IJOEM International Journal of Occupational and Environmental Medicine

Review

Global Climate Change and Infectious Diseases

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Abstract

Climate change is occurring as a result of warming of the earth's atmosphere due to human activity generating excess amounts of greenhouse gases. Because of its potential impact on the hydrologic cycle and severe weather events, climate change is expected to have an enormous effect on human health, including on the burden and distribution of many infectious diseases. The infectious diseases that will be most affected by climate change include those that are spread by insect vectors and by contaminated water. The burden of adverse health effects due to these infectious diseases will fall primarily on developing countries, while it is the developed countries that are primarily responsible for climate change. It is up to governments and individuals to take the lead in halting climate change, and we must increase our understanding of the ecology of infectious diseases in order to protect vulnerable populations.

Keywords: Climate change; Infectious disease medicine; Greenhouse effect; Ecology; Disease vectors; Malaria; Dengue; West Nile fever; Diarrhea; Cholera

Introduction

Climate change

In general, climate change occurs as a result of imbalance between incoming and outgoing radiation in the earth's atmosphere.[1] Solar radiation enters the atmosphere, some of which is absorbed by the earth's surface and re-emitted as infrared radiation. Greenhouse gases—primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—in the atmosphere from both naturally-occurring and human sources, absorb infrared radiation, generating heat and therefore warming the earth's troposphere (the lower portion of the atmosphere). Fluctuations in the temperature of the troposphere have occurred over time due to variations in concentrations of the naturally-occurring greenhouse gases in the earth's atmosphere. However, emissions from human activity now contribute substantially to the concentration of greenhouse gases in the atmosphere. CO_2, which accounts for 81% of greenhouse gas emissions, is produced from combustion of petroleum products, natural gas, and coal (the fossil fuels).[2] The other primary greenhouse gases include CH_4 (10% of emissions), which comes from landfills, coal mines, oil and natural gas operations, and agriculture; and N_2O (5% of emissions), which results from use of nitrogen fertilizers, burning of fossil fuels, and industrial and waste management processes. In addition to emissions, deforestation has contributed about 15%–20% of greenhouse gas concentrations in the atmosphere, as plants are the primary storers of CO_2.

There is now convincing evidence that human activity has indeed led to warming of the earth's troposphere with resulting global climate change. Based on studies of trapped air bubbles in Antarctic ice, we

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Table 1: Important examples of infectious diseases transmitted by insect vectors.[5, 6, 8]

Infectious disease	Causative micro-organism	Insect vector	Geographic distribution	Percent of world population currently at risk	Nature of illness
Malaria	Plasmodium species	Mosquito (Anopheles species)	Sub-Saharan Africa, Southeast Asia, Central and South America	45%	Destruction of red blood cells, severe illness or death in those with limited immunity (*e.g.*, young children)
Dengue fever	Dengue fever virus	Mosquito (Aedes species)	Tropical areas worldwide	40%	Fever, rash, joint pain, can lead to severe bleeding and death
West Nile virus infection	West Nile virus	Mosquito (Culex species)	Essentially worldwide	N/A	Often asymptomatic but can cause encephalitis

know that atmospheric levels of greenhouse gases have increased more rapidly since the mid-1800s (corresponding with the beginning of the human industrial age) than at any point in the preceding 10 000 years.[3] Since the pre-industrial era, mean CO_2 concentrations in the atmosphere have increased from 280 to over 380 parts per million. At the same time greenhouse gas concentrations in the atmosphere have reached record levels, global temperatures have risen at a faster rate than at any time since records were kept starting in the 1850s, with a gain of 0.6 °C since the 1950s.[4] If CO_2 emissions remain at current or projected levels, global temperatures are expected to rise on average an additional 1.8–5.8 °C by the end of the 21st century. As a result, ocean temperatures will increase as well, and sea levels will rise by 9–88 cm as sea ice melts. The hydrologic cycle will be disrupted due to the ability of warmer air to retain more moisture. Some areas will see more rainfall and some drought, and severe weather events including heat waves and storms are expected to become more common. Between 1951 and 2000, about 3.3% of the earth's surface changed from one climate category to another, with an overall loss of polar and boreal (northern coniferous forest) climates and an increase in arid (dry) climates, and this trend is largely expected to continue. Because of the potential for changing rainfall patterns and severe weather events, climate change is expected to have a significant impact on human health, particularly with regard to certain infectious diseases.

Important vector-borne and water-borne infectious diseases

Many infectious diseases of humans are transmitted by insect vectors. These infections typically cannot be transmitted directly from person to person and result in a wide range of clinical illness. Many vector-borne diseases such as malaria are also considered to be water-borne since transmission is associated with factors such as rainfall which will be discussed further later in this article. Important examples of vector-borne infectious diseases are outlined in Table 1.

The global health impact of vector-borne diseases, particularly malaria and dengue fever, is tremendous. Currently, 300–500 million people worldwide develop malaria annually, of whom one million die.[5] Ninety percent of the deaths occur in Sub-Saharan Africa, and malaria causes one out of every five childhood deaths in Africa. While malaria is an ancient human disease, dengue fever became widespread only in the middle of the last century.[6] This disease now affects 50–100 million people annually, with 500 000 developing the most severe form of the disease—dengue hemorrhagic fever. There are 22 000 deaths annually due to dengue fever, most of which occur in children.

Many infectious diseases are transmitted by ingestion of, inhalation of, or contact with contaminated water. These infections can also lead to a wide range of clinical illness, but herein we will only focus on infections causing diarrheal disease since this is currently the second leading cause of death among children under the age of five worldwide.[7] Important examples of water-borne infectious causes of diarrheal disease are outlined in Table 2.

Climate Change and Infectious Diseases

General impact of climatic conditions on infectious diseases

Before humans understood that microorganisms caused epidemic diseases, they knew that these diseases were intimately related to climate. For example, ancient Romans retreated to cooler hillside resorts in the summer to avoid malaria.[9] We now have an understanding as to why epidemics of infectious diseases are strongly tied to climate. For those infectious diseases transmitted by insect vectors, we know that vectors are more active at higher temperatures.[10] Tropical species of mosquitoes such as *Anopheles* require temperatures above 16 °C to complete their life cycles, and malaria parasites are able to develop more rapidly within mosquitoes at higher temperatures (>20 °C). In the case of malaria due to *Plasmodium falciparum*, one mosquito can infect 200 individuals if temperature conditions are ideal, allowing for rapid spread of the disease. Vector-borne diseases such as malaria are also thought of as water-borne diseases, since mosquitoes typically thrive in aquatic habitats, where they lay their eggs in water-filled containers. Thus, epidemics of malaria and dengue fever tend to occur annually during rainy seasons in the tropics and inter-annually after weather events such as those associated with El Niño-Southern Oscillation (the warm phase in the atmospheric temperature oscillation over the

Table 2: Important waterborne infectious causes of diarrheal disease.[7]

Type of Microorganism	Examples
Bacteria	*Escherichia coli, Vibrio species* (including *V. cholerae*, which causes cholera), *Campylobacter, Salmonella, Shigella*
Viruses	Norovirus
Parasites	*Cryptosporidium, Giardia, Entamoeba histolytica*

TAKE-HOME MESSAGE

- Greenhouse gases—primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—in the atmosphere absorb infrared radiation, generating heat and therefore warming the earth's troposphere.
- Climate change is expected to have a significant impact on human health, particularly with regard to certain infectious diseases.
- Some diseases are tied to climate such as malaria, dengue fever, diarrheal disease and cholera. Therefor, international efforts should be aimed at stopping climate change and developing early warning systems that may allow populations to prepare for such epidemics in advance.

tropical Pacific Ocean). On the other hand, epidemics of the mosquito-borne West Nile virus infection can occur during times of drought. This happens because mosquitoes and birds—the primary hosts of the virus—are brought into close proximity at scarce water sources, enhancing transmission of the disease between mosquitoes and birds (and thus to humans). In addition, natural predators of mosquitoes are greatly reduced during times of drought as wetlands dry up.

Like vector-borne diseases, water-borne diseases are also strongly impacted by climate, particularly the effect of climate on the hydrologic cycle. During times of drought, water scarcity results in poor sanitation and exposure of much of the population to potentially contaminated water. For example, an epidemic of cholera occurred in late 2009 in northern Kenya after a severe drought, with over 4700 cases reported in one month, including 119 deaths.[11] The mainstay of treatment for diarrheal disease such as cholera is rehydration, which further exacerbates the situation due to the lack of adequate potable water available for this purpose. Excess rainfall and flooding, like drought, can also contribute to epidemics of water-borne infectious diseases, in this case due to poor sanitation resulting from run-off from overwhelmed sewage lines or contamination of water by livestock. An example is the 1993 outbreak of diarrheal disease due to *Cryptosporidium* in Milwaukee, Wisconsin after heavy spring rains.[12] In this outbreak, there were over 403 000 reported cases, demonstrating how widespread diarrheal disease can become when community water sources become contaminated.

Current impact of climate change on infectious diseases

We currently know more about the effect of climate change on the distribution of animals and plants than on infectious diseases.[10] In general, species ranges have shifted away from the poles and the equator and toward higher altitudes. However, these changes cannot be attributed entirely to climate change, as habitat destruction played an important role as well. At the same time, it is difficult to determine what impact climate change has had thus far on the distribution of infectious diseases, as many other factors play a role as well. Important examples of such factors include extensive travel and migration of human populations, drug and pesticide resistance, urbanization and increased population density, and availability of health services. In particular, health services tend to break down in the setting of natural disasters, making it more difficult to determine if epidemics following such disasters are related to the event itself or to poor delivery of health care.

Despite our fairly limited knowledge, there are some widely cited examples demonstrating that climate change has indeed resulted in the introduction of certain infectious diseases into previously unaffected areas. One such example is the spread of malaria beginning in the 1950s into highland regions of East Africa where this disease previously did not exist.[13] This occurred in the setting of much warmer and wetter weather than usual, although deforestation was also occurring at the same time, which may have contributed somewhat to the warming trend. During the same time as the expansion of malaria into the African highlands, there was a sharp reduction in the prevalence of malaria in the Sahel, an arid region of West Africa which was experiencing a particularly severe drought.[14] Thus, climate change may not always result in overall expansion of tropical infectious diseases, but rather may be followed by shifts in geographic ranges. In the case of malaria in the highlands of Africa, this geographic range shift resulted in high morbidity and mortality due to introduction of the disease into a largely non-immune population.[13]

While it is helpful to examine specific case studies such as those detailed above, it is also useful to look at the effect of climate change on human health thus far on a more global scale. In 2002, the World Health Organization (WHO) released data from a statistical model regarding the impact of climate change on human health as of the year 2000.[9] The aspects of climate change considered in the model included direct effects of heat and cold, drought and famine, population displacement due to natural disasters or resource shortages, breakdown of health infrastructure in natural disasters, and conflict over scarce resources. The health outcomes examined were diarrheal disease, vector-borne disease (specifically, malaria), malnutrition, and injury due to natural disasters. Outcomes were measured in disability-adjusted life years (DALY)—a commonly used measure which includes years of life lost and years of life lived with disability. The outcomes are summarized in Table 3.

What is readily apparent from these data is that developing regions of the world have been dramatically affected by climate change in comparison with developed countries. This stands in stark contrast with CO_2 emissions, which are accounted for almost entirely by developed countries such as the US and countries with rapidly developing economies such as China and India. According to the most recent data from the United Nations (UN) Millennium Development Goals in 2006, developing regions (excluding China and India) pro-

Table 3: Global health outcomes due to climate change as of the year 2000, expressed in disability-adjusted life years (DALYs).[9]

Region	Total DALYs (1000s)	DALYs/million population
Africa	1894	3071.5
Southeast Asia	2572	1703.5
Eastern Mediterranean	768	1586.5
Latin America and Caribbean	121	188.5
Western Pacific	169	111.4
Developed countries	8	8.9

duced just 6.2 billion tons (about 22%) of the global total of 28.7 billion tons of CO_2 emissions.[15]

Future impact of climate change on infectious diseases

The 2002 WHO report also used a statistical model to estimate the global burden of disease that will occur in the future as a result of climate change.[9] According to this model, by 2030, there will be 10% more diarrheal disease than if climate change did not occur, which will primarily impact the health of young children. If global temperatures increase by 2–3 °C, as they are expected to, it is estimated that the population at risk for malaria will increase by 3%–5%, which means that millions of additional people would likely develop malaria each year. Others have developed models as well in an attempt to predict the future impact of climate change on infectious diseases. Hales, *et al*, estimated that 5–6 billion people (about 50% of the population) would be at risk for dengue fever by 2085, using projections based on the expected effect of climate change on humidity.[16] However, the authors were careful to state that being at risk for getting a disease does not necessarily translate into getting the disease, and that further modeling studies are needed to estimate what the actual impact on human health will be.

Others have focused on predicting the impact of climate change on local epidemics of infectious diseases, with an emphasis on developing early warning systems that may allow populations to prepare for such epidemics in advance. For any disease, early warning systems are developed based on models derived from disease surveillance data in combination with climate data. Cholera has served as popular disease for such studies since cases must be reported to the WHO within 24 hours as part of a large-scale surveillance system. For example, elaborate modeling studies have been performed in Bangladesh in order to predict cholera outbreaks on the basis of weather patterns.[17] Developing early warning systems for vector-borne diseases is more difficult because accounting for the unique biology of the vector adds another layer of complexity. However, there is significant interest in developing such early warning systems. For example, models for early warning systems for dengue fever have now been developed in Thailand and Puerto Rico, where robust surveillance data is available.[9] While many models for early warning systems have been developed, the systems themselves are not widely used at this point. As noted previously regarding the impact of climate change on infectious diseases, the development of truly useful early warning systems is affected by difficulty measuring the impact of non-climatic factors (*e.g.*, migration, population immunity) on susceptibilities of different populations to disease.

Proposed Solutions

Preventing further climate change

The primary method for preventing climate change from impacting human health is to stop climate change altogether. While some degree of climate change has already occurred, the idea is to reduce greenhouse gas emissions to the point where this phenomenon is considerably slowed. The Intergovernmental Panel on Climate Change has determined that a 50% reduction in greenhouse gas emissions (compared with 1990 levels) by 2050 will be necessary to stabilize the global temperature increase at 2–2.4 °C compared with preindustrial times.[4] Some international efforts to reduce emissions have already been put in place. The Kyoto Protocol, which was developed in 1997 by the UN Framework Convention on Climate Change, has now been ratified by 187 nations (but most notably not by the US) and was put into effect in 2005.[18] Under the protocol, 37 developed countries have agreed to reduce their collective greenhouse gas emissions by 5.2% compared with 1990 levels by 2012. This can be accomplished using a variety of mechanisms including emissions trading, where countries can trade credits for greenhouse gas emissions.

More recently, the UN Climate Change Conference took place in Copenhagen in late 2009 to establish a framework for tackling climate change beyond 2012, when the Kyoto Protocol expires. The European Union put forth the most ambitious proposal, which would require developed countries to reduce CO_2 emissions by 30% (15%–30% for developing countries) below 1990 levels by 2020. This would be accomplished by emissions trading, development of new emissions standards for cars, promoting energy efficiency among the residential sector, investment in renewable energy sources (rather than fossil fuels), reduction in deforestation, and advancement of technologies to capture and store carbon from the atmosphere. However, the meeting ended without passage of a binding resolution. Instead, several countries (including the US) developed a nonbinding agreement to halt the global temperature increase to 2 °C, with no mention of targets for emissions. One of the major issues at the conference was the responsibility of developed countries to assist developing countries (including China and India) in reducing emissions.

While governments must take the lead in halting climate change, it is also our responsibility as individuals to do our part to reduce our own contributions to greenhouse gas emissions. At home, we can use more energy efficient appliances and light bulbs, properly insulate our houses, and recycle. We should drive more fuel efficient vehicles and use public transportation whenever possible. Tools are available to help us calculate our personal carbon emissions to identify areas where we could potentially improve.[2]

Investing in infectious diseases research and prevention efforts

While reducing emissions to halt climate change is of the utmost importance, we must remember that the best case scenario would be a global temperature increase of around 2 °C. Therefore, we must also focus our efforts on mitigating the effects of climate change, including its potential impact on the global distribution of infectious diseases. In order to accomplish this, additional research is needed on the epidemiology and ecology of the infectious diseases that will likely be affected by climate change. However, these diseases typically fall under the category of "neglected diseases," meaning that they primarily affect people living in poverty. In 2007, the National Institutes of Health (NIH) in the US spent less than one percent of its entire operating budget on research related to the neglected diseases. More recently, the Institutes launched the Therapeutics for Rare and Neglected Diseases Program, which focuses on the molecular mechanisms of neglected diseases in an attempt to develop new therapeutic options.[19] This type of research is vitally important, but research on the epidemiology and ecology of these diseases is equally important and remains drastically underfunded. We must fully understand the epidemiology and ecology of infectious diseases such as malaria to anticipate what effect climate change will have on their distributions, and to develop early warning systems to help populations prepare for impending epidemics.

To ensure that this necessary research is being done, we must provide funding mechanisms and logistical support. The best means to accomplish this would be to incorporate research on the impact of climate change into existing infrastructures provided by large international organizations such as the WHO. For example, in 2007 the Bill and Melinda Gates Foundation, which has been a major source of funding and innovation for research and problem-solving in developing countries, announced an ambitious plan to work toward eradication of malaria.[20] The Malaria Eradication Research Agenda was established as an international collaborative effort, and one of the items on this agenda must be to study the potential impact of climate change on malaria. As we move forward, it is absolutely imperative that organizations such as the WHO and Gates Foundation continue their missions to treat and prevent the neglected infectious diseases as part of a multi-faceted approach at improving global health. Effective treatments and vaccines will go a long way in preventing human suffering that may occur as a result of climate change.

Conclusions

In summary, climate change is a very real phenomenon which has already impacted the global distribution of infectious diseases. If climate change continues unabated, it is likely that the range of deadly diseases such as malaria will expand or shift, resulting in sickness and death as populations without pre-existing immunity are increasingly affected. It is our responsibility to take action now to prevent this from occurring. We must reduce greenhouse gas emissions by developing an international treaty, enacting legislation locally, and acting responsibly as individual citizens of the world. Finally, we must continue to seek answers as to how climate change will affect our most vulnerable populations, and we must do what we can to protect them.

Conflicts of Interest: None declared.

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