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Environmental health implications of global climate change

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This paper reviews the background that has led to the now almost-universally held opinion in the scientific community that global climate change is occurring and is inescapably linked with anthropogenic activity. The potential implications to human health are considerable and very diverse. These include, for example, the increased direct impacts of heat and of rises in sea level, exacerbated air and water-borne harmful agents, and—associated with all the preceding—the emergence of environmental refugees. Vector-borne diseases, in particular those associated with blood-sucking arthropods such as mosquitoes, may be significantly impacted, including redistribution of some of those diseases to areas not previously affected. Responses to possible impending environmental and public health crises must involve political and socio-economic considerations, adding even greater complexity to what is already a difficult challenge. In some areas, adjustments to national and international public health practices and policies may be effective, at least in the short and medium terms. But in others, more drastic measures will be required. Environmental monitoring, in its widest sense, will play a significant role in the future management of the problem.


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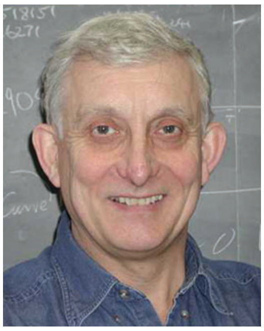
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1. Introduction

It is a recurring theme that science should play a strong role in environmental policy. Unfortunately, the nature of science does not always fit the popular picture held by society at large, which likes to believe that science can resolve complex issues by identifying precisely what will happen under a given set of circumstances. So, when science fails to provide definitive answers, public mistrust often arises. In turn, policy makers and politicians lose confidence in the ability of science to be useful to them. Meanwhile, incomplete science can be misused to support particular ideological viewpoints, and the tendency of the media to polarize issues can further distort perceptions about the state of knowledge. Paradoxically, when scientists try to respond by characterizing the scientific uncertainties, the public can become even more confused and mistrustful. It is in this atmosphere that the role of science in environmental policies may appear to be secondary to non-scientific factors.

The issue of global climate change, the role of human activity in such change, and the potential impact of climate change on the health of human populations is a prime example, and is of great public interest. Here, as elsewhere, policy makers must grapple with how to respond to potential threats and how to assess the relative costs and benefits. It is important to ensure that the debate is conducted through a balanced discussion of the basic science on the one hand and public policy on the other. How we handle the interface between these represents one of the greatest challenges ever in environmental management.

This paper reviews the important issues at hand, identifying the diverse approaches that are required in order to address this difficult problem.† Environmental monitoring in its widest sense is central, including not only the measurement of the levels of atmospheric gases and physical properties (notably temperature) that has long constituted traditional environmental monitoring but also the determination of indices that reflect the effects of relevant atmospheric changes (including changes in ecological systems, effects on populations, *etc.*), many of which lie outside the natural sciences.[1] The paper provides selected citations, and more extensive bibliographies are available in the report of the National Assessment Synthesis Team of the United States Global Change Program,[2] and in the Third Assessment Report of the Intergovernmental Panel on Climate Change.[3]

2. The science and politics of climate change

Global issues: WEHAB

Five development priorities were identified at the World Summit on Sustainable Development in Johannesburg, South Africa in August 2002: (a) water, where 1.3 billion people live without clean water and 2 billion without sanitation; (b) energy, where 2 billion people live without modern energy services, including electricity; (c) health, where 1.3 billion people are exposed to dangerous levels of outdoor pollution and about 2 billion to dangerous levels of indoor air pollution, and nearly all inhabitants of the earth are at some risk of infectious diseases; (d) agriculture, where 800 million people are currently malnourished; and (e) biodiversity, where genetic, species and ecosystem-level diversity is being lost at an unprecedented rate. These priorities, widely known by the acronym 'WEHAB', represent pressing environmental and development challenges, and are described in detail in the proceedings of the Johannesburg meeting.[4] Climate change is a key factor in all of them, and is emerging as a major threat in some. Climate change is a development issue in that it threatens the alleviation of poverty. It is also an inter- and intragenerational equity issue, since our actions today will affect future generations and countries that currently have no control over the factors that are influencing climate change. More broadly, environmental conditions (*e.g.*, air and water pollution and vector-borne diseases) contribute to about 20% of the global burden of disease in developing countries.[5]

The reality of climate change, and the associated role of anthropogenic activity have been debated at length in many forums. The scientific community has now established beyond doubt that a number of key indicators have changed markedly since the pre-industrial era. The first indicator is the rate of carbon dioxide emission to the atmosphere, for which emissions for the past 1000 years have been reconstructed[2*b*] from data assembled by Houghton and Hackler,[6] Houghton,[7] Marland *et al.*[8] and Andres *et al.*[9] (refer also to the Carbon Dioxide Information Analysis Center[10]). The results show a sharp increase in carbon dioxide emissions during the period since the industrial revolution, with as much as 80% associated with the combustion of fossil fuels and the rest with changes in land use. The second indicator is the concentration of atmospheric carbon dioxide. Analyses of air samples taken from Antarctic ice cores reflecting atmospheric conditions back as far as 420 000 years reveal sharp increases during the past 150 years in the atmospheric concentrations of carbon dioxide as well as methane and other gases.[11] The third indicator is the temperature of the atmosphere. Here, Mann *et al.*[12] used paleoclimatic records to reconstruct annual-average Northern Hemisphere surface temperatures, and showed an increase of about 1 °C over the past 150 years.

It is a scientific fact that such temperature changes can be driven by change in atmospheric level of carbon dioxide through the 'greenhouse effect'. This depends critically on the balance between the rates of emission of carbon dioxide and the rates of uptake by plants, soil and large bodies of water, as described by the 'global carbon cycle'. The unprecedented observed sharp increases in the atmospheric level of carbon dioxide provide evidence that this fine balance has been disturbed. The parallel rises in the three indicators mentioned above strongly suggest an association between the observed trends and human activity, most notably through the combustion of fossil fuels. In addition, climate models that only consider the impact of natural phenomena (*e.g.*, changes in solar activity and volcanic eruptions), cannot explain the observed changes in temperature. By contrast, models that include the observed increases in the atmospheric concentrations of greenhouse gases and aerosols simulate the observed changes in temperature, not only globally but also continentally. The current best assessment, therefore, is that the balance of evidence does indeed suggest a significant human influence on global climate. The strength of that view is increasing as more evidence emerges, as is reflected in the changing language contained in reports of authoritative bodies such as the IPCC. For example, in its earlier report of 1995, the IPCC[13] concluded that 'The balance of evidence suggests a discernible human influence on global climate', but later strengthened its position in 2001[3] to 'There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities'. In 1996, Bray and von Storch[14] surveyed more than 400 German, American and Canadian climate researchers and summarized responses to the statement '(it is) certain that, without change in human behavior, global warming will definitely occur sometime in the future'. The scientists surveyed rated this statement at 2.6 on a scale from 1 to 7, with 1 indicating complete agreement and

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† On March 26th 2004, a one-day symposium was organized at the University of Michigan, Ann Arbor, Michigan, to bring together a range of viewpoints, and provide a forum for discussion of the many facets of this complex issue. This symposium was the third in a series organized by the Department of Environmental Health Sciences in honor of the late Professor Isadore A. Bernstein, reflecting Professor Bernstein's keen interest and efforts in areas where the environmental health sciences and policy converge. This paper reflects the discussion that took place.

Fig. 1 Climate change is likely to cause decreases of precipitation over already arid regions. © Photodisc 2005.

7 indicating complete disagreement. Elsewhere, while Michaels and Balling[15] acknowledge the influence of human activity on the observed climate change, they argue that future climate change will be relatively small and 'within manageable bounds'. However, the vast majority of informed scientific opinion now leans towards the conclusion that global warming is indeed extremely serious—indeed, potentially catastrophic—and that the association with human activity is unavoidable.

Climate change and its impacts

Whatever the rationale, environmental monitoring over the past century or more for a wide range of climate-related indices confirms that climate change is a reality. We now know that the land and oceans have warmed during the past 150 years, by as much as 1 °C on average in large parts of the northern hemisphere. There are, however, just a few relatively small pockets; for example, in certain ocean regions in the southern hemisphere, where temperatures have fallen slightly. At the same time, precipitation patterns have changed significantly, with increases over some land masses in both the northern and southern hemispheres and decreases over the already arid regions in the subtropics (Fig. 1). The latter is most worrying in parts of Africa, compounding the already difficult situation embodied in the WEHAB framework. Meanwhile, records going back 300 years show that sea levels have risen by more than 200 mm since 1700, most of that since 1900 (*e.g.*, Woodworth[16]) (Fig. 2).

Climate models can be used to simulate past changes in climate, current conditions and projected changes in climate, incorporating chemical, physical, biological and meteorological processes embodied in the Earth's system, as well as the effects of anthropogenic emissions of greenhouse gases and aerosol precursors.[3] Projected changes in climate are based on the following changes between 1990 and 2100: (a) the world's population will rise from about 5.3 billion to between 7 and 15 billion; (b) the world's gross national product (GDP) will rise from 21 to between 235 and 550 $\times$ 10^{12} 1990 US$; (c) the *per capita* income ratio (developed/developing countries) will fall from 16.1 to between 1.5 and 4.2; (d) final energy intensity will fall from 16.7 to between 1.4 and 5.9 $\times$ 10^6 J US$$^{-1}$; (e) primary energy will rise from 351 to between 514 and 2226 $\times$ 10^6 J US$$^{-1}$; (f) the share of coal in primary energy will change from 24% to between 1 and 53%; and (g) the share of zero carbon in primary energy will rise from 18% to between 28 and 35%. Based on these assumptions, ranges of greenhouse gas emissions and associated changes in climate (with uncertainties) are projected. In particular, if emissions continue unabated, with continuing increases in carbon dioxide emissions, carbon dioxide atmospheric concentrations will increase from current levels (about 370 ppm) to between 540 and 970 ppm during the next 100 years, with a corresponding global average surface temperature increase between 1.4 and 5.8 °C. Land areas will warm more than the oceans, with the greatest warming at higher latitudes. In terms of precipitation, some areas will continue to be progressively wetter and others drier. There will be increases in severe weather, including more severe heat waves, less cold spells, more intense precipitation events in some areas and less in others, and increases in peak tropical cyclone wind and precipitation intensity. In turn, there will be intensified flooding in some areas and serious drought conditions in others. The inevitable consequences will be damage to property, loss of life and significant other impacts on human populations. And while some benefits likely will accrue in some middle and high latitude regions, there will be net significant adverse impacts to human health (including weather-related mortality, changes in the distribution of infectious diseases,

Fig. 2 Climate change is likely to cause rises of sea levels as the ice caps melt. © Photodisc 2005.

Fig. 3 Climate change is likely to cause greater extremes of weather. © iStockphotos 2005.

worsening air quality leading to respiratory disease, *etc.*), agriculture (including crop yields, irrigation demands, desertification, *etc.*), forestry (including forest composition, geographic range of forests, forest health and productivity, *etc.*), water resources (including water supply, water quality, *etc.*), coastal areas (including erosion of beaches, inundation of coastal land, *etc.*), and species and natural areas (including loss of habitat and species) (Fig. 3).

Climate change and WEHAB

In specific terms of the WEHAB framework, model simulations project that: (W) water availability and quality will decrease in many arid and semi-arid regions, with increased risk of floods and droughts; (E) the reliability of hydropower and biomass production will decrease in many regions; (H) the incidence of some vector-borne diseases (*e.g.*, malaria and dengue) and water-borne diseases (*e.g.*, cholera) will increase in some regions and some will decrease in others, and similarly for heat/cold stress mortality and nutrition threat, along with severe weather traumatic injury and death; (A) agricultural productivity will decrease in the tropics and subtropics for almost any amount of warming but will increase in temperate regions, and there will be an adverse effect on fisheries; and (B) many ecological systems (*e.g.*, coral reefs and mangroves) will be damaged and biodiversity adversely impacted, including the extinction of some species in some areas and introduction of undesirable exotic species in others.

State of policy formulation for climate change

What is 'dangerous anthropogenic interference' with the global climate system? The answer involves a value judgment determined not solely through science but invokes a socio-political process informed by technical and socio-economic information. Its basis varies by region and sector, and depends on the rate and magnitude of climate change on the one hand, and the available adaptive and mitigative capacity on the other. The 1997 Kyoto Protocol represents an attempt to produce a legal instrument associated with the United Nations Framework Convention on Climate Change to address the growing global threat associated with the emissions of greenhouse gases and their projected impact on the Earth's climate. Ratification requires the participation of 55 developed countries and an overall reduction of 55% of a set of industrialized greenhouse gas emissions. Europe, Japan, Canada and Russia have now ratified it, and it came into effect in February 2005. The United States and Australia declined to ratify from the outset. Arguments against ratification include the magnitude of the scientific uncertainties, the magnitude of the costs of compliance, and the perception in some quarters that the Protocol would not be fair. Nor would it be effective without the participation of the largest of the developing countries (*e.g.*, China and India). However, not withstanding the politics, it is inescapable that stabilization of atmospheric concentrations of carbon dioxide at any level between 450 to 750 ppm (compared to a pre-industrial level of 280 ppm and today's level of about 370 ppm) will eventually require significant reductions in global projected emissions much more stringent even than those required by the Kyoto Protocol.

3. Hot spots in climate change and health

As already noted, climate change has the potential to significantly influence the health of people around the world. The initial specific driving forces are temperature, hydrologic extremes and sea level rise. These in turn may lead directly to adverse impacts on public health effects in a range of aspects: extremes in heat, exacerbated air pollution, changes in vector-borne and water-borne diseases, water and food resources, and—ultimately—environmental refugees (Patz *et al.*[17]).

Heat and cold

The more than 20 000 deaths in Europe associated with the unprecedented heat wave of Summer 2003 provides a stark example of the direct role of temperature on the public health aspect of climate change. Even as far north as England, temperatures exceeded the 'magic' 100 °F day after day for the first time since records began, and even healthy people were adversely affected. Heat disorders encountered during such episodes include heat exhaustion (accompanied by headache, nausea, fainting, *etc.*) and, worse, heat stroke (where the body's thermoregulatory system fails and core temperatures rise to undesirable levels). While heat exhaustion responds rapidly to prompt treatment, heat stroke represents a medical emergency, and the people most likely to be adversely affected are the infirm or elderly. Those living in urban environments are at greater risk than those in rural ones, due to the phenomenon known as the 'urban heat island effect'. Here, it is well known that late-afternoon temperatures in large cities can be several degrees higher than in surrounding rural areas in the same region, and that this effect is increasing (*e.g.*, Streutker[18]).

Air pollution

Certain aspects of air pollution are exacerbated by higher temperatures, notably the formation of photochemical smog and ozone. Ozone is of special climate-related public health interest. As summarized by the United States Protection Agency (EPA), ozone associated with a wide range of adverse respiratory conditions, including non-specific respiratory effects (*e.g.*, airway irritation, coughing), reductions in lung function, aggravation of asthma in sensitive individuals, and the worsening of symptoms of individuals already suffering from emphysema and bronchitis (EPA[19]). In addition, prolonged exposures may lead to permanent structural and cellular damage to the respiratory tract. Data published by the EPA[2c] show that ground level ozone levels in large American cities (such as Atlanta and New York) may rise from 60 ppb at 20 °C to 180 ppb at 35 °C, of the same order as the 100 °F levels mentioned earlier. In relation to health effects in people, ozone levels between 80 and 120 ppb can significantly increase the risk of conditions like those mentioned, especially during even moderate outdoor exertion. At higher levels, health risks inevitably increase further. One factor in ozone production is the availability of volatile organic compounds (or VOCs), one significant source of which is biogenic (*i.e.*, coming from vegetation, trees, *etc.*). The release of VOCs from such sources is highly temperature sensitive.

Airborne allergens may also be significantly influenced by climate change. It has been shown that pollen counts rise with increasing temperatures (Tamura *et al.*, Ahlholm *et al.*).[20,21] In addition, increased atmospheric carbon dioxide provides enhanced 'fertilization' of pollens such as ragweed (Ziska and Caulfield, 2000).[22] Elsewhere, the increased flooding that may be one outcome of climate change may promote further growth of mold and fungal growth in affected areas, leading in turn to increases in associated respiratory ill-health.

Extreme climate-related occurrences can also contribute to air pollution. The forest fires in Malaysia and Indonesia in 1998 are now known to have been linked with the El Niño episode—and associated lack of monsoon rains—that year (Sastry[23]). As much as 7500 km^2 of forests were destroyed, and 300 million people were affected in six countries. Resultant atmospheric aerosol concentrations in the particle size range capable of inhalation into the lung exceeded levels considered to be hazardous, and the emission of greenhouse gases was greater than that for all cars and power plants in Europe in one year. Such air pollution is believed to have been responsible for over 260 deaths from respiratory diseases, along with diarrhea, skin disease and eye irritation. In addition, hospitals reported a 30% increase in outpatient attendance, and a 70% increase in patients with worsened symptoms of respiratory infections.

Water-borne disease

Water-borne diseases have long been considered to be a major public health problem throughout the world, especially in developing countries. In general, these include such serious diseases as cholera, cyclospora, cryptosporidiosis, campylobacter and leptospirosis. One of the effects of climate change is the increased incidence of local extreme weather episodes, including extreme precipitation events. For these, observations in the United States over the last 100 years indicate that precipitation events with more than two inches of rain in 24 hours have increased by about 20% (Karl and Knight[24]). Studies of precipitation in the 18 hydrological regions in the United States show a strong correlation between the incidence of the outbreak of water-borne disease and the occurrence of extreme levels of precipitation (in the upper 10-percentile and within a two month time lag) (Curriero *et al.*[25]). By way of illustration, one notorious such episode was the *cryptosporidium* outbreak in the city of Milwaukee, Wisconsin, in 1993 (Fox and Lytle[26]), with more than 400 000 cases reported, contributing to more than 100 fatalities. This outbreak was preceded by the heaviest rainfall in that area for 50 years, resulting in a large discharge of waste and storm overflow water. As this sort of episode is likely to increase during the expected continued climate change in the decades ahead, it is sobering that one study for an agricultural region in the United States showed that over 60% of livestock operations tested positive for crypto oocysts (the dormant form of cryptosporidium) in manure (Graczyk *et al.*[27]).

Fig. 4 Climate change is likely to facilitate the spread of vector-borne diseases. © USDA-ARS 2005.

Environmental refugees

Climate change along the lines discussed is already leading to significant rises in sea level. If it continues, this, along with extreme weather events, may cause the displacement of large populations by forced migration, leading to overcrowding elsewhere, along with associated human conflicts and rises in the level of infectious disease. Coastal populations are inevitably at the greatest risk, especially among poorer, developing countries that cannot provide the preemptive resources to handle such challenges. For example, in Bangladesh, nearly 20% of the land area would be lost from a 1 m rise in sea level, affecting over 10% of the population, while in Egypt, the corresponding figures are 13% and 10% respectively (Myers[28]).

4. The role of climate change in the 20th century resurgence of vector-borne diseases

General trends

Vector-borne diseases involve the transmission of infectious agents (viruses, bacteria and parasites) by hematophagous (*i.e.*, blood-sucking) arthropods such as mosquitoes (Fig. 4). Vector-borne parasitic diseases of concern during the latter part of the 20th and early 21st centuries included malaria (in South America, Southern Africa and Asia), leishmaniasis (in North America, North Africa and India) and trypanosomiasis (in Central Africa). Major epidemics of vector-borne bacterial diseases emerging during this period included Lyme disease (in North America and Europe) and plague (South America, Southern Africa and Asia). Major epidemics of vector-borne viral diseases during the same period included dengue (globally in the tropics), West Nile (North America, Europe and North Africa), eastern equine encephalitis (in North America), Japanese encephalitis (Asia and the Pacific), yellow fever (Africa and South America), Chikungunya (Asia), Rift Valley Fever (Africa and the Middle East), and many other lesser known viral diseases.

In the United States, the infection and death rates from vector-borne diseases of all types fell dramatically from about 800 to about 50 per 100 000 people during the 20th century. The same trend was observed in other developed countries, but was less marked in less developed countries that lacked the same levels of public health infrastructure. For the developed countries, however, the noted trend leveled off during the 1960s and 1970s, and actually increased in the last 25 years of the century. There are now concerns about the emergence of new vector-borne diseases, along with the resurgence of some that were previously controlled, along with expanded geographical distribution and increased epidemic activity. Certainly, major demographic and societal changes in the past 50 years are known to be main contributing factors to this resurgence of infectious diseases. But due to inadequate long-term health databases, it is unknown how global climate change has contributed to changing disease incidence in the past (Kovats *et al.*[29]).

Emergence or resurgence of vector-borne diseases

A number of vector-borne diseases have emerged for the first time or resurged as significant public health threats during the past 25 years. These include lyme disease, dengue and the more serious dengue hemorrhagic fever, yellow fever, Japanese encephalitis, West Nile virus, Alkhurma virus, a subtype of Kyasanur Forest disease virus, Venezuelan equine encephalitis, epidemic polyarthritis, Barmah Forest, Rift Valley fever, oropouche, California encephalitis and Crimean-Congo hemorrhagic fever.

Lyme disease, involving the infection of humans following an infected deer tick bite, has become a significant public health problem in the United States, especially in the northeast and upper Midwest. First identified in 1976, the number of reported cases has risen at an increasing rate, reaching more than 18 000 in 1980 (Steere *et al.*).[30] The mosquito-borne West Nile virus, first isolated in Uganda (in the West Nile district), until recently was distributed only in Africa, Europe, West and Central Asia, Australia and the Middle East. It was not documented in the Western Hemisphere until 1990, when 60 human cases were reported in New York City. The incidence of this illness rose sharply in the following years, and more than 9000 cases were reported to the Centers for Disease Control (CDC) in 2003, with 233 deaths. Since its introduction, there have been over 16 000 cases reported in the country.[31]

Dengue/dengue hemorrhagic fever occurs throughout tropical regions of the world. Epidemic dengue was first recorded in the late 1700s in Asia, Africa and North America. Although there were repeated epidemics, typically at intervals of from 10 to 40 years, the current global pandemic began in Southeast Asia during and after World War II, and has sharply intensified during the past two decades. In the 1950s, less than 10 countries reported cases of the more serious dengue hemorrhagic fever. But this number rose to 60 by the year 2000. During this time the total number of cases reported to the World Health Organization rose from less than 2000 to more than 500 000. South America is of special interest in this pandemic. The marked increase in number of cases there during the past three decades correlates strongly with the widening regional distribution of the mosquito species *Aedes aegypti*, the primary mosquito vector for this disease. By 2004, dengue has now become the most important mosquito-borne viral disease affecting humans. Its global distribution is comparable to that of malaria, and an estimated 2.5 billion people live in areas at risk for epidemic transmission.[32]

Many factors can be introduced to explain the increases that have been observed in these, and other, vector-borne diseases. These may include complacency on the part of governments and institutions, leading to changes in public health policy and decreased resources. In addition, there have been significant demographic changes, including unprecedented population growth and urbanization in many tropical developing countries, along with changes in agricultural practice, the introduction of modern transportation, modern technology and lifestyle changes. Further, at the biological level, microbial evolution and adaptation have given rise to pathogen strains that have greater virulence, epidemic potential and drug resistance. In the light of current debate about the changes that are taking place in the Earth's atmosphere, the role of climate change must also be considered.

Influence of climate change on vector-borne diseases

Vector-borne infectious diseases are maintained in complex transmission cycles that are influenced by many extrinsic and intrinsic factors. Local and global climate considerations are likely to be important. The specific climatic variables that can influence the distribution and incidence of vector-borne disease include temperature, rainfall patterns and extreme weather events. In turn, changes in these variables in the directions consistent with global warming trends may be expected to influence—more likely exacerbate—the emergence or resurgence of many vector-borne diseases like those described. For example, in one study carried out in Zimbabwe, a strong relationship between malaria and altitude was shown, where altitude was taken as a good surrogate for temperature (where the average temperature decrease with height was approximately 6 °C per 1000 m) (Taylor and Mutambu[33]). But, more broadly, can the influence of all the influential factors be predicted? Probably not. The potential disease impacts of climate variability are uncertain, and may be critical. Further, prediction—and ultimately prevention—appears to need a fuller understanding of the disease ecology than we have at present.

At the practical level, disease early warning systems cannot be based on climate forecasts alone, but must be developed with the active participation of the public health community. Here it is quite possible that the adverse effects of climate change on infectious diseases can in principle be accommodated, at least in the shorter term, by the development of good public health systems. So, even in the presence of significant climate change, which may indeed relate to the observed changes in the distributions and incidences of the various vector-borne diseases, changing threats could be neutralized by appropriate adjustments in public health infrastructure and practice. However, with the widespread current state of grossly under-valued (and under-funded) public health infrastructures around the world, major budgetary reprioritization would need to occur to achieve effective adaptive strategies. But, notwithstanding the reality of the role of climate change in the observed increases in some vector-borne diseases, it remains the case that the primary driving force behind the observed trends likely derives from a combination of demographic and societal changes.

5. Responses to the environmental health impacts of climate change

The challenge

The magnitude of the emerging climate change-related environmental problem requires discussion of how countries can respond, both now and in the future. Possible responses fall into four classes: (a) dealing with the effects of climate change, (b) identifying and dealing with the causes, (c) establishing processes to sustain and adapt both these types of efforts over the long periods required for managing climate change, and (d) trying to learn more. The projected impacts of climate change are diverse in character and severity, and are specific to particular places, people, and activities (Parson *et al.*[34]).

What does it mean to deal with the effects of climate change? The projected impacts of climate change are diverse in character and severity, and specific to particular places, people, and activities. They are likely to comprise some benefit (at least in middle and high latitudes for the modest changes projected over the next few decades), much harm (especially in developing countries), and many changes whose effects are mixed (*i.e.*, that benefit some places, people, and activities, and harm others). At present, best-guess climate-change impacts for temperate-latitude countries (like most of the United States and Europe) that are more or less rich and well-governed, are likely to be uncomfortable and disruptive, but far from catastrophic, at least over the 21st century. This does not apply, however, for less fortunate regions, where impacts are likely to be much more serious. Nor does it apply beyond this century, unless there are large, meaningful decreases in the emissions of greenhouse gases.

As reflected in the title of this paper, human health is one important domain of climate change-related environmental impacts. But there are other significant ones, including large-scale changes in the climatic conditions for agriculture, damages to coastal zones through loss of land to gradual sea-level rise, all exacerbated by storm surge and a potential increase in the intensity of tropical storms. In addition there will be shifts in the total quantity, regional distribution (and timing) of freshwater availability, with a particular risk of acute summer shortages in regions that depend on snow-fed rivers. Overall, there will be major disruption of natural ecosystems.

Peoples have long adapted to changes in climate, including by adjustment of settlement patterns, building, resource use, livelihoods and infrastructure. There is the implicit expectation that such adaptation will continue indefinitely. However, with the increasing capability to predict climate changes, there exists the opportunity to do better than just adapting in response to changed conditions as and when they emerge. Better, we are now able to anticipate projected changes well into the future, and so to integrate them into decisions, including investment and policy decisions at all levels, that have longer-term consequences (*e.g.*, zoning and development plans, building infrastructure criteria, re-definition of '100-year flood' areas, *etc.*). In that time scale, there are many ways that government policy can be proactive in promoting effective and better-informed adaptation, thus contributing directly to remediation of the various impacts. However, it is important to recognize that the projected changes in the rate and magnitude of temperature are greater than any observed in the last 10 000 years, and many sectors are maladapted to current climate variability. Most developing countries do not possess the financial, technological or institutional capabilities to deal with current climate variability, let alone adapt to changing climatic conditions. So they are the ones most vulnerable to the projected changes in climate.

Many things can be done to limit the adverse health effects of global climate change, most through public health measures that reduce the general vulnerability of people to environment-related health risks, whether or not related to climate change. But there are other measures that may be taken to reduce vulnerability of people specifically to climate-change impact, including reduction of poverty and promotion of economic development and the degree of dependence of poor communities on subsistence agriculture (particularly in climatically marginal regions), and to strengthen emergency preparedness and response systems. Some of these are easy to say but much harder to actually accomplish. Nonetheless, consideration of the potential impact of climate change provides a significant additional reason to do things that are already beneficial on other grounds.

But, however effectively adaptation measures are pursued, they are unlikely to be an adequate response to the threat of climate change by themselves. Although the precise rate, nature and impacts of climate change are uncertain, the judgment that future impacts will be within the range that countries can adequately adapt to is much less supportable if changes lie near the upper end of the range of present projections, or if any of the potential mechanisms of abrupt, larger changes should be realized. The scope for adaptation is also limited by the fact that adaptation measures bring predominantly private benefits. Individual households and firms do them for their own perceived self-interest, and governments at all levels do them for the perceived welfare of their own citizens. Because people and communities vary greatly in their likely capacity for adaptation, an adaptation-only response will mean abandoning those with the least capacity to their own, limited, resources. Moreover, even in places that appear to have ample capacity to adapt, there is even evidence of maladaptation to climatic conditions. In one example, peoples throughout the world continue to build in locations that are highly vulnerable to flood and fire, and even repeatedly re-build there after property is destroyed. In another example, intensive agriculture in semi-arid regions in many countries, where there are high levels of dependence on the unsustainable extraction of groundwater, continues regardless. It is hoped that, in the future, with improved knowledge and wider discussion, peoples will better adapt to future changes.

Overall, any coherent response to the climate change issue must involve major efforts directed towards addressing both effects and causes. The real questions of how to manage climate change relate to how to maximize the effectiveness of each of these types of effort, and how to choose, and adjust over time, the precise margin of allocation of effort between the two.

Reduction of emissions

Based on the now-overwhelming weight of scientific opinion linking the changes in the earth's temperature in the past few decades with human activity, a significant part of the approach for dealing with the causes of climate change, and in turn the impacts, involves taking meaningful measures to reduce greenhouse-gas emissions. As stated earlier, this was the goal of the 1997 Kyoto Protocol. So, stabilizing the global climate will require a large reduction in future emissions through the deployment of low-emitting and (preferably) non-emitting energy technologies. One approach to the problem would be to set long-term targets. For example, we might aim to limit the rate of change of global mean surface temperature to 0.2 °C per decade, and to limit the equilibrium average temperature change to 2 °C above the pre-industrial level. Probability analyses suggests that limiting warming to 2 °C above the pre-industrial level with a relatively high certainty requires the equivalent concentration of CO_2 to stay below 400 ppm. Conversely, if concentrations were to rise to 550 ppm, then it is unlikely that global mean temperatures would stay below 2 °C above the pre-industrial level. It is generally believed that energy production and use technologies of today, with some evolution, can put us on the right track until about the year 2050. A broad portfolio of energy production technologies including fuel switching (coal/oil to gas), increased power plant efficiency, carbon dioxide capture and storage, pre- and post-combustion, and increased use of renewable energy technologies (*e.g.*, biomass, solar, wind, run-of-the-river and large hydropower, geothermal, *etc.*) and nuclear power, complemented by more efficient use of energy in the transportation, buildings and industry sectors, is currently available to reduce greenhouse gas emissions. But significant further improvements will be needed after 2050, and hence there is an urgent need for an aggressive energy research and development program. This will be challenging, but the setting of such targets would send a strong signal to the private sector and governments that there will be a market for technologies that efficiently produce and use energy. Mid-range projections suggest that the required supply of new, non-emitting energy sources by the middle of the century will be at least as large as the present total world energy supply. Stabilization of carbon dioxide equivalent concentration at or near 450 ppm requires emission cuts to begin immediately using today's technologies, but must be supported by investments in new technology and the development of policy-based incentives to support climate-friendly technologies.

Politically, there is the inevitable question of equity and the fair allocation of emissions rights. There are several options, each with their own political difficulties. In these, emissions would be permitted: (a) in proportion to current emissions—unlikely to be acceptable to developing countries; (b) in proportion to GDP—also unlikely to be acceptable to developing countries; and (c) *per capita* emissions rights—unlikely to be acceptable to developed countries. A possible solution might be some form of 'contraction and convergence' whereby total global emissions are reduced over time (*i.e.*, contraction) and the *per capita* emissions of developed and developing countries are made to converge over a suitably long time period. In addition, international 'carbon trading' between countries—that is, agreement to offset increases in carbon emissions by one country with corresponding decreases by another—may provide some flexibility.

There is a wide range of projected costs for implementation of the Kyoto Protocol and to ultimately stabilize the atmospheric concentrations of carbon dioxide. The long term costs of stabilization of carbon dioxide at 450 ppm will have a negligible effect on the growth of global GDP. The cost of stabilization depends on the stabilization level, the baseline emissions scenario, and the pathway to stabilization. The reduction in projected GDP increases moderately when passing from a 750 ppm to a 550 ppm concentration stabilization level, but with a much larger increase in passing from 550 ppm to 450 ppm. The percentage reduction in global average GDP over the next 100 years for stabilization at 450 ppm ranges from about 0.02 to 0.1% per year, compared to annual average GDP growth rates of between 2 and 3% per year.[3] Current estimates of the cost of stabilizing greenhouse-gas concentrations to about twice the pre-industrial level range from less than 1% to about 8% of the global GDP. If future economic growth averages 2% per annum, even a cost this large can be understood as simply delaying future GDP increases by only 1 to 3 years. The ultimate actual costs will depend on many assumptions, the most important concerning factors determining the rate and character of future emission-reducing technological innovations. The most hopeful prospect, once mitigation efforts and associated incentives to develop and apply new technologies are in place, lies in the possibility of positive feedbacks in emission-reducing innovation. Experience with many other environmental issues (*e.g.*, eliminating stratospheric ozone-depleting chemicals), suggests that innovations substantially reduce the costs of meeting environmental targets once they are adopted. In that event, projections of costs made in advance—including possibly the present cost estimates for stabilizing greenhouse-gas concentrations—may well be overestimates. In addition, many of the technologies that reduce greenhouse gas emissions yield ancillary human health benefits through the reduction of local and regional air pollutants (Fig. 5).

Fig. 5 Technologies that reduce greenhouse gas emissions yield ancillary human health benefits through the reduction of local and regional air pollutants. © Photodisc 2005.

Policy in the light of uncertainty

Inevitably there is uncertainty about climate change and all of its potential impacts. As noted earlier, there now remains little credible scientific argument about global warming itself, or counter to the prediction that global warming will continue through most or all of the 21st century, even regardless of future carbon dioxide emission trends. However there remains considerable uncertainty about the actual rate of warming we can expect, the consequences for climate and weather changes in specific places, and the precise nature and magnitude of the environmental health and other impacts. Nonetheless the magnitudes and ranges of the uncertainties do not argue against the need for an urgent and vigorous effort to reduce future emissions. Steps to limit emissions will greatly influence where in the predicted range future warming will actually lie. It should be noted, however, that even the bottom of the range indicated represents a doubling of the warming observed over the previous century, and would very likely bring substantial disruptive impacts across the whole spectrum of possibilities, including environmental health. Global warming towards the upper end of the projected estimates would be much worse and carry the risk of very serious impacts, as well as an increasingly serious risk of unanticipated abrupt climate instabilities. Another uncertain factor that should be taken into account is the inertia in the Earth's response system. Once a change in the Earth's climate occurs, even with draconian reductions in greenhouse gas emissions, the time for the climate to recover may well be in the hundreds to thousands of years.

Some use the generic presence of uncertainty in climate-change to deflect calls for action by requesting 'further research'. Such arguments seek to invoke the standard of evidence or demonstration used in Western criminal trials; that is, 'guilt' must be demonstrated 'beyond a reasonable doubt'. However, given the complexity of the climate system, this would mean not accepting the reality of any climate change until it had actually happened, renouncing any attempt to forestall future risks. Clearly this standard of demonstration is inappropriate for managing environmental or public health risks. The '*precautionary principle*' that—it is widely argued—should underpin all considerations of the environment states that, where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.

Risk management

In the practical management of environmental risks, it is necessary to balance the likelihood and costs of various degrees of impact with the cost of remediation efforts. But in the case of global climate change, given the high risks associated with high-emission futures, the sensible balancing of risks, costs and benefits makes a particularly strong case for serious mitigation efforts. In view of the long lags in atmospheric and ecosystem responses, these should begin as soon as possible, consistent with the Kyoto Protocol, and globally within the next 10 to 20 years. These efforts should be tackled through a combination of: (a) emissions reductions using current technologies; (b) support for energy-technology research and development, and (c) deployment of incentives through efficient policies such as tradable emission permit or emission tax systems. They must eventually be coordinated internationally, beginning with a smaller 'coalition of the willing'.

Importantly, no individual technology or policy will achieve the effort that will be needed over many decades. Rather, processes are needed that will trigger and support sustained efforts to better understand both causes and effects over many decades, and to adapt these in response to evolving new scientific knowledge about climate-change and its impacts, along with technological, institutional, and social capacity for mitigation and adaptation. Through all this, it is important that overall risk management should be through an integrated approach, one that involves not only the reduction of greenhouse gas emissions but also efforts to control the sizes, distributions and behaviors of populations, along with reductions in deforestation and illegal land use.

Continuing need for new knowledge

The final component of the response to climate change is the continued search for improved knowledge, in part to further narrow uncertainties and in part to expand technology research aimed at developing non-emitting alternatives to present energy systems. Learning more and applying what is learned to inform future decisions will require not just scientific research, but also ongoing scientific assessment by which to provide reliable commentary on the state of scientific knowledge in order to properly inform policy debates, thus forming a bridge between science and political decision-making. With enough participating experts of appropriate and recognized stature, and a sufficiently clear and fair deliberative process, such assessment processes can make statements of scientific knowledge that may come to be treated as authoritative by most or all participants in policy debates.

6. Overview

It is now widely agreed that climate change, loss of biodiversity, and land and water degradation threaten poverty alleviation and sustainable economic growth. In the scenario that has been described, industrialized countries are primarily the cause of human-induced climate change, but developing countries are the most vulnerable. But it is reasonable to expect that, provided that political will and moral leadership are brought to bear, cost-effective and equitable solutions can be found. However it is important to ensure the development and implementation of more effective disease prevention strategies and public health infrastructures, involving improved community-based preventive medicine, health education, control of communicable diseases, application of sanitary measures and environmental monitoring.

There is significant evidence, some of it summarized in this paper, that changes in the health of peoples around the world, as reflected in a number of health-related indices, may be plausibly associated with climatic changes like those described. The responses to what appears to be a growing climate-related global health problem will need to include arresting the driving force. In the first instance that will require a significant reduction of anthropogenic emissions that underlie the rise in atmospheric concentrations of carbon dioxide and other greenhouse gases, in turn limiting the rise in global temperature. This will need full participation in international agreements (such as the Kyoto Protocol) to reduce emissions. But, in addition, for many of the health effects mentioned, much can be achieved by individual governments by the development and application of appropriate and responsive public health, governmental and administrative procedures. In the United Kingdom, for example, it is thought that any emergence and spread of vector-borne diseases such as malaria can be prevented by appropriate public health infrastructure (Hunter[35]).

Overall, the study of the problem of climate change and its impacts on human health, and in turn the development of workable policies for corrective actions by the nations of the world, will require a concerted multidisciplinary approach to environmental monitoring and surveillance. This will include monitoring in its widest sense, including not only measurement of the chemical and physical properties of the atmosphere and pollutants within it, locally and globally, but also the responses of biological systems to changing climatic conditions, and the dynamics of the health and well-being of human populations. The latter would include the application of epidemiology to associate human health effects with changing environmental factors. This is far from what may be traditionally thought of as environmental monitoring, and may include the monitoring of population-based indices such as, for example, the rates of mortality associated with specific illnesses, hospital admissions, insurance claims, *etc*. But it is an important reflection of the widening disciplinary spectrum within environmental science—and environmental monitoring.

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