Chapter 3
Climate and Infectious Diseases

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Abstract Climate plays an important role in the transmission of many infectious diseases; it not only determines spatial and seasonal distributions, but influences inter-annual variability, including epidemics, and long-term trends. This paper collates published scientific literature on climate and 20 infectious diseases that cause considerable morbidity and mortality worldwide. It highlights what has been done to date, identifies gaps and assesses the role of climate information in improving health system performance, especially in developing countries.

Parasitic, viral and bacterial diseases are discussed in the light of climate impacts on classified according to geographic distribution, seasonality, interannual variability, or climatic shifts. Study methods range from simple comparisons in seasonality, to detailed risk analyses, predictive models and early warning systems for epidemics. Malaria and dengue were found to be the most researched diseases with respect to climate, followed by meningococcal meningitis, schistosomiasis, rotavirus, and leishmaniasis. Studies on diseases with long development periods tended to focus on spatial patterns for the creation of risk maps while acute diseases focused inter-annual variability and the creation of climate-driven early warning systems. An emerging area identified in this review is the potential for climate information to improve the quality of intervention impact assessment where diseases are climate sensitive. We note that despite an extensive literature for some diseases very little research has been done in the countries with the highest number of child deaths and under-five mortality rates. This review provides a platform from which to launch future research and policy development in relation to climate-sensitive disease, and suggests that vulnerable countries should be the priority focus of this effort.

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3.1 Introduction

The importance of infectious disease as a determinant and outcome of poverty in developing countries is a prominent argument for international and national investment in controlling patterns of infectious disease transmission (WHO 1999, 2001; Black et al. 2003). This argument is reflected in the United Nations Millennium Development Goals (MDGs) (UN 2002; Sachs 2004; Sachs and McArthur 2005). Although the infectivity and transmission processes unique to many diseases are likely complex, several factors have been identified as direct drivers of disease risk. Among these are climatic factors such as rainfall and temperature. Indeed, climate plays an important role in the transmission of many of the diseases whose control is important to the achievement of the MDGs to the extent that in some ecological and economic settings climate variability may undermine the potential for achieving these goals. Climate not only determines the spatial and seasonal distribution of many infectious diseases (Burke et al. 2001), but is likely a key determinant of interannual variability, including epidemics (Kovats et al. 1999, 2003; WHO 2004; Kuhn et al. 2005), and long-term trends (Haines and Patz 2004; Patz et al. 2005). More specifically, climate information can be used to improve our assessment of interventions for climate-sensitive diseases and human health (McMichael et al. 2003; Hansen et al. 2004; IRI 2005; Connor et al. 2006). While many other factors undoubtedly play critical roles in disease propagation (e.g. immune status, socio-economic status, etc.), this review focuses specifically on how climate is associated with disease incidence in the human population.

There is heightened interest in supporting health systems to improve the management of climate-sensitive diseases. A special report to the third IPCC (Intergovernmental Panel on Climate Change (IPCC) 2001) stated that '*An effective health system can help to address the adverse health impacts of climate change*' and '*Thus, in terms of technology transfer there is a need to ensure that technologies are available at national and local levels for coping with any changes in the burden of disease that might be associated with climate change*'.

Despite a rapidly increasing interest in the use of climate data by the public health sector (Kovats et al. 1999, 2003; Burke et al. 2001; IPCC 2001; McMichael et al. 2003; Haines and Patz 2004; Hansen et al. 2004; WHO 2004; Kuhn et al. 2005; Patz et al. 2005; IRI 2005), a considerable effort is still required to develop policy-relevant evidence for decision-makers involved in controlling climate-sensitive diseases. In order to achieve the MDGs it is crucial that appropriate polices are developed and implemented to improve health system performance (Anon 2004; Travis et al. 2004; Wyss 2004). Climate information services may play a role in this if appropriate tools and analysis can be used effectively to improve the ability of those engaged in promoting, preventing or improving the health of populations to (a) detect and treat diseases, (b) monitor and predict epidemics, (c) implement intervention and control strategies, and (d) monitor the impact of interventions (Connor et al. 2006).

This review collates published scientific literature on climate and infectious diseases. It focuses on 20 major diseases, which are influenced by climatic factors and cause considerable morbidity and mortality worldwide. Studies included herein are restricted to those that have quantified the relationship between climate and human infectious disease through statistical association. These range from simple comparisons in seasonality, to detailed risk analyses, predictive models and early warning systems for epidemics. Additionally, these studies are classified according to climates impact on their spatial distribution, seasonality, interannual variability, and trends. This extensive compilation of historical and contemporary literature will highlight what has been done to date, identify gaps and assess the role of climate in improving health system performance, especially in developing countries. It will provide a platform from which to launch future research and policy development in relation to climate-sensitive disease.

The diseases presented in the Table 3.1 are grouped as parasitic, viral and bacterial and include those with both short and long development periods. Their sensitivities to climate differ; those with a short development period tend to be highly seasonal or epidemic in nature, with clinical manifestations readily identified (often severe), and usually the basis of epidemiological research. Recently, several diseases were identified as candidates for climate-based early warning systems as a means of improving preparedness for and in response to epidemics (Kuhn et al. 2005) (Table 3.2). In contrast, chronic diseases with long development periods, in which the pathogen may survive for many years in the human host (e.g. lymphatic filariasis), may exhibit little or no seasonal or interannual variability, even though transmission may be driven by climatic factors. In this case, subclinical infections or preliminary disease are detected by other means, such as skin biopsies/snips (e.g. onchocerciasis; Botto et al. 2005), thick blood films (e.g. loa loa; Wanji et al. 2005) and urine or stool samples (e.g. schistosomiasis; Brooker et al. 2001; Kabatereine et al. 2004).

3.2 Geographical/Spatial Distribution

Defining the geographical distribution of a disease within a country or region is a fundamental step to understanding its epidemiology, as it allows health systems to identify epidemic/endemic zones and vulnerable groups at risk. It also allows comparisons among diseases, analysis of temporal trends and identification of climatic and other factors that may influence the spatial heterogeneity of disease. No disease is uniformly distributed, even though there appear to be broad influential spatio-climatic parameters, patterns and trends. For instance, mosquito-borne parasitic and arboviral diseases are commonly found in hot, humid regions of the world, while

Table 3.1 Disease, transmission mechanism, climate and environmental drivers, country of study and references

Disease/Transmission Characteristics	Country	References
Parasitic		
1. Malaria	*Space*	
Plasmodium sp.		
	Africa	Le Sueur et al. 1997; Craig et al. 1999; Snow et al. 1999; Small et al. 2003
Mosquitoes *Anopheles* sp.	**Brazil**	Camargo et al. 1996
	China	Yang et al. 2002
Rainfall, humidity, temperature, surface water puddles, river margins, irrigation, altitude, NDVI	**China**	Bi et al. 2003b
	East Africa	Hay et al. 2002b; Omumbo et al. 2005a; Omumbo et al. 2005b
	Ecuador	Cedeno 1986; Moreira 1986 Belize Hakre et al. 2004
	Ethiopía	Abeku et al. 2003; Teklehaimanot et al. 2004a, b
	India/Pakistan	Christophers 1911; Gill 1921, 1923; Yacob and Swaroop 1945, 1946; Mathur et al. 1992; Bouma and van der Kaay 1994; Akhtar and McMichael 1996; Gupta 1996; Singh and Sharma 2002; Bouma et al. 1996
	IndoChina	Nihei et al. 2002
	Kenya	Omumbo et al. 2004
	Peru	Guthmann et al. 2002
	Peru	Guthmann et al. 2002
	Philippines	Leonardo et al. 2005
	South Africa	Craig et al. 2004
	Sri Lanka	Gill 1936; Ramasamy et al. 1992; Van Der Hoek et al. 2003
	Tanzania	Bodker et al. 2003
	Tanzania	Bodker et al. 2003
	Thailand	Rosenberg et al. 1990; Nacher et al. 2004a, b;
	West Africa	Kleinschmidt et al. 2001
	Zimbabawe	Siziya et al. 1997; Mabaso et al. 2005
	Seasonal	
	Cameroon	van der Kolk et al. 2003; Akenji et al. 2005
	Ethiopia	Abeku et al. 2002, 2003; Teklehaimanot et al. 2004a, b
	Ghana	Afari et al. 1993; Baird et al. 2002; Koram et al. 2003
	Kenya	Hay et al. 2001; Shanks et al. 2002; Munyekenye et al. 2005
	Mali	Bouvier et al. 1997; Dicko et al. 2005
	Rwanda	Loevinsohn 1994
	Sudan	Giha et al. 2000

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
Malaria cont.	**The Gambia**	Greenwood et al. 1987; Brewster and Greenwood 1993
	Uganda	Kilian et al. 1999; Lindblade et al. 1999; Odongo-Aginya et al. 2005
	Interannual	
	Botswana	Thomson et al. 2005, 2006a
	China	Bi et al. 2005
	Colombia	Bouma et al. 1997; Poveda et al. 2001
	East Africa	Zhou et al. 2004, 2005
	Ethiopia	Abeku et al. 2002; Teklehaimanot et al. 2004a, b
	India/Pakistan	Gill 1923; Swaroop 1946
	India/Sri Lanka	Bouma and van der Kaay 1996
	Indonesia	Anon 1999
	Kenya	Hay et al. 2001
	Kenya	Hay et al. 2001
	Madagascar	Bouma 2003
	Niger	Julvez et al. 1997
	Peru	Valencia Tellería 1986
	Senegal	Ndiaye et al. 2001
	South America	Organization 1998; Gagnon et al. 2002
	Southern Africa	Anon 2002; DaSilva et al. 2004; Grover-Kopec et al. 2005; Connor et al. 2007
	Tanzania	Lindsay et al. 2000
	Thailand	Hay et al. 2000
	Uganda	Kilian et al. 1999; Lindblade et al. 1999
	Venezuela	Bouma and Dye 1997
	Trend	
	Africa	Small et al. 2003
	East Africa	Hay et al. 2002b
	Pakistan	Bouma et al. 1996
	Rwanda	Loevinsohn 1994
	West Africa	Brewster and Greenwood 1993; Trape 1999
2. African Trypanosomiasis / Sleeping Sickness, Ngana	*Space*	
e.g. *Trypanosoma brucei gambiensis*	**Africa**	Rogers 1991; Rogers and Williams 1993
	Togo	Hendrickx et al. 1999, 2000
	Uganda	Rogers 2000; Odiit et al. 2005
Tsetse *Glossina* sp.	*Seasonal*	
Gallery forests, savannah woodland, temperature, NDVI	**Africa**	Rogers and Williams 1993
	Kenya	Wellde et al. 1989
	Uganda	Rogers 2000

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
3. Schistosomiasis / Bilharzias	*Space*	
Schistosoma sp.	**Brazil**	Bavia et al. 1999, 2001a; 2005c
Snails e.g. *Bulinus* ***Africanus***	**China**	Zhou et al. 2001; Yang et al. 2005a; 2005c
	Cote d'Ivoire	Raso et al. 2005
Surface water, NDVI, temperature, rainfall, elevation	**Egypt**	Malone et al. 1994
	Ethiopia	Kristensen et al. 2001
	Philippines	Cross et al. 1984; Leonardo et al. 2005
	Tanzania	Brooker et al. 2001
	Uganda	Kabatereine et al. 2004; Stensgaard et al. 2005
	Seasonal	
	Brazil	Bavia et al. 1999, 2001
4. Leishmaniasis	*Space*	
genus *Leishmania*	**Brazil**	Thompson et al. 2002; Werneck and Maguire 2002; Bavia et al. 2005
e.g. Phlebotomine Sandflies	**Colombia**	King et al. 2004
	Sudan	Elnaiem et al. 2003 Thomson et al. 1999
Rainfall, temperature, NDVI, land cover, elevation	**Tunisia**	Ben Salah et al. 2000
	Seasonal	
	Brazil	Thompson et al. 2002; Martins et al. 2004
	French Guiana	Nacher et al. 2001, 2002
	Turkey	Uzun et al. 1999
	Turkmenistan	Neronov and Malkhazova 1999
	Interannual	
	Bolivia	Gomez et al. 2006
	Brazil	Franke et al. 2002a, b
	Costa Rica	Chaves and Pascual 2007
5. Lymphatic filariasis	*Space*	
e.g. *Wuchereria bancrofti* in Africa	**Africa**	Lindsay and Thomas 2000
	Egypt	Thompson et al. 1996; Hassan et al. 1998a, b
Mosquitoes: *Anopheles, Aedes* and *Culex* sp.	**West Africa**	Kelly-Hope et al. 2006
	Seasonal	
Rainfall, humidity, temperature, surface water, NDVI	**Ghana**	Gyapong et al. 1996
6. Onchocerciasis / River Blindness	*Space*	
	Ethiopia	Gebre-Michael et al. 2005
Onchocerca volvulus	**Venezuela**	Botto et al. 2005
Blackflies: *Simulium* sp.	*Seasonal*	
	Ethiopia	Gebre-Michael et al. 2005

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
Rainfall, temperature, NDVI, wind, river discharge	**Nigeria**	Nwoke et al. 1992
	Interannual	
	Sierra Leone	Thomson et al. 1996
7. African Eye Worm	*Space*	
Loa loa	**Cameroon**	Wanji et al. 2003; Thomson et al. 2004a
Chrysops sp. Forest canopy, forest soils, NDVI		
8. Guinea worm	*Space*	
Dracunculus medinensis	**Ghana**	Belcher et al. 1975; Hunter 1997
Cyclops sp.	*Seasonal*	
	Burkina Faso	Steib and Mayer 1988
Surface water, high and low rainfall	**Ghana**	Belcher et al. 1975
	Interannual	
	Ghana	Hunter 1997
	Trend	
	Ghana	Hunter 1997
Viral		
9. Yellow Fever	*Seasonal*	
Flavivirus	**Brazil**	Vasconcelos et al. 1997, 2001
Mosquitoes *Aedes, Haemagogus* and *Sabethes* sp.)	**West Africa**	Traore-Lamizana et al. 1996
	Trend	
	Brazil	Vasconcelos et al. 1997, 2001
Rainfall, Temperature		
10. Rift Valley Fever	*Space*	
Phlebovirus	**Africa**	Anyamba et al. 2002
Mosquitoes *Aedes* and *Culex* sp.	**Kenya**	Linthicum et al. 1987
	Saudi Arabia	Elfadil et al. 2006
	Seasonal	
Rainfall, humidity, surface water, temperature, NDVI	**Kenya**	Davies et al. 1985; Linthicum et al. 1987, 1999
	Nigeria	Olaleye et al. 1996
	Interannual	
	Kenya	Linthicum et al. 1999; Anyamba et al. 2001
	Senegal	Thonnon et al. 1999' Thiongane and Martin 2003
11. St Louis encephalitis	*Seasonal*	
Mosquitoes *Culex* sp.	**United States**	Anon 1994; Barker et al. 2003
	Interannual	
Low rainfall, drought high temperature, land surface wetness	**United States**	Shaman et al. 2004

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
12. Japanese encephalitis	*Space*	
	China	Okuno et al. 1975
Mosquitoes *Culex* sp.	*Seasonal*	
Monsoon, rainfall, temperature,	**China**	Okuno et al. 1975; Bi et al. 2003a
	India	Kanojia et al. 2003; Phukan et al. 2004
	Interannual	
	Thailand	Suwannee et al. 1997
13. Murray Valley encephalitis/ Australian encephalitis	*Space*	
	Australia	
Mosquitoes *Culex, Anopheles* and *Mansonia* sp.	*Seasonal*	
Wet season, rainfall, flooding	**Australia**	Broom et al. 2002, 2003; Whelan et al. 2003; Cordov et al. 2000
14. Ross River virus/Epidemic polyarthritis	*Space*	
Alphavirus	**Australia**	Done et al. 2002; Tong et al. 2002; Woodruff et al. 2002; Kelly-Hope et al. 2004a, 2004b, 2004c, Gatton et al. 2005
Mosquitoes mainly *Culex, Ochlerotatus, Aedes, Man sonia* and *Anopheles* sp.	*Seasonal*	
	Australia	Tong et al. 1998; Tong and Hu 2001; Done et al. 2002; Kelly-Hope et al. 2002; Tong et al. 2002; Whelan et al. 2003; Hu et al. 2004; Kelly-Hope et al. 2004a, 2004c; Tong et al. 2004, 2005; Gatton et al. 2005
	Interannual	
Rainfall, flooding temperature, humidity, high tides	**Australia**	Harley and Weinstein 1996; Maelzer et al. 1999; Done et al. 2002; Woodruff et al. 2002; Kelly-Hope et al. 2004b
15. Hemorrhagic fever with renal syndrome	*Seasonal*	
HFRS group	**China**	Chen and Qiu 1993, 1994; Bi et al. 1998, 2002
	Croatia	Mulic and Ropac 2002; Mulic et al. 2003
Rodents mainly *Rattus, Apodemus* and *Clethrionomys* sp.	**Russia**	Nurgaleeva et al. 1988
	Interannual	
	China	Bi et al. 2002, 2005; Bi and Parton 2003
Rainfall, temperature, humidity, flooding		

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
16. Dengue and Dengue Hemorrhagic Fever	*Space*	
Flavivirus	**Global**	Hales et al. 2002
	Mexico	Peterson et al. 2005
Mosquitoes *Aedes* sp.	**Taiwan**	Wu et al. 2006
Temperature, rainfall, humidity	*Seasonal*	
	Bangladesh	Amin et al. 1999
	Barbados	Depradine and Lovell 2004
	India	Chakravarti and Kumaria 2005
	Indonesia	Corwin et al. 2001
	Malaysia	Li et al. 1985
	Mexico	Koopman et al. 1991; Peterson et al. 2005
	Thailand	Nakhapakorn and Tripathi 2005; Thammapalo et al. 2005
	Venezuela	Barrera et al. 2002
	Interannual	
	Colombia	Gagnon et al. 2001 Surinam Gagnon et al. 2001
	French Guiana	Gagnon et al. 2001
	Indonesia	Depradine and Lovell 2004, Kovats 2000; Corwin et al. 2001; Gagnon et al. 2001
	Mexico	Hurtado-Diaz et al. 2006
	Puerto Rico	Schreiber 2001
	South Pacific	Hales et al. 1996, 1999
	Thailand	Hay et al. 2000; Cazelles et al. 2005
	Trend	
	Global	Hales et al. 2002
17. Rotavirus	*Seasonal*	
Filth flies e.g. *Musca* sp. via mechanical transmission	**Africa**	Cunliffe et al. 1998
	Bangladesh	Ahmed et al. 1991; Fun et al. 1991
Humidity, cool/winter, dry months, low rainfall, water shortages, flood	**Brazil**	Coiro et al. 1983; Bittencourt et al. 2000; da Rosa e Silva et al. 2001
	Ghana	Armah et al. 1994
	Global	Cook et al. 1990
	India	Ram et al. 1990; Phukan et al. 2003
	Indonesia	Corwin et al. 2005
	Japan	Konno et al. 1983 Kuwait Al-Nakib et al. 1980
	Kenya	Mutanda et al. 1984 Zambia Mpabalwani et al. 1995
	Nigeria	Gomwalk et al. 1990, 1993
	South Africa	Steele et al. 1986; Haffejee and Moosa 1990
	South America	Kane et al. 2004

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
	The Gambia	Hanlon et al. 1987; Brewster and Greenwood 1993
	United Arab Emirates	Ijaz et al. 1994
Bacterial		
18. Meningococcal meningitis	*Space*	
Neisseria meningitides	**Africa**	Lapeyssonnie 1963; Cheesbrough et al. 1995; Molesworth et al. 2003
Airborne aerosol	**Benin**	Besancenot et al. 1997
	Seasonal	
Absolute humidity, dry, dusty, wind, temperatures	**Cameroon**	Cunin et al. 2003 Democratic Rep. of Congo/Zaire Cheesbrough et al. 1995
	Egypt	Girgis et al. 1993 Djibouti Haberberger et al. 1990
	Mali	Sultan et al. 2005
	Mongolia	Skalova 1984
	Niger	Campagne et al. 1999; Molesworth et al. 2001 Benin Besancenot et al. 1997
	Nigeria	Greenwood et al. 1979, 1984
	The Gambia	Greenwood et al. 1985; Brewster and Greenwood 1993
	West Africa	Cvjetanovic et al. 1978; Skalova 1984
	Interannual	
	Mali	Sultan et al. 2005
	West Africa	Thomson et al. 2006b
19. Trachoma	*Space*	
Chlamydia trachomatis	**Australia**	Tedesco 1980
Flies e.g. *Musca sorbens* via mechanical transmission	**India**	Gupta and Preobragenski 1964
	Kenya	Schwab et al. 1995
Aridity, dust, environmental/ dryness, relative humidity	**Mali**	Schemann et al. 2002
	Sudan	Salim and Sheikh 1975
	Seasonal	
	India	Cooper 1964; Gupta and Preobragenski 1964
	Sudan	Salim and Sheikh 1975
20. Cholera	*Space*	
Vibrio cholerae	**Bangladesh**	Huq et al. 2005
Fecal/oral route and filth flies e.g. *Musca* sp. via mechanical transmission	*Seasonal*	
	Bangladesh	Huq et al. 2005; Koelle et al. 2005a
	Peru	Franco et al. 1997; Lama et al. 2004

(continued)

Table 3.1 (continued)

Disease/Transmission Characteristics	Country	References
Water and air temperature, water depth, rainfall and conductivity, algal blooms, flooding, sunlight, SST	**Mexico**	Chavez et al. 2005
	Interannual	
	Bangladesh	Lobitz et al. 2000; Pascual et al. 2000; Rodo et al. 2002; Koelle et al. 2005b
	Peru	Speelmon et al. 2000; Lama et al. 2004
	West Africa	Constantin et al. 2006
	Ghana	de Magny et al. 2006

Table 3.2 Climate-sensitive diseases, include those with EWS potential (Kuhn et al. 2005)

Early warning system potential
Malaria
African trypanosomiasis
Leishmaniasis
Yellow fever
Rift Valley fever
Dengue and dengue hemorrhagic fever
St. Louis encephalitis
Japanese encephalitis
Murray Valley encephalitis
Ross River virus
Meningococcal meningitis

bacterial infections such as trachoma and epidemic meningococcal meningitis prevail in countries with a prolonged dry season. (Cooper 1964; Sarkies 1967; Schwab et al. 1995). Specifically, high rates of trachoma in northwest India have been associated with low humidity, winds (*Arabian*) and dust storms (Cooper 1964), and in Kenya and Sudan with climatic aridity (Salim and Sheikh 1975; Schwab et al. 1995). Winds (*Harmattan*) and dusty conditions have also been linked to meningococcal epidemics the Sahel region of West Africa (Greenwood et al. 1984; Besancenot et al. 1997; Sultan et al. 2005), an area known as the 'Meningitis Belt' which coincides with 300–1,100 mm annual rainfall (Lapeyssonnie 1963; Molesworth et al. 2003). Notably, meningococcal outbreaks tend not to occur in humid, forested or coastal region areas, as high continuous humidity appears to reduce transmission (Haberberger et al. 1990; Cheesbrough et al. 1995; Molesworth et al. 2003). Changes to the micro-climate as a result of landuse/cover change is an important driver of changes in transmission in some areas. For example, deforestation in the Amazon has increased the abundance of anopheline vectors which thrive in open sunlight than the jungle breeding sites, thereby increasing the risk of disease (Vittor et al. 2006).

Defining exclusion zones based on climate is also useful. It provides further insight into a disease's ecology, and helps allocate human and financial resources to high-risk areas. This is exemplified in Uganda with schistosomiasis, in which a large parasitological survey found no transmission at altitudes >1,400 m, or where total annual rainfall was <900 mm. Subsequently, this information helped the design and implementation of the national control program currently underway (Kabatereine et al. 2004). The filarial worm *Loa loa* has recently emerged as a parasite of significant public health importance as a consequence of its impact on the African Programme for Onchocerciasis Control. Severe, sometimes fatal, encephalopathic reactions to ivermectin (the drug of choice for onchocerciasis control) have occurred in some individuals with high *Loa loa* microfilarial counts in West and Central Africa including Cameroon. A modeled distribution map of the *Loa loa* prevalence in Cameroon has been created based on epidemiological data, altitude (as a proxy for temperature), satellite derived vegetation indices and knowledge of transmission dynamics. The map indicates areas where the risk of *Loa loa* is exceeding low and ivermectin distribution may be undertaken safely (Thomson et al. 2004a).

Similarly, as part of the global elimination program for lymphatic filariasis, prevalence surveys have been conducted to identify high/low risk locations prior to mass drug administration (Gyapong et al. 2002). In West Africa, filariasis prevalence was found to be high in the Sahel region, and positively correlated with low rainfall and low vegetation greenness (Kelly-Hope et al. 2006). Interestingly, a negative spatial association was found with malaria, which was more prevalent in the humid savanna zone of this region. This suggests that within defined regions, different climate and ecological factors may drive different disease distributions. This is also evident in the Philippines, where the magnitude and distribution of malaria and schistosomiasis differ in two distinct regions (Leonardo et al. 2005).

In addition to spatial differences, identifying the locations where diseases overlap is valuable. This can help to identify common risk factors, ecological niches and may facilitate coordinated control and intervention strategies. This is becoming increasingly relevant with the number of disease elimination and control programs currently underway globally (Molyneux 2004; Molyneux et al. 2005). Unfortunately, data on different diseases are not usually collected simultaneously, and are rarely examined in relation to climate variables. As shown in Table 3.1, our comparisons were restricted by the spatial distributions of studies of malaria, Rift Valley fever and trachoma in Kenya, trypanosomiasis and schistosomiasis in Uganda, and leishmaniasis and schistosomiasis in Brazil, which have all been examined using different climate parameters, on different scales, at different times. This disparate data collection process prevents any meaningful comparisons. We posit that the formation of a *disease atlas* comprising high resolution, subnational data may be useful to national health systems, for policy discussions, guiding interventions and cost-effective monitoring at a range of spatial scales. However, standard ways in which to collect and analyze field data are first needed to optimize such an endeavor.

Maps are useful visual tools, and have long been used for displaying prevalence and infection intensity data. Mapping the spatial relationship between climate and disease has been described during the early 1900s in India (Punjab) (Christophers 1911; Gill 1921, 1923; Yacob and Swaroop 1945, 1946) and Sri Lanka (Gill 1936), where factors defining malaria outbreaks were compared. Throughout the 1940–1970s, a series of simple maps, graphs and methodologies were used to examine the climatic impact on diseases such as meningitis (Lapeyssonnie 1963), Japanese encephalitis (Okuno et al. 1975), lymphatic filariasis (Brengues 1975) and trachoma (Cooper 1964; Salim and Sheikh 1975). However, it was not until the introduction and widespread availability of environmental satellite images and computer-based geographic methods in the early 1980s that more sophisticated spatial and statistical methods have been developed and utilized. Geographic information systems (GISs) and remote sensing (RS) were used initially to define the ecological parameters of schistosomiasis in the Philippines (Cross et al. 1984) and Rift Valley fever in Kenya (Linthicum et al. 1987). Since then, scientists have studied many more diseases in different geographical regions, largely due to the increased affordability and accessibility of computers, specialized software and geo-referenced spatial data. Recently, a number of malaria risk maps, based on climatic parameters, have been modeled for Africa (Le Sueur et al. 1997; Craig et al. 1999; Snow et al. 1999; Kleinschmidt et al. 2001; Omumbo et al. 2005b), and an international collaboration of scientists and institutions have developed an Atlas of Malaria for Africa available via the internet(MARA/ARMA 1998). Recently, researchers have linked climate with many other infectious diseases, including trypanosomiasis in Uganda (Odiit et al. 2005), schistosomiasis in Philippines (Leonardo et al. 2005), China (Yang et al. 2005a), Cote d'Ivoire (Raso et al. 2005) and Uganda (Stensgaard et al. 2005), dengue and dengue hemorrhagic fever in Thailand (Nakhapakorn and Tripathi 2005), leishmaniasis in Brazil (Bavia et al. 2005), onchocerciasis in Ethiopia (Gebre-Michael et al. 2005), filariasis in West Africa (Kelly-Hope et al. 2006) and Ross River virus disease in Australia (Gatton et al. 2005), using these advances in GIS and RS technologies.

3.3 Seasonality

Climate-sensitive diseases usually have distinct seasonal patterns, especially those with short development periods. Knowing a specific disease's incubation period and associated climatic influences will help health workers determine when to expect high incidences or outbreaks of the disease, aid diagnosis and direct timely interventions. Clearly, broad temporal climatic patterns exist, and it is useful to recognize that the prevalence of diseases such as malaria, dengue and Rift Valley fever increase during and immediately following the warm, rainy season, while that of meningococcal meningitis and trachoma peak in the dry pre-monsoonal period, and rotavirus prevails during the dry and/or cold months of the year. However, it is also important to be aware that one disease may exhibit different seasonal patterns in different ecological zones. In West Africa, for example, guinea worm transmission occurs during the dry season in the humid savanna zone (southern) (Belcher et al. 1975), but during the wet season in the dry savanna zone (northern) (Steib and Mayer 1988). Similar differences have been noted for malaria in Asia, where an outbreak in the dry region of India (Punjab) occurred with the onset of the monsoonal rainfall (Christophers 1911; Gill 1923; Yacob and Swaroop 1945, 1946). Conversely, drought and a rise in humidity seemed to be important malarial onset factors in the wet zone of Sri Lanka (Gill 1936). This latter pattern is supported by local knowledge noted by Gill (1936), '*it has long been known to medical men and laymen alike that a wet year in the Wet Zone is a healthy year, and that in this zone a failure of the monsoon is almost invariably followed by an unusual prevalence of malaria*', and highlights the importance of engaging local people and their knowledge in directing empirical research to quantify climate and disease patterns.

Clearly, identifying the specific climatic factors driving high risk disease outbreak and transmission periods is important, as they can vary greatly among diseases and regions. Many studies have compared morbidity and mortality variables among the wet, dry, hot and/or cold seasons, but few have conducted any time series analyses on more than one disease. Developing a calendar, namely a *disease calendar*, depicting the high-risk months of a few key diseases may useful for national health systems. It may help to determine when and where human and financial resources should be allocated, and help regional health workers detect and treat diseases appropriately (Mabaso et al. 2005, 2007a). For example, in India high rates of Japanese encephalitis (June–October) (Kanojia et al. 2003; Phukan et al. 2004) occur during the rainy season, dengue is prevalent in the post-monsoonal period (October–December) (Chakravarti and Kumaria 2005) and rotavirus peaks during the winter months (November–February) (Ram et al. 1990; Phukan et al. 2003). Furthermore, retrospective analyses of historical disease data may elucidate climate connections, which are now more readily achievable with the recent advances in GIS and RS technology and access to climate datasets. In addition to seasonal differences, a number of studies have quantified associations among specific climatic variables and the time to disease onset or peak period. For example, scientists identified correlations between rainfall, temperature and cholera with a 4–8-week lag time in Bangladesh (Huq et al. 2005), between heavy rainfall and dengue with a 2–3-month lag in Malaysia (Li et al. 1985), and between high rainfall and guinea worm with a year lag period in West Africa (Steib and Mayer 1988). These studies provide some insight into climatic factors that are potentially important for the disease-causing organism's incubation, development and transmission periods, and may help to develop early warning protocols.

Defining low risk periods of disease outbreak and transmission identifies specific factors that may inhibit or halt disease transmission. Though anecdotal, reports have indicated a lack of malaria during drought years in Sudan (Theander 1998; Giha et al. 2000), the cessation of meningococcal disease epidemics with the onset of rains in West Africa (Lapeyssonnie 1963), and a reduced threat of meningococcal meningitis during the hot summer months in Djibouti (Haberberger et al. 1990). Similarly, an area of Honduras was considered too hot for anopheline mosquitoes to survive, which accounted for a drop in malarial cases (Almendares et al. 1993), and in Thailand the transmission of dengue ceased with the onset of the cold dry season (Barbazan et al. 2002).

3.4 Inter-Annual Variability

3.4.1 Extreme Events

Extreme or adverse weather conditions have the potential to either promote or inhibit disease transmission, and are often linked to long-term, large-scale or cyclic climate phenomena. Furthermore, it has been suggested that climate changes could also affect large-scale weather patterns by increasing the frequency and intensity of extreme events, such as prolonged droughts and heavy rainfall, including severe tropical storms and floods (McMichael et al. 2003) see Hewitt this book.

For example, the incidence of hemorrhagic fever with renal syndrome (HFRS; e.g. Korean hemorrhagic fever, epidemic hemorrhagic fever, and nephropathis epidemica) carried and transmitted by rodents, may be negatively associated with heavy rainfall in China which destroys rodent habitats in some instances (Bi et al. 1998). Likewise dengue and/or dengue hemorrhagic fever is negatively associated with anomalously high rainfall in Malaysia (Li et al. 1985), Thailand (Thammapalo et al. 2005) and Barbados (Depradine and Lovell 2004), which may be related to the fact that the *Aedes* mosquito larvae are washed away from containers during heavy downpours.

This has potentially important public health implications for disease incidence forecasting, as extra rainfall does not necessarily imply an immediate risk of dengue or other vector/ rodent borne disease. This type of prediction may be important for other vector-based diseases like malaria and Japanese encephalitis, whose vectors have different environmental requirements. However, it is possible that the risk of dengue will be greater following heavy rainfall when mosquitoes can re-establish breeding sites and the seasonal larval index of *Aedes* mosquitoes increases (Strickman and Kittayapong 2002), which may have occurred in Delhi, India where an unexpected outbreak followed the wettest monsoon in 25 years (Chakravarti and Kumaria 2005).

The potential consequences of extreme events are evident, as torrential rainfall from Hurricane Mitch in 1998 killed 11,000 people in Central America, and Honduras reported 30,000 cholera, 30,000 malaria and 1,000 dengue cases (Epstein 1999). Similarly, severe flooding in southern Mozambique in 2000 killed hundreds of people, displaced thousands and caused the spread of malaria, typhoid and cholera (Kondo et al. 2002; Ahern et al. 2005). During this period, roughly 17,000 cases of cholera were reported. The impact of natural disasters is devastating worldwide (as recently shown by hurricane Katrina), but particularly in developing countries where populations are highly vulnerable, frequently displaced, homes and livelihoods are destroyed and local infrastructure is severely damaged (Allan et al. 1998; Few et al. 2004). Such events also have a severe impact on the health care sector and its ability to respond adequately. This further emphasizes the value of developing early warning systems – including cyclone warning systems – to aid health systems and health workers to be better prepared for impending disaster. This would, in turn, reduce the population's vulnerability to disasters and improve disaster management. A detailed international disaster database (EM-DAT http://www.em-dat.net/)

collates data from various sources, and provides some insight into the magnitude of the effect and the economic losses that have occurred due to disasters over the past century (Ahern et al. 2005; EM-DAT 2005).

Climate-sensitive diseases frequently exhibit interannual variability associated with unusual weather conditions, which may recur periodically. It is useful for national health systems to be aware of the various interannual climatic patterns that could impact on disease patterns in their country. Gill (1936) was among the first to describe the varying temporal patterns of malaria in different regions of the world. Epidemics were noted to occur every 5 years in Sri Lanka, every 10 years in India (Punjab), every 11 years in Argentina and every 12 years in Algeria, and it was suggested that the 11 year sunspot cycle (or certain phases thereof) may be related to the epidemics in the latter three countries, as well as the great malaria epidemic in Mauritius in 1867. Similar trends were observed in East Africa and elsewhere with yellow fever outbreaks.

Seasonal climate anomalies result from complex interactions between the atmosphere and the underlying surfaces: that is, the world oceans and land surfaces. The atmosphere, which fluctuates very rapidly on a day-to-day basis (weather), is tied to the more slowly evolving components of the earth system, which are capable of exerting a sustained influence on climate anomalies extending over a season or longer, far beyond the 1–2-week limit of deterministic predictability of the weather. The atmosphere is particularly sensitive to tropical sea surface temperature (SST) anomalies such as those that occur in association with the El Niño/Southern Oscillation (ENSO) (Goddard et al. 2001) but other phenomena may also be important. A range of indices are used to assess the links between large-scale climate fluctuations and disease incidence.

3.4.2 ENSO

ENSO is the most commonly studied driver of cyclical climate phenomenon with regard to human disease (Kovats et al. 1999, 2003). It is characterized by exceptionally marked and prolonged warm periods of sea surface temperature (SST) that appear in the central and eastern equatorial Pacific Ocean every 3–7 years. Extreme phases of the ENSO phenomenon have been linked to precipitation anomalies in many areas of the world (Ropelewski and Halpert 1987). In some areas precipitation may increase during warm (El Niño) or cold (La Niña) ENSO events, while in others drought may be more likely. For example, in southern Africa droughts and drought disasters tend to occur in the December–March rainy season following the onset of an El Niño event (Thomson and Abayonmi 2003).

An El Niño event, or the impact of one a year later, correlates with increased malarial risks in Sri Lanka (1870–1945), India/Pakistan (1867–1943) (Bouma and van der Kaay 1996), Pakistan (1970–1993) (Bouma and van der Kaay 1994), India (Rajasthan) (1982–1992), Venezuela (1975–1990) (Bouma and Dye 1997) and Colombia (1960–1992) (Bouma et al. 1997, 2001). A large El Niño event in 1997/98 led to widespread flooding in East Africa, and a sixfold increase in malaria in Kenya during the first 2 months of 1998, compared with 1997, which also coincided with outbreaks of Rift Valley fever and cholera (Allan et al. 1998; McLigeyo 1998; Linthicum et al. 1999). Significant El Niño associations have also been found with dengue outbreaks in Thailand (Cazelles et al. 2005), South Pacific (Hales et al. 1996, 1999) and South America (Gagnon et al. 2001), with Ross River virus disease in Australia (Woodruff et al. 2002) and with cholera in Bangladesh (Pascual et al. 2000; Rodo et al. 2002) and Peru (Speelmon et al. 2000; Lama et al. 2004). In South America, ENSO related flooding in the dry coastal region of north Peru was associated with a malaria epidemic, while drought conditions were important factors for malaria outbreaks in Columbia, Guyana and Venezuela (Gagnon et al. 2002)

Rather than relating ENSO events to particular outbreaks it may be more useful to use the underlying indices which determine an ENSO or similar event and thus provide a continuous indication of climate conditions. Numerous indices of the ENSO phenomenon have been derived, but a simple average of sea-surface temperatures (SSTs) over the area 5° N–5° S, 170°–120° W, known as the Niño 3.4 region (Barnston et al. 1997) is widely used because of its conceptual simplicity and ease of calculation. A relationship between the associated NINO 3 index and leishmaniasis in Brazil has been demonstrated (Franke et al. 2002b). Recently in Botswana, the NINO 3.4 index was significantly correlated with standardized malaria incidence anomalies (Thomson et al. 2005). The correlation of malaria anomalies with SST has been shown to be a regional phenomena (Mabaso et al. 2007b). These studies suggest the potential use of SSTs for disease forecasting through their influence on regional climate variability. Acquisition of climate datasets and the use of GIS and RS technology may enable research teams to develop more specific regional disease models, which could be used by the national health systems.

While SST patterns in the eastern equatorial pacific drive ENSO events variations in sea surface temperature elsewhere, e.g. the Western Indian Oceans are also important factors that drive climate variability, and are useful guides to predicting regional climate patterns and related diseases. In East Africa, outbreaks of Rift Valley fever have been associated with above-average rainfall and elevated SSTs in the western Indian Ocean and El Niño events in the Pacific (Linthicum et al. 1999). It is well understood that the interannual variability of Rift Valley fever in sheep and goats relates directly to *Aedes* mosquitoes that emerge from transovarially infected eggs found on the edges of *dambos* (depressions located in the valley bottoms of many headwater catchments) after periods of excessive rainfall and flooding (Linthicum et al. 1985). Humans may become infected with RVF through mosquito bites but are more commonly infected through contact with blood, body fluids or organs of infected animals or ingestion of raw milk. For some diseases it has been suggested that changes in SST may increase the risk of disease outbreaks directly. High SSTs during the 1991/92 El Niño may have contributed to the reemergence of cholera in Peru, and its subsequent spread across the South American subcontinent, affecting thousands of people (Colwell 1996). Correlations between SSTs in the Bay of Bengal and cholera cases in Dhaka have been observed (Lobitz et al. 2000).

Indices based on atmospheric phenomena have also be related to climate-sensitive disease outbreaks. One such index is the Southern Oscillation Index (SOI) which represents the atmospheric expression of ENSO, with records dating back to the late 19th century. Specifically, the SOI measures the normalized difference in sea level pressure between Tahiti and Darwin, Australia, and variations indicate changes in the locality of convective rainfall. Negative values of the SOI are associated with warmer than average sea surface temperatures in the central-eastern equatorial Pacific and a shift of convective rainfall from the Austral-Indonesian region to the central tropical Pacific, or El Niño conditions. Positive SOI values are associated with cooler than average sea temperatures and intensification of convective rainfall in the far western Pacific, or La Niña conditions.

An SOI analysis may also highlight differences between diseases. Such an analysis was conducted with data from China, where analysis of two decades of data on malaria and hemorrhagic fever with renal syndrome indicated that there were positive and negative associations, respectively, between the SOI and the monthly incidence of each disease (Bi et al. 2005).

Other indices of large-scale climate fluctuations include the Quasi-Biennial Oscillation (QBO) index (formally known as Singapore Winds), which was studied with regard to the Ross River virus disease incident in Australia, and was found to account for 77% of the disease variance in cases (Done et al. 2002).

3.5 Early Warning Systems

While nature has conspired to limit our ability to forecast day-to-day weather, there exists a firm scientific basis for the prediction of seasonal mean climate anomalies (i.e., departures from normal of averages and other statistics of weather over a season or longer) largely based on our ability to monitor global SSTs, which, as we note above, constitute the primary forcing of seasonal climate variability (Stockdale et al. 1998; Goddard et al. 2001). The scientific basis for seasonal forecasting is described in detail by Mason (this book). Recently, a system for forecasting anomalously high and low malaria incidence anomalies using dynamically based seasonal-timescale ensemble predictions of climate has been reported (Thomson et al. 2006a). Several European models of the coupled ocean–atmosphere system are combined into a multi-model ensemble forecast system and successfully applied to the prediction of malaria risk in Botswana, where links between malaria and climate variability are well established (Thomson et al. 2005). The practical application of this work in Southern Africa has been documented (Connor and Mantilla, this volume; Connor et al. 2007). What characterizes this approach is that climate forecasting and monitoring is integrated into an early warning system which includes vulnerability assessment and routine case surveillance. The monitoring component is supported by a web-based tool provides timely alerts to control programs and international organizations (i.e. Roll Back Malaria partners) about increased epidemic risks in Africa (Anon 2002; Grover-Kopec et al. 2005).

An early warning system based on this approach has recently been developed in Eritrea for operational use (Ceccato et al. 2008). Eritrea has two distinct rainy seasons in different parts of the country. The seasonal forecasting skill from Global Circulation Models was low for both seasons with the exception of the June–July–August season on the Eastern border. For epidemic control, shorter range warning based on remotely sensed rainfall estimates (rain gauge data are too few) and an enhanced epidemic early detection system were recommended. The Highland Malaria Project (HIMAL) is another initiative being developed for the early warning and detection of epidemics, using weather monitoring and a network of sentinel sites in four pilot districts of Kenya and Uganda (Abeku et al. 2004).

Although these computer-based tools are currently limited to organizations with advanced technological resources, these approaches will become increasingly more commonplace, as developing countries attain requisite computer hardware and software tools, access to the internet and staff are trained in appropriate methodologies and tools.

Other examples of early warning systems include 'The Global Emerging Infections System' run by the US Department of Defense (DoD-GEIS 2005). In collaboration with NASA, a system was designed for predicting Rift Valley fever in East Africa, based on a combination of warmer-than-normal equatorial Pacific Ocean temperatures associated with El Niño and rising SSTs in the western equatorial Indian Ocean. Outgoing Longwave Radiation (OLR) anomalies and increases in the normalized vegetation index (NDVI) A recent advance in this area of enquiry has been detailed evidence of the high level of predictability of NDVI following the East African Short rains from global climate models (Indeje et al. 2006).

Although this system provides no information on the size of the impending epidemic the spatial risk maps produced by this process, once validated, could help identify high-risk locations, which in turn could lead to domestic animal vaccinations and the implementation of appropriate interventions such as mosquito control programs and public health. Monthly risk maps are available through the internet (DoD-GEIS 2005). A recent survey of the literature (published and grey) (Savory et al. 2006) has shown that recent epidemics of meningococcal meningitis in Africa largely fall within the risk areas identified in a previous study from a climate–landcover derived spatial risk model (Molesworth et al. 2003).

One important reason for the limited number of early warning systems is the fact that many epidemic prone countries lack good epidemiological surveillance systems to enable early detection and provide the baseline data to improve the understanding of the drivers of epidemics (Cox and Abeku 2007).

Several smaller scale (national and subnational) studies have developed early warning indices or models based on weather factors, seasonal trends and past disease cases. For example, studies have been conducted on malaria in Ethiopia (Abeku et al. 2002; Teklehaimanot et al. 2004a, b), dengue in Thailand (Bartley et al. 2002), Ross River virus disease in Australia (Gatton et al. 2005), meningitis in Mali (Sultan et al. 2005) and on cholera in Bangladesh (Koelle et al. 2005a). The advantage of these smaller studies is that they may provide more specific localized information. These studies use a range of climate indicators and statistical methods, and provide a framework for future studies. The scale of the study is secondary to the availability and utility of an appropriate seasonal reference tool to predict any impending disease risk.

3.6 Trends

Longer-term trends in health data may be caused by a number of drivers including 'climate shifts' (used here to describe changes in the climate which occur abruptly over the period of a decade or two or as significant trends). The best example is that of the Sahelian drought during which the region lost approximately 30% of its annual rainfall over a 30-year period. Such shifts in climate may have profound effects on the spatial and temporal distribution of climate-sensitive diseases (Thomson et al. 2004b).

In the Gambia, several studies have suggested that the epidemiological course of malaria is slowly displaying more epidemic and unstable patterns, possibly owing to the shorter rainy seasons associated with the protracted Sahelian drought, with devastating consequences on the acquisition of childhood immunity (Brewster and Greenwood 1993). In Rwanda, an upsurge in malaria during the late 1980s was linked to enhanced transmission resulting from increased trend in temperature and rainfall (Loevinsohn 1994). In Pakistan, the climate records gathered since 1876 showed mean increases in temperature by 1.5–2°C during November and December, October rainfall, and mean humidity (since 1950) (Bouma et al. 1996). It was suggested that these changes rendered climate conditions more favorable for malaria transmission, and may account for the increase in the number of malaria cases during the mid-1990s.

The potential impact of climate changes over longer time-frames on climate-sensitive diseases remains uncertain (McMichael et al. 2003). However, it is hypothesized that global warming and associated temperature increases will expand the geographical and temporal ranges, and thus the prevalence of these diseases (Epstein 2001, 2002, 2005). Most vulnerable to these changes are vector-borne diseases such as malaria, dengue, leishmaniasis and schistosomiasis, because of the climate dependencies of the vectors such as mosquitoes, flies and snails (Patz et al. 2005) and in particular the important role of temperature in the disease transmission dynamics. Although there has been much discussion in the literature regarding the importance of climate change as a driver of recent epidemics in the East Africa highlands (Hay et al. 2002a; Patz et al. 2002; Pascual et al. 2006) there is a general consensus that malaria is among the most sensitive diseases to such changes. Indeed, small increases in temperature have a disproportionate effect on malaria infection risk, especially in fringe communities where malaria is unstable or epidemic in nature. Mathematical modeling suggest an increase in the number of people at risk to malaria as a direct consequence of climate change is highly probable (McMichael et al. 2003) although human factors are likely to play a dominant role in many areas of the world. The risk of contracting other diseases will certainly change, and in some cases increase, as suggested in a recent study in China, which determined that an average temperature increase of 1°C over the last 30 years in

January would put at risk an additional 20.7 million people for contracting schistosomiasis (Yang et al. 2005b).

As pointed out by Cazelles and Hales (2006) a major consideration in the analysis of health and climate data over long time periods (especially in the context of a changing climate) is the potential nonstationarity of the relationship including (a) nonstationarity of the *average*, leading to a trend in the observed time series (b) nonstationarity of the v*ariance*, including changes in dominant periodic components over time, and (c) nonstationarity of the relationships between several observed signals. This has important public health implications as nonstationarity associated with climate change may limit the opportunity to create forecasting models based robust relationships between climate drivers and health outcomes.

3.7 Other Factors

Much of the impact of climate on disease transmission is mediated through the impact of climatic factors on the environment including creation of breeding sites (flooding) and landcover (vector or animal reservoir habitat). For example, high malaria in India has been attributed to a high water table, soil type, irrigation and water quality (Srivastava et al. 1999). In Belize, high malaria outbreaks have been linked to vegetation and its proximity to rivers (Hakre et al. 2004). In Uganda, land use change may alter malaria transmission rates by modifying temperature in a highland region (Lindblade et al. 2000), while in Asia rice cultivation and pig breeding have increased the spread of Japanese encephalitis. In Africa, livestock movements have been linked to the dissemination of Rift Valley fever (Chevalier et al. 2004) and the prevalence of schistosomiasis to local water development and dam construction (Ernould et al. 1999). These examples highlight the likelihood that climate-sensitive diseases are complex and influenced by a multitude of auxiliary factors that interact to promote disease infectivity and transmission. Other non-climatic factors controlling disease status are also important, and although not highlighted in this chapter, should be considered. Climate is but one aspect of the spatial and temporal variability of climate-sensitive diseases. Infectious diseases typically possess a complex aetiology, and are likely caused and propagated by many different processes. Social, biological and economic factors such as population immunity, local topography, population migration, urbanization, land use patterns, housing conditions, health service provision, drug resistance and mosquito control measures also may act as important drivers in disease transmission.

3.8 Conclusion

This review highlights the range of studies conducted on climate and 20 infectious diseases of major public health importance. The literary gaps are highlighted in the accompanying Table 3.1, and demonstrate that malaria and dengue are the most researched of the infectious diseases, with a variety of studies conducted on different continents at different times. Studies on chronic diseases were more focused on spatial patterns, with regard to climatic factors, while acute diseases tended to be studied with respect to seasonality and interannual variability. Few studies examined seasonal climate forecasts or climate shifts, which may be related to the lack of high resolution long-term disease datasets necessary for such studies. The studies cited come from many countries, however, mostly only 1–3 reports of the 20 diseases investigated come from the same country. The countries with the broadest range of diseases studied included India (malaria, dengue, Japanese encephalitis, trachoma, rotavirus), Kenya (malaria, trypanosomiasis, Rift Valley fever, trachoma, rotavirus) and Brazil (malaria, schistosomiasis, leishmaniasis, yellow fever, rotavirus). The 20 diseases chosen highlights those climate-sensitive diseases that are high-level health care concerns, and are highly prevalent in many countries. Prioritizing diseases (listing 1–5 most prevalent/burdensome) may help national health systems to focus on improving data collection, defining diseases and identifying interventions and cures.

In general, very little research on climate and disease published in English in peer review journals has been conducted in the countries with the highest numbers of child deaths (India, Nigeria, China, Pakistan and the Democratic Republic of Congo), especially under-five mortality rates (Sierra Leone, Niger, Angola, Afghanistan, Liberia) (Black et al. 2003). If MDGs are to be met, then these countries should be the focus of future research, interventions, health worker training and infrastructure development. For those countries in where natural or political disasters have created a state of emergency or regions emerging from periods of political instability, where rapid progress must be made to re-establish health services then predictive studies in neighboring countries, and extrapolations may help to identify high risk locations and times, and facilitate the appropriate health care via NGOs, for example (Thomson et al. 1999). Although this review elucidates many disease-specific gaps, it helps to define areas in need of future research and how climate analysis or tools may aid this endeavor. For example, very little information is documented on cholera climate interactions outside of Asia (Griffith et al. 2006) although recent studies from West Africa indicate that regional climate variability may be a driver (de Magny et al. 2006; Constantin et al. 2006). This disease is of particular concern on the continent, since over 90% of the cases reported to WHO occur in Africa. Whilst it is difficult to collect accurate data, especially when most cases are from epidemics occurring from natural disasters and/or political instability, retrospective analysis of selected outbreaks and meteorological data may highlight putative climatic risk factors. Furthermore, we have restricted this review to 20 climate-sensitive diseases, but other disease such as Chagas disease (American trypanosomiasis), Crimean-Congo hemorrhagic fever, tick-borne encephalitis, shigellosis, typhoid and influenza should also be considered in future climate-related studies of disease.

Understanding the effects of weather and climate variability and change on the epidemiology of infectious diseases is important for planning specific disease related interventions and monitoring their impact. Specifically, climate information can help national health systems to define where, when and who is the most at-risk. It is essential, however, that more 'ground truth' epidemiological time series data is collected. Without these 'standardized' data sets an understanding of basic epidemiology and associated risk factors is limited. As part of international initiatives and elimination programs, baseline and monitoring data are now being collected for diseases such as malaria, schistosomiasis, lymphatic filariasis, onchocerciasis, trypanosomiasis and trachoma in many regions of the world in order to assess the burden of disease and the impact of interventions. Similar datasets are needed to aid in the control of many other diseases. It is also important that while these datasets are utilized for programmatic operational research purposes on the one hand they are available for local decision making on the other (Macfarlane et al. 2007). For this to be possible methodologies and tools should be designed that are appropriate for local and regional use and capacity to use these must be developed throughout the health sector and with appropriate partners. Since the climate and environmental information required for such studies comes from outside of the health sector, it is essential that sustainable multi-sectoral collaborations be established. Overcoming current constraints to such partnerships (IRI 2006) is a pre-requisite for moving forward.

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Chapter 4
Integration of Seasonal Forecasts into Early Warning Systems for Climate-Sensitive Diseases such as Malaria and Dengue

Stephen J. Connor[1,] * and Gilma C. Mantilla[2]

Abstract Effective prevention and control of epidemics has been a key element of global, regional and national disease control policies for many years. Epidemics are by their nature abnormal events and will clearly challenge the normal routine approaches to control and provision of treatment. Epidemics are caused by unusual changes in the existing equilibrium between the human host, the pathogen and its vector. While the level of risk may be exacerbated by social factors, climate variability plays an important role and indeed it is most often abnormality in meteorological and environmental conditions that 'triggers' epidemics of the climate sensitive diseases.

Malaria and dengue are considered climate-sensitive diseases and in recent years there have been attempts to develop and test integrated early warning systems which seek to provide advance warning of changes in epidemic risk, through incremental indicators that allow control services greater opportunity to plan, choose and implement more timely and focused response in the areas affected. This paper uses the example of malaria early warning system applications in Southern Africa to illustrate the elements of the system, evidence of its potential benefits, including the control options it may provide and some of the current challenges and opportunities for its broader implementation in Africa and elsewhere.

Keywords Malaria, dengue, seasonal forecast, early warning system, climate variability, climate change, global warming

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4.1 Climate and Health

Certain diseases and ill health are associated with particular environmental conditions, season, and climate. This was recognized by the ancient writers of Vedic literature, by Hippocrates, and remains the focus of considerable research today. Climate may impact on health through a number of mechanisms, directly through cold or heat stress or, more commonly, indirectly through:

(a) Its role in determining agricultural output and consequently food security which directly affects nutritional status
(b) Its role in the economy and income opportunities, which affects the ability to maintain nutritional status, prevent infection and obtain curative health care as necessary
(c) Its role in determining seasonal and inter-annual demographic processes (e.g. seasonal labour migration and environmental refugees)
(d) Its impact on the spatial and temporal distribution of climate-sensitive infectious diseases – commonly, but not always, transmitted by vectors (Thomson et al. 2004a, b; Kelly-Hope and Thomson, Chapter 3, this volume)

The World Health Organization have recently identified a number of climate-sensitive infectious diseases, some of which including: malaria, cholera and dengue; they describe as being promising candidates for the development of climate informed early warning systems (WHO 2002a; Kelly-Hope and Thomson, Chapter 3, this volume).

4.2 Climate and Infectious Disease in Africa

There is currently intense concern over the growing public health problems posed by infectious diseases in the developing world, especially HIV-AIDS, TB and malaria. These three diseases compound each other: HIV increases susceptibility to TB and severe malaria; malaria and TB hasten the progression of HIV-AIDS (WHO 2002b, 2005b) making care of sufferers particularly challenging to resource-poor health services and communities in sub-Saharan Africa. Infectious diseases disproportionately affect the poorer countries and are seen as a significant constraint to economic development and progress towards the Millennium Development Goals, particularly in sub-Saharan Africa. Therefore calls for massive investment in health services and control programmes in the most affected countries have been made (WHO 2001a). The enormous impact and scale of infectious diseases in Africa often leads to their being described as ‘epidemic’. However this term may be inappropriate for a disease such as malaria which has been with us since time immemorial, and where the greatest burden continues to occur in regions where the disease has been continuously present in the community. For instance, malaria transmission throughout much of Africa has long been described as ‘stable’ or endemic transmission, meaning that it is expected to