10 Human Health

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10.1 Nature of the problem

Health is defined by the constitution of the World Health Organization as “a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity” (WHO, 1946). The sustainable health of human populations is an integrating measure of our long-term environmental and ecological stewardship. Environmental degradation, whether from chemical contamination or other forms of ecosystem disruption, can affect both acute and chronic human health problems. Thus, human health should be considered one essential criterion of the “dangerous interference” with the climate system that is described in Article 2 of the UNFCCC. The ability to assess the human health impacts of climate change, however, is still at a very early stage of development.

There are a number of reasons for this relative scarcity of well-developed methods for the assessment of health impacts from climate change. Since the germ theory of medicine acquired dominance in Western thought in the nineteenth century, the focus of health research has been on specific agents of disease and methods of combating them. Understanding the relations between environmental factors such as climate and human diseases has received less emphasis than understanding in exquisite detail the biochemical workings of pathogens and the drugs created to control them. As a

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consequence, our ability to describe and simulate the interactions between climate and other environmental factors and human diseases is very limited.

Research methods in human health differ from those in the physical sciences. Much of the data required for other sectors are measurements of physical states such as water flow rates or chemical composition. Even where data types are similar, significant differences remain: one example is that acquisition of data in health research depends on human behaviours and co-operation. Consider the following: determining the level of disease in an agricultural product or in a human population involves sampling. In a human population, however, that sampling requires extensive co-operation of many individuals, whether they are subjects who must co-operate with an interview or medical test, or health providers who must accumulate and submit measurements of diseases during their work day. Sampling an agricultural product either in the field or during production is comparatively simpler. This makes the acquisition of similar types of data much more expensive, difficult to do, and inherently uncertain for health as compared to the other sectors. This barrier alone impedes the progress of high quality research in health-environment interactions.

Lastly, human health is arguably more complex than most of the outcomes of other sectors. In most cases, health outcomes cannot be simply correlated with climate factors. Numerous other factors such as the level of economic development, state of sanitation and public health systems, and group and individual behaviour have a significant effect on human health. Understanding the interactions among these factors, climate variables, and human health in the present day is a difficult task. Being able to predict how these interrelated factors will change in the future and then analysing their effects on future climate changes and human health is a daunting task. This difficulty is compounded by the fact that anticipated climate changes are beyond the range of observable events for most areas (McMichael, 1993)

As a result, this chapter differs from other sectoral chapters. It is not possible to place before the reader an array of methods that have already been developed and applied for predicting impacts. Rather, a suggested approach to performing a comprehensive impact assessment for human health is offered and some general principles of climate impacts on health are explained. Next, methods that are being used to gain insight into relations between climate and human health are described. These methods should not be considered capable of providing predictions of human health under conditions of climate change. This chapter is intended to assist the handbook user in two different tasks: first, to provide a short-term answer to what the health impacts of climate change might be for a particular country or region, and second, to begin laying the foundation for greater understanding of climate-health interactions through acquisition of relevant data and development of research capability.

At the outset, two points must be emphasised. Because of the uncertainty regarding predictions of human health, resources should be devoted to understanding current serious human health problems and how they may be affected by climate change. Similarly, adaptation measures should be relevant to the current situation, and not be based solely on predictions of future events. Second, the past two decades have demonstrated the suddenness with which health problems may emerge. Diseases such as

AIDS, the Central and South American cholera outbreak, and the hantavirus pulmonary syndrome could not have been predicted prior to their emergence. While it is essential to ensure that public health measures for climate change have relevance for current problems, it is equally essential that countries enhance their ability to detect and react to unforeseen health problems. Public health and biological surveillance and monitoring will be a critical element of any national plan for human health impacts of climate change (see Levins et al., 1994).

Recent articles and monographs have described the range of human health problems that may be affected by climate change (McMichael et al, 1996a; McMichael et al., 1996b; Patz et al., 1996) and these effects are summarised in Table 10.1. Some countries have also undertaken national reviews of potential health impacts (e.g., Longstreth, 1989; NHMRC, 1991; CCIRG, 1996). One of the major impacts of climate change on health may be changes in the transmission of vector-borne diseases. A comparison of the public health impact and likely climate sensitivity of the major vector-borne diseases appears in Table 10.2.

Table 10.1 Summary of anticipated direct and ecosystem-mediated effects of global climate change.

Environmental alteration	Direct health effects	Ecosystem-mediated health effects
Higher temperatures and altered precipitation patterns	Increased heat -related mortality and morbidity. Increase in photochemical and possibly other forms of air pollution, with resulting increase in respiratory illness.	Changes in distribution and seasonal transmission of vector-borne diseases. Increase in toxic algal blooms and possibly in transmission of water-borne diseases.
	Increased frequency of floods, storms, and natural disasters.	Decreased agricultural production and food shortages.
Sea level rise	Loss of habitable land, contaminated freshwater supplies, damage to public health infrastructure.	Decreased fish stocks due to loss of coastal wetlands.

Tables 10.1 and 10.2 do not represent all possible climate-related health problems. For example, moulds producing food spoilage or direct toxicity may become more prevalent, and respiratory illness caused by plant pollens may shift in geographic distribution or seasonality because of climate change. Country teams should rely on their internal expertise, and consider Tables 10.1 and 10.2 to be guidelines in assessing the possible health impacts of climate change.

Table 10.2 Estimated impacts of climate change on major vector-borne diseases around the world (after McMichael et al., 1996b).

Disease	Population at risk (millions)	Number infected or new cases per year	Present distribution	Possible change of distribution as a result of climate change
Malaria	2400	300-500 million	tropics/subtropics	+++
Schistosomiasis	600	200 million	tropics/subtropics	++
Lymphatic filiariases	1094	117 million	tropics/subtropics	+
African trypanosomiasis	55	250-300 000 cases/year	tropical Africa	+
Dracunculiasis	100	100 000 cases/year	tropics (Africa/Asia)	?
Leishmaniasis	350	12 million infected, 500,000 new cases/year	Asia/Southern Europe/ Africa/ South America	+
Onchocerciasis	123	17.5 million	Africa/Latin America	++
American trypanosomiasis	100	18-20 million	Central and South America	+
Dengue	2500	50 million	tropics/subtropics	+
Yellow fever	450	<5000 cases/year	Africa/Latin America East/Southeast Asia	+

10.2 Selection of health impacts

The WHO definition emphasises that assessing health impacts requires more than merely predicting future incidence of specific diseases. Deleterious effects of altered climate on the foundations of public health (i.e., nourishing food, safe and adequate drinking water, and secure shelter) need to be considered in addition to changes in specific diseases. This will require input from other sectors performing parallel impact analyses, such as agriculture (Chapter 8), coastal zones (Chapter 7), and water resources (Chapter 6). Changes in these fundamental public health factors may drastically alter a population's susceptibility to a number of diseases, both climate sensitive and climate insensitive. While such comprehensiveness of analysis makes the process more difficult, it is essential to integrate these fundamental health factors into the overall assessment to be able to formulate relevant responses.

The following is a possible sequence of initial steps in a comprehensive health impact assessment.

1. Review major national or regional causes of morbidity and mortality, especially infectious diseases. For infectious diseases, any geographic boundaries (such as those between areas of endemic and epidemic transmission, or between areas of epidemic transmission and no known disease) should be noted. National experts in public health should be consulted for opinions on reasons for such boundaries (i.e.,

is disease transmission limited by climate factors such as temperature or precipitation?).

2. Identify populations at risk. This would include refugee and migrant populations, populations with marginal nutritional reserves or safe water supplies, populations with poor sanitation infrastructure, populations in low-lying coastal areas, and non-immune populations bordering zones of infectious diseases.

3. Review results of other sectoral climate change impact assessments. Specifically, results from water resources, agriculture, forestry, coastal zones, and economic assessments should be assessed for impacts on:
   a. supplies of food and water;
   b. habitability of low-lying areas; and
   c. economic future of currently vulnerable or impoverished regions and populations.

4. Integrate the information gathered thus far. From this information, the existence of critical areas can be proposed. Similarly, the potential for populations fleeing uninhabitable or economically non-viable areas, with attendant health problems, can be assessed. Conversely, positive impacts on health (such as might be seen because of a decrease in seasonal rainfall in an area in which malaria is dependent on such rainfall) may also be assessed at this point.

10.2.1 Selection of health impacts, populations, and regions

Once the initial assessment is completed, the need for further study should be addressed. The direction of further study will be determined by the types of health problems identified in the initial assessment and the current status of understanding and data collection for a specific disease system and a specific area. For example, further study of health problems related to heat mortality and morbidity, if this is identified as an area of concern, may involve the application of existing models to region-specific data in a relatively straightforward way. Further study to quantify impacts on malaria or dengue fever, however, should be directed by the level of analysis already performed on those diseases in a specific area. For example, the ability to apply quantitative models to malaria in Africa has been limited by the lack of geographically referenced (georeferenced) data on disease incidence or even vector density (see Box 10.1). Before accurate quantitative estimates of the future can be made, accurate quantitation of historical and current disease dynamics is essential. Therefore, collection of such data may be the most useful form of further study for those regions. Where baseline data and validated models of the current situation exist, further study may involve extrapolation of the existing models or application of integrated models. Because of the time, money, and expertise required for such studies, decision makers should consider alternatives carefully before embarking on a specific direction for further study.

Box 10.1 Example: Building a georeferenced data base for Africa: The MARA/ARMA Collaborative

One of the greatest weaknesses with the current status of climate change research is that the building blocks are not in place for it to move beyond the scenario stage. The lack of adequate, spatially georeferenced, disease data sets means that existing models attempting to define current distribution remain invalidated. Following on from this is the conclusion that climate change impacts in the future will not be assessed because no baseline of existing conditions against which to quantify impacts is available. Similarly, the resolution and temporal detail of spatial climate data sets suitable for accurately defining existing conditions remain a limitation.

To overcome the limitations of adequate surveillance systems for malaria in Africa, the Mapping Malaria Risk in Africa/Atlas du Risque de la Malaria en Afrique (MARA/ARMA) collaboration has used the parasite ratio (percent infected) in surveys of children as a marker of intensity of transmission. The entire initiative has to date been operating on only 50 percent of the originally proposed budget. Only $235 000 has been secured (International Development and Research Centre, Canada; South African Medical Research Council; and Wellcome Trust). Thus activities have restricted country visits by regional data co-ordinators. Visit are essential as initial activities indicate that up to 71 percent of data is unpublished (Le Sueur, 1997; Omumbo et al., in press,).

To establish MARA/ARMA, the continent was sub-divided to establish five regional centres. A number of steps were taken to ensure uniformity of activities of the geographically dispersed centres:

A standardised 11 page pro forma and a set of operating procedures were compiled to guide the data co-ordinators.

Different regional centres were using different database applications (Dbase, MSAccess, Foxpro); thus, to ensure standardisation, a stand-alone application conforming to the pro forma was created with MSAccess/Visual Basic. A users guide was also developed.

Central to MARA/ARMA is the ability to geo-reference collected data within a completed pro forma. To facilitate this, two steps had to be carried out:

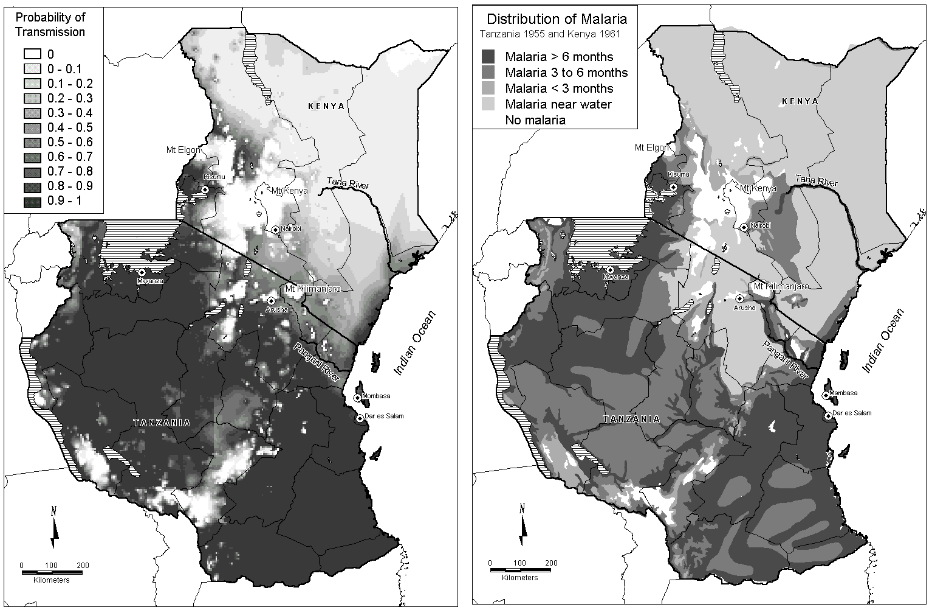
The data co-ordinators were brought to Durban and trained in the use of a vector GIS package (Mapinfo). This was done using a customised manual compiled by the co-ordinating centre in Durban, which uses local malaria data sets for the training exercises.

Continental digital data sets which were capable of supporting the geo-referencing procedures within Mapinfo were acquired. These then were converted into Mapinfo format for use by the data co-ordinators. These include data sets such as the African Data Sampler, which includes administrative boundaries, populated centres, rivers, roads, etc., and GeoName, an electronic gazetteer of place names.

A copy of all completed pro formas and a digital copy were then forwarded to the co-ordinating centre in Durban.

To date, over 2000 independent parasite surveys in children aged 1-9 have been collated. In addition, incidence data and other associated data (drug resistance, vector distribution, agricultural practice, etc.) have been collected. These data as well as data defining historical distribution are being used to define the boundaries of malaria transmission within Africa. Current models are based upon long-term mean interpolations (Hutchinson, 1995) and use the raster GIS package IDRISI. However, recently, new annual surfaces have been commissioned by MARA/ARMA which allow the periphery of distribution to be more accurately defined in terms of spatio-temporal (inter-annual) variation (New and Hulme, 1997). Inherent in the above is the fact that the numerical-eco-physiological models defining the limits of distribution are validated. The figure illustrates the validation of such a model derived from climatic data (Craig et al, in preparation) and in terms of existing country level maps of distribution.

Thus the MARA/ARMA collaboration has demonstrated that despite geographic dispersion, a methodology for creating a database can be successfully instituted; in the future, this will allow the issue of the impact of climate change on malaria in Africa to be moved beyond the scenario level. The MARA/ARMA collaboration with its existing skills and methodology also has the potential to serve as a vehicle for collecting data important to other African diseases.



Box 10.1, Figure 1 Comparison of climate based numeric distribution model and existing country specific malaria maps.

Further study of other health problems such as water-borne diseases or diseases related to environmental refugeeism may be limited by complexity or lack of current understanding. Additional analysis may be limited to comparison with historical and geographical analogues. In general, it is suggested that the decision to perform further analysis be guided by an estimation of the overall public health impact of the problem to be studied as well as the usefulness of the additional information obtained by quantitative study over and above the initial qualitative assessment.

The selection of populations and areas to be studied further will be driven by two factors: the vulnerability of that population or area to climate change and the availability of relevant data. Ideally, data will be available for the population or area determined in the initial assessment to be most at risk from specific impacts of climate change. If not, a decision must be made of whether to invest resources in developing data for the most vulnerable population or area or in conducting the analysis on a population or other health problem that may not be the most critical.

An example of a critical geographic area would be the land at the edge of an endemic zone for vector-borne diseases. In this area, small changes in temperature or rainfall may promote disease transmission to the extent that the disease becomes endemic. For example, in East Africa, there are regions where malaria is endemic in the lowlands.

The highlands surrounding these endemic zones experience unstable epidemic malaria when small local environmental or climate changes allow disease transmission within vulnerable, non-immune populations. These highlands are thus critical areas, where further studies (as well as surveillance and monitoring efforts) will need to be focused.

10.2.2 Selection of time scales

It is unlikely that one time frame will be appropriate for the entire health impact assessment. Rather, a variety of time frames may be more useful. Because of the increasing uncertainty inherent in long time frames (i.e., 2050 scenarios), short-term, incremental analyses (i.e., 5 year steps) may be of more use to policy makers.

For many human disease systems, a threshold exists, such that once a given mean or minimum temperature is reached, a significant change in disease transmission occurs. Thresholds may exist for precipitation levels as well. The time it takes to reach a threshold will depend on a number of factors, including the inertia of the climate system and the response times of different levels of ecosystems. In some cases, it may be more appropriate to determine the threshold for changes in disease transmission, and then determine a range of time frames for that threshold to be reached.

Health impacts may occur rapidly with small climate changes if the relevant climate factor is the only limitation on the range of disease transmission. For example, the transmission of dengue at higher altitudes with increases in temperature is an effect seen within months of extreme climate variability (Herrera-Basto et al., 1992). Alternatively, changes in the incidence of diseases related to sea water temperature (toxic algal blooms, shellfish poisoning) may lag changes in air temperatures by years because of slower warming of the oceans.

The time scale of data collected for the analysis of regional sensitivity of diseases to climate change will also vary depending on the data available and the health impact studied. For example, assessment of heat mortality requires daily data. The study of infectious diseases, however, will usually require weekly or monthly incidence and climate data.

10.3 Methods

This section describes the variety of methods by which climate-health interactions have been studied. For certain health problems such as weather-related mortality (whether due to heat or extreme weather events), these methods may be useful to estimate impacts of future climate changes. For other health problems, especially the vector-borne diseases, these methods may be more useful to understand relations between climate and health in a specific region in the present day. An attempt is made to discuss the general advantages and disadvantages of the different methods in this section, and a summary appears in Table 10.3. Section 10.5 discusses the details of these various methods in the context of specific health problems.

Table 10.3 Summary of approaches to assess human health impacts of global climate change.

Method	Personnel required	Time required	Data needs	Advantages	Disadvantages	Applications
Expert judgement	Interdisciplinary team including public health experts	Minimal	Current morbidity and mortality data, region-specific climate projections	Inexpensive, rapid, able to integrate multiple factors	Imprecise, may be subjective	Initial assessment; all problems
Simple mapping Conceptual modelling Ecologically based risk assessment	Cartographers, GIS specialists	Minimal to moderate	Current areas of endemicity and sporadic disease, case or outbreak data. Georeferenced climate projections. GIS requires spatially indexed data, layers need compatible resolution	Inexpensive, rapid, able to visually represent important information for policy makers	Unable to integrate numerous factors and model dynamic interactions.	Vector-borne diseases; health problems due to sea level rise
Regression modelling historical analogues Geographical analogues	Epidemiologists, biostatisticians	Minimal to moderate	Must have appropriate historical data to validate models.	Simpler computation than numeric models; may be able to apply published methods.	Limited applications, decreasing validity out of range of observations.	Heat stress, extreme event-related health problems; vector-borne diseases; respiratory disease due to air pollution
Numerical modelling	Generally requires services of model author, computer specialists	Requires greater time and money	Baseline disease, vector ecology and socio-economic data. Must have appropriate historical data to validate models.	Able to integrate multiple factors, explore interactions among factors.	More expensive, time consuming, large uncertainties.	Vector-borne diseases, water-borne diseases; heat stress

10.3.1 Conceptual model

For the major current health problems, especially infectious diseases, a conceptual model should be developed that describes the interactions among the various factors contributing to the severity of the problem. Such a model assists in three processes: 1) the initial qualitative assessment of climate impacts on health, 2) the quantitative analysis of regional relations between climate factors and disease, and 3) the identification of possible intermediate endpoints (for example, changes in critical host species for vector-borne diseases) that can be used for monitoring and surveillance. One possible paradigm for approaching the development of such conceptual models has been described by the USEPA in a 1992 report entitled "Framework for Ecological Risk Assessment" (Risk Assessment Forum, 1992). This framework emphasises the importance of integrating input from multiple scientific disciplines, including health professionals, biologists, entomologists, and agriculture and forestry experts, in the development of conceptual models of disease systems.

The process of ecologically-based risk assessment is divided into three phases: problem formulation, analysis, and impact characterisation. The initial phase requires a multidisciplinary team to identify critical interactions among climate factors and ecosystem mediators of the disease system as well as specific human health endpoints. Following the identification of these critical interactions, intermediate ecosystem indicators which will aid in both the monitoring of ecosystems for climate change effects and further quantitative analysis can be selected. For example, dengue fever outbreaks are thought to be dependent on high temperatures and moisture availability (influencing mosquito and viral life cycles), human behaviour (regarding water storage practices), human migration, demographics and urbanisation patterns, and human habitation (i.e., screened windows). Thus, analysis of climate impacts on dengue will need to include not only mosquito survival and viral replication rates, but also forecasts of human settlements and water provision systems. Key indicators to be monitored could include mosquito larval populations in selected water storage utensils.

Along with the development of conceptual disease system models, the initial phase involves characterising the essential elements of the system stressors. For climate stressors, care must be given to account for the complexity of climate-ecosystem interactions. Rate of change, frequency of events, and climate variability may be more detrimental to ecosystems than magnitude of change (Mearns, 1993). This introduces a level of complexity to the analysis which is beyond the capacity of current GCM models, which agree on average temperature projections but differ greatly on estimates of regional precipitation and extreme weather events. For now, addressing issues of variability will require simplifying assumptions and use of fixed estimates of certain parameters.

Intermediate ecosystem changes due to climatic stress may also be conceived of as stressors in a human disease system, since many of the human health impacts from climate change are anticipated to be ecologically mediated. Thus, changes in insect vector habitats or marine vegetation may be considered both an outcome of climate change and an intermediate stressor for human disease.

The analysis phase applies the conceptual model developed in the problem formulation phase to the particular area and time frame being analysed. The first stage, ecosystem characterisation, builds on the ecosystem description of the first phase, and involves choosing specific geographic borders and time scales. Because elements within an ecosystem can be both responders and stressors, it is essential in ecosystem characterisation to identify potential areas where this bi-directional dynamic interaction may occur. For example, land use changes may affect micro-climates, which in turn may alter the effects of climate change on mosquitoes, or irrigation of agricultural land may alter a drought's impact on crops (while simultaneously providing potential breeding sites for insect or snail vectors). Exposure analysis then superimposes the spatial and temporal distribution of stressors developed in the first phase on relevant ecological components identified in the ecosystem characterisation to determine points of contact between stressors and responding species (or abiotic elements such as water levels) within an ecosystem.

The responsiveness of ecosystem indicators to climate stressors is assessed in the stressor-response analysis. For each of the endpoints identified in the first phase, the magnitude and nature of the response to the aggregate stresses are estimated. By the end of this stage in the analysis, those human health endpoints that are likely to be affected by climate change should be apparent, and the final stage of risk characterisation will begin actual impact assessment. Understanding of climate-related sensitivity and the existence of threshold values for each given endpoint are critical in this central step. The term sensitivity as used here refers to the amount a given endpoint is affected by a given amount of change in a climate variable. This is analogous to the slope of the dose-response curve in conventional risk assessment. In an ecological risk assessment, the ultimate "sensitivity" of a human disease to climate change may reside in the life cycle of an organism in the disease system which displays marked alterations in reproductive or other types of behaviour in response to changes in climate variables. For example, cold-blooded insect vectors are quite sensitive to small changes in temperature and moisture. Diseases whose infectious agents (viral or protozoal) must reproduce within insect vectors are thus susceptible to subtle climate variations (Dobson and Carper, 1993) .

A concept related to sensitivity is that of threshold. For relatively simple systems, a threshold refers to a sudden change in the slope of the dose-response curve. For example, human sensitivity to temperature extremes varies on a physiologic basis. Heat-related mortality occurs at different temperatures, depending on the latitude and typical temperatures for that area. For example, data from Montreal, Canada, show an exponential increase in heat-related mortality at 29°C, whereas data from Dallas, Texas, USA, do not show a similar increase until 39°C (Kalkstein and Smoyer, 1993). Thus, Montreal may be said to have a temperature threshold at 29°C, and Dallas exhibits a threshold at 39°C.

When considering ecological risk assessment, the threshold may be better conceptualised as a point of non-linear behaviour of an ecosystem endpoint in response to a combination of stressors. Multiple effects of different aspects of climate make it difficult to think of thresholds in relation to a single parameter. For example, elevated temperatures decrease the survival of dengue-carrying mosquitoes. At the same time, other parameters in the dengue disease system include biting rates (related to adult insect size) and infectivity of mosquitoes (related to maturation time of the virus in the mosquito), both of which increase with temperature. Thus, at temperatures increasing within the range of mosquito viability, the effect of a decreasing survival rate may be more than offset by the combined effects of increased biting rates and infectivity, resulting in an exponential rise in disease transmission (Focks, 1995). Further increases in temperature outside of the range of mosquito viability would then be expected to result in decreased disease activity. Thresholds may occur temporally, as changing climate within a given geographic area alters the behaviour of an already-present human disease. They may also manifest geographically, as changing climate conditions allow migration of human disease into a previously unaffected area.

The final stage, impact characterisation, attempts to translate changes in disease intensity or distribution into terms useful for decision makers, such as demand for health care services or loss of productivity. The result may be qualitative or quantitative. Essential parts of this final phase are assessments of the uncertainty of the results and integration of the results for a given disease system with other analyses.

10.3.2 Empirical studies

10.3.2.1 Historical analogues

Analysis of damage produced, societal responses, and attendant health problems from past events and trends can allow some prediction of impacts of similar severe weather events and trends in the future. Similarly, analysis of anomalous historical climate periods can give considerable insight into the relations between climate and infectious disease. For example, Leovinsohn (1994) found that malaria incidence increased during an atypically warm and wet period in Rwanda in 1987. Several studies have also examined the relationship between malaria outbreaks and temperature and precipitation changes due to the El Niño-Southern Oscillation (ENSO) (e.g., Bouma et al., 1994; Bouma and van der Kaay, 1996). Boxes 10.2 and 10.3 give details on two examples of empirical studies of historical analogues.

An advantage of the use of historical analogues is the regional specificity that comes from analysing the area of interest. The difficulty of accounting for the complexity of confounding factors, as would be required of a free-standing mathematical model, can be avoided to some degree in the creation of empirical models. A disadvantage of models based on historical analogues includes their limited ability to be extrapolated to other regions or to climate changes out of the range of observed data. It should be emphasised, however, that understanding historical climate-disease relations is a prerequisite for being able to develop models that can address changes out of the range of historical data. Moreover, empirical models which have been developed and validated based on historical data should have relevance for short-term changes. Box 10.1 describes the development of a georeferenced historical data base to support future climate predictions.

Box 10.2 Example: Heat-related mortality in US cities (Kalkstein and Greene, 1997).

Daily mortality associated with heat episodes can be assessed with several different approaches to characterising climate. For example, in a study by Kalkstein and Smoyer (1993), six meteorological variables were entered into a stepwise regression procedure to select those with the most explanatory power. In addition, variables relating to the number of days of heat and the timing of a given heat wave during the summer season were included to consider the impact of acclimatisation. Other studies have used standard composite meteorological indices such as the temperature-humidity index (e.g., Karacostas and Downing, 1996). The most sophisticated approach, developed by Kalkstein and colleagues, is the characterisation of air masses for a given locality (Kalkstein, 1991; Kalkstein et al., 1996a). This “synoptic” approach uses statistical methods to separate air masses into area-specific categories based on a large number of meteorological parameters, and is believed to provide a more meaningful tool to assess the health impacts of the specific climatic conditions on a given day. Daily mortality in 44 US cities with populations greater than 1 million were analysed in relation to the frequency of particular air masses. Two air masses associated with particularly high mortality were identified. This method has also been used to develop a weather watch/warning system in Philadelphia to prevent heat-related deaths (Kalkstein et al., 1996b).

Box 10.3 Example: Climate and malaria incidence in Rwanda (Loevinsohn, 1994).

Monthly malaria incidence in catchment centres in Rwanda was modelled with monthly precipitation and mean, minimum, and maximum monthly temperatures. A least-squares technique was used to select the best fitting model, and separate models were also developed for each of three altitude zones. The best-fitting equation for the study area as a whole was:

$$\ln I_{m} = -4.32 + 1.64\, Tn_{m-1} + 0.83 Tn_{m-2} + 5.34 \times 10^{-4} R_{m-2} + 7.7 \times 10^{-4} R_{m-3}$$

where I_m is the monthly incidence, Tn_m the minimum monthly temperature, and R_m the monthly rainfall. This equation demonstrates the importance of lagging the climate variables, as the rainfall from three months previous was more highly associated with incidence than more recent rainfall. This study also demonstrated that at low altitudes, the amount of rainfall was the most important predictor of disease incidence, whereas at high altitudes, minimum temperature was the most important independent variable.

10.3.2.2 Spatial analogues

In establishing empirical relations between climate and disease, areas which display more interannual climate variability are more likely to yield results than areas with less variability. Areas affected by meso-scale climate systems are particularly useful. One such meso-scale system, the ENSO, affects rainfall and temperature every 4 to 5 years in certain areas around the world. The ENSO may be seen as a valuable natural experiment (Bradley, 1997): variations in excess of 1°C have been associated with ENSO, providing a temperature signal comparable with decades of anticipated global warming. These areas (such as western South America or South Asia) where ENSO strongly affects local climate are therefore promising study locations (Bouma et al., 1994).

Reeves et al. (1994) used a geographical analogue situation to assess the potential impact of climate change on arbovirus transmission. Field and laboratory studies have shown that temperature is an important factor in determining the transmission of a viral agent by its mosquito vector. Reeves took advantage of a 5°C temperature differential between two nearby valleys to compare seasonal transmission and vector abundance in the two areas.

10.3.2.2 Techniques and tools for empirical studies

Geographical analysis/mapping

Health problems which have special associations to local geography, such as those associated with coastal flooding and especially vector-borne disease, can be effectively analysed through mapping techniques. In simplest form, these techniques start by plotting the current boundaries of a health problem (e.g., flood areas, intensities of disease transmission or incidence). The factors responsible for the geographic boundaries (e.g., altitude in the case of flooding, or temperature or rainfall in the case of vector-borne diseases) are similarly plotted. Projected changes in those factors, either from fixed projections or predictive models (e.g., GCMs), are then plotted, and the changes in the boundary of the health problem are noted with respect to population centres. An example of such an approach to malaria in Sri Lanka is shown in Box 10.4.

Geographic information systems

Box 10.1 describes the use of GIS for both current and future analysis of malaria in Africa. A discussion of GIS is given in Chapter 1, Getting Started. Other GIS-based studies include changes in vector distributions mapped by Rogers and colleagues in southern Africa (Hulme, 1996). The use of GIS systems as data platforms to assist in predicting disease incidence is still under development, but especially in combination with satellite remote sensing (see below), there appears to be promise in using ecosystem parameters such as vegetation types to help predict locations of disease outbreaks or changes in disease vector distribution (Washino and Wood, 1994).

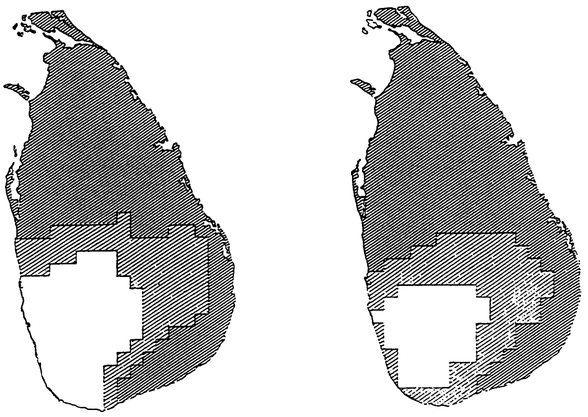
Use of remotely-sensed images

For many parts of the world, it is very difficult to acquire high quality, geographically referenced data on ecological factors related to disease transmission (such as types of vegetation or temperature and composition of surface waters). Political or geographic obstacles may impede the collection of such data through traditional field methods. Technological advances have enabled the use of remote sensing devices to assist in providing these data. Using low-flying aircraft or satellites, these devices are able to measure either directly or indirectly water and air temperatures, vegetative cover, and even water flows. Those entities measured indirectly often require significant initial field work to establish the relations between factors which can be measured directly, such as light absorption, and the desired entity, such as vegetative cover.

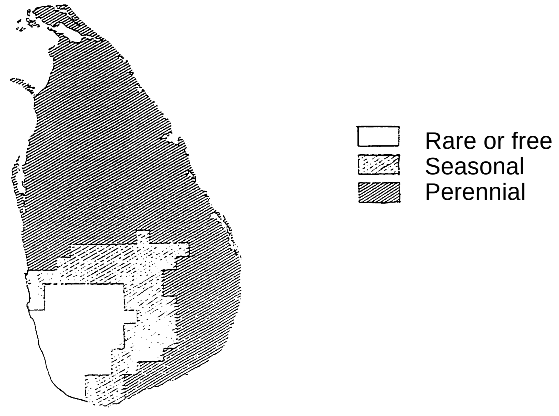
Box 10.4 Example: Malaria transmission in Sri Lanka.

Dhanapala (1998) used mapping used to study potential malaria transmission in Sri Lanka. Zones of perennial and seasonal malaria transmission and malaria-free zones were defined under present climate conditions. These zones were then correlated with a moisture index using historical temperature and precipitation data, and the threshold moisture indices which defined the three zones were determined. Temperature outputs from two global circulation models were combined with assumptions of either increased or decreased total precipitation (due to uncertainty) and moisture indices were calculated for each pixel of GCM output. The IDRISI GIS was used to store and display this geographically-based data. Threshold moisture indices between current malaria transmission zones were applied to the new map and new borders of malaria transmission zones were estimated. It was estimated that the area of malaria-free zone might decrease by 45.6% to 55.1% and the area of the perennial transmission zone would increase by 45.1% to 65.1%. Further analyses could assess the implications of the shifts in transmission zones for specific population centres, and begin to formulate possible adaptive strategies.

Clear limitations to this method include the fact that other geographic and anthropogenic factors affect malaria transmission, for example, pesticide use. It is not possible to account for these other factors either in the present situation or in the projections. Nonetheless, this exercise provides a number of benefits. First, the relation between areas potentially vulnerable to increases in malaria transmission can be estimated and compared to existing population centres. Second, areas which may have decreases in malaria transmission can be noted as well.



Present (1xCO$_2$) Climate CFDL-R30 (2xCO$_2$)



CCCm (2xCO$_2$)

Box 10.3, Figure 1 Annual malaria potential transmission.

An example of the use of remote sensing for vector-borne disease is the study on human African trypanosomiasis by Rogers and colleagues. Vegetation indices (specifically the NDVI, normalised vegetation index) obtained from satellite images and tsetse fly abundance have been correlated for regions in Central and East Africa (Rogers and Randolph, 1991; Hay et al., 1996). Two important points are evident. First, the ability to use remote sensing for a given area is dependent on sufficient ground-based study in that area. The linkage of remotely sensed vegetation indices and vector populations was made possible by previous studies associating climate factors such as saturation deficit with vector survival. By associating both vector survival and vegetation indices to the same climate variables, the remotely sensed data could then be applied to human disease prediction. The second point is that different local species of vector may have very different responses to changes in climate. In this study, it was shown that the population of the species *Glossina palpalis* increased with increasing vegetation index (indicative of greater moisture), while the species *G. tachinoides* decreased in number with increasing vegetation index. This emphasises the need for regional models developed along with expert judgement.

10.3.3 Numerical models

Although numerical modelling is often used by epidemiologists – to gain insights into the observed dynamics of infectious disease epidemics, for example, or to estimate future time trends in diseases – the complex task of estimating future trends and outcomes in relation to global climate change and human health may ultimately require the use of integrated, systems-based numerical models (Rotmans et al., 1990; McMichael and Martens, 1995). Once empirical studies have clarified current relations between climate factors and human diseases, numerical models can be used to highlight the effects of a wide variety of scenarios on those relations. For example, the impacts of changes in demographics, health care investment, immunisations, and nutrition can be better assessed with numerical models than with standard empirical models. The information gathered from such analysis can be of great importance to policy makers.

One example of numerical modelling is MIASMA (Modelling framework for the health Impact Assessment of Man-induced Atmospheric changes), developed by Maastricht University (Martens, 1997). MIASMA is an acronym devised to refer to several models: a vector-borne disease model, a thermal stress model, and a skin cancer model. This modelling framework is designed to describe the major cause and effect relationships between atmospheric changes and human population health. The models are driven by scenarios of population figures and atmospheric changes, superimposed on baseline data regarding disease incidence, climatic conditions, and ozone-layer thickness. Global atmospheric changes directly influence the exposure to health risks via changes in ambient temperature and received UV-B radiation, as well as indirectly, in influencing the dynamics and distribution of vector-borne diseases. Changes in the pattern of health risks demarcate the changes in the levels of incidence of the diseases influenced by the determinants. The mortality rates associated with cardiovascular diseases are directly influenced by thermal stress, mainly in urban areas.

The modelling approach is orientated toward a vertical integration of global atmospheric disturbances and their respective health effects. The models try to cover as much as possible of the cause-effect relationship with respect to global atmospheric changes and human health. In the vector-borne disease model, the dynamics of malaria, schistosomiasis, and dengue are simulated in relation to climate changes. Relationships between temperature, precipitation, and vector characteristics are based on a variety of field and laboratory data. Changes in transmission dynamics of malaria and schistosomiasis are modelled using the basic infectious disease models described in Anderson and May (1991); for dengue a well-validated, dynamic life-history model of dengue transmission (Focks et al., 1993a,b) is used. Recognising the need for continuing cross-validation of large-scale and small-scale studies (Root and Schneider, 1995), simulations have been performed of the transmission potential of malaria in Zimbabwe and dengue in five cities (Bangkok, San Juan, Mexico City, Athens, and Philadelphia) (Focks, 1993 a and b; Jetten and Focks, 1997; Patz et al., 1998). The historical data available for these locations are used for validation, i.e., testing the performance of the model.

To represent a wide range of climatic conditions and levels of socio-economic developments, effects of thermal stress on cardiovascular, respiratory, and total mortality have been simulated for 20 cities throughout the world. The association between winter and summer temperatures and mortality rates has been estimated by means of a metanalysis, aggregating the results of several epidemiological studies on the subject. Projections of future risks are then simulated by simple extrapolation of this calculated relationship. Effects of acclimatisation to increasing temperatures, physiological as well as technological, are simulated.

10.4 Selecting scenarios

Chapters 2 and 3 describe in detail the use and development of socio-economic and climate change scenarios.

Scenarios specific to health impact studies include demographic and socio-economic projections. In the study of vector-borne diseases, vector resistance to pesticides and parasite resistance to drugs are also included in numerical models. In general, baseline data are obtainable from WHO and World Bank sources (e.g., WHO, 1992; World Bank, 1993).

10.5 Impact assessment

10.5.1 General considerations

This section is meant to provide more specific information on impact assessment for particular human health problems. Because the best method of assessing impacts will differ for different health problems, this section cites examples of analysis and discuss some of the issues particular to specific health problems.

The optimal method of expressing human health impacts is not clear. In addition to the traditional public health parameters of disease incidence and prevalence, there has been increasing use of terms that express the economic burden of human diseases. Because different countries may have different costs associated with addressing the same incidence or prevalence of disease, and because analysis of human health impacts will be reported next to analyses of sectors with clearer economic ties, the use of economic terms may be desirable. Measuring the economic impact of climate-related changes in human health, however, is clearly a complex task. Unlike other sectors whose products are inherently economic in nature, such as agriculture and water resources, human health is historically difficult to quantify and associate with economic value. Changes in disease incidence for different diseases can be compared by attempting to measure lost productivity due to the disease. This requires knowing the average age of onset of the disease, case fatality rates, and the average extent and duration of disability due to the disease. These data are likely to be very difficult to obtain, and the levels and types of studies from which the data come need to be examined and found comparable (Aron and Davis, 1993). Should these data be obtainable, an estimate of healthy years of economically productive life lost can be made. The further valuation of this measure in economic terms is quite problematic. Regional differences in wages, employment, and even gender roles will complicate the comparison of disease impacts.

Uncertainty analysis must accompany the overall integrated assessment. Uncertainty will be present at all levels of the risk assessment (McMichael and Martens, 1995). During the conceptual model phase, incorrect assumptions may prove difficult to resolve. The inevitability of incomplete data must be addressed throughout the analysis, and errors in measurement and sampling will need to be transparent throughout the assessment process. Finally, the natural variability, or "stochasticity", within climate and ecological systems must be adequately represented (Risk Assessment Forum, 1992). Communication regarding uncertainties must take place between scientists and policy makers early on in the process to ensure that the results of the risk assessment are accurately represented to constituencies at risk.

10.5.2 Impact assessment of public health infrastructure damage

Although it is not currently possible to predict the frequency and severity of extreme weather events for a given region, historical data on the impact of severe storms for a given region can be used to extrapolate the impact of climate change on public health infrastructure damage. Until severe weather predictions are available, a range of possible conditions based on expert judgement can be used, and infrastructure damage extrapolated from past experience. Local experts will also need to consider the range and extent of possible adaptive responses. An additional important element for assessing the impact of climate change on infrastructure damage will be the quality of socio-economic and demographic predictions of vulnerable populations.

Projections of future water supply are available for many countries (e.g., World Bank, 1992). These projections in general do not account for alterations in demand due to climate change, and can therefore serve as the baseline for impact assessments. Estimates of alterations in water supply and demand should be either obtained from or co-ordinated with results from the water resources sector assessment (Chapter 6).

Impaired agricultural food production and distribution could have substantial adverse health effects, through mortality from starvation and through increased susceptibility to infectious diseases from malnutrition. One study examining this issue on an international scale estimated 40 to 300 million additional people at risk from hunger because of climate-related decreases in food production (Parry and Rosenzweig, 1993). This study accounted for projected improvements in world-wide food distribution as a result of decreased trade barriers as well as potential beneficial effects of increased carbon dioxide on food crops. Smaller scale impact assessments should account for these effects as well.

10.5.3 Impact assessment of vector-borne diseases

The assessment of the impacts of climate change on vector-borne diseases can be performed with a variety of methods, including mapping and integrated modelling. Some vector-borne diseases have been well-characterised in terms of the effects of temperature and precipitation on the life cycles of the vector and disease agent based on laboratory studies. Data from field studies are less common. Establishing current geographic boundaries on the basis of current climate conditions, applying climate projections, and estimating changes in geographic boundaries and transmission rates are the essential steps in the assessment.

The eradication campaigns of malaria in the mid-1950s resulted in dramatic changes in the ecology of many vector-borne diseases. Variations in the quantity and type of insecticide used and the level of resistance in the vectors are difficult to estimate and incorporate into models. These factors, however, may have a greater local impact on disease transmission than climate factors. Therefore, historical disease data from before the mid-1950s, where available, may allow the study of climate-disease relations with fewer potentially confounding variables (Bouma and Van der Kaay, 1996).

Sometimes data are limited to the distribution of the vector rather than human case data, and often this means merely presence or absence of the vector. More rarely, historical information about vector density is available. However, this would have to be specifically collected and therefore is less likely to available, or less likely to be freely accessible. Since presence of the vector is not sufficient for disease activity, the additional factors either facilitating or preventing disease transmission will have to be analysed. Factors important for the transmission of many vector-borne diseases include geographic and climatic features such as altitude. If possible, other relevant information such as pesticide use, surface water distribution, and vegetative cover should be included in the analysis as these are related to vector habitats.

Integrated models offer the additional feature of exploring the effects of changes in other diseases and socio-economic parameters on a given vector-borne disease. Examples of the use of integrated models for malaria on a global scale can be found in Martens et al. (1995, 1997) and Martens (1995) and for dengue in Focks et al.

(1993a,b). To date, there have been no published quantitative assessments of vector-borne diseases on a local or regional basis using integrated models.

10.5.4 Impact assessment of heat mortality and pollution-related respiratory disease

Current studies of heat mortality indicate that acclimatisation plays a critical role in determining the level and extent of sensitivity to temperature. It is not clear how long populations would take to acclimatise to an increased frequency and severity of extreme heat events, if at all (McMichael et al., 1996b). In addition, GCMs cannot predict the frequency of extreme events with accuracy, so quantitative assessment must rely on the superposition of assumed variability parameters on average temperature projections.

In extrapolating historical data to future predictions, attention should be paid to the characterisation of climate as well as the case definition of heat-related illness and mortality. Synoptic analysis (Kalkstein, 1991; Kalkstein et al., 1996), which characterises air masses on the basis of multiple parameters such as maximum temperature, humidity, and wind speed, is one method for organising climate model outputs. The frequency and severity of certain offensive air masses, specifically those appearing early in the summer season, can then be used to extrapolate future mortality from heat waves.

Usually urban populations are studied for heat-related mortality and morbidity, largely because a dense population is required to be able to observe a significant number of heat-related deaths (e.g., Kalkstein and Greene, 1997). Urban areas also tend to absorb and retain heat more than rural areas. Studies show that within the urban population (as with most health problems), the most vulnerable are the elderly, the very young, and the poorly housed.

There are no published estimations of health impacts of air pollution in the setting of climate change; studies are under way to attempt to model the interactions between climate and air pollution. Because increased air temperatures will accelerate the formation of tropospheric ozone from increased reactions between ultraviolet radiation and primary pollutants (i.e., NO_x), potential worsening of urban air pollution in association with climate change should be considered. Current impact assessment will need to be qualitative until these interactions are better understood.

10.5.5 Impact assessment for water-related diseases

Climate change may affect water-borne diseases via several mechanisms. One mechanism will be alterations in precipitation leading to flooding and biological contamination of water supplies, or leading to possibly drought and a shortage of safe drinking water. Linking climate prediction models with water budget or runoff models can provide an assessment of potential changes in precipitation effects from climate change. Both bacterial water-borne illnesses such as cholera and parasitic diseases such as cryptosporidiosis may be approached in these ways.

The relation between algal blooms in nutrient-rich warming coastal water and cholera outbreaks is still under investigation. There is growing evidence that in areas of endemic cholera, coastal waters provide an aquatic reservoir for *Vibrio cholerae* bacteria (Islam et al., 1993). What is not understood is exactly how the bacteria reproduce in the environment, and what factors cause the return to an infectious state. Thus, the presence of Vibrio bacteria in nutrient-rich coastal waters and sporadic cholera outbreaks may indicate a sensitivity to climate change, but the quantitative prediction of impacts would be very difficult. Some quantitative estimates of algal blooms and densities may be available to assist with projections, but the linkage between that data and actual cholera incidence remains to be determined. One study has shown a link between sea surface temperatures and cholera cases in Bangladesh (Colwell, 1996).

10.6 Autonomous adaptation

Given the complexity of most human disease systems, attempts to account for autonomous adaptation within the impact analysis will be prohibitively difficult in many cases.

For problems related to direct physiological stress, such as heat-related mortality, physiological acclimatisation may already be accounted for in the use of historical human data to project future mortality, although this is not clear from all studies. Non-physiological adaptations, e.g., building design, behaviour, and use of air conditioning, need to be addressed.

For infectious diseases, the development of immunity can be considered an inbuilt autonomous adaptation. Malaria is an important example because the loss of immunity in a population (i.e., when a population shifts from stable to unstable malaria) can lead to significantly higher morbidity and mortality rates (e.g., Martin and Lefebvre, 1995). Repeated infection with dengue, however, may lead to the serious complication of dengue haemorrhagic fever rather than immunity if the infections are with different serotypes of the dengue virus.

In the methods discussed above, autonomous adaptation is not considered because of the lack of data. However, changes in population immunity have been considered in malaria integrated models (Martens, 1997). For simpler assessment exercises, however, the range of uncertainty of future estimates will most likely be far greater than the potential impact of immunity or other autonomous adaptation within the population.

Many autonomous adaptations are behavioural, such as wearing protective clothing, reducing exertion levels, or obtaining drinking water from different sources. Because of the difficulty of predicting human behaviour, it may be reasonable to use a set of scenarios with different levels of behavioural changes in the impact assessment stage, and thereby investigate the possible impact of such autonomous adaptations.

For certain problems, what might be considered autonomous adaptations may have considerable public health or societal consequences of their own. For example, migration in response to local changes in climatic and environmental conditions could be considered an autonomous adaptation, but will by itself cause considerable societal strain and possibly lead to outbreaks of disease due to crowding, malnutrition, etc.

Similarly, widespread use of pesticides to combat new vector-borne disease outbreaks may contribute to both pesticide-related toxicity and further ecosystem disruption. If such adaptations are considered in an impact assessment, both the positive and negative implications need to be included.

10.7 Planned adaptation

10.7.1 General considerations

Just as the differing conditions among countries necessitate different approaches to health sensitivity and impact assessments, so too will the approaches to adaptation differ by region. For many developing countries, the health problems that are likely to be exacerbated by climate change are significant current problems. Thus, adaptive strategies developed in anticipation of future climate conditions may have substantial utility for the present situation. Many of the adaptations discussed here are not specific to climate change and, in fact, should not be viewed in isolation from the more generalised problem of global environmental degradation and compromised public health infrastructure in much of the developing and developed world.

10.7.1.1 Levels of prevention and hierarchy of controls

While cost and feasibility are clearly important considerations in evaluating adaptation options, two sets of concepts borrowed from preventive medicine and occupational health can also be applied to prioritise different adaptation options (Patz, 1995). The first set of concepts involves levels of prevention. Primary prevention consists of those measures that reduce or prevent the risk of developing a disease. This may involve protection from an infectious or harmful agent (e.g., immunisation or use of bed nets) or the removal of the harmful agent or exposure from the environment (e.g., eradication of disease vectors or replacement of a dangerous chemical in an industrial process). Secondary prevention involves the detection and treatment of a disease at a stage early enough to prevent serious clinical illness. Examples would be screening for malnutrition or asymptomatic parasitic infections. Tertiary prevention involves limiting long-term health deterioration from disease. Examples would include treatment of infectious diseases and rehydration therapy for diarrhoea. Primary prevention measures are often more cost-effective than higher level interventions, and clearly reduce the burden of human disease and suffering. There may, however, be instances where primary prevention measures are either unfeasible or have unacceptable financial or ecological costs (e.g., pesticide use in large areas), and secondary prevention measures will need to be considered. It should be noted that greenhouse gas mitigation represents an even earlier level of prevention. Mitigating the process of global warming might be viewed, therefore, as "pre-primary" public health prevention. Clearly, the discussion in this chapter addresses the results of the failure to adequately mitigate the ecosystem and human health effects of greenhouse gas emissions, and does not in any way intend to distract attention from the need to address the root cause of the problem.

The second set of concepts, called the hierarchy of controls, is derived from occupational health. Among primary prevention options, some may involve individual motivation and behaviour to a greater extent than others. For example, asking people to wear long sleeves and apply insect repellent requires significant individual co-operation, unlike using measures to decrease the insect vector population. In general, measures that require less individual behavioural change will be more efficacious than those that require significant individual co-operation. Because individual responses to health threats are highly variable and misperceptions of relative health risks are common in the public, only selected groups within a population are likely to take appropriate preventive steps. Among measures that do not involve personal behaviour, those that reduce or eliminate the potential for exposure to harmful situations are preferable to measures that merely reduce the duration or intensity of exposure.

Thus, in the hierarchy of controls, the first level of attention is given to measures that eliminate the harmful exposure, either by eliminating the agent (e.g., killing of insect vectors or substitution of less harmful chemicals) or by constructing a mechanism to protect the individual from exposure (e.g., engineering controls such as enclosure of industrial exposures or construction of architecturally heat-resistant housing). The second level of attention is given to administrative controls which reduce the amount of exposure, such as limiting work hours for outdoor workers in a situation of potential heat stress. It should be noted that in applying these industrial concepts to country-wide adaptation strategies, measures that correspond to engineering controls, such as housing or infrastructure construction, may require administrative action such as local or national legislation. The third level of attention is given to the individual use of protective measures, such as respirators for harmful air-borne chemicals or insect repellent for vector-borne diseases. Again, first level adaptation options may not always be available or feasible. These concepts can be used, however, along with considerations of cost, to help prioritise among a list of available options.

10.7.1.2 Expecting the unexpected

As stated above, it is likely that there will be unforeseen consequences of climate change for human health. It is essential that adaptation policies reflect this uncertainty and do not focus only on the specific anticipated changes in existing human diseases. Thus, in addition to disease-specific measures, improving surveillance and monitoring systems will be highly valuable. Furthermore, since our understanding of the linkages between climate and health is poorly developed, the commitment to fund and facilitate ongoing research is an essential part of adaptation.

10.7.1.3 Surveillance and monitoring

Ongoing monitoring, both of human diseases and of critical ecosystem indicators, will be essential to the timely institution of interventions as disease systems change. To the extent possible, the early indicators that have been identified during the development of conceptual models should be used rather than the incidence of actual diseases. Because of the inertia of large ecosystems, and the fact that changes in human diseases due to climate factors generally represent the end result of ecosystem changes, substantial ecosystem changes will have occurred by the time an increase in disease incidence is detected, and intervention will be far more difficult. Where feasible, monitoring efforts should be integrated with existing surveillance systems established for certain infectious disease categories.

Long-term field data gathering and surveillance of vector-borne disease are essential. Such data not only allow the study of seasonal and inter-annual variations in disease associated with climate variability but also provide information of early climate-related changes in incidence (Haines et al., 1994). Unfortunately, institutional changes and the apparent success of vector control methods (before widespread resistance emerged) led to a decline in the long-term prospective observations necessary to understand the mechanisms by which environmental impacts influence infectious disease risk. For example, local surveillance of vector species has been employed in the United States to try to predict outbreaks of St. Louis encephalitis and eastern equine encephalitis (MMWR, 1990). Domestic chickens and wild sparrows have been tried as sentinel indicators of increased viral transmission, but the focal nature of arboviral outbreaks and the inability to survey a broad enough area have limited the usefulness of this application for certain arboviral diseases (Monath and Tsai, 1987).

A strategy for global monitoring of health effects of climate change has been proposed involving remote sensing and extensive telecommunications networks of environmental and health professionals (Haines et al., 1994). Such an effort is strongly needed on a global scale, but smaller efforts on a regional scale, targeted at the critical geographic areas identified in the sensitivity analysis, will be important for regional adaptation strategies as well. An example of large-scale physical and ecological monitoring is the new United Nations interagency Global Observing System. This consists of the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS), and the Global Oceans Observing System (GOOS) (Patz, 1995). While such an effort is beyond the capacity of a single country, participation in such international efforts will have benefits not only on a global scale but also on a regional scale.

10.7.1.4 Infrastructure development

Water treatment facilities and shelter, already in short supply in many areas, may be further threatened by severe storms and sea level rise. For these threatened areas, investment in expanded facilities may have substantial current benefit, and attention paid to safe location of the facilities with respect to sea level rise and extreme weather events will be of use in adapting to future conditions. Consideration should also be given to improving the efficiency of existing water systems as well as reducing demand for water where possible. The involvement of local communities in planning and developing water systems is essential (World Bank, 1992). This is another area in which present-day investment will have public health benefits with or without impacts of climate change.

10.7.1.5 Public education

Human behaviour has a considerable influence on disease incidence. Some behaviours such as the storage of open water containers or the improper disposal of human wastes create favourable environmental conditions for disease-causing agents to reproduce. Other behaviours such as the type of clothing worn and the filtering of drinking water affect exposure to disease-causing agents. Public education efforts will be needed, both to inform about the causes of disease and human impacts on disease and to instruct on ways to minimise the health impacts of climate change. The need may be greatest in the critical areas where experience with disease is limited but the risk of the spread of disease is high.

Educating diverse groups of people in a way that does not conflict or negate present belief systems can be quite difficult. Experience with public education efforts in Tanzania on malaria has shown that educational methods need to be adapted to the local ethnic belief systems. Without the education and involvement of local communities, regional adaptation efforts will not succeed (C. Schiff, Johns Hopkins School of Hygiene and Public Health, personal communication, 1996). Conversely, when public education is presented in a culturally appropriate and creative manner, the effort can be far more successful. An example of such an effort resulting in widespread behavioural change is the “slip, slap, slop” campaign in Australia to convince the population of the need to use clothing, hats, and sunscreen lotion to protect against ultraviolet radiation.

10.7.1.6 Technological or engineering strategies

In certain cases, technological controls such as genetic or biological pest management systems may be useful. For certain diseases such as dengue and malaria, modification of the environment by engineering methods may reduce breeding sites and therefore reduce vector populations. In all cases, consideration must be given to potential negative consequences of the use of technological adaptation methods. For example, increased use of air conditioning to combat heat stress may have unacceptable costs in terms of increased energy use, and draining of wetlands may reduce fish production.

10.7.1.7 Medical interventions

Where possible, primary preventive medical interventions such as vaccinations should be used. Unfortunately, at present, the only disease anticipated to be sensitive to climate change for which a vaccine is available is yellow fever. It has not been possible to develop a vaccine for dengue. Work is continuing on the development of a malaria vaccine; however, it is recognised that an integrated approach is needed to combat the disease, involving local initiatives for vector surveillance and control.

Medical interventions for water-borne diseases or respiratory diseases may play a role as further research determines the potential for increases in those diseases from climate change.

10.7.2 Specific adaptation strategies

In addition to the general adaptive strategies discussed above, a variety of impact-specific options are available (Table 10.4). In general, these are measures that have been employed for present-day problems. The list of options in Table 10.4 is not intended to be complete, but rather to initiate discussion and evaluation of a variety of options that will be decided upon by local and regional health experts and policy makers. Furthermore, it should be emphasised that many of these measures will only be temporary in their effects; this list should not be viewed as an alternative to addressing the root causes of global warming through policy initiatives.

10.8 Summary and implications

As an integrator of ecosystem changes, human health is influenced by many of the factors that will be analysed in other sectors of global climate change impact assessments. Assessments of nutritional health will depend on the outputs of the following sectors: agriculture, fisheries, water resources, coastal zones, and biodiversity. Projections of the adequacy of shelter and water supplies will require the outputs of coastal zones and water resources. Since disruption of ecosystems through deforestation, water re-distribution, and other land uses can be associated with alterations in human disease systems, particularly vector-borne diseases, the future projections of these factors should be provided to those performing human health assessments by the forestry, agriculture, and water resources sector assessments. It should be noted that impacts on primary factors in public health, i.e., food, water and shelter, will have secondary impacts on sensitive disease systems for both vector- and water-borne diseases.

Impaired or improved human health will affect most other sectors via changes in productivity and resource allocation. As discussed in the section on impact assessment, however, the quantification of changes in productivity is very problematic, as is the prediction of medical and public health resource allocation into the future. Qualitative changes in diseases (e.g., the appearance or spread of diseases to new areas) may be of primary importance to trade and tourism.

As has been demonstrated, the health impacts of global climate change are likely to be multiple for any given region and highly variable between different regions. A country by country approach is warranted to ensure applicability of any health impact assessment. While there is likely to be difficulty obtaining the data, resources, and time necessary for a fully comprehensive quantitative impact assessment, a qualitative initial approach, as outlined in this chapter, may be of significant benefit to policy makers. Continuing surveillance and research activities will enable more accurate assessments in the future.

Table 10.4 Matrix of possible adaptation strategies for specific health impacts of climate change.

Adaptation measures	Heat-related mortality	Extreme weather events	Vector-borne diseases	Water-borne diseases
Public education	Publicise precautions to take during heat waves		Educate public to encourage elimination of artificial breeding sites	Educate public on sources of infection
Surveillance and monitoring	Establish new weather watch/warning systems that focus on health-related adverse conditions such as oppressive air masses	Maintain disaster preparedness programs, including tools for local public health facilities to conduct rapid health needs assessments	Institute surveillance for both disease incidence and vector populations or other intermediate hosts	Create early warning systems based on algal blooms to predict cholera
Ecosystem intervention	Plant trees within cities to reduce the urban heat-island effect	Adopt land-use planning to minimise erosion, flash-flooding, precarious residential placements; restore wetlands	Release sterilised male insects to reduce reproductive capacity of vector populations	
Infrastructure development		Site intakes for water facilities far enough upstream to tolerate saline intrusion from storm surges and sea level rise	Anticipate effects of irrigation projects on vector breeding sites	Construct water treatment facilities, waste treatment measures (privies, sewers, etc.)
Technological/engineering	Design buildings to be more heat resistant	Strengthen sea-walls; require building contractors to follow hurricane standards in coastal areas	Promote the use of pyrethroid impregnated mosquito bed-nets; install window screens in areas endemic to insect-borne diseases	Distribute low-technology water filtration systems (e.g., nylon mesh, cloths)
Medical interventions	Schedule work to avoid peak daytime temperatures for outdoor labourers		Sensitise health care givers in geographically vulnerable regions	

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