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Adaptation to the infectious disease impacts of climate change

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Abstract Climate change has the potential to increase the challenge of preventing and controlling outbreaks of infectious diseases. An adaptation assessment is an important aspect of designing and implementing policies and measures to avoid, prepare for, and effectively respond to infectious diseases outbreaks. The main steps in conducting an adaptation assessment include: 1) evaluating the effectiveness of policies and measures that address the burden of climate-sensitive infectious diseases; 2) identifying options to manage the health risks of current and projected climate change; 3) evaluating and prioritizing the options; 4) identifying human and financial resources needs, and possible barriers, constraints, and limits to implementation; and 5) developing monitoring and evaluation programs to ensure continued effectiveness of policies and measures in a changing climate. Optimally, relevant stakeholders are optimally included throughout the adaptation assessment. Although the process of conducting an assessment is similar across nations and regions, the context and content will vary depending on local circumstances, socioeconomic conditions, legal and regulatory frameworks, and other factors. The European Centers for Disease Prevention and Control developed guidelines for conducting assessments, with sufficient consistency to facilitate learning lessons across assessments.

1 Introduction

Although public health has considerable experience with policies and measures to reduce health burdens of infectious diseases, some of which are climate-sensitive, current strategies, policies, and measures were not typically designed to account for alterations in the burdens of infectious disease associated with a changing climate. Adaptation assessments are designed to identify options to reduce the current and projected health risks attributable to climate change

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by preventing exposures to weather and climate hazards, reducing the consequences of exposure, and/or reducing vulnerabilities. Assessing the potential infectious disease risks of climate change also requires considering the non-climatic factors that drive their incidence and distribution, including demographics, socioeconomic development, land use, urbanization, technology, and the political and health care context (Suk and Semenza 2011; Weiss and McMichael 2004). The options identified can then be evaluated for their significance, benefits and effectiveness, costs, and feasibility, to facilitate communication of prioritization to policy and decision makers.

The magnitude and extent of health risks is a function of the interactions among hazards posed by changing weather and climate patterns, who or what is exposed to those changes (e.g. individuals, communities, water infrastructure, ecosystems of importance for disease occurrence and transmission, etc.), and their vulnerabilities (e.g. demographic structure, wealth and income distribution, status of the public health infrastructure, access to medical care, behavioral factors, and individual physiological factors). Hazards, for the purposes of this paper, are changes in the frequency and intensity of extreme weather events as well as changes in mean temperature, precipitation, and other weather variables that affect transmission pathways of infectious diseases.

Awareness, motivation for action (at political, institutional, societal, and individual levels), human and financial resources, and institutional capacity are essential for any response to climate change (Fig. 1). Thus, national and local policy making processes, institutions, and resources influence the choices of which policies and measures to implement to address the current and likely future health risks of climate change.

This manuscript describes the context and process for conducting an adaptation assessment, developed by the European Centers for Disease Prevention and Control as part of a handbook for vulnerability, impact and adaptation assessment (ECDC 2010). It identifies possible options to improve current and future management of the burden of infectious diseases attributable to climate change, with a focus on developed countries and economies in transition in Europe. The potential health impacts of climate change from infectious diseases have been described elsewhere (Lindgren et al. 2012; Semenza et al. 2012a;

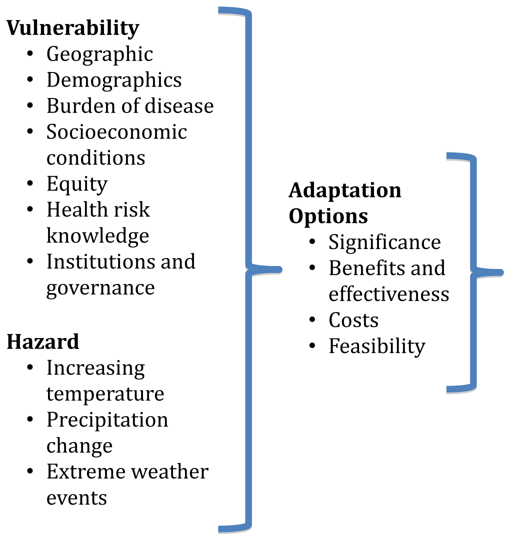

Fig. 1 Determinants of climate change adaptation

Semenza and Menne 2009). Thus, here we present a discussion of the public health and health care context for conducting an adaptation assessment, a review of the key public health activities to address the health risks of climate change, a discussion of the steps involved in conducting an adaptation assessment, and provide two examples. Handling uncertainties is considered before a final discussion.

2 Public health and health care context for conducting an adaptation assessment

There is an urgent need for public health and health care to develop adaptation strategies for the impacts of climate change on infectious diseases (Ebi 2008; Lafferty 2009; Paaijmans et al. 2010; Zhang et al. 2008). The health sector is not a single entity, and adaptation options may need to be coordinated across institutions and agencies. In many countries, the health sector is comprised of, at the least, a ministry of health, health care services managed separately, and, particularly in low-income countries, non-governmental organizations helping both to achieve their goals. Ministries of health typically focus on public health policies and measures, where public health is defined as efforts at preventing disease, prolonging life, and promoting health through the organized efforts and informed choices of society, organizations, public and private, communities, and individuals (Winslow 1920). Public health aims to prevent epidemics and the spread of disease; protect against environmental hazards; prevent injuries; promote and encourage healthy behaviors; and respond to disasters and assist communities in recovery (Public Health Functions Steering Committee 1994).

Individual health care is often organized through local and national health services, and includes nurses, doctors, and other health providers. Their focus is on identifying and treating causes of ill health. Particularly in low-income countries, non-governmental organizations, such as the International Federation of Red Cross and Red Crescent Societies, often fill gaps in human and financial resources for ministries of health and health care providers.

3 Public health policies and measures to manage the infectious disease risks of climate change

As with other sectors, effectively managing the risks of climate change requires policies and programs to explicitly include processes to address risks that are changing over time and space. For the health sector, these include risks from a changing climate and from changes in other factors that determine the distribution and incidence of climate-sensitive infectious diseases.

Current policies and programs to control climate-sensitive infections fall within basic public health functions, including surveillance and interpretation of data related to the impacts of climate change, outbreak investigation and response, regulations, education, enhancing partnerships, and conducting research (Frumkin et al. 2008; Semenza and Menne 2009). These can be modified to incorporate projections of changes in the climate as well as other risk factors for infectious diseases (Ebi 2011a).

Surveillance is the core activity for identifying the current incidence and distribution of infectious diseases, and the factors responsible (Last 2001). Surveillance is designed to keep local, regional, national, and global public health departments and ministries of health informed about the health status of the populations they serve, and the real and potential problems they face (Wilson and Anker 2005). Surveillance involves systematically collecting data, including on risk factors and potential exposures that affect the incidence and distribution of a disease, and interpreting and distributing information to all relevant actors (including public health decision makers, health care providers, and others) so that informed decisions can be taken. Surveillance is one of the key responses for controlling climate-sensitive infectious diseases (Table 1).

In addition to traditional public health approaches, possibilities for integrating environmental variables into the surveillance of infectious diseases are under development. The predictive capacity of models based on satellite imagery of environmental changes and how these correlate to disease outbreaks has improved markedly in recent years, even if more work is needed to leverage satellite data relevant for infectious disease spread, such as temperature, sea surface temperature, vegetation indices, precipitation, and water quality data. Early examples of these systems include malaria early warning systems and the implementation of an European Environment and Epidemiology (E3) Network (Semenza and Menne 2009).

4 Conducting an adaptation assessment

Vulnerability and adaptation assessments share similar features across sectors (Preston et al. 2011). Basic aims include identifying modifications to current and planned programs, and opportunities for new policies and measures, to reduce burdens of climate-sensitive infectious diseases. In most cases, an adaptation assessment builds on the results of a

Table 1 Examples of public health activities in Europe include (adapted from (Semenza and Menne 2009))

Indicator-based surveillance: collection, (trend) analysis, and interpretation of data related to climate change:	○ Routine data analysis from mandatory notification (e.g. the 49 infectious diseases and conditions notifiable at the EU level)
	○ Pharmacy-based monitoring of prescription and non-prescription drug sale or health-related data preceding diagnosis
	○ Sentinel surveillance (collection and analysis of high quality and accurate data at a geographic location; e.g. tick-borne encephalitis, Lyme borreliosis, etc.)
	○ Vector surveillance (monitor distribution of vectors, e.g. *Aedes albopictus*)
	○ Real time surveillance (instantaneous data collection with dynamic and sequential data analysis, e.g. hospital admissions or dead bird surveillance)
	○ Mortality from infectious diseases (monitor cause-specific deaths from infectious diseases based on medical records, autopsy reports, death certificates, etc.)
	○ Syndromic surveillance (e.g. monitor emergency room admissions for symptoms indicative of infectious diseases)
Event-based epidemic intelligence; early identification of infectious disease threats related to climate change:	○ Screening of (international) news media and other sources
	○ Case reports (e.g. clinician-based reporting)
	○ Science watch (e.g. screening scientific reports for discoveries and new findings)
	○ Interdisciplinary reporting on infectious disease threats (e.g. from agriculture, industry, environment, etc.)

vulnerability assessment (ECDC 2010). This process is intended to characterize the present situation, including population characteristics, health care systems, disease burden, and information from non-health sectors. High priority diseases and vulnerable populations can be identified through careful consideration of such factors. Assuming a vulnerability assessment identified how the current burden of infectious disease could change with climate change over specific temporal and spatial scales, the main steps in conducting an adaptation assessment include:

- Evaluating the effectiveness of policies and measures that address the burden of climate-sensitive infectious diseases
- Identifying adaptation options to manage the health risks of current and projected climate change
- Evaluating and prioritize adaptation options
- Identify human and financial resources needs, and possible barriers, constraints, and limits to implementation
- Developing monitoring and evaluation programs to ensure continued effectiveness of policies and measures in a changing climate

Assessments may focus on shorter or longer-term time horizons. In the shorter term, assessments aim to ensure that current vulnerabilities to climate variability are effectively addressed (i.e. focusing on shorter-term decisions, such as development of early warning systems). Determining where populations are affected by current climate variability can facilitate identifying the additional policies and measures that are needed now. At the same time, implementing options that only address current vulnerabilities is not sufficient to protect against health risks from future and possibly more severe climate change; this includes changes in the mean and variance of meteorological variables.

Identifying, prioritizing, and implementing strategies, policies, and measures to address the burden of climate sensitive infectious diseases must be based on an evaluation of the strengths and weaknesses of current policies and measures to address current climate variability and recent climate change (Ebi 2009; Frumkin et al. 2008; Jackson and Shields 2008). Because a health ministry, NGOs, and others may have individual or joint responsibility for these programs, representatives from all relevant organizations and institutions should be consulted to determine what is working well, what could be improved, and the capacity of the policies and measures to address possible increases in incidence or changes in the geographic range of the infectious disease of concern.

Possible measures to evaluate vectorborne and zoonotic diseases include surveillance and control programs, early warning systems, maternal and child health programs, and educational programs for individuals, communities, and health care workers on identifying and treating diseases. Examples for water- and foodborne diseases include watershed protection laws, water quality regulations, regulations to control foodborne diseases and contaminants, surveillance and monitoring programs, and educational programs on food handling.

Modifying or expanding current surveillance programs may be recommended in areas where changes in weather and climate may increase the incidence or facilitate the spread of infectious diseases. For example, because the risk of salmonella may increase with warmer ambient temperatures that favor the growth and spread of the bacteria (Kovats et al. 2004), enhancing current salmonella control programs and improving measures to encourage adherence to proper food-handling guidelines can lower current and future disease burdens. The design and implementation of incremental policy changes should be grounded in an understanding of the adequacy of existing policies and measures, and how their effectiveness could change under different scenarios of climate and socioeconomic change.

For some diseases, early warning systems can be designed based on data collected from surveillance programs to provide timely interventions to reduce the magnitude or extent of a disease outbreak (Kuhn et al. 2009). Appropriately designed early warning systems can be adjusted over time to incorporate projected increases in climate variability and change, thus increasing future resilience. For example, an early warning system was developed in the Czech Republic for tick-borne encephalitis (TBE), which has been a notifiable disease since late 1950s. Since 1971, all reported TBE cases are laboratory confirmed. The incidence of TBE demonstrated a significant increasing trend in the country since the early 1990s, and the seasonal variations in TBE are related to climate variations (Daniel et al. 2011). The emerging disease situation led the Centre for Epidemiology and Microbiology (CEM) at The National Institute of Public Health (SZU) in Prague in collaboration with the Czech Hydrometeorological Institute (CHMI) to develop in 2000 an early-warning system for tick activity and, hence disease risk. It consists of forecasts that predict daily tick activity several days to a week in advance, published twice a week at the websites of CEM and CHMI.

Policies and measures also may be needed to address situations where increases in mean temperature could lead to gradual increases in rates of health outcomes, and situations where thresholds could be crossed, leading to large increases in infectious disease rates. Further, policies and measures may be needed to address new risks. For example, rising ocean temperatures appear to have contributed to one of the largest known outbreaks of *V. parahaemolyticus* in the US (McLaughlin et al. 2005). Broadening the scope and increasing the capacity of public health institutions, particularly surveillance programs and environmental monitoring, could effectively address new and emerging risks.

Adaptation options should include strong monitoring and evaluation components to ensure continued effectiveness in a changing climate (Ebi 2009; Frumkin et al. 2008; Jackson and Shields 2008). The only difference from monitoring and evaluating of other public health policies and measures is that the effectiveness of adaptation options are likely to change with changing climate and socioeconomic conditions, thus requiring vigilance that these options will continue to provide appropriate levels of infectious disease control.

There are many metrics that can be used to measure the effectiveness of implemented programs and to identify modifications to address less than maximum effectiveness, including measures that track changes in vulnerability or resilience, the incidence and geographic range of climate-sensitive infectious diseases, relevant environmental variables (i.e. changes in temperature, precipitation, and other weather variables), land use change, as well as possible confounding variables (i.e. associated with the environmental variables and the outcomes; this includes demographic change, status of the public health infrastructure, economic development, etc.). English et al. selected indicators for the United States that describe elements of environmental sources, hazards, exposures, health effects, and prevention activities (English et al. 2009). Some indicators were measures of environmental variables that can directly or indirectly affect human health, such as maximum and minimum temperature extremes, while others could be used to project future health impacts based on changes in exposure, assuming exposure-response relationships remain constant over temporal and spatial scales. Indicators were categorized into: environmental; morbidity and mortality; vulnerability; and policy responses (i.e. implementation of adaptation and mitigation policies and measures). These indicators are similar to those used to monitor the effectiveness of all public health policies and measures, but are adjusted to take into account environmental and socioeconomic factors that could alter their effectiveness.

5 Examples of health adaptation assessments

Examples of assessments include a comprehensive assessment in the European Union (EU) and one in Sweden on climate change risks to drinking water. Of the 27 EU member states, 9 countries have conducted a national assessment of the potential health impacts of climate change (Semenza et al. 2012b). These countries were predominantly western European countries. However, in 14 countries, there are regional/local planning and coordination institutions to monitor and control climate-sensitive infectious diseases and the National Climate Change Team/Committees explicitly include consideration of the infectious disease health risks of climate change. In 15 countries there are plans to alter current vector-borne disease surveillance and control programs to address the threats of climate change; they include changing the frequency or location of monitoring and surveillance programs to detect changes in the geographic range or incidence of vector-borne diseases; plans to alter monitoring of water sources or water treatment regulations; plans to alter food safety and other regulations; or plans to increase the human and material resources devoted to climate change risks. Nevertheless, only five countries considered the current surveillance systems to be adequate to deal with climate change impacts. Collaboration with the veterinary sector was also considered to be inadequate as well as the management of animal disease outbreaks.

Tap water is the main drinking water source in Sweden, and is provided by the local municipalities. Half of the country's drinking water supply consists of lakes and running watercourses. The drinking water in the city of Stockholm originates mainly from Lake Mälaren. Because the quality of untreated water is generally good, water purification techniques are basic. The chlorine doses used are not sufficient to deal with viruses and are ineffective for protozoan control, making tap water quality vulnerable to impacts that negatively affect water supplies and the water system. In addition, about 13 % of the population uses private drinking water sources, with an additional 10 % seasonal usage in summer cottages. One third of these private wells are dug wells. Risks from climate change include increases in water temperatures and intensifying heavy rain events during all seasons that can results in pathogens from sewage, animals, and soil contaminating water sources and increasing growth of microorganisms in water supply. In 2005, the Swedish Government commissioned a major national climate change vulnerability, impacts, and adaptation assessment that included all sectors of society (The Commission on Climate and Vulnerability 2007). Among the main recommended strategies and actions stated by the Commission was the need for adapting local water supplies and water systems to impacts of climate change. This has been further evaluated at the national level by main governmental agencies and at the regional, county, and municipality levels. The combined cost for a gradual adaptation of the Swedish water system to impacts of climate change during the period 2011–2100 is estimated to at least 5.5 billion SEK for municipal water supplies, and some 2 billion SEK for private water supplies (The Commission on Climate and Vulnerability 2007). There also will be additional increasing operational costs for local actions to reduce contamination of protected catchment areas and water sources. However, the costs for society if no adaptation measures should be taken will be substantial. Many municipalities are now evaluating how they can best adapt their drinking water system to impacts from increased water surface contamination, increased water amounts, and higher temperatures. Some municipalities are considering switching from surface water to ground water supplies as an adaptive measure. Targeted information is crucial. The Swedish Board of Health and Welfare conducted a survey on water quality in private wells in 2007. Of 5,000 water tests taken from 110 municipalities, 20 % showed that the water was unfit for consumption; for dug wells the number was 33 %. One conclusion was that information should be given to households with private water wells about increased health risks after heavy rain and during periods with higher temperatures.

6 Describing uncertainties

There are deep uncertainties when projecting future health risks due to climate change. The exposure, vulnerability, and any potentially confounding variables vary depending on the infectious disease being considered, the geographic region of interest, and modifying or interacting factors. Uncertainty also arises because many of the potential infectious disease impacts of climate change are indirect or nonlinear, with less than full understanding of how the dynamics of these systems could be affected by climate change (Confalonieri et al. 2007). There are many unresolved empirical questions about the sensitivity of particular infectious diseases to weather, climate, and climate-induced changes in environmental conditions critical to disease transmission, such as water resources. There are also critical uncertainties in projections of the future health status of potentially affected populations, and how sensitivities might change with changing demographics, socioeconomic development, technology development, and deployment, etc. Approaches to managing uncertainties include:

- Reduce uncertainties in key areas by using complementary data collection and different analysis methods and tools.
- Perform sensitive and uncertainty analyses to evaluate the robustness of the results. Sensitivity analyses can be used to explore how impacts of the options could change in response to variation in key parameters and how they could interact.
- Use storylines to illustrate how some key factors may change in the future and what that could imply. It is important to not only focus on the most probable outcome, but also on low probability and high consequence events. Decision makers need to know about the larger risks, including worst-case scenarios. It will be useful to explore vulnerabilities to different storylines and to make the preparations needed to manage them (Ebi and Semenza 2008).

7 Conclusion

Public health has a long and impressive history of preventing and controlling outbreaks of infectious diseases. Increasing concern about the infectious diseases changing their geographic range or incidence with climate change is one factor driving national and regional assessments of the possible health impacts of and responses to climate variability and change (Confalonieri et al. 2007). Ministry of Health professionals, university and NGO-based researchers, and others are being asked to conduct these assessments, often because of their expertise in one or a few climate-sensitive infectious diseases (Semenza et al. 2012b). However, expertise in climate variability and change is infrequently included in these assessments. Development of consistent guidelines for conducting such assessments can help ensure the products are informed and useful, and can facilitate consistency across assessments so that comparisons can provide lessons learned for the next iteration. To this end, ECDC developed a handbook intended as a resource to encourage planning activities that anticipate and address the possible impact of climate change on communicable disease spread (ECDC 2010). The handbook is not only based on assessments from Europe, but also from best practices and experiences in Australia, Canada, New Zealand and the USA. Although the context and content of vulnerability and adaptation assessments will inevitably vary from country to country and region to region, the process is essentially similar. This handbook stresses a strategy that involves as many different stakeholders as is feasible, is iterative in nature, and is carefully managed throughout all phases.

Assessments can build capacity within public health and health care organizations and institutions to assess how options implemented outside the health sector might affect population health (Table 2) (e.g. whether changes in land use proposed to address

Table 2 Example vulnerabilities to climate change risks that can increase infectious disease outbreaks, with selected climate change adaptation options

Sectors	Examples of climate change vulnerability/impacts	Examples of adaptation options
Agriculture	Salmonella and campylobacter in poultry farms are temperature sensitive	Altered animal husbandry practices such as eradication of pathogens in poultry flocks
Nature conservation	Recreational exposure to ticks infected with tick-borne encephalitis virus and borrelia	Vaccination and/or protective clothing
Coastal management	Exposure to coastal waters during bathing at contaminated beaches	Prevention of untreated sewage discharge into coastal waters due to combined sewer overflow during extreme rain events
Communication	Climate change misinformation by interest groups	Social marketing and media advocacy targeting susceptible populations
Civil infrastructure	Exposure to vector and water and food born diseases during and after flooding emergencies	Weather-proofing of central infrastructure to minimize adverse impacts
Emergency services	Slow response to climate-related outbreaks/disasters	Strengthen response capacity in order to quickly contain an outbreak
Energy	Peak energy consumption and/or brownouts during heat waves	Assure energy supply during extreme weather events
Fishery	Elevated water temperature has been linked to microbial contamination of shellfish (e.g. oysters)	Restrict shellfish harvesting after rain events or high levels of indicator bacteria
Health sector	Lack of resources can expose vulnerable populations to infectious agents	Target public health services to populations at risk
Hunting	Range shifts of disease vectors might create new risk zones in hunting areas	Minimize exposure with protective clothing
Industry	There are temperature-sensitive processes in the food industry that might be prone to contamination.	Stricter food regulations
Land use	Fragmentation of habitats results in wild life exposure which could result in pathogen transmission	Habitat restoration
Soil management	Susceptible to erosion	Divert storm flows from sensitive areas
Transport	Weather sensitive disruption of food supply chains	Local food production
Tourism	Importation of tropical pathogens can result in sporadic autochthonous transmission.	Surveillance and alert systems with immediate medical care
Water resource management	High precipitation events can overwhelm the water treatment plants	Upgrading the water treatment and distribution systems

climate change could alter vector breeding sites, or if the capacity of infrastructure such as water run-off systems and water treatment plants will be exceeded).

Effectively addressing the health risks of climate change offers opportunities to develop and deploy proactive modification of existing policies and measures, and implementation of new policies and measures, to prevent and control climate-sensitive infectious diseases (Lindgren et al. 2012). Taking advantage of these opportunities requires moving beyond 'business-as-usual' approaches in public health by explicitly considering risks over changing spatial and temporal scales, in the context of high degrees of uncertainty as to the rate and magnitude of changes in a particular location at a particular time. However, public health policies and programs have typically not been designed and implemented within an iterative risk management framework (Ebi 2011b). Mainstreaming systems-based and iterative management approaches into national and local policies and measures will facilitate creating the flexibility and creativity needed to proactively prevent avoidable morbidity and mortality in a changing climate.

Further, managing the infectious disease risks of climate change crosses disciplinary, institutional, and geographic boundaries, which means that coordination is required across agencies, organizations, and universities engaged in these issues. Key public health programs - including surveillance and monitoring; field, laboratory, and epidemiologic research; model development; development of decision support tools; and education and capacity building of the public and public health and health care professionals - should consider how climate change could alter the effectiveness of current and planned policies and programs (Semenza et al. 2012b). Formal coordination mechanisms should be established across all relevant ministries and organizations, including those dealing with environment, water resources, agriculture, transport, and urban planning.

Barriers to action include the complexities of disease transmission systems and the inherent uncertainties with projections of future health impacts under different scenarios. These complexities and uncertainties can be managed using a systems-based 'learning by doing' approach that places increased emphasis on monitoring and evaluation to provide early information on changes that could increase program efficiency and effectiveness under different environmental conditions. At the same time, climate change is one of many public health issues that needs to be addressed; therefore policies and measures need to ensure that actions to reduce climate-related infectious disease risks support current policies and measures to reduce avoidable infectious disease burdens.

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