IIASA

Abrupt Changes
The Achilles' Heels of the Earth System

Will Steffen, Meinrat O. Andreae, Bert Bolin, Peter M. Cox, Paul J. Crutzen, Ulrich Cubasch, Hermann Held, Nebojša Nakićenović, Robert J. Scholes, Liana Talaue-McManus, and B.L. Turner II

RR-04-006
June 2004

REPRINT
RESEARCH
REPORT

Abrupt Changes
The Achilles' Heels of the Earth System

Will Steffen
Meinrat O. Andreae
Bert Bolin
Peter M. Cox
Paul J. Crutzen
Ulrich Cubasch
Hermann Held
Nebojša Nakićenović
Robert J. Scholes
Liana Talaue-McManus
B.L. Turner II

RR-04-006
June 2004

Reprinted from *Environment*, **46**(3):8-20 (2004).

International Institute for Applied Systems Analysis • Schlossplatz 1 • A-2361 Laxenburg • Austria
Tel: (+43 2236) 807 • Fax: (+43 2236) 71313 • E-mail: publications@iiasa.ac.at • Web: www.iiasa.ac.at

Reprinted with permssion from *Environment* **46**(3): 8-20 (2004).

Abrupt Changes
The Achilles' Heels of the Earth System

Will Steffen
Meinrat O. Andreae
Bert Bolin
Peter M. Cox
Paul J. Crutzen
Ulrich Cubasch
Hermann Held
Nebojša Nakićenović
Robert J. Scholes
Liana Talaue-McManus
B.L. Turner II

The ways in which global change will unfold over the coming century and beyond are usually conceptualized in terms of Intergovernmental Panel on Climate Change (IPCC)–type scenarios in which important climate parameters are projected into the future.[1] In most of these scenarios, the projections are for an optimistically smooth increase in global mean temperature, for example, or for percentage increases or decreases in precipitation. The often unwritten or unstated assumption is that the Earth System (see the box on page 10) will continue to operate largely in the state in which it has since the Holocene epoch began (at the end of the last ice age) and that global change will be manifested as perturbations on this state. Such assumptions have led to first-order analyses of the economic consequences of global change (see the box on page 11) and to strategies for adapting to rather than mitigating it.

In reality, Earth's environment shows significant variability on virtually all time and space scales.[2] Records from the past (see Figure 1 on page 11) show that the very short modern period of instrumental monitoring of the global environment does not reveal the magnitude and rate of change that are possible. Nonlinear, abrupt changes in key environmental parameters appear to be the norm, not the exception, in the functioning of the Earth System. Thus, global change is not likely to be played out as a steady or pseudolinear process under any conceivable scenario but will almost surely be characterized by abrupt changes for which prediction and adaptation are very difficult.

Here, the term "abrupt" refers to changes in major features of Earth System functioning that occur at an unexpectedly rapid rate. The definition of "unexpectedly rapid" depends on the time scale considered. From a geological perspective the contemporary rise of atmospheric carbon dioxide (CO_2) concentration is an abrupt change,[3] as is the rise in mean northern hemisphere surface temperature over the past few decades.[4] The rather sudden change in the nature of the ocean ecosystem in the 1970s in terms of bottom-dwelling communities in the northeast Pacific Ocean—from domination by invertebrate shrimps to domination by cod and other ground-fishes—is an example of an abrupt change in a large ecological system.[5] Abrupt changes can also occur in human aspects of the Earth System, such as the precipitous collapse of the Soviet Union around 1990 and subsequent globalization of the world's economy in less than a decade.[6] Perhaps the most dramatic example of a coupled human-environment system reaching a tipping point is the collapse of the Aral Sea over a brief 30-year period (1960-1990), owing to the development of large-scale irrigation systems that withdrew the flow of freshwater to the sea.[7]

From a human perspective, changes that occur over many decades or a century may not appear to be so

THE EARTH SYSTEM

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

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

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

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

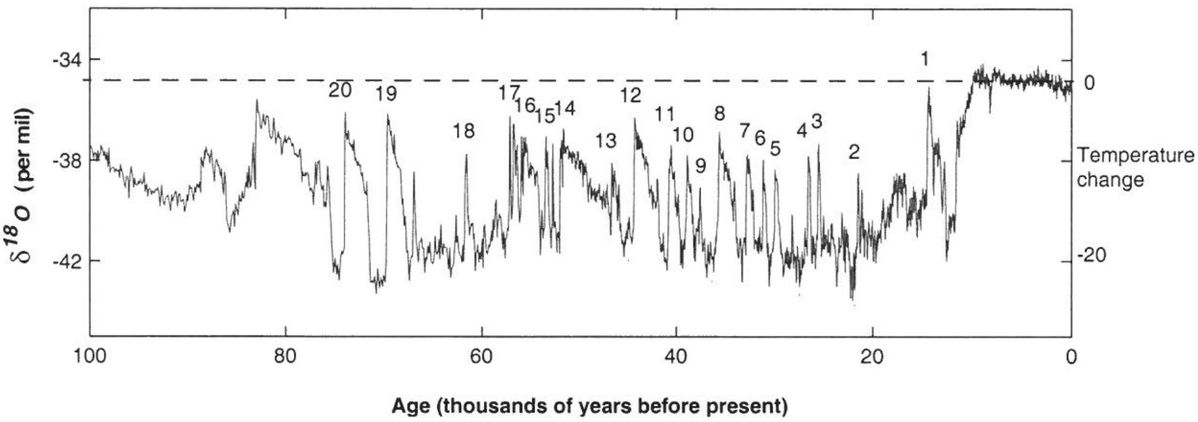
Edited from F. Oldfield and W. Steffen, "The Earth System," in W. Steffen et al., *Global Change and the Earth System: A Planet Under Pressure*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2004), 7.

rapid. However, as several examples below will demonstrate, changes are now occurring in Earth System functioning that appear rapid even from the perspective of one human lifetime. Such changes are especially significant, because they may prove difficult or impossible for human societies to adapt to.

From a more technical perspective the term "abrupt change" can refer to two types of events. First, the term can be used to mean changes in state that occur out of proportion to the changes in the forcing function(s)—those process(es) that drive the changes. The second, related type of change referred to as an abrupt change—perhaps more common under global change—is the transition from one state to another caused when a threshold is passed. In this case, a well-buffered system appears to be unresponsive to a steadily increasing forcing function, giving a false sense of security in terms of the stability of the system. With little or no warning, however, an incremental increase in the forcing function can cause a threshold to be passed and the system to shift abruptly to another state (see Figure 2 on page 12). This phenomenon can be particularly dangerous in the case of global change: Societies may be lulled into believing that an anthropogenic forcing is having little or no effect on the global environment when in fact a dangerous threshold is being approached.

The paleo-record gives unequivocal evidence of abrupt change in the recent past.[8] The significance of abrupt changes such as those seen in the North Atlantic region during the transition from the most recent glacial state to the Holocene is threefold: They involve a scale of change (up to 10°C in a decade or so) that would devastate modern civilizations, they have occurred during the time of human occupation of the planet, and they have occurred in regions now heavily populated. They cannot be dismissed as either implausible or irrele-

Figure 1. Record of delta oxygen-18 ($\delta^{18}O$) from the Greenland Ice Sheet Project core



NOTE: The Greenland Ice Sheet Project core is a proxy for atmospheric temperature over Greenland. This figure shows the relatively stable Holocene climate during the past 10,000 years and the Dansgaard-Oeschger warm events (numbered 1–20) during the preceding colder glacial climate.

SOURCE: A. Ganopolski and S. Rahmstorf, "Rapid Changes of Glacial Climate Simulated in a Couple Climate Model," *Nature*, 11 January 2001, 153–58.

vant in terms of spatial or temporal scales. On the other hand, an abrupt change in the chemistry of the atmosphere—the formation of the Antarctic ozone hole—has already occurred and can be unequivocally attributed to human activities.[9] Such evidence gives a strong warning that human activities could trigger similar or even as-yet unimagined instabilities in the Earth System, in its physical, chemical, or biological components, or in coupled human-environment systems.

Some fundamental questions are now being asked more frequently and seriously in connection with what we know now about the nature of abrupt changes in the Earth System (or in large regions or sub-systems) and the probability that human actions could trigger such changes: What are the Achilles' heels in the Earth System? Can abrupt changes in the operation of the Earth System be anticipated and predicted? Can the abrupt changes that are most susceptible to triggering by human actions be identified?

Abrupt Changes in the Physical Earth System

Possible abrupt changes in the physical climate system have already raised considerable concern, especially those involving changes in ocean circulation. The best-known example is the ocean's thermohaline circulation (THC), which transports heat from equator to pole in

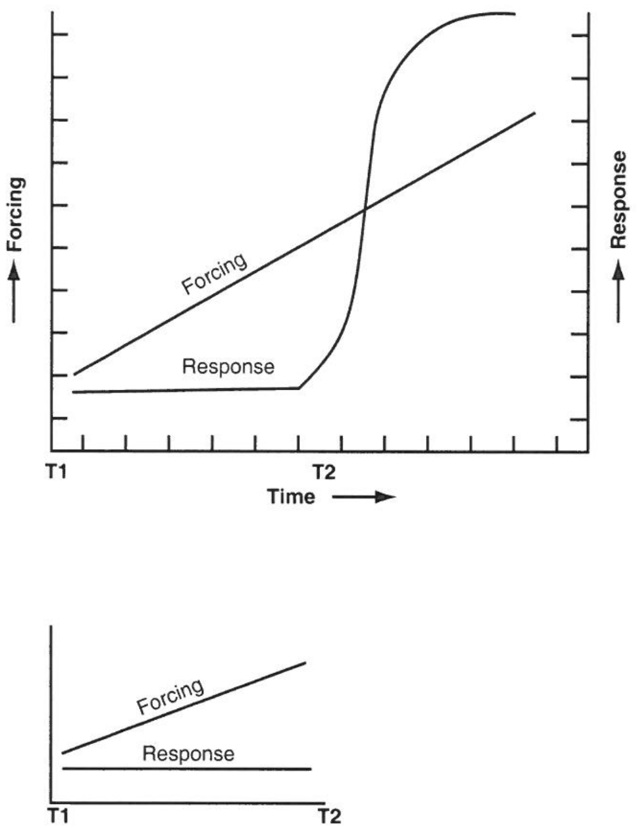
GLOBAL CHANGE

The term "global change" usually refers to the broad suite of biophysical and socioeconomic changes that are altering the functioning of the Earth System at the global scale. In essence, it refers to the remarkable change in the human-environment relationship that has occurred over the last few centuries.

Global change encompasses change in a wide range of global-scale phenomena: population; the economy, including magnitude and distribution; resource use, especially for production of energy; transport and communication; land use and land cover; urbanization; globalization; coastal ecosystems; atmospheric composition; riverine flow; the nitrogen cycle; the carbon cycle; the physical climate; marine food chains; and biological diversity. It is important to note that the linkages and interactions between these various changes are also part of global change and are just as important as the individual changes themselves.

Another feature of global change is that many changes do not occur in linear fashion but rather exhibit strong nonlinearities. Finally, global change is being played out in contrasting ways in different places, each with its own set of characteristics, leading to location-specific impacts resulting from a mix of interacting changes at a number of scales.

Figure 2. Thresholds and abrupt changes



NOTE: Many processes within the Earth System are well-buffered and appear to be unresponsive to a forcing factor (T1 and T2 in the lower figure) until a threshold is crossed (just beyond T2 in the upper figure).

SOURCE: W. Steffen et al., *Global Change and the Earth System: A Planet under Pressure*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2004).

the North Atlantic Ocean. The warm surface waters of the Gulf Stream cool in the North Atlantic, release their heat to the atmosphere, become denser, and sink to deeper levels. In doing so, they help to keep Western Europe unusually warm for its latitude. This circulation has shown remarkably abrupt behavior in the past. During the last glacial period, from 120,000 to 10,000 years ago, the climate in the North Atlantic region underwent repeated, extremely abrupt warming events followed by a slower relaxation to the glacial state.[10] The warming was dramatic, by up to 10°C in Greenland in only a decade or two. The most likely explanation for these occurances, known as Dansgaard-Oeschger events, is a sudden surge of the warm surface current northward into the North Atlantic Ocean and then a slower retreat back to the glacial state: in effect, a switch between two modes of THC.[11]

Perhaps more relevant for the current state of the Earth System are Heinrich events, which are typified by sudden, dramatic cooling in the North Atlantic region when the Earth is coming out of the glacial state or is in an interglacial state. The most well-known Heinrich event was the sudden cooling of the Northern Hemisphere in the Younger Dryas, an event that occurred about 12,000 years ago. Heinrich events are thought to have been caused by massive surges of North America's Laurentide Ice Sheet, which released large amounts of ice and freshwater through Hudson Strait.[12] The freshwater input to the ocean's surface decreased the density of the surface waters and inhibited deep-water formation in the North Atlantic. Such a mechanism is plausible in the future, as a warming climate leads to increased melting of ice in Greenland and in the Arctic Ocean, a warming of surface waters, and an intensification of the hydrological cycle (more rainfall in high latitudes). Could global warming thus lead to abrupt regional cooling?

Models of the thermohaline circulation exhibit both "on" and "off" states with the potential for rapid switching between these states based on the freshwater input to the North Atlantic. The current "on" state can be destabilized by additional freshwater inputs to the North Atlantic.[13] Coupled climate-ocean circulation models vary greatly in their simulation of the future behavior of THC, from little (10 percent) reduction to a near-shutdown (80 percent reduction) of the circulation in the next 100 years based on various scenarios of CO_2 emissions. Longer-term simulations using Earth System Models of Intermediate Complexity (EMICs) show threshold behavior and an irreversible collapse of THC, with the threshold depending on both the rate and amount of greenhouse-gas induced warming (see Figure 3 on page 13).[14] It is difficult to determine just where the threshold lies, but it may well be within the range of warming that is expected under a business-as-usual scenario over the next century. A robust

IIASA

Abrupt Changes The Achilles' Heels of the Earth System

Will Steffen, Meinrat O. Andreae, Bert Bolin, Peter M. Cox, Paul J. Crutzen, Ulrich Cubasch, Hermann Held, Nebojša Nakićenović, Robert J. Scholes, Liana Talaue-McManus, and B.L. Turner II

RR-04-006
June 2004

REPRINT
RESEARCH
REPORT

Abrupt Changes
The Achilles' Heels of the Earth System

Will Steffen
Meinrat O. Andreae
Bert Bolin
Peter M. Cox
Paul J. Crutzen
Ulrich Cubasch
Hermann Held
Nebojša Nakićenović
Robert J. Scholes
Liana Talaue-McManus
B.L. Turner II

RR-04-006
June 2004

Reprinted from *Environment*, **46**(3):8-20 (2004).

International Institute for Applied Systems Analysis • Schlossplatz 1 • A-2361 Laxenburg • Austria
Tel: (+43 2236) 807 • Fax: (+43 2236) 71313 • E-mail: publications@iiasa.ac.at • Web: www.iiasa.ac.at

Reprinted with permssion from *Environment* **46**(3): 8-20 (2004).

Abrupt Changes
The Achilles' Heels of the Earth System

Will Steffen
Meinrat O. Andreae
Bert Bolin
Peter M. Cox
Paul J. Crutzen
Ulrich Cubasch
Hermann Held
Nebojša Nakićenović
Robert J. Scholes
Liana Talaue-McManus
B.L. Turner II

The ways in which global change will unfold over the coming century and beyond are usually conceptualized in terms of Intergovernmental Panel on Climate Change (IPCC)–type scenarios in which important climate parameters are projected into the future.[1] In most of these scenarios, the projections are for an optimistically smooth increase in global mean temperature, for example, or for percentage increases or decreases in precipitation. The often unwritten or unstated assumption is that the Earth System (see the box on page 10) will continue to operate largely in the state in which it has since the Holocene epoch began (at the end of the last ice age) and that global change will be manifested as perturbations on this state. Such assumptions have led to first-order analyses of the economic consequences of global change (see the box on page 11) and to strategies for adapting to rather than mitigating it.

In reality, Earth's environment shows significant variability on virtually all time and space scales.[2] Records from the past (see Figure 1 on page 11) show that the very short modern period of instrumental monitoring of the global environment does not reveal the magnitude and rate of change that are possible. Nonlinear, abrupt changes in key environmental parameters appear to be the norm, not the exception, in the functioning of the Earth System. Thus, global change is not likely to be played out as a steady or pseudolinear process under any conceivable scenario but will almost surely be characterized by abrupt changes for which prediction and adaptation are very difficult.

Here, the term "abrupt" refers to changes in major features of Earth System functioning that occur at an unexpectedly rapid rate. The definition of "unexpectedly rapid" depends on the time scale considered. From a geological perspective the contemporary rise of atmospheric carbon dioxide (CO_2) concentration is an abrupt change,[3] as is the rise in mean northern hemisphere surface temperature over the past few decades.[4] The rather sudden change in the nature of the ocean ecosystem in the 1970s in terms of bottom-dwelling communities in the northeast Pacific Ocean—from domination by invertebrate shrimps to domination by cod and other ground-fishes—is an example of an abrupt change in a large ecological system.[5] Abrupt changes can also occur in human aspects of the Earth System, such as the precipitous collapse of the Soviet Union around 1990 and subsequent globalization of the world's economy in less than a decade.[6] Perhaps the most dramatic example of a coupled human-environment system reaching a tipping point is the collapse of the Aral Sea over a brief 30-year period (1960-1990), owing to the development of large-scale irrigation systems that withdrew the flow of freshwater to the sea.[7]

From a human perspective, changes that occur over many decades or a century may not appear to be so

THE EARTH SYSTEM

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

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

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

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

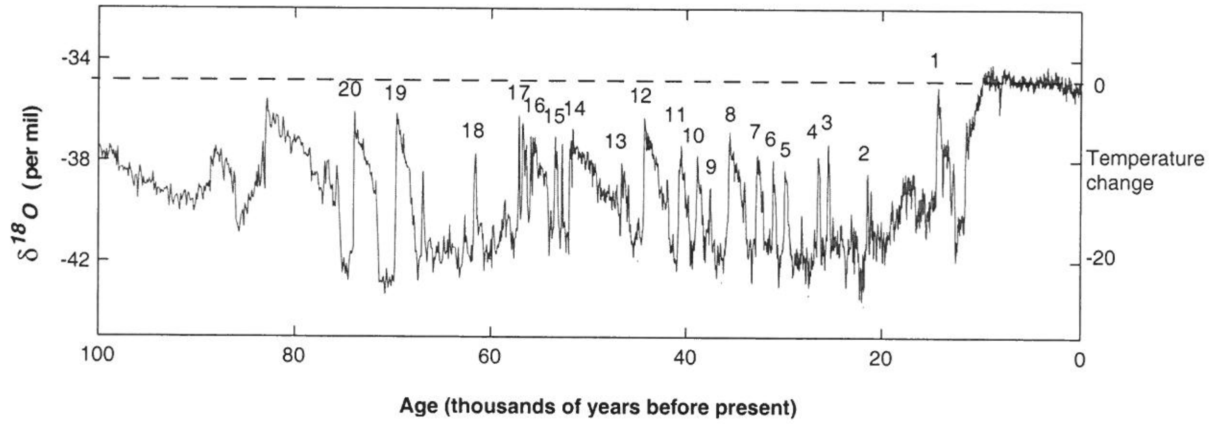
Edited from F. Oldfield and W. Steffen, "The Earth System," in W. Steffen et al., *Global Change and the Earth System: A Planet Under Pressure*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2004), 7.

rapid. However, as several examples below will demonstrate, changes are now occurring in Earth System functioning that appear rapid even from the perspective of one human lifetime. Such changes are especially significant, because they may prove difficult or impossible for human societies to adapt to.

From a more technical perspective the term "abrupt change" can refer to two types of events. First, the term can be used to mean changes in state that occur out of proportion to the changes in the forcing function(s)—those process(es) that drive the changes. The second, related type of change referred to as an abrupt change—perhaps more common under global change—is the transition from one state to another caused when a threshold is passed. In this case, a well-buffered system appears to be unresponsive to a steadily increasing forcing function, giving a false sense of security in terms of the stability of the system. With little or no warning, however, an incremental increase in the forcing function can cause a threshold to be passed and the system to shift abruptly to another state (see Figure 2 on page 12). This phenomenon can be particularly dangerous in the case of global change: Societies may be lulled into believing that an anthropogenic forcing is having little or no effect on the global environment when in fact a dangerous threshold is being approached.

The paleo-record gives unequivocal evidence of abrupt change in the recent past.[8] The significance of abrupt changes such as those seen in the North Atlantic region during the transition from the most recent glacial state to the Holocene is threefold: They involve a scale of change (up to 10°C in a decade or so) that would devastate modern civilizations, they have occurred during the time of human occupation of the planet, and they have occurred in regions now heavily populated. They cannot be dismissed as either implausible or irrele-

Figure 1. Record of delta oxygen-18 ($\delta^{18}O$) from the Greenland Ice Sheet Project core



NOTE: The Greenland Ice Sheet Project core is a proxy for atmospheric temperature over Greenland. This figure shows the relatively stable Holocene climate during the past 10,000 years and the Dansgaard-Oeschger warm events (numbered 1–20) during the preceding colder glacial climate.

SOURCE: A. Ganopolski and S. Rahmstorf, "Rapid Changes of Glacial Climate Simulated in a Couple Climate Model," *Nature*, 11 January 2001, 153–58.

vant in terms of spatial or temporal scales. On the other hand, an abrupt change in the chemistry of the atmosphere—the formation of the Antarctic ozone hole—has already occurred and can be unequivocally attributed to human activities.[9] Such evidence gives a strong warning that human activities could trigger similar or even as-yet unimagined instabilities in the Earth System, in its physical, chemical, or biological components, or in coupled human-environment systems.

Some fundamental questions are now being asked more frequently and seriously in connection with what we know now about the nature of abrupt changes in the Earth System (or in large regions or sub-systems) and the probability that human actions could trigger such changes: What are the Achilles' heels in the Earth System? Can abrupt changes in the operation of the Earth System be anticipated and predicted? Can the abrupt changes that are most susceptible to triggering by human actions be identified?

Abrupt Changes in the Physical Earth System

Possible abrupt changes in the physical climate system have already raised considerable concern, especially those involving changes in ocean circulation. The best-known example is the ocean's thermohaline circulation (THC), which transports heat from equator to pole in

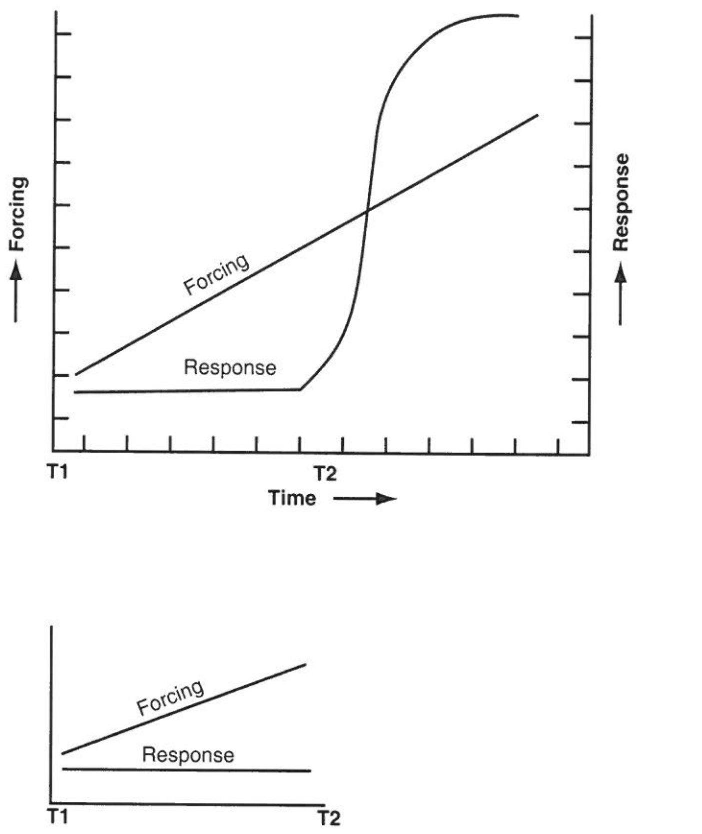
GLOBAL CHANGE

The term "global change" usually refers to the broad suite of biophysical and socioeconomic changes that are altering the functioning of the Earth System at the global scale. In essence, it refers to the remarkable change in the human-environment relationship that has occurred over the last few centuries.

Global change encompasses change in a wide range of global-scale phenomena: population; the economy, including magnitude and distribution; resource use, especially for production of energy; transport and communication; land use and land cover; urbanization; globalization; coastal ecosystems; atmospheric composition; riverine flow; the nitrogen cycle; the carbon cycle; the physical climate; marine food chains; and biological diversity. It is important to note that the linkages and interactions between these various changes are also part of global change and are just as important as the individual changes themselves.

Another feature of global change is that many changes do not occur in linear fashion but rather exhibit strong nonlinearities. Finally, global change is being played out in contrasting ways in different places, each with its own set of characteristics, leading to location-specific impacts resulting from a mix of interacting changes at a number of scales.

Figure 2. Thresholds and abrupt changes



NOTE: Many processes within the Earth System are well-buffered and appear to be unresponsive to a forcing factor (T1 and T2 in the lower figure) until a threshold is crossed (just beyond T2 in the upper figure).

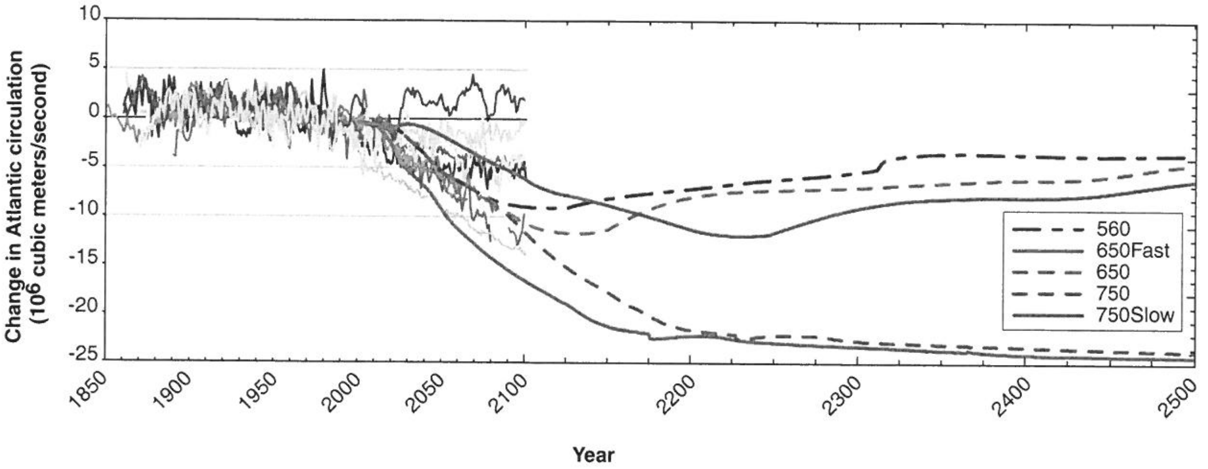
SOURCE: W. Steffen et al., *Global Change and the Earth System: A Planet under Pressure*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2004).

the North Atlantic Ocean. The warm surface waters of the Gulf Stream cool in the North Atlantic, release their heat to the atmosphere, become denser, and sink to deeper levels. In doing so, they help to keep Western Europe unusually warm for its latitude. This circulation has shown remarkably abrupt behavior in the past. During the last glacial period, from 120,000 to 10,000 years ago, the climate in the North Atlantic region underwent repeated, extremely abrupt warming events followed by a slower relaxation to the glacial state.[10] The warming was dramatic, by up to 10°C in Greenland in only a decade or two. The most likely explanation for these occurances, known as Dansgaard-Oeschger events, is a sudden surge of the warm surface current northward into the North Atlantic Ocean and then a slower retreat back to the glacial state: in effect, a switch between two modes of THC.[11]

Perhaps more relevant for the current state of the Earth System are Heinrich events, which are typified by sudden, dramatic cooling in the North Atlantic region when the Earth is coming out of the glacial state or is in an interglacial state. The most well-known Heinrich event was the sudden cooling of the Northern Hemisphere in the Younger Dryas, an event that occurred about 12,000 years ago. Heinrich events are thought to have been caused by massive surges of North America's Laurentide Ice Sheet, which released large amounts of ice and freshwater through Hudson Strait.[12] The freshwater input to the ocean's surface decreased the density of the surface waters and inhibited deep-water formation in the North Atlantic. Such a mechanism is plausible in the future, as a warming climate leads to increased melting of ice in Greenland and in the Arctic Ocean, a warming of surface waters, and an intensification of the hydrological cycle (more rainfall in high latitudes). Could global warming thus lead to abrupt regional cooling?

Models of the thermohaline circulation exhibit both "on" and "off" states with the potential for rapid switching between these states based on the freshwater input to the North Atlantic. The current "on" state can be destabilized by additional freshwater inputs to the North Atlantic.[13] Coupled climate-ocean circulation models vary greatly in their simulation of the future behavior of THC, from little (10 percent) reduction to a near-shutdown (80 percent reduction) of the circulation in the next 100 years based on various scenarios of CO_2 emissions. Longer-term simulations using Earth System Models of Intermediate Complexity (EMICs) show threshold behavior and an irreversible collapse of THC, with the threshold depending on both the rate and amount of greenhouse-gas induced warming (see Figure 3 on page 13).[14] It is difficult to determine just where the threshold lies, but it may well be within the range of warming that is expected under a business-as-usual scenario over the next century. A robust

Figure 3. Composite changes in meridional overturning in the Atlantic Ocean



NOTE: To illustrate the possible long-term behavior of the thermohaline circulation—which transports heat from equator to pole in the North Atlantic Ocean—simulations using a coupled model of reduced complexity are overlaid. They use artificial carbon dioxide (CO_2) emissions scenarios that are identified in the inset. CO_2 increases by rates of 0.5, 1, and 2 percent per year up to maximum concentrations of 560, 650, and 750 parts per million, and constant thereafter. Depending on the rate of CO_2 increase and the maximum CO_2 concentration, and hence warming, the THC crosses a threshold beyond which the circulation stops and remains collapsed.

SOURCE: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton et al., eds.] (Cambridge, United Kingdom and New York: Cambridge University Press, 2001); and T. F. Stocker and A. Schmittner, "Rate of Global Warming Determines the Stability of the Ocean-Atmosphere System," *Nature*, 28 August 1997, 862–65.

conclusion based on a synthesis of modeling studies simulating the behavior of THC is that the crossing of thresholds and associated irreversible changes of ocean circulation cannot be excluded within the range of projected climate change over the next century.[15]

Potential abrupt changes in the physical Earth System are also connected with the behavior of the cryosphere (the frozen portion of the Earth's surface, made up mostly of snow and ice). The mechanism here is straightforward; the latent heat—the amount of heat (calories) required to convert a given amount of solid water (usually 1 gram) into liquid water at the same temperature (usually 0°C)—of melting of ice is very large. Thus, ice sheets will show little or very slow response to increasing air temperatures for a considerable period, but when the amount of heating resulting from the temperature increase reaches a value close to the latent heat of melting, the change can be sudden with a strong hysteresis, or path-dependence: An apparently small amount of (final) warming can melt the ice, and a correspondingly small amount of cooling will not create the ice again. Strong cooling over a long period will be required to reverse the change.

This effect is most clearly seen now in the behavior of permafrost. Warming so far has been strongest in the high latitudes of the Northern Hemisphere, with increases of 2–4°C in northern Alaska from 1900 to the mid-1980s and a further 3°C since the late 1980s. In the permafrost regions of Canada, temperature has increased by nearly 2°C over the last decade. Despite these very high rates of

POTENTIAL ABRUPT CHANGES IN THE PHYSICAL EARTH SYSTEM ARE ALSO CONNECTED WITH THE BEHAVIOR OF THE CRYOSHPERE.

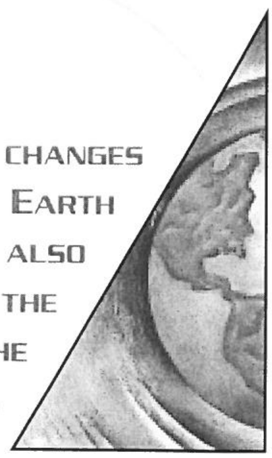
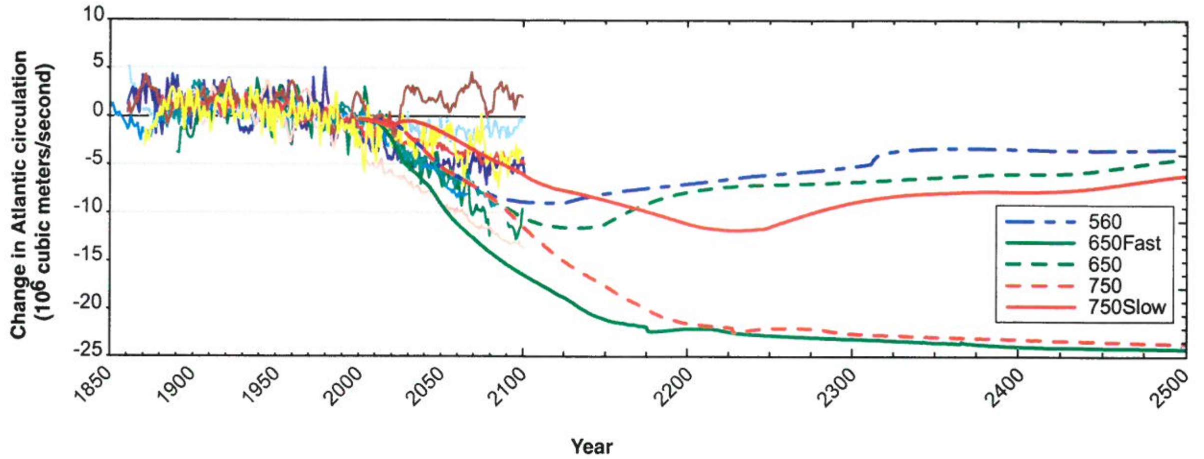


Figure 3. Composite changes in meridional overturning in the Atlantic Ocean



NOTE: To illustrate the possible long-term behavior of the thermohaline circulation—which transports heat from equator to pole in the North Atlantic Ocean—simulations using a coupled model of reduced complexity are overlaid. They use artificial carbon dioxide (CO_2) emissions scenarios that are identified in the inset. CO_2 increases by rates of 0.5, 1, and 2 percent per year up to maximum concentrations of 560, 650, and 750 parts per million, and constant thereafter. Depending on the rate of CO_2 increase and the maximum CO_2 concentration, and hence warming, the THC crosses a threshold beyond which the circulation stops and remains collapsed.

SOURCE: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton et al., eds.] (Cambridge, United Kingdom and New York: Cambridge University Press, 2001); and T. F. Stocker and A. Schmittner, "Rate of Global Warming Determines the Stability of the Ocean-Atmosphere System," *Nature*, 28 August 1997, 862–65.

conclusion based on a synthesis of modeling studies simulating the behavior of THC is that the crossing of thresholds and associated irreversible changes of ocean circulation cannot be excluded within the range of projected climate change over the next century.[15]

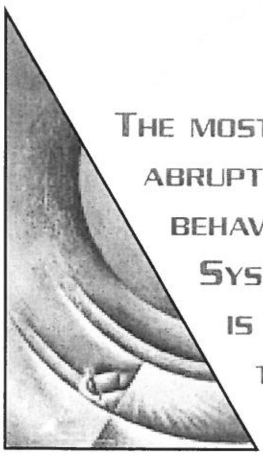
Potential abrupt changes in the physical Earth System are also connected with the behavior of the cryosphere (the frozen portion of the Earth's surface, made up mostly of snow and ice). The mechanism here is straightforward; the latent heat—the amount of heat (calories) required to convert a given amount of solid water (usually 1 gram) into liquid water at the same temperature (usually 0°C)—of melting of ice is very large. Thus, ice sheets will show little or very slow response to increasing air temperatures for a considerable period, but when the amount of heating resulting from the temperature increase reaches a value close to the latent heat of melting, the change can be sudden with a strong hysteresis, or path-dependence: An apparently small amount of (final) warming can melt the ice, and a correspondingly small amount of cooling will not create the ice again. Strong cooling over a long period will be required to reverse the change.

This effect is most clearly seen now in the behavior of permafrost. Warming so far has been strongest in the high latitudes of the Northern Hemisphere, with increases of 2–4°C in northern Alaska from 1900 to the mid-1980s and a further 3°C since the late 1980s. In the permafrost regions of Canada, temperature has increased by nearly 2°C over the last decade. Despite these very high rates of

POTENTIAL ABRUPT CHANGES IN THE PHYSICAL EARTH SYSTEM ARE ALSO CONNECTED WITH THE BEHAVIOR OF THE CRYOSHPERE.

temperature increase, the retreat of permafrost has been slow, owing to the large latent heat required to melt the ice.[16] However, there is now evidence that thawing of permafrost in these regions is accelerating, suggesting that a threshold is possibly being approached and more rapid changes in permafrost depth and extent will be observed in the near future.[17]

A more dramatic abrupt change in the cryosphere would be the melting of the Greenland ice cap, which by itself would raise sea level about 6 meters around the world, leading to catastrophic impacts on many low-lying coastal cities. Although even the more drastic scenarios of climate change do not predict the loss of Greenland ice for several hundred years, the possibility of such a loss cannot be discounted in the longer term. Model-derived results suggest that Greenland can support both ice-covered and ice-free conditions under current CO_2 conditions. The Greenland ice cap displays hysteresis in its response to control variables such as CO_2-induced warming. Thus, under sustained increases in CO_2 level, the Greenland ice sheet is expected to melt in an irreversible manner, such that considerably lower CO_2 values would be required before it would return.



THE MOST WELL-KNOWN OF ABRUPT CHANGES IN THE BEHAVIOR OF THE EARTH SYSTEM THAT HAVE OCCURRED IS THE FORMATION OF THE OZONE HOLE OVER ANTARCTICA.

Abrupt Changes in the Chemistry of the Atmosphere

The most well-known of abrupt changes in the behavior of the Earth System that have already occurred is the formation of the ozone hole over Antarctica. The ozone hole was the unexpected result of the release of synthetic chemicals—in particular chlorfluorocarbons (CFCs) used in aerosols and refrigerants—thought to be environmentally harmless. The event was one of chemical instability in the atmosphere rather than an abrupt change in the physical climate system. In addition, it occurred in a far distant part of the planet, well away from the origin of the cause. In fact, at the time the ozone hole was discovered, it was thought that the ozone in the lower stratosphere at high latitudes was largely inert. The chemical detective work that eventually unravelled the processes that caused the ozone hole showed that a number of conditions must occur simultaneously for the hole to form.[18] First, low temperatures (at least -80°C) are required to produce ice particles. Second, hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$) react on the surface of the ice particles to produce chlorine (Cl_2) and nitric acid (HNO_3), which is incorporated into the ice particles. Third, the Cl_2 produced is converted to two highly reactive chlorine (Cl) atoms by solar radiation when sunlight begins to return to Antarctica in the austral spring. Fourth, the Cl atoms trigger a chain reaction that leads to the destruction of ozone molecules. Finally, the chlorine monoxide (ClO) molecule, which is dependent on the amount of chlorine in the atmosphere, plays a strong role, to the power two, in the chain reaction. Thus, the provision of excess Cl in the atmosphere via CFCs was the factor that triggered, in combination with the other four conditions, the abrupt change in the chemistry of the lower stratosphere and led to the formation of the ozone hole.

In several ways, humankind is lucky that the ozone hole is not global rather than regional, year-round rather than seasonal, and much deeper than it actually is. Fortuitously, scientists with the British Antarctic Survey had routinely and consistently measured the column ozone concentration over Antarctica since the 1950s and thus observed the unexpected loss of ozone in the southern high latitudes. In addition, atmospheric chemists had been studying the likely effects on the stratosphere of a proposed fleet of supersonic aircraft and were therefore well placed to quickly develop the elegant understanding of the chemistry that explained the formation of the ozone hole. Finally, humankind was lucky that the chemical engineers who first designed the CFCs chose chlorine and fluorine as the halogens rather than bromine, which is at least 30–40 and perhaps 100 times more reactive in the atmosphere than chlorine. Coauthor Paul Crutzen thus noted that "this brings up the nightmarish thought that if the chemical industry had developed organobromine compounds instead of the CFCs—or, alternatively, if chlorine chemistry would have run more like that of bromine—then without any preparedness, we would have been faced with a catastrophic ozone hole everywhere and at all seasons during the 1970s, probably before the atmospheric chemists had developed the necessary knowledge to identify the problem and the appropriate techniques for the necessary critical measurements. Noting that nobody had given any thought to the atmospheric consequences of the release of Cl or Br before 1974, I can only conclude that mankind has been extremely lucky."[19]

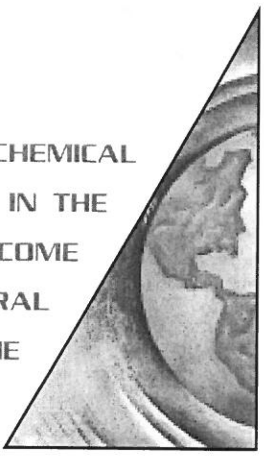
The stability of chemical systems in the atmosphere has become of more general concern given the ozone hole episode. Tropospheric chemistry, as well as stratospheric chemistry, is critical for the health and well-being of humans and for the functioning of the Earth System. The troposphere is an oxidizing medium, removing compounds emitted naturally by the terrestrial and marine biospheres and pollutants emitted by human activities. It also affects the Earth System by the destruction of compounds that affect the planet's radiative balance, such as the potent greenhouse gas methane (CH_4). Without this cleansing ability, a large range of natural and man-made compounds would accumulate in the atmosphere to very high concentrations. The hydroxyl radical (OH) is the most important of the oxidizing species in the atmosphere. OH is formed through the photolysis (a general class of reaction whereby a compound is converted to something else through the action of light) of ozone by solar ultraviolet radiation, yielding electronically excited oxygen atoms. These react with water vapor to form OH radicals.

Given the significant human alteration of the composition of the atmosphere over the past century or so, there is concern that its cleansing efficiency may be changing, possibly leading to an abrupt change. The observed increase in tropospheric ozone due to anthropogenic causes should lead to an increase in OH. On the other hand, increased production of CH_4 and CO due to human activities leads to a destruction of OH radicals. The net result of these opposing effects is difficult to determine. A major problem is that the OH radical shows large variations in space and time; the direct observation of changes in mean OH concentration is thus difficult. This is particularly true in the tropics, where most of the self-cleansing reactions occur but where, as of yet, there are no measurements. Indirect measurements elsewhere of OH concentration over recent decades[20] generally show small changes. One study shows a small, decreasing trend since 1988,[21] although the significance of this trend is still strongly debated. The apparent stability of the OH system that is observed now may be due to the inherent robustness of the tropospherical chemical system or to the opposing anthropogenic effects that are noted above. If the latter is the case, the cleansing ability of the atmosphere may change significantly in the future, possibly abruptly, as trace gas emissions vary in amount and type.

Ecological Systems and Abrupt Change

Ecological systems can also be involved in abrupt changes at large scales, usually acting in concert with physical and chemical components of the Earth System. For instance, about 6,000 years ago the climate in northern Africa was much more humid than today, supporting savanna vegetation throughout the region with little or no desert. The area abounded in life, including all of the large African fauna as well as humans. The change that occurred about 5,500 years ago was both abrupt and severe, leading to a complete desertification of much of this area—the formation of the present Sahara Desert.

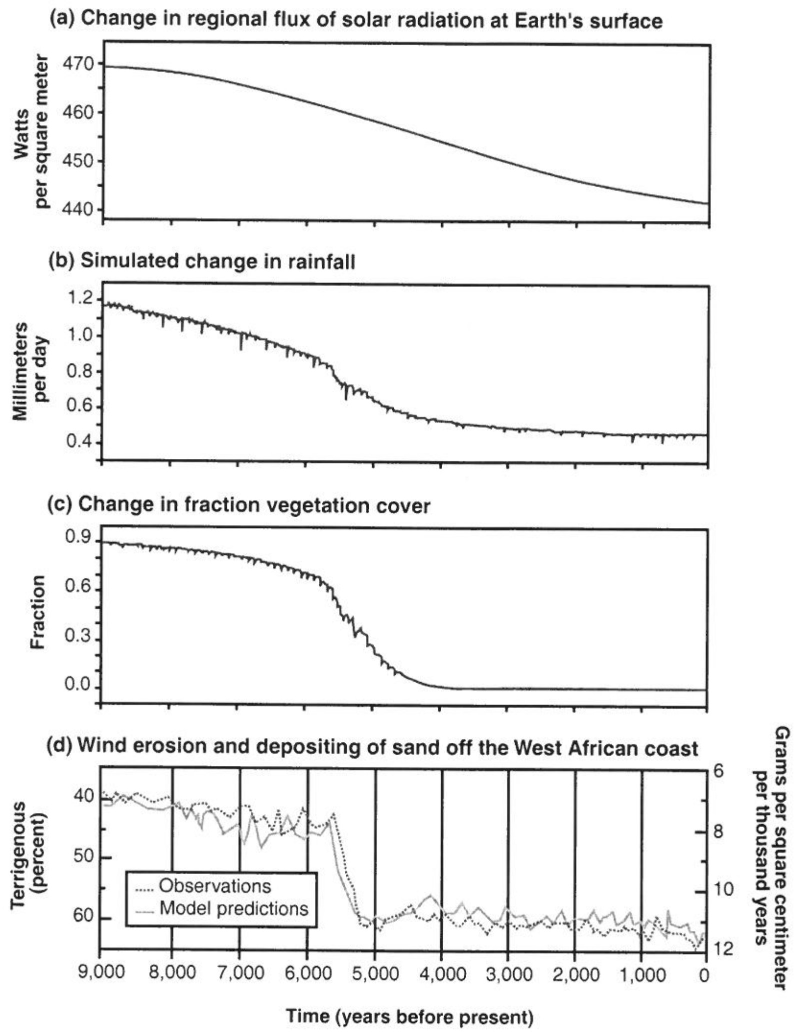
THE STABILITY OF CHEMICAL SYSTEMS IN THE ATMOSPHERE HAS BECOME OF MORE GENERAL CONCERN GIVEN THE OZONE HOLE EPISODE.



The ultimate trigger for the shift was a small change in the distribution of incoming solar radiation in the region due to a subtle change in the Earth's orbit (see Figure 4a on page 16). This change by itself was not significant enough to drive the vegetation shift but rather nudged the Earth System across a threshold that triggered a number of biophysical feedbacks that led rapidly to a drying climate (see Figure 4b on page 16) and then to an abrupt change in vegetation (see Figure 4c on page 16). Model predictions of the timing of dust deposition in the Atlantic Ocean to the west of the region agree remarkably well with observations (see Figure 4d on page 16). Model simulations of this abrupt change[22] suggest that it was an interplay of atmosphere, ocean, sea ice, and vegetation changes in widely separated parts of the planet that formed the feedback loops, which in turn amplified the original orbital forcing. This episode demonstrates the complexity of the dynamics that lie behind the type of abrupt change that is triggered when a critical threshold is crossed.

The behavior of the terrestrial carbon cycle is an aspect of Earth System functioning that may experience abrupt change, particularly in the second half of this century. At present, terrestrial ecosystems absorb about 25–30 percent of the CO_2 emitted by human activities, thus providing a valuable free service to slow the rate of climate change. Simulations of the evolution of terrestrial carbon sinks from 1850 to 2100 show the devel-

Figure 4. North Africa's abrupt change from savanna to desert during the mid-Holocene



SOURCE: M. Claussen et al., "Simulation of an Abrupt Change in the Saharan Vegetation at the End of the Mid-Holocene," *Geophysical Research Letters* 24 (1999): 2037–40; and P. B. DeMonocal et al., "Abrupt Onset and Termination of the African Humid Period: Rapid Climate Response to Gradual Insolation Forcing," *Quaternary Science Review* 19 (2000): 347–61.

opment of the current strong sink through the second half of the twentieth century.[23] The sink will continue to grow in size through the first half of this century, according to these simulations, but is likely to saturate around 2050 with no further increase. One simulation shows a rapid collapse of the sink through the second half of the century, with the terrestrial biosphere as a whole perhaps even becoming a net source of CO_2 to the atmosphere by 2100.

The primary mechanism behind the projected collapse of the terrestrial carbon sink is an acceleration in the rate of heterotrophic respiration of terrestrial ecosystems, that is, the decomposition of woody and other carbonaceous debris (leaves, dead roots, and soil carbon) by microorganisms. This process is both temperature- and moisture-dependent, so the rate is dependent on climate as well as on substrate. A secondary cause of the collapse is an abrupt change in the vegetation of the Amazon Basin, with the conversion of tropical forest to savanna or grassland due to a sharp increase in fire frequency caused by a warming and drying climate. The interactive coupling of the Dynamic Global Vegetation Model that projected this abrupt change in the terrestrial carbon sink with a global climate model gives a strong positive feedback loop that significantly accelerates climate change.[24]

Marine ecosystems commonly show threshold–abrupt change behavior, sometimes called regime shifts. For example, there appear to have been dramatic and synchronous changes to marine ecosystems in the North Pacific Ocean in the late 1970s.[25] Such changes cannot be ascribed to local ecological interactions only; they involve many different biological and environmental parameters (more than 100 in the case of the North Pacific), show coherence over large spatial scales, and are correlated to very large-scale external forcings in the climate system. The 1977 regime shift in the North Pacific, for example, is correlated to a sharp increase in mean global surface temperature.

Human impacts can also trigger abrupt changes in marine ecosystems, particularly through overfishing and eutrophication. Recent reports claim that about 90 percent of the large predatory fish biomass has been removed from the world's oceans, with removal rates being highest with the onset of post–World War II industrial fisheries.[26] Given the importance of top-down controls (from large predators down to tiny organisms) on the dynamics of marine ecosystems, there is the possibility that such overfishing could lead to regime shifts in marine ecosystems, with reverberations through to lower trophic levels such as zooplankton. On a smaller scale, overfishing is already known to cause sharp regime shifts in coastal ecosystems (see Figure 5 on page 18).[27] The removal of large vertebrates (such as sea otters) that prey on sea urchins in the kelp forests of coastal North America has led to a population explosion of sea urchins, in turn increasing the grazing pressure on kelp and leading to a dramatic population decline.

Human-dominated waste loading on the coastal zone has also led to abrupt changes (from an Earth System perspective) in the functioning of marine ecosystems in the form of eutrophication. If the level of nutrient loading is high enough, significant changes can occur to the species composition of the ecosystem, often leading to a simplification of ecosystem structure (that is, domination by one or a few species).[28] Severe eutrophication can lead to the formation of hypoxic zones, in which the dissolved oxygen concentration is below that necessary to sustain animal life.[29] Drastic changes to ecosystem structure normally occur. Regions where these zones are common include a portion of the Gulf of Mexico near the mouth of the Mississippi River and the Baltic Sea in northern Europe. In certain cases, hypoxic zones—such as those that seasonally occur on the west Indian shelf—release nitrogen oxide, a greenhouse gas.[30]

It remains to be seen how overfishing and eutrophication in concert will alter global biogeochemical cycles and the resulting global inventories of carbon, nitrogen, phosphorus, and silica. Despite the seemingly large capacity of marine ecosystems to assimilate the impacts of waste loading and overfishing, the imminent collapse of many coastal ecosystems is a warning that human and systemic global pressures may act synergistically to trigger large-scale regime shifts in global marine ecosystems.

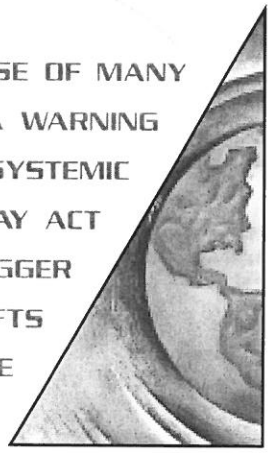
Abrupt Change in Human Systems

Critical thresholds and switches in the Earth System may also lie in the largely unexplored domain of interactions among climate and environmental change, socioeconomic development, and human and animal health. The preeminent feature of the Anthropocene era is that human activities have become a geophysical and biogeochemical force that rival natural processes. This implies that major discontinuities in the domain of socioeconomics may lead to corresponding disruptions in the biogeochemical/physical domain. Thus, abrupt socioeconomic changes could attenuate or amplify changes occurring in other aspects of the coupled human-environment system.

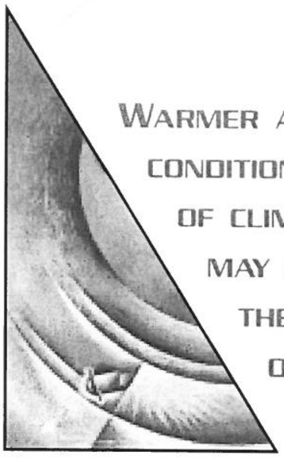
Abrupt changes in socioeconomic systems have occurred in the past. The archaeological and paleoecological records indicate that major shifts in societal conditions in the past often appear to have been linked with abrupt changes in the biophysical environment.[31] For example, despite land-use adjustments that sustained large populations in the central Maya lowlands for more than a millennium, recent evidence suggests that the magnitude of regional deforestation and overall land stresses may have challenged Mayan economic capacities.[32] This critical condition may have been tipped by climatic desiccation in the region, leading to the collapse of the classical period civilization and large-scale abandonment of the central lowlands in less than a century, beginning about A.D. 850–900.[33]

More recently, the rapid collapse of the former Soviet Union has led to significant feedbacks to the biophysical part of the Earth System. For example, the resulting sharp reduction of greenhouse gas emissions and changes in forestry management have affected carbon sources and sinks. Future disruptions of world trade and economic development could lead to abrupt changes in the structure of energy supply and production patterns, with significant implications for the Earth System. For example, a return to domestic coal use in some countries would increase emissions of sulfur aerosols and other particulate matter, affecting the biosphere *and* human health. Insufficient pace in economic development and its concomitant technological transitions in some regions (in southern Asia, for example) threaten to offset many of the environmental advances made elsewhere in industrial technology. This along with the continuation of materials-intensive patterns of consumption in other regions could lead to more abrupt changes in the human forcing on the Earth System.

THE IMMINENT COLLAPSE OF MANY COASTAL ECOSYSTEMS IS A WARNING THAT HUMAN AND SYSTEMIC GLOBAL PRESSURES MAY ACT SYNERGISTICALLY TO TRIGGER LARGE-SCALE REGIME SHIFTS IN GLOBAL MARINE ECOSYSTEMS.



One of the most important of such potential discontinuities is the spread of a new disease vector



WARMER AND WETTER CONDITIONS AS A RESULT OF CLIMATE CHANGE MAY FACILITATE THE SPREAD OF DISEASES.

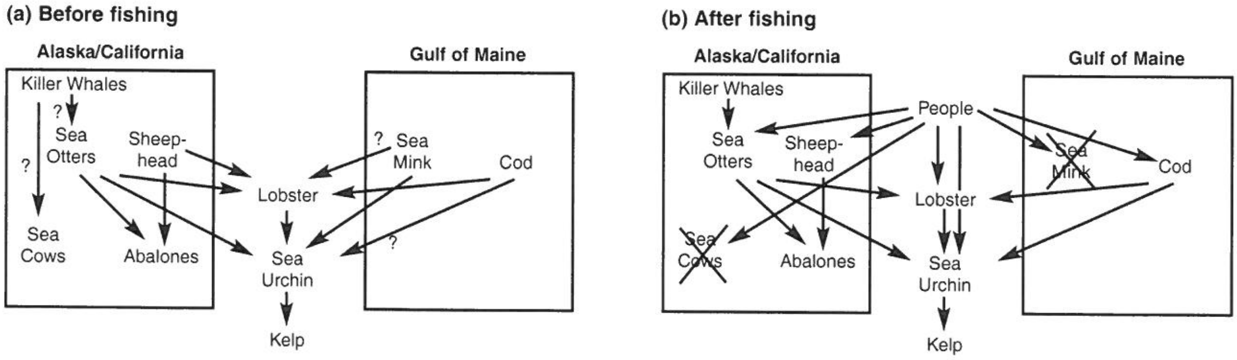
resulting in a pandemic. High population densities in close contact with animal reservoirs of infectious disease facilitate rapid exchange of genetic material, and the resulting infectious agents can spread quickly through a worldwide, contiguous, highly mobile human population with few barriers to transmission. The almost instantaneous outbreak of SARS (Severe Acute Respiratory Syndrome) in different parts of the world is an example of such potential, although rapid and effective action contained its spread.

Warmer and wetter conditions as a result of climate change may also facilitate the spread of diseases. Malnutrition, poverty, and inadequate public health systems in many developing countries provide large populations that are immune compromised with few immunological and institutional defenses against the spread of an aggressive infectious disease. An event similar to the 1918 Spanish Flu pandemic, which is thought to have killed 20–40 million people worldwide, could now result in more than 100 million deaths within a single year.[34] Such a catastrophic event, the possibility of which is being seriously considered by the epidemiological community, would probably lead to severe economic disruption and possibly even rapid collapse in a world economy dependent on fast global exchange of goods and services.

How robust is an increasingly interlinked, globalized world economy? It is urgent that this question be addressed. There will almost surely need to be significant increases in the future in the provisioning of resources, and despite technological advances, meeting these needs will have impacts on the Earth System. There is a high probability that droughts, floods, and severe storms will increase, and the probability is increasing that the more drastic, abrupt changes of the types described in this article could also occur. Coping with such stresses would take an increasing share of economic activity away from the evolution and growth of the economy in general. How many such stresses, occurring when and where, would it take for the global economic system to begin a downward, self-reinforcing spiral that would lead to a rapid collapse? Should such a collapse occur, it could lead to a significant and probably long-lasting change in the fundamental human-environment relationship.

Finally, the societal response to environmental problems is often slow (as opposed to responses to human health issues and the stock market, where panics are common). The situation is even more complex for abrupt changes, for which there may be little advance warning apart from a risk assessment from the scientific community. The response to the ozone hole via the Montreal Protocol, however, offers insights into those conditions that can foster a rapid, global

Figure 5. Change to coastal food webs due to overfishing



SOURCE: J. B. C. Jackson et al., "Historical Overfishing and the Recent Collapse of Coastal Ecosystems," *Science*, 27 June 2001, 184–87.

response. There was a startlingly brief interval of time between global public recognition of the role of CFCs in thinning the ozone layer in the stratosphere in the mid-1980s to the first iteration of the Montreal Protocol, which banned the use of ozone-depleting substances in 1987. The quick response involved public perception that this environmental change was harmful to human health, scientific agreement on the agent and cause of the change, and a technological solution (chemical substitutes) that did not require changes in societal behavior.[35] In this case, societal response was apparently sufficient to reverse the changes under way in the ozone layer. Other kinds of potential abrupt changes, however, may prove less amenable to such rapid and effective response, given the need for all three of the conditions above to be met.[36]

Conclusions

As more is learned about the nature of the Earth System, it is clear that abrupt changes may well be the most important aspect of global change in terms of impacts and consequences. Although there has been relatively little research to date on abrupt changes per se (apart from much work on the stability of the thermohaline circulation in the North Atlantic), a number of insights can be discerned from paleo-records and from complex systems theory. These can be summarized as follows:

• Abrupt changes in major features of Earth System functioning can occur and indeed have occurred. Prominent examples include the formation of the Antarctic ozone hole and the well-documented Dansgaard-Oeschger and Heinrich events in the North Atlantic region.

• Some of the 'switch and choke points' in the Earth System where abrupt changes can occur are already known.[37] In addition to the examples given above, the switching of northern African vegetation between savanna and desert and the potential melting of the Greenland ice sheet are further aspects of Earth System functioning in which abrupt changes can occur.

• Early indications of abrupt changes can sometimes be detected (as in the case of the Antarctic ozone hole) through careful analysis of data. However, such indications may often be overlooked as 'outliers' in the data.

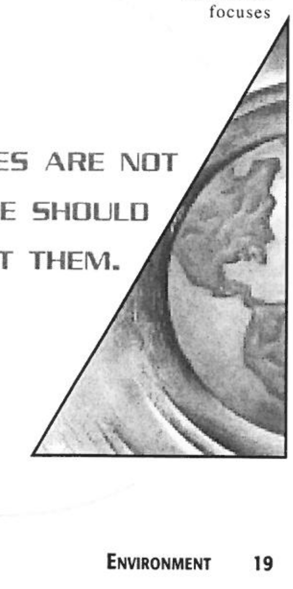
• It will not be possible to anticipate all of the potential abrupt changes in all components of the Earth System (climate, chemical, biological, human, and the interactions among all four). Thus, further surprises are not only possible; we should expect them.

• Even if a potential abrupt change is known to exist, it is more difficult to determine what triggers abrupt changes or how close a system may be to a threshold.

• Both the magnitude and rate of human forcing are important in determining whether an abrupt change is triggered in the Earth System. In general, the probability of abrupt changes in complex systems increases with the magnitude and rate of forcing.

• The Earth System as a whole in the late Quaternary period appears to exist in two states, glacial and interglacial, with well-defined boundary conditions in atmospheric composition (particularly in terms of CO_2, CH_4) and climate (as represented by the temperature over Antarctica inferred by the delta oxygen-18 (an oxygen isotope) record).[38] The controls on the boundary conditions are not known nor are the consequences of the large, human-driven excursion beyond these boundaries.[39] Model-based exploration of Earth System phase space cannot yet find another equilibrium state at a warmer, higher CO_2 level than the interglacial.[40]

Lead author Will Steffen is the executive director of the International Geosphere-Biosphere Programme (IGBP) in Stockholm, Sweden. His research focuses on Earth System science and the global carbon cycle. He is the coauthor and coeditor of two books, *Global Change and the Earth System* (Springer-Verlag, 2004) and *Challenges of a Changing Earth* (Springer-Verlag, 2002) and has contributed articles to numerous magazines and journals, including *Environment*, *Nature*, and *Science*. Steffen may be reached at will@igbp.kva.se. Meinrat O. Andreae is the director of the Max Planck Institute for Chemistry in Mainz, Germany. His research interests include biosphere/atmosphere interactions, biomass burning, and aerosol/cloud interactions. He may be reached at biogeo@mpch-mainz.mpg.de. Bert Bolin is professor emeritus at the University of Stockholm, where he focuses on global biogeochemical cycles, and climate research. He may be reached at bolin.bert@telia.com. Peter M. Cox is the head of climate, chemistry, and ecosystems at the Hadley Centre for Climate Prediction and Research, the Met Office, in Exeter, UK. He is a climate modeler with special expertise in the modeling of biospheric feedbacks on anthropogenic climate change. He may be reached at peter.cox@metoffice.com. Paul J. Crutzen is professor emeritus at the Max Planck Institute for Chemistry and and senior scientist at Scripps Institution of Oceanography at the University of California in San Diego. His current research focuses on the impact of atmospheric brown clouds on climate and hydrological cycles, especially in Asia. He was awarded the 1995 Nobel Prize in Chemistry with Mario Molina and Sherwood Rowland. Crutzen may be reached at air@mpch-mainz.mpg.de. Ulrich Cubasch is a professor at the Institute of Meteorology at the Freie Universität Berlin and an IPCC convening lead author. His research interests include climate variability and climate change. He may be reached at cubasch@zedat.fu-berlin.de. Hermann Held is a project leader for the Potsdam Institute for Climate Impact Research's Interdisciplinary Environmental Research program in Germany. His research interests include uncertainty propagation in Earth System models, integrated assessment of climate change mitigation options and risk assessment for environmental management. Held may be reached at held@pik-potsdam.de. Nebojša Nakićenović is a leader of the Transitions to New Technologies and Greenhouse Gas Initiative at the International Institute for Applied Systems Analysis in Laxenburg, Austria, and a professor of energy economics at the Vienna University of Technology. His research focuses



FURTHER SURPRISES ARE NOT ONLY POSSIBLE; WE SHOULD EXPECT THEM.

on technological change, long-term economic development, and climate change mitigation. He may be reached at naki@iiasa.ac.at. Robert J. Scholes is a Council for Scientific and Industrial Research Fellow with the Division of Water, Environment, and Forest Technology in Pretoria, South Africa. His research interests include systems ecology, particularly in relation to savannas and global change. He may be contacted at bscholes@csir.co.za. Liana Talaue-McManus is an associate professor at the University of Miami's Rosenstiel School of Marine and Atmospheric Science, Division of Marine Affairs, where she focuses on anthropogenic drivers of environmental change in the coastal zone. She has also worked on the application of coastal science in formulating policies for integrated resource management. She may be reached at lmcmanus@rsmas.miami.edu. B. L. Turner II is the Higgins Professor of Environment and Society at Clark University's Graduate School of Geography in Worcester, MA, and a member of the G. P. Marsh Institute. His research interests include human-environment studies and land-change science. Turner may be reached at bturner@clarku.edu. This article is adapted with permission from a group report from W. Steffen et al., "Earth System Dynamics in the Anthropocene," in H.-J. Schellnhuber, P. J. Crutzen, W. C. Clark, M. Claussen, and H. Held, eds., *Earth System Analysis for Sustainability, Dahlem Workshop Report 91* (Cambridge, MA: The MIT Press, forthcoming in 2004). Material has also been drawn from W. Steffen et al., *Global Change and the Earth System: A Planet under Pressure*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2004).

NOTES

1. Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis, Third Assessment Report of the Intergovernmental Panel on Climate Change 2001* [J. T. Houghton et al., eds.] (Cambridge, United Kingdom, and New York: Cambridge University Press), 739–68.

2. W. Steffen et al., *Global Change and the Earth System: A Planet Under Pressure*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2004).

3. P. Falkowski et al., "The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System," *Science*, 13 October 2000, 291–96.

4. M. E. Mann, R. S. Bradley, and M. K. Hughes, "Northern Hemisphere Temperatures during the Past Millennium: Inferences, Uncertainties, and Limitations," *Geophysical Research Letters* 26 (1999): 759–62.

5. L. W. Botsford, J. C. Castilla, and C. H. Petersen, "The Management of Fisheries and Marine Ecosystems," *Science*, 25 July 1997, 509–15.

6. P. Dickin, *Global Shift: Transforming the World Economy* (New York: Guildford Press, 1998).

7. P. Micklin, *Managing Water in Central Asia* (London: Royal Institute of International Affairs, 2000).

8. See, for example, P. M. Grootes, M. Stuiver, J. W. C. White, S. Johnsen, and J. Jouzel, "Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Cores," *Nature*, 9 December 1993: 552–54.

9. P. J. Crutzen, "The Ozone Hole," in Steffen et al., note 2 above, pages 236–37.

10. P. U. Clark, N. G. Pisias, T. F. Stocker, and A. J. Weaver, "The Role of the Thermohaline Circulation in Abrupt Climate Change," *Nature*, 21 February 2002, 863–69; and S. Rahmstorf, "Ocean Circulation and Climate during the Past 120,000 Years," *Nature*, 12 September 2002, 207–14.

11. There is no consensus yet on what triggers such switches, although one hypothesis invokes a process associated with stochastic resonance. See R. B. Alley, S. Anandakrishnan, and P. Jung, "Stochastic Resonance in the North Atlantic," *Paleoceanography* 16 (2001): 190–98; and A. Ganopolski and S. Rahmstorf, "Abrupt Glacial Climate Changes Due to Stochastic Resonance," *Physical Review Letters*, DOI: 10.1103/PhysRevLett.88.038501.

12. S. R. Hemming, "Heinrich Events: Massive Late Pleistocene Detritus Layers of the North Atlantic and Their Global Impact," *Reviews of Geophysics*, forthcoming.

13. S. Rahmstorf and T. F. Stocker, "Thermohaline Circulation: Past Changes and Future Surprises?" in Steffen et al., note 2 above, pages 240–41.

14. R. Knutti and T. F. Stocker, "Limited Predictability of the Future Thermohaline Circulation Close to an Instability Threshold," *Journal of Climate* 15 (2002): 179–86; and T. F. Stocker and A. Schmitter, "Rate of Global Warming Determines the Stability of the Ocean-Atmosphere System," *Nature*, 28 August 1997, 862–65.

15. Ramstorf and Stocker, note 13 above.

16. O. Anisimov, "Global Change and the Cryosphere: Impacts on Snow, Ice and Permafrost," in Steffen et al., note 2 above.

17. Ibid.

18. P. J. Crutzen, "The Ozone Hole," in Steffen et al., note 2 above, pages 236–37.

19. P. Crutzen, *My Life with O_3, NO_x and Other YZO_xs, Les Prix Nobel* (The Nobel Prizes) (Stockholm: Almqvist & Wiksell International, 1995), 123–57.

20. See M. Krol, P-J. van Leeuwen, and J. Lelieveld, "Global OH Trend Inferred from Methylchloroform Measurements," *Journal of Geophysical Research* 103 (1998): 10697–711.

21. R. G. Prinn et al., "Evidence for Substantial Variations of Atmospheric Hydroxyl Radicals in the Past Two Decades," *Science*, 8 June 2001, 1882–87.

22. M. Claussen et al., "Simulation of an Abrupt Change in Saharan Vegetation at the End of the Mid-Holocene," *Geophysical Research Letters* 24 (1999): 2037–40.

23. W. Cramer et al., "Global Response of Terrestrial Ecosystem Structure and Function to CO_2 and Climate Change: Results from Six Dynamic Global Vegetation Models," *Global Change Biology* 7 (2001): 357–73.

24. P. M. Cox, R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell, "Acceleration of Global Warming Due to Carbon-Cycle Feedbacks in a Coupled Model," *Nature*, 16 November 2000, 184–87.

25. S. R. Hare and N. J. Mantua, "Empirical Evidence for North Pacific Regime Shifts in 1977 and 1989," *Progress in Oceanography* 47 (2000): 103–45.

26. R. A. Myers and B. Worm, "Rapid Worldwide Depletion of Predatory Fish Communities," *Nature*, 15 May 2003: 280–83.

27. J. B. C. Jackson et al., "Historical Overfishing and the Recent Collapse of Coastal Ecosystems," *Science*, 27 June 2001, 629–37.

28. J. S. Gray, R. S. Wu, and Y. Y. Or, "Effects of Hypoxia and Organic Enrichment on the Coastal Marine Environment," *MEPS* 238 (2002): 249–79.

29. N. Rabalais, "Nitrogen in Aquatic Ecosystems," *Ambio* 31 (2002): 102–12.

30. S. W. A. Naqvi et al., "Increased Marine Production of N_2O Due to Intensifying Anoxia on the Indian Continental Shelf," *Nature*, 16 November 2000, 346–49.

31. K. Alverson, R. Bradley, and T. Pedersen, eds., *Paleoclimate, Global Change and the Future*, IGBP Global Change Series (Berlin and New York: Springer-Verlag, 2003).

32. B. L. Turner II, P. Klepeis, and L. Schneider, "Three Millennia in the Southern Yucatán Peninsular Region: Implications for Occupancy, Use, and 'Carrying Capacity,'" in A. Gómez-Pompa, M. Allen, S. Fedick, and J. Jimenez-Osornio, eds., *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface* (New York: Haworth Press, 2003), 361–387.

33. D. A. Hodell, J. H. Curtis, and M. Brenner, "Possible Role of Climate in the Collapse of Classic Maya Civilization," *Nature*, 1 June 1995, 391–94; and G. H. Haug et al., "Climate and the Collapse of Maya Civilization," *Science*, 14 March 2003, 1731–35.

34. P. Davies, *The Devil's Flu: The World's Deadliest Influenza Epidemic and the Scientific Hunt for the Virus that Caused It* (New York: Henry Holt, 2000).

35. P. M. Morrisette, "The Evolution of Policy Responses to Stratospheric Ozone Depletion," *Natural Resources Journal* 29 (1989): 793–820; and S. Schneider, B. L. Turner II, and H. Morehouse Garriga, "Imaginable Surprise in Global Change Science," *Journal of Risk Research* 1 (1998): 165–85.

36. National Research Council, *Abrupt Climate Change: Inevitable Surprises* (Washington, DC: National Academy of Sciences Press, 2002).

37. H. J. Schellnhuber, "Coping with Earth System Complexity and Irregularity," in W. Steffen, J. Jäger, D. Carson, and C. Bradshaw, eds., *Challenges of a Changing Earth: Proceedings of the Global Change Open Science Conference, Amsterdam, The Netherlands, 10–13 July 2001* (Berlin and New York: Springer-Verlag, 2002), 151–56.

38. J. R. Petit et al., "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica," *Nature*, 3 June 1999, 429–36.

39. C. D. Keeling and T. P. Whorf, "Atmospheric CO_2 Records from Sites in the SIO Air Sampling Network," in *Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory (ORNL), Trends: A Compendium of Data on Global Change* (Oak Ridge, TN: ORNL, 2000).

40. Falkowski et al., note 3 above.

Ordering Information

Orders must include the publication number and should be sent to the Publications Department, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria.

Telephone: +43 2236 807
Telefax: +43 2236 71313
E-mail: publications@iiasa.ac.at

A full list of IIASA publications is available at www.iiasa.ac.at/Publications

IIASA
International Institute for Applied Systems Analysis
Schlossplatz 1, A-2361 Laxenburg, Austria
Tel: +43 2236 807 Fax: +43 2236 71313
www.iiasa.ac.at