of carbon dioxide per country, in which developing countries rank low.

To improve the standard of living in many developing countries, those countries need the services provided by more energy. How they acquire it, and what systems they use, is dramatically important. One concept that needs to be considered is "planetary bargaining," trading off rapid population growth or inefficiency or corruption in underdeveloped countries for moderated growth of affluence in developed countries, with the latter largely financing both – at least initially.

One example of planetary bargaining applies Asia and its staple rice crop. Flooded rice paddies produce lots of methane gas. There may be alternative "dry" paddy agricultural techniques that produce less methane gas, but the question is, "Will anybody use those techniques?" What are the tradeoffs in ways to produce the food that is needed to feed people as populations increase, without producing as much extra methane gas? Who will pay to get the process started? These questions form the basis for bargaining between developed and developing countries.

Another example of planetary bargaining concerns deforestation. A tree is made up largely of carbon, which comes from carbon dioxide in the air through photosynthesis. When we cut trees down and burn them, we dump back into the atmosphere all the carbon that it took trees thirty years to take out of the air – in the space of thirty minutes. There is about as much carbon in all the trees on Earth as in the air. However, if we add carbon dioxide to the air, aren't trees going to photosynthesize more and grow faster? Yes, probably, because more carbon dioxide would mean more such "fertilizer." However, other factors are involved. After all, adding carbon dioxide is likely to warm the climate, so overall there could be a negative feedback: Trees are going to take some of the extra carbon dioxide out of the air, holding back some of the warming potential. Is this the end of the feedback story? The amount of carbon in the soils – in dead leaves, dead roots, dead organic matter – is about twice that in trees. Getting carbon from the soil back into the air is the job of trillions upon trillions of microbes that decompose organic material. The rate at which they produce either carbon dioxide or methane depends upon the temperature of the soils. Consequently, if we remove the trees, the soil become hotter, and organic matter is going to decompose faster. Likewise, if carbon dioxide and methane increase global warming, we might experience a positive "biogeochemical feedback."

Based on a host of variables – how many people there will be in the world, how they use land, what kinds of energy systems they'll use, what their standards of living will be, and what the feedback mechanisms are in the physical and biologic systems – Earth systems scientists attempt to project what the climate will be like in the future, often using mathematic models.

FUTURE POSSIBILITIES: THE COMMON LANGUAGE OF COST/BENEFIT ANALYSIS

Global temperatures for the past 100 years exhibit a warming trend of about 0.5°C. This trend is consistent with the 30 percent increase in carbon dioxide and 150 percent increase in methane since preindustrial times, but it is not a large enough temperature trend to rule out the possibility that it is simply an unusual natural warming that occurs perhaps one century out of ten. If we are extremely lucky and the negative feedbacks dominate, or there is a breakthrough in the costs and use of solar energy, or if we are unlucky economically and experience a world economic depression that means little growth in energy use of any kind, the lowest number that most current assessments project for future warming over the next 100 years is approximately another 1°C. That increase may sound trivial; however, the sustained natural global average rate of change between the end of the last ice age and our present interglacial is approximately 1°C per 1000 years. Even the most conservative anthropogenic global change estimate is projected to be approximately five times faster than the natural rate. If the positive feedbacks dominate and the economy booms so that energy use triples, then a warming rate fifty times faster than the sustained natural global averaged rate would be expected, as shown in Figure 1.2.

To see what this warming trend could mean in terms of an impact on the environment, consider the case of a certain cool-climate-adapted squirrel living in a restricted habitat in the American Southwest, restricted perhaps to the uppermost regions of a range of mountains. Even a 0.5°C warming could "lift" the physiologic needs of its habitat a few hundred meters higher. However, if the squirrel's habitat already is at the top of the peak, then for that species of squirrel, a "trivial" change of 0.5°C might mean death – extinction of the entire species, perhaps. If we were unlucky and a change in temperature of 5°C in a century were to occur, that would likely be ecologically catastropic for a large fraction of species on Earth – particularly when combined with habitat fragmentation. It would rearrange species ranges and ecosystems everywhere.

Consider a wildlife reserve, which is an area similar to a national park that is designed to preserve particular species

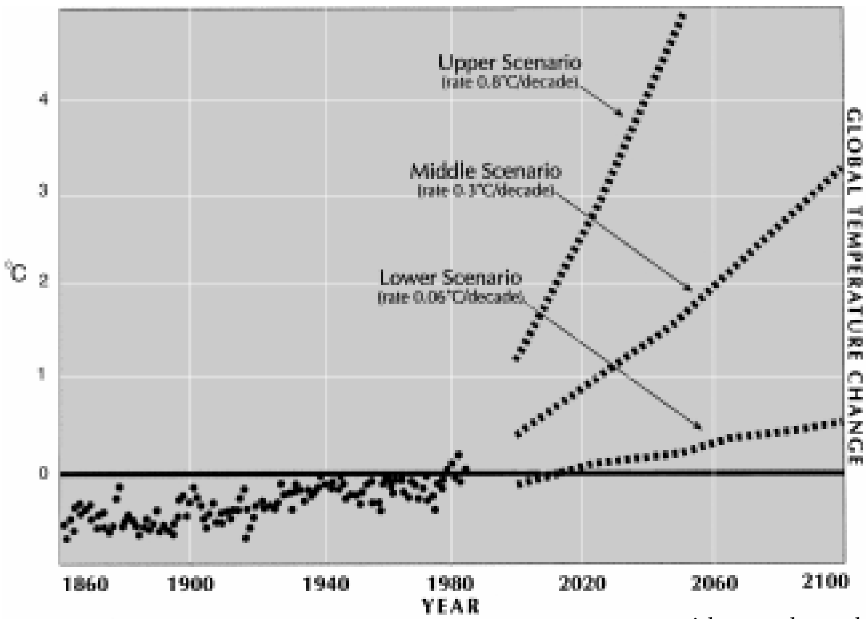


Figure 1.2. Three scenarios for global temperature change to 2100 derived from uncertainties in future trace gas projections combined with those of the biotic and climatic response projections. Sustained global changes beyond 2°C (3.6°F), unprecedented during recent geologic history, represent climatic changes at a pace tens of times faster than the natural average rates of change. (*Source:* Adapted from Stephen Schneider, Degrees of certainty, *Research and Exploration*, 1993.)

and habitats. If we look at range limits of certain trees or birds in a given reserve, they are often there because they cannot exist in other areas (e.g., where it is too hot, or too wet) (see Chap. 21). If the climate were to change suddenly (i.e., within less than 100 years), by +3°C, a new range limit would be established for each species. In a naturally occurring change, a tree would ''march'' its way poleward, with birds spreading its seeds, or by other slower dispersal mechanisms, depending on particulars, if the climate change were slow enough. What happens if the climate change is occurring at 10 to 100 times the sustained natural rate at which present habitats have evolved? Many trees may be stranded, and many species might even go extinct. What happens if they do have the capacity to move but, as mentioned earlier, encounter farms and interstate highways in their ''march?''

The middle range of projected climate change (Fig. 1.2) – several degrees Celsius in a century – is the ''best guess'' of the majority of the knowledgeable scientific community. There is massive debate about these projections. The literature from groups that are worried about social intervention in economic activities argues that there is so much uncertainty that we should not do anything to slow down our ''progress.'' The literature from environmental advocates often asks what sane person could take a planetary-scale risk with the Earth even if there is much uncertainty.

Economists typically ask, ''How much is it going to cost to cut out, say, 20 percent of carbon dioxide emissions?'' They might estimate such costs by considering a tax on carbon in fuels. That would, in turn, show up at the gas pump and in heating bills and in the prices of energy-intensive products. Price increases also have a disproportionate impact on poor versus rich people.

The relevant questions for Earth systems scientists are: What is the price tag economically and politically to reduce environmental risks, and how much is the environment really ''worth?'' These questions are consistent with those asked by most policy makers in the worlds of business and government. It is essential for us to understand the nature of these arguments before we can expect to replace standard priorities with a set that values nature more highly. We need to understand in some depth the philosophy behind so-called cost/benefit analysis and how it is done (see Chaps. 26 and 27). Only then can we judge whether a modification may be cost effective or morally preferable.

CONCLUSION

The issues introduced in this chapter involve the kinds of interdisciplinary questions so fundamental to Earth system studies. Complex, thorny subjects increasingly will become part of the technology, education, science, and policy agendas of the twenty-first century, including such mind bogglers as: What are the synergisms between habitat fragmentation, chemical dumping, new population pressures, development strategies, introduction of new species, technological choice, and climate change – all happening simultaneously?

The problems of our time are not those of our grandparents or even our parents. With increasing population and information-sharing technology, the realm of human knowledge grows exponentially in fantastically short periods of time. From the masses of highly skilled, detail-oriented disciplinarians, we must reconnect to solve complex, interdisciplinary, real-world problems. Our grandparents' mission was to specialize, to track details within the details, to demystify the minutiae in order to understand the macroscale phenomena of the world. *Our* generation's mission includes pursuit of ever more specialized fields of knowledge, and also to synthesize that newfound knowledge. We must train people such as Earth systems scientists to communicate among disciplines so that disciplinarians may learn from and build on one another's work in the context of real-world problem solving. Good examples of historic success with interdisciplinary knowledge include the great naturalists of the nineteeth century (e.g., Darwin applied his background in geology to his biologic observations, which was essential to his grasping the fact that physical barriers can drive speciation). In this age of specialization, we need Renaissance individuals once again – we must not lose sight of the forest for the trees, even while we catalogue the DNA of each species.

Earth systems science is designed to look at how these and other related real-world problems connect. It will take decades for Earth systems scientists to answer only a few of the many detailed questions that need to be addressed to each of the subdisciplines that constitute Earth systems science. However, human pressures on the Earth's systems are already documented. Policies to alter some of the activities forcing global changes cannot wait decades to reduce uncertainties without taking many risks. These difficult questions must be dealt with now. Earth systems science attempts to bring the relevant content of physical, biologic, and social science disciplines to bear in the context of the real, interdisciplinary problems of environment and development. It aims to analyze causes and assess solutions, recognizing that any solutions will not be perfect or certain, but that on balance they will be better than either wild guesses or actions based upon narrow, specialized views. Finally, this integrated approach necessitates grappling with problems at the scale at which they exist, not ignoring or postponing them, or pretending that they are not the stuff of real scientists or technologists. It is an exciting journey, and we welcome students to this lifelong adventure in learning and doing.

QUESTIONS

1. Think of a familiar environmental problem. Now try to imagine the way a roomful of ''disciplinarians'' or advocates would speak on the subject. What would an economist have to say? A biologist? A groundwater hydrologist? How about a policy maker, a coal miner, or an environmentalist? Do you think that people from different disciplines or advocacy positions could communicate effectively with one another about the problem? What barriers exist? Who would facilitate communication among them?

2. A positive/negative feedback question: Think of a dynamic system (such as driving a car, or the flow rate of traffic) and list as many positive and negative (stabilizing and destabilizing) feedback mechanisms as you can in three minutes.

3. How would you mediate a dispute between a coal mining company and an environmental organization trying to slow down carbon dioxide emissions? Can you find any ''win–win'' solutions? How about a similar dispute between a less developed country dependent on coal and a small island state whose existence is threatened by a rising sea level from global warming?

FURTHER READING

Bruce, J., Hoesung Lee and Haites, E. 1996. *Climate change 1995 – economic and social dimensions of climate change: contribution of working group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* New York: Cambridge University Press.

Houghton, J. J., Meiro Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell K. (eds.) 1996. *Climate change 1995 – the science of climate change: contribution of working group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* New York: Cambridge University Press.

Levin, S. A. 1992. The problem of pattern and scale in ecology. *Ecology* 73:1943–1967.

Peter, R., and Lovejoy, T. 1992. *Global warming and biological diversity.* New Haven, CT: Yale University Press.

Root, T. L., and Schneider, S. H. 1995. Ecology and climate: research strategies and implications. *Science* 269:334–341.

Schneider, S. H. 1997. *Laboratory Earth: the planetary gamble we can't afford to lose.* New York: Basic Books.

Watson, R. T., Zinyowera, M. C., and Moss, R. H. (eds.) 1996. *Climate change 1995 – impacts, adaptations and mitigation of climate change – scientific-technical analyses: contribution of working group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* New York: Cambridge University Press.