The Health Risks of Climate Change

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Climate change has the potential to affect any health outcome that is seasonal or that is associated with weather and climate. Climate-sensitive health outcomes include injuries, illnesses and deaths directly associated with extreme weather events and illnesses and deaths associated with water- and food-borne diseases, vector-borne and zoonotic diseases, malnutrition, and poor air quality. Climate change also may result in resource depletion and other processes that could lead to large-scale migration, with associated negative health outcomes. While negative health effects are projected for all countries, the largest impacts are expected in lower-income populations living predominantly within tropical/subtropical countries.[1] For instance, loss of healthy life years as a result of global environmental change (including climate change) is predicted to be 500 times greater amongst poor African populations than amongst European populations.[2] It has been estimated that 182 million people in sub-Saharan Africa could die of disease directly attributable to climate change by the end of the 21st century. Millions more could become climate change refugees.

Climate change will affect health via a complex set of interdependent relationships that include factors such as wealth, distribution of income, status of the public health infrastructure, high-risk behaviour and access to medical care.[3] Therefore, current and future vulnerabilities will be at least as important as changing climatic patterns in determining future burdens of climate-sensitive health outcomes. The severity of future impacts will be determined by changes in climate as well as by concurrent changes in non-climatic factors, and by the mitigation and adaptation measures implemented to reduce greenhouse gas emissions and negative health impacts. In all regions, effective adaptation strategies, policies, and measures need to be designed and implemented, taking into account existing vulnerabilities.

This chapter summarises potential climate change-related health impacts and aggregate assessments projecting future health burdens attributable to climate change. The categories of health impacts considered are those associated with extreme weather events, infectious diseases (including water-, food-, and vector-borne diseases), health outcomes associated with poor air quality, and malnutrition. Particularly vulnerable regions and populations are then discussed, followed by approaches for designing timely and effective adaptation options.

Health risks of climate change

Infectious diseases

Climate is a primary determinant of whether a particular location has environmental conditions suitable for the transmission of a range of infectious diseases. Non-climatic factors include drug and pesticide resistance, deterioration of health care and public health infrastructure (including vector control efforts), demographic changes, and land use change. Warming will affect vector and rodent borne diseases, both in terms of the density of insects and rodents in a particular area, and hence the likelihood of infection, and also by changing the geographic range of the vector and pathogen. Expansion in range could expose new populations who have little or no immunity to new infections. Vector reproduction, survival and bite frequency generally rise with temperature, so malaria (*Anopheles* mosquitoes), tick-borne encephalitis (*Ixodesricinus*), and dengue fever (*Aedes aegypti*) will have increased transmission unless higher temperatures affect longevity. In some cases, extreme events such as very heavy rains, can wash away eggs and larvae and decrease vector populations.

Although understanding of the potential impacts of climate change on infectious diseases is still in its relatively early stages, an expert solicitation conducted by the UK government concluded that climate change is widely expected to be among the most important drivers of infectious disease in the future.[4] The review looked ahead 10–25 years to consider infectious diseases in humans, animals, and plants, focusing on the UK and sub-Saharan Africa, and aimed to produce a vision of new systems needed for disease detection, identification and monitoring. The key driver in the UK was expected to be rising ambient temperature. In Africa, where people, animals and crops live in conditions of much greater moisture stress, rising temperature were still considered to be important but less so than changes to rainfall patterns and the frequency of droughts. Climate-change mediated spread of infectious diseases was expected to cause direct human suffering, especially in Africa and increasingly challenge current production systems of livestock and crops in the UK and Africa.

Malaria is the most important vectorborne disease in the world; it is also a preventable disease. About 40% of the world's population is at risk of contracting malaria, and roughly 75% of cases occur in Africa, with the remainder occurring in Southeast Asia, the Western Pacific and the Americas.[5] In sub-Saharan Africa, malaria remains the most common parasitic disease and is the main cause of morbidity and mortality among children less than five years of age and among pregnant women.[6] Up to three million deaths from the direct effects of malaria occur annually in Africa, more than 75% of them in children.[7] This estimate could double if the indirect effects of malaria (including malaria-related anemia, hypoglycemia, respiratory distress and low birthweight) are included when defining the burden of malaria.[8] The 1990 Global Burden of Disease study estimated that malaria accounted for approximately 10.8% of years of life lost across all sub-Saharan Africa.[9]

There has been a great deal of interest in modeling how the incidence and geographic range of malaria could change under different climate change projections. Results from several models suggest that climate change could alter the season of transmission and geographic range of malaria in Africa, particularly sub-Saharan Africa[10]. The results suggest that climate change will be associated with geographic expansions of the areas suitable for stable falciparum malaria in some regions and with contractions in others; the projected areas of expansion are larger than the projected areas of contraction. For instance, Ethiopia, Zimbabwe, and South Africa are projected to show increases of more than 100% in person-months of exposure later in this century, changes that could dramatically increase the burden of those suffering with malaria[11].

Studies have shown that some areas in Asia are projected to be at increased risk of malaria, while reductions have been projected for some areas in Central America and around the Amazon, due to decreases in rainfall.[12] An assessment in Australia based on climatic suitability for the main anopheline vectors projected a likely southward expansion of habitat, although the future risk of endemicity would remain low due to the capacity to respond[13]. It is important to note that all these analyses are based upon projected changes in average temperatures, rather than the more rapid increase in minimum temperatures being observed; and thus may underestimate the actual biological responses.

Several food- and waterborne diseases that cause significant numbers of cases of illness are climate sensitive, suggesting that climate change may affect their incidence and distribution. For example, an approximately linear association between temperature and common forms of food-borne diseases such as *salmonellosis* suggests increasing cases with increasing temperature[14].

Air pollution

In some regions, climate change may increase concentrations of selected air pollutants, particularly ozone, and could decrease concentration of other pollutants, such as particulate matter (due to increasing heavy precipitation events). Air pollution concentrations are the result of interactions among local weather patterns, atmospheric circulation features, wind, topography, and other factors. It is challenging to establish the scale (local, regional, global) and direction of change (improvements or deterioration) of air quality[15].

There is extensive literature documenting the adverse health impacts of exposure to elevated concentrations of air pollutants. In 2000, there were 800,000 deaths from respiratory problems, lung disease, and cancer that were attributed to urban air pollution, with the largest burden in low-income countries in the Western Pacific and South East Asia[16]. In addition, there were 1.6 million deaths attributed to indoor air pollution caused by burning biomass fuels, such as wood and dung.

More is known about the potential impacts of climate change on ground-level ozone than on other air pollutants. Acute exposure to elevated concentrations of ozone is associated with increased hospital admissions for pneumonia, chronic obstructive pulmonary disease, asthma, allergic rhinitis and other respiratory diseases, and with premature mortality[17]. The total costs of asthma in Australia and the UK (adjusted to 1991 US dollars for comparison purposes) are estimated at US $457 million and US $1.79 billion respectively[18]. For developing nations and for those in poor communities, the health impacts of asthma can be significantly higher.

Changes in concentrations of ground-level ozone driven by scenarios of future emissions and /or weather patterns have been projected for Europe and North America, with most projections suggesting increasing concentrations.[19, 20] Higher ozone concentrations will likely increase a range of health problems and increase premature mortality in susceptible individuals.[21] Despite the heavier pollution burdens, no studies have been conducted for cities in low- or middle-income countries.

Anecdotal evidence supports an increasing frequency of forest fires with warmer temperatures and drier regimes. Forest fires in Southeast Asia and in the Amazon are generating significant quantities of respiratory irritants, while harming wildlife and releasing large pulses of carbon into the atmosphere.

Malnutrition

Climate change threatens human health through its effect on under-nutrition and food insecurity. More than 800 million people are undernourished, causing over 15% of the total global disease burden, and over three billion people are micronutrient deficient[22]. The prevalence of undernourishment has fallen over recent decades, with reductions in Asia and Latin America partly offset by increases in Africa and the Middle East. Almost 60% of the world's undernourished people live in South Asia, while the highest incidence of undernourishment is in Sub-Saharan Africa, where more than one-third of the population is underfed.

Food insecurity arises when people do not have physical and economic access to sufficient safe, nutritious, and culturally acceptable food to meet their dietary needs. The four dimensions of food security are food availability (i.e. production and trade), stability of food supplies, access to food, and food utilization; all could be affected by climate change. An adequate intake of calories does not ensure that the need for micronutrients has been met. Underweight due to wasting (i.e. low weight-for-height, indicating acute weight loss) or stunting (i.e. low height for age, indicating chronic restriction of a child's nutrition), micronutrient deficiencies, as well as overweight are forms of malnutrition. Malnutrition, in addition to causing serious health consequences, increases the risk of dying from an infectious disease.

Recent projections suggest that half of the world's population could face severe food shortages by the end of the century as rising temperatures take their toll on farmers' crops; a greater proportion of this will be in Africa[23]. Harvests of staple food crops such as rice and maize could fall by between 20% and 40% as a result of higher temperatures during the growing season in the tropics and sub-tropics. Although data are limited, malnutrition associated with drought and flooding may be one of the most important consequences of climate change due to the large number of people that may be affected.[1]

Extreme Weather Events

Extreme weather events, including heat waves, floods, windstorms[24], and droughts, affect millions of people and cause billions of dollars of damage annually. The impacts of an extreme event, including loss of life and livelihood, infrastructure damage, population displacement, and economic disruption, are determined by the physical characteristics of the event, attributes of the location affected, and interactions of these with human actions and social, economic, institutional, and other systems. There is a growing scientific consensus that climate change will further accelerate the frequency and intensity of extreme weather events,[25] suggesting that the associated health impacts also are likely to increase.

The adverse health consequences of flooding and windstorms often are complex and far-reaching, and include the physical health effects

experienced during the event or clean-up process, effects brought about by damage to infrastructure related to water supply, sanitation and drainage, and population displacement. The physical effects largely manifest themselves within weeks or months following the event, and may be direct (such as injuries) and indirect (such as loss or contamination of potable water, food shortages and increased rates of vector-borne and other diseases).[26] Extreme weather events are also associated with mental health effects, such as post-traumatic stress disorder, resulting from the experience of the event or from the recovery process. These psychological effects tend to be much longer lasting and may be worse than the direct physical effects.[27] More than 90% of the disasters that occurred in 2007 were the result of extreme weather- or climate-related events, together accounting for 95% of the reported fatalities and 80% of the total US$ 82 billion economic losses. The health impacts of extreme events in low- and middle-income countries are substantially larger.

Heat waves affect human health via heat stress, heatstroke, and death,[28] as well as exacerbating underlying conditions that can lead to an increase in mortality from all causes of death.[29] Older adults, children, city-dwellers, the poor, and people taking certain medications are at the highest risk during a heat wave. The numbers of heat-related deaths are projected to increase with climate change.[30] Adaptive responses, including behavioural, physiological, and technological factors, may reduce the projected negative impacts. More than 35,000 excess deaths were attributed to the extended heat wave in Europe in 2003.[31] In Greater London it was estimated that the 2003 heat wave was associated with a 40% increase in mortality, compared to an excess of 16% in 1995 and 15% in 1976.[32] Excess mortality in England and Wales was 10% in 1976 compared to 16% in 2003.

Projections suggest that regions affected by moderate droughts are set to double by the end of the century, with areas struck by extreme droughts increasing from 1% today to 30% in 2100. The most striking

Table 1: Climate-Sensitive Health Outcomes and Particularly Vulnerable Groups

Climate-Sensitive Health Outcome	Particularly Vulnerable Groups
Heat-related illnesses and deaths	Elderly, chronic medical conditions, infants and children, pregnant women, urban and rural poor, outdoor workers
Diseases and deaths related to air quality	Children, pre-existing heart or lung disease, diabetes, athletes, outdoor workers
Illnesses and deaths due to extreme weather events	Poor, pregnant women, chronic medical conditions, mobility and cognitive constraints
Water- and foodborne illness	Immunocompromised, elderly, infants
Vectorborne illnesses	
Lyme disease	Children, outdoor workers
Hantavirus	Rural poor, occupational groups
Dengue	Infants, elderly
Malaria	Children, immunocompromised, pregnant women, genetic

Source: Balbus and Malina (2009)

Table 2: Adaptation Measures to Reduce Climate Change-Related Health Risks

	Heatwaves	Extreme Weather Events	Vectorborne Diseases	Waterborne Diseases	Air Quality
Decision Support Tools	Enhance early warning systems	Enhance early warning systems and emergency response plans	Enhance early warning systems based on climate and environmental data for selected diseases	Develop early warning systems based on climate and environmental data for conditions that may increase selected diseases	Enhance alert systems for high air pollution days
Technology Development	Improve building design to reduce heat loads during summer months		Develop vaccines for West Nile virus and other vectorborne diseases Develop more rapid diagnostic tests	Develop more rapid diagnostic tests	
Surveillance and Monitoring	Alter health data collection systems to monitor for increased morbidity and mortality during a heatwave	Alter health data collection systems to monitor for disease outbreaks during and after an extreme event	Enhance vector surveillance and control programmes Monitor disease occurrence	Enhance surveillance and monitoring programmes for waterborne diseases	Enhance health data collection systems to monitor for health outcomes due to air pollution
Infrastructure Development	Improve urban design to reduce urban heat islands by planting trees, increasing green spaces, etc.	Design infrastructure to withstand projected extreme events	Consider possible impacts of infrastructure development, such as water storage tanks, on vectorborne diseases	Consider possible impacts of placement of sources of water- and foodborne pathogens (e.g., cattle near drinking water sources)	Improve public transit systems to reduce traffic emissions
Other	Conduct research on effective approaches to encourage appropriate behaviour during a heatwave	Conduct research on effective approaches to encourage appropriate behaviour during an extreme event			

Source: Balbus and Malina (2009)

impact is expected in parts of southern Europe, North, West and Southern Africa, western Eurasia, and the US. The loss of livelihoods due to drought is a major trigger for population movements that may cause additional adverse health burdens. The effects of drought on health include malnutrition (protein-energy malnutrition and/or micronutrient deficiencies), infectious and diarrheal diseases, and respiratory diseases.[33] The loss of livelihoods due to drought is a major trigger for population movements, which can cause additional disease burdens. Droughts, especially in rural areas, have a tendency to influence migration into cities, increasing urbanisation and stressing the socio-economic conditions already exacerbated by high levels of city population growth. It is estimated that 72% of the dwellers in African cities live in slums that, having particularly poor drainage facilities, are especially prone to flooding and ill health.

Overall, extreme weather events are having even more profound impacts on public health than increasing temperature alone. Prolonged droughts fuel fires, releasing respiratory pollutants, while floods can create mosquito breeding sites, foster fungal growth, and flush microbes, nutrients and chemicals into bays and estuaries, causing waterborne disease outbreaks from organisms like *E. coli* and *cryptosporidium*[34].

Global assessments of the health impacts of climate change

The most comprehensive evaluation of the health burden due to climate change used a comparative risk assessment approach to estimate total health burdens from climate change in 2000 and 2030, and to project how much of this burden might be avoided by stabilizing greenhouse gas (GHG) emission[35]. The health outcomes included (diarrhoea, malaria, malnutrition, heat-related mortality, and injury from floods and landslides) and were chosen based on sensitivity to climate variations, likely future importance, and availability of quantitative global models (or the feasibility of constructing them) for analysis. The projected relative risks attributable to climate change in 2030 vary by health outcome and region, and are largely negative, with the majority of the projected health burden due to increases in diarrheal disease and malnutrition, primarily in low-income populations already experiencing a large burden of disease.

These results are consistent with a review that concluded that health risks are likely to increase with increasing global mean surface temperature, particularly in low latitude countries.[36] Actual health burdens depend on assumptions of population growth, future baseline disease incidence, and the extent of adaptation.

The relative direction, magnitude, and certainty of climate change-related health impacts, as summarized by the Human Health chapter of the Intergovernmental Panel on Climate Change 4th Assessment Report, are shown in Figure 1.

Particularly vulnerable populations and regions

Sub-populations that are most vulnerable to the health impacts of climate change depend on the region, the health outcome, and population characteristics, including human, institutional, social, and economic capacity.[8] Individual vulnerability depends on genetic, developmental, acquired, and socioeconomic factors. In general, the most vulnerable include slum dwellers and homeless people in large urban areas, particularly in low-income countries, those living in water-stressed regions, settlements in coastal and low-lying areas, and populations highly dependent on natural resources. Table 1 summarizes vulnerable populations by health outcome. As shown during Hurricane Katrina (2005) and the 2003 heat wave in Europe, developed countries are not immune to these climate-related health risks and may not be prepared to cope with the projected increase in the frequency and intensity of extreme weather events.

Addressing existing health risks in adaptation policies

Individuals, communities, governments, and organisations currently engage in a wide range of actions to avoid, prepare for, and effectively respond to climate-sensitive health outcomes. Although these actions have been largely successful, recent extreme events and outbreaks of vectorborne diseases highlight areas for improvement. Further, climate change is projected to challenge the ability of public health agencies and organisations to control climate sensitive health determinants and outcomes. Preventing additional morbidity and mortality requires evaluation of current programmes and activities in light of climate change projections to identify modifications that will increase resilience to the full range of health risks that may arise with climate change, and to ensure that these modifications reduce the sensitivity of those populations and regions most at risk[37]. In most cases, the primary response will be to enhance current health risk management activities. In some cases, programmes will need to be implemented in new regions; in others, climate change may reduce current infectious disease burdens. Although there are uncertainties about future climate change, failure to invest in adaptation may leave communities and nations poorly prepared, and increase the probability of severe adverse consequences[38]. Examples of adaptation measures are shown in Table 2. Adaptation policies and measures need to be integrated into developmental processes that aim to achieve sustainable development.

Conclusions

Climate change is already causing injuries, disease, and death from a range of climate-sensitive health outcomes. Health impacts are projected to increase over the coming decades, particularly in lower-income populations and regions that currently suffer from high burdens of these health outcomes. The degree to which impacts will be experienced will depend not only on the rate and degree of climate change, but also on the effectiveness and timeliness of adaptation and mitigation policies, strategies, and measures. However, even effective and timely actions will not prevent all health impacts. ◆

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References

1. Confalonieri U, Menne B, Akhtar R, Ebi K.L, Hauengue M, Kovats R.S, Revich B, and A. Woodward (2007): Human health. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 2007, 391-431.
2. McMichael A.J, Friel S, Nyong A, and C. Corvalan (2008): Global environmental change and health: impacts, inequalities, and the health sector. *BMJ*. Jan 26;336 (7637):191-4.
3. Woodward, A, Hales, S. and P. Weinstein, 1998: "Climate change and human health in the Asia Pacific region: who will be the most vulnerable?" *Climate Research* 11:31-7.
4. Brownlie, J., Peckham, C., Waage, J., Woolhouse, M., Lyall, C., Meagher, L., Tait, J., Baylis, M. and Nicoll, A. (2006): Foresight. Infectious Diseases: preparing for the future. Future Threats. Office of Science and Innovation, London
5. Snow, R. W., Guerra, C. A., Noor, A. N., Myint, H. Y. and S. I. Hay (2005): The global distribution of clinical episodes of Plasmodium falciparum malaria. *Nature* 434, 214-217.
6. WHO (2004): Malaria epidemics: forecasting, prevention, early warning and control – from policy to practice. Report of an informal consultation, Leysin, Switzerland, 8–10 December 2003. World Health Organization, Geneva, 52 pp.
7. WHO (2003): *Africa Malaria Report 2003*. World Health Organization, Geneva, Switzerland.
8. Breman, J. G. (2001): The ears of the hippopotamus: manifestations, determinants and estimates of the malaria burden. *Am. J. Trop. Med. Hyg.* 64 (Supplement 1), 1-11
9. Murray, C. and A. Lopez (1996): *Global Burden of Disease*. Harvard University Press, Boston, MA,
10. Ebi K.L., Hartman, J. McConnell, J. K. Chan, N. and J. Weyant (2005): "Climate suitability for stable malaria transmission in Zimbabwe under different climate change scenarios." *Climatic Change* 73:375-393; Tanser F.C., Sharp, B. and and D. le Sueur (2003): "Potential effect of climate change on malaria transmission in Africa." *Lancet* 362:1792-1798; Thomas C.J., Davies, G. and C.E. Dunn, (2004): "Mixed picture for changes in stable malaria distribution with future climate in Africa." *Trends Parasitol* 20:216-220; Van Lieshout M., Kovats, R. S., Livermore, M.T.J. and P. Martens, (2004): "Climate change and malaria: analysis of the SRES climate and socio-economic scenarios." *Global Environmental Change* 14:87-99.
11. Van Lieshout, M., Kovats, R. S., Livermore, M., et al. 2004. Climate change and malaria: Analysis of the SRES climate and socio-economic scenarios. *Global Environmental Change* 14, 87-99; Tanser, F. C., Sharp, B. & LeSueur, D. 2003. Potential effect of climate change on malaria transmission in Africa. *Lancet* 362, 1792-1798.
12. Van Lieshout et al., *Op.Cit*
13. McMichael,A.J., Woodruff, R. Whetton, P. Hennessy, K. Nicholls, N. Hales, S. Woodward A. and T. Kjellstrom (2003): *Human Health and Climate Change in Oceania: Risk Assessment* 2002. Department of Health and Ageing, Canberra, 128 pp.
14. E.g. D'Souza, R.M., N.G. Becker, G. Hall, and K.B. Moodie, 2004: "Does ambient temperature affect foodborne disease?" *Epidemiology* 15:86-92; Kovats, R.S., S.J. Edwards, S. Hajat, B.G. Armstrong, K.L. Ebi, and B. Menne, 2004: "The effect of temperature on food poisoning: a time-series analysis of salmonellosis in ten European countries." *Epidemiol Infect* 132, 443-453; Fleury, M., D. Charron, J. Holt, O. Allen, A. Maarouf, 2006: "A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in to Canadian provinces," *Int J Biometeorol* 50:385-91.
15. Ebi, K.L, and G. McGregor, 2008: "Climate change, tropospheric ozone and particulate matter, and health impacts," Environ Health Perspect 116: 1449-1455; Kinney, P.K., 2008: "Climate change, air quality, and human health," *Am J Prev Med* 35: 459-467.
16. WHO, 2002: World Health Report 2002: reducing risks, promoting healthy life (Geneva: World Health Organization).
17. See Mudway, I.S. and F.J. Kelly, 2000: Ozone and the lung: a sensitive issue. *Mol. Aspects Med*., 21, 1-48.; Gryparis, A., B. Forsberg, K. Katsouyanni, A. Analitis, G. Touloumi, J. Schwartz, E. Samoli, S. Medina, H.R. Anderson, E.M. Niciu, H.E.Wichmann, B. Kriz, M. Kosnik, J. Skorkovsky, J.M.Vonk and Z.Dortbudak, 2004:Acute effects of ozone on mortality from the "Air Pollution and Health: A European Approach" project. *Am. J. Respir. Crit. Care Med*., 170, 1080-1087.; Bell,M.L., F. Dominici and J.M. Samet, 2005:Ameta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study. *Epidemiology*, 16, 436-445.; Ito, K., S.F. De Leon and M. Lippmann, 2005: Associations between ozone and daily mortality: analysis and meta-analysis. *Epidemiology*, 16, 446-457. Levy, J.I., S.M. Chemerynski and J.A. Sarnat, 2005: Ozone exposure and mortality: an empiric bayes metaregression analysis. *Epidemiology*, 16, 458-468.; Bell, M.L., R.D. Peng and F. Dominici, 2006: The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations. *Environ.Health Persp*., 114, 532-536.).
18. Weiss, K. B., Gergen, P. Hodgson T.A., et al. (1992): An economic evaluation of asthma in the United States. *N. Engl. J. Med*. 326, 862-866.
19. Stevenson, D.S., C.E. Johnson, W.J. Collins, R.G. Derwent, and J.M. Edwards, 2000: "Future estimates of tropospheric ozone radiative forcing and methane turnover - the impact of climate change" *Geophys Res Lett* 27: 2073-2076; Derwent, R.G., W.J. Collins, C.E. Johnson, and D.S. Stevenson, 2001: "Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects," Climatic Change 49: 463-487; Johnson, C.S., D.S. Stevenson, W. Collins, R. Derwent, 2001: "Role of climate feedback on methane and ozone studied with a coupled ocean-atmosphere-chemistry model," *Geophys Res Lett* 28: 1723-1726; Taha, H., 2001: Potential impacts of climate change on troposphereic ozone in California: a preliminary episodic modeling assessment of the Los Angeles Basin and the Sacramento Valley (Berkeley, CA: Lawrence Berkeley National Laboratories); Hogrefe, C., J. Biswas, B. Lynn, K. Civerolo, J.Y. Ku, J. Rosenthal, C. Rosenzweig, R. Goldberg, and P.L. Kinney, 2004: "Simulating regional-scale ozone climatology over the eastern United States: model evaluation results," *Atmos Environ* 38: 2627.
20. Future emissions are, of course, uncertain, and depend on assumptions of population growth, economic development, and energy use.
21. Knowlton, K., J.E. Rosenthal, C. Hogrefe, B. Lynn, S. Gaffin, R. Goldberg, C. Rosenzweig, K. Civerolo, J.Y. Ku, and P.L. Kinney, 2004: "Assessing ozone-related health impacts under a changing climate," *Environ Health Perspect* 112: 1557-1563.
22. Herran H, Wakhungu J, (Co-chairs). (2008). International Assessment of Agricultural Knowledge, Science, and Technology for Development. Executive Summary of the Synthesis Report. http://www.agassessment.org/docs/IAASTD_EXEC_SUMMARY_JAN_2008.pdf
23. Battisti DS and Naylor RL. (2009). Historical Warnings of Future Food Insecurity with Unprecedented Seasonal Heat, *Science*, 323 (5911), pp. 240 –244.
24. Windstorms include hurricanes and cyclones.
25. Easterling, D.R., J.L. Evans, P.Y. Groisman, T.R. Karl, K.E. Kunkel, and P. Ambenje, 2000: "Observed variability and trends in extreme climate events," *Bulletin of the American Meteorological Society* 81:417-425; Meehl G. and C. Tebaldi, 2004: "More intense, more frequent and longer lasting heat waves in the 21st century," Nature 305:994-997.
26. Ahern, M.J., R.S. Kovats, P. Wilkinson, R. Few, and F. Matthies, 2005: "Global health impacts of floods: epidemiological evidence," Epidemiol Rev 27:36-45; Hajat S., K. Ebi , S. Kovats, B. Menne, S. Edwards, and A. Haines, 2003: "The human health consequences of flooding in Europe and the implications for public health: A review of the evidence," *Applied Environmental Science and Public Health* 1:13–21.
27. Ibid.
28. Kilbourne, E.M., 1997: "Heat waves and hot environments," in The public health consequences of disasters, edited by E.K. Noji (New York: Oxford University Press) 245-269.
29. Kovats, R.S. and C. Koppe, 2005: "Heat waves: past and future impacts, Integration of Public Health with Adaptation to Climate Change: Lessons Learned and New Directions, edited by K.L. Ebi, J.B. Smith, and I. Burton (London: Taylor & Francis) pp. 136-160.
30. Keatinge, W.R., G.C. Donaldson, R.S. Kovats, and A. McMichael A, 2002: "Heat and cold related mortality morbidity and climate change," in Health Effects of Climate Change in the UK (London: Department of Health); Dessai, S., 2003: "Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change," *Int J Biometeorol* 48:37-44; McMichael, A., R. Woodruff, P. Whetton, K. Hennessy, N. Nicholls, S. Hales, A. Woodward, and T. Kjellstrom, 2003: *Human Health and Climate Change in Oceania: Risk Assessment* 2002 (Canberra: Commonwealth of Australia); Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K. Nicholas Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalkstein, J. Lenihan, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Verville, 2004: "Emission pathways, climate change, and impacts on California" *PNAS* 101:12422-427.

References continued

[31] Kosatsky, T., 2005: "The 2003 European heat waves," *Euro Surveill* 10:148-9.

[32] Rooney C, McMichael A.J, Kovats R.S, Coleman M. Excess mortality in England and Wales, and in Greater London, during the 1995 heatwave: *Journal of Epidemiology and Community Health* 1988; 52: 482-486. McMichael A.J, Kovats R.S. Assessment of the Impact on Mortality in England and Wales of the Heatwave and Associated Air Pollution Episode of 1976. 1998. Report to Dept of Health. London, Dept of Epidemiology and Population Health, LSHTM.

[33] Menne B; Bertollini R,. 2000. The health impacts of desertification and drought. The Newsletter of the Convention to Combat Desertification,

[34] See Kovats, R. S., Bouma, M. J. & Haines, A. El Niño and Health. (World Health Organization, WHO/SDE/PHE/99.4,Geneva, 1999).; Dearborn, D. G., Yike, I., Sorenson, W. G., Miller, M. J. & Etzel, R. A. Overview of investigation into pulmonary hemorrhage among infants in Cleveland, Ohio. *Environmental Health Perspectives*, 495-499 (1999); Mackenzie, W. R., Hoxie, N. J., Proctor, M. E. & Gradus, M. S. A massive outbreak in Milwaukee of cryptosporidium infection transmitted through public water supply. *New England Journal of Medicine* 331, 161-167 (1994).

[35] McMichael A.J., D. Campbell-Lendrum, S. Kovats, S. Edwards, P. Wilkinson, T. Wilson, R. Nicholls, S. Hales, F. Tanser, D. LeSueur, M. Schlesinger, and N. Andronova, 2004: "Global Climate Change." *In: Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors*. Eds. Ezzati M, Lopez A, Rodgers A, Murray C. World Health Organization, Geneva, pp 1543-1649.

[36] Hitz S., and J. Smith, 2004: "Estimating global impacts from climate change." *Global Environmental Change* 14:201-218.

[37] Ebi, K.L., J. Smith, I. Burton, and J. Scheraga, 2006: "Some lessons learned from public health on the process of adaptation," Mitigation and Adaptation Strategies for Global Change 11: 601-620.

[38] Haines, A., R.S. Kovats, D. Campbell-Lendrum, and Corvalan, C. 2006: "Climate change and human health: impacts, vulnerability, and public health." *Lancet* 367: 1-9.