GLOBAL WARMING, CLIMATE CHANGE, AND SUSTAINABILITY

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Summary

The Earth's temperature is approximately 33°C warmer because of the presence of trace gases that trap radiant heat from escaping back into space. All of the natural greenhouse gases are growing in concentration from human activity and additional industrial gases are being added to the atmosphere. The "radiative forcing" from these added greenhouse gases is now equivalent to an increase by 0.7% in the solar energy reaching the earth's surface. The current rise in global average temperature since 1861 is estimated to be +0.6 ±0.2°C, and to lie outside the range of normal variance in the climate record for the

past 1000 years. The twentieth century and the decade of the 1990s have been the warmest during that millennium. The year 1998 was the warmest single year recorded since records were kept. It was 1.1°C warmer than the average expected temperature extrapolated from the 900 years before 1900. Many consequences of global warming and climate change have been measured, including lengthened growing seasons in northern latitudes, thinning arctic ice sheets, retreating glaciers, declining coral reefs, rising sea level, increased precipitation and droughts, and altered migration patterns of birds and mammals.

Each economic sector is analyzed for its contribution of greenhouse gases. Carbon dioxide from fossil fuel combustion is the most important, but other gases from industry, agriculture, and waste management also contribute significantly. Technical opportunities for reducing greenhouse gas emissions and their cost are identified, and policies and treaties designed to reduce greenhouse gases are described.

The implications of the potential changes in climate for human well-being are one measure of future sustainability. The mitigation options that are identified for each economic sector suggest ways in which economic and technological choices can improve the likelihood of sustainable development. To the extent that climate changes are irreversible and adversely affect future generations, the less sustainable are those choices and the greater will be the amount of adaptation required.

1. The Earth's Climate

1.1. Sustainability and Climate Change

Climate has played a dominant role in shaping human culture and the structure of civilization over the past 12 000 years. As the glaciers of the last ice age retreated, the climate became suitable for the domestication of a small number of plants and animals. The Neolithic revolution marked the birth of agriculture, and the construction of permanent settlements. These settlements in turn either joined together or were conquered to form kingdoms and empires. The ability of ever-growing human populations to survive has depended upon a relatively benign climate that has a sufficiently long growing season and adequate precipitation. Likewise, the manner in which appropriate shelter is constructed and most commerce and trade is conducted depends on a predictable and relatively stable climate. Even though the industrial revolution insulated some aspects of human activity from the vagaries of the weather, climate still plays a significant role in the form of the infrastructure of cities, power generation, and the transport system. If the climate is unstable, highly variable, or subject to wild swings in precipitation, drought, or storms, people and economies can become vulnerable.

The principle embodied in sustainability is that the current generation should meet its own needs without compromising the ability of future generations to meet theirs. A drastically or irreversibly altered climate system has the potential to compromise the ability of future generations to meet their needs if the climate system changes so that people will find it more difficult to grow food, protect themselves from weather-related events, or if they suffer more severe pollution, diseases, or pest infestations. Future generations will also be impoverished if there is a significant decline in the number of species or the population of plants and animals that survive under an altered climate system.

An additional equity issue is that the people who are most vulnerable to these changes are those who are poorer, and who depend on the reliable delivery of ecosystem services to provide goods and services such as food and shelter. While subsistence farmers, fishers, and forest dwellers might suffer the greatest consequences of climate change, they will have contributed the least to causing those changes. Adverse climate consequences are likely more severely to affect people in developing countries.

1.2. Climate Science

The earth's climate is determined by the interaction between the radiation received from the sun, and the distribution and transformation of that energy by the atmosphere, oceans, land-based (terrestrial) ecosystems, and ice and snow. The one constant of climate over millions of years is its variability. The geological record reveals that at various times the earth has been either warmer or colder, and sometimes wetter or dryer than it is now. The reason for the intense interest in climate and climate change is that there is evidence that human activities are directly and indirectly altering the earth's climate system. This article will attempt to summarize the state of knowledge about the earth's climate system, how human activities might be altering it, and the consequences of human-induced climate change both for natural systems and human society. This will conclude with a description of the technologies, policies, and measures that are proposed and that are being implemented to mitigate climate change, and to adapt to it. These efforts will be discussed in the context of sustainable development.

Climate is defined as a 30- to 40-year average of measurements such as average seasonal and annual temperature, day and night temperatures, daily highs and lows, precipitation averages and variability, drought frequency and intensity, wind velocity and direction, humidity, solar intensity, variability and cloudiness, and storm frequency and intensity. Global climate is the globally averaged set of all climate variables. Climate is therefore a 40-year average of daily weather events, and climate change is the change that takes place in the moving average of weather events and measurements. Global warming refers only to the change in average temperature of the planet. Often the terms global warming and climate change are used interchangeably, but climate change is much the more comprehensive of all the climate variables.

Understanding the complex planetary processes and their interaction requires the effort of a wide range of scientists from many disciplines. Solar astronomers carefully monitor the intensity of the sun's radiation and its variation. The current average rate at which solar energy strikes the earth is 342 watts per square meter (W/m^2). It is found that most of the visible light (168 W/m^2) reaches the earth's surface; 67 W/m^2 is absorbed directly by the atmosphere, while 77 W/m^2 is reflected by clouds, and 30 W/m^2 is reflected from the earth's surface.

As will be explained later, a number of trace gases in the atmosphere are transparent to the sun's visible light, but trap the radiant heat that the earth's surface attempts to emit back into space. The net effect is that instead of being a frozen ball averaging -19°C, earth is a relatively comfortable +14°C. This difference of 33°C arises from the natural greenhouse effect. Human activities appear to have increased the temperature by an additional +0.6 ± 0.2°C during the twentieth century. The French physicist Fourier coined the term "greenhouse effect" in 1827. The transmission of visible light from the sun and the trapping of radiant heat from the earth by gases in the atmosphere occurs in much the same way as the windows of a greenhouse or an automobile cause the interior to become much hotter than the surrounding outside air when it sits in the sun. The analogy is somewhat imperfect since glass also keeps the warm air from mixing with the cooler outside air.

Atmospheric scientists study not only the composition of the atmosphere, but also its circulation that distributes heat by wind and through the evaporation of water, and the melting of snow and ice. Oceanographers identify how oceans store heat and how ocean currents redistribute it throughout the globe. Terrestrial and other ecologists study how plants and soils absorb and emit greenhouse gases, and where industrial and agricultural emissions of greenhouse gases go.

Geologists identify past climate conditions by studying ice cores from glaciers, the ice caps of Antarctica and Greenland, examine ocean and freshwater sediments and coral reefs, and compare them with the findings of botanists who study ancient plant samples and currently growing trees. Planetary astronomers compare climate conditions on Earth with the climate and atmospheric composition and conditions of other planets such as Venus, Mars, and the moons of Jupiter and Saturn.

A consistent model has developed for explaining the general relationship between surface temperatures and the atmospheric composition and distance from the sun for most of these bodies. Finally, climate modelers build complex models of the earth's atmosphere, oceans, and land, and utilize information on human population, land-use patterns, and economic and technological projections to account for past and present climate and to project future ones.

Every five years since 1990, a group of nearly 2000 natural and physical scientists, economists, social scientists, and technologists assemble under the auspices of the United Nations sponsored Intergovernmental Panel on Climate Change (IPCC). These scientists spend nearly three years reviewing all of the information on climate change and produce a voluminous report following a public review by others in the scientific community and by governments.

Climate Change 2001 consists of three volumes that summarize and explain the scientific knowledge of the cause of climate change, its impacts, and the mitigation and adaptation options that are available to address it. This report is 2665 pages long and contains over 10 000 references.

Much of the information in this article uses this report and the references in it to assure accurate, up-to-date information. The IPCC also publishes special reports on forests, global warming scenarios, technologies, policies and measures, equity, and sustainable development.

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Biographical Sketch

William R. Moomaw is professor of international environmental policy at the Fletcher School of Law and Diplomacy, Tufts University, USA, where he directs the International Environment and Resource Policy Program. He teaches courses on international and environmental policy and the use of multidisciplinary methods to develop sound solutions to problems of sustainability. He received his B.A. at Williams College in chemistry and his Ph.D. in physical chemistry from the Massachusetts Institute of Technology. After 25 years carrying out research in photochemistry and spectroscopy, Dr. Moomaw shifted his research and teaching to policy science, translating science and technology of national and global environmental issues into policy-relevant terms. He was a coordinating lead author for the third Intergovernmental Panel on Climate Change in 2001 assessing the technological and economic potential for greenhouse gas reductions, and coauthored the *Summary for Policy Makers*. He was also a lead author for the industry chapters of the second assessment report in 1996, and recently chaired a long-range study of climate mitigation strategies for the Dutch government. In addition to his academic career that includes his roles as director of environmental studies at Williams College and of the Tufts Institute of the Environment, he also served as the first director of the Climate, Energy and Pollution Program at the World Resources Institute and as an AAAS Science Fellow working for the U.S. Congress on stratospheric ozone depletion and energy policy. He helped to found an NGO, Clean Air-Cool Planet, to effect real reductions in greenhouse gas emissions by corporations, institutions, and other members of civil society. He also serves on the boards of Earthwatch Institute, a science research and education organization in the service of conservation, and the Consensus Building Institute, an NGO devoted to finding sustainable, negotiated solutions to development environment conflicts.