CHAPTER 5

The Regional Network for Asian Schistosomiasis and Other Helminth Zoonoses (RNAS^{+}): Target Diseases in Face of Climate Change

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Abstract

Climate change—according to conventional wisdom—will result in an expansion of tropical parasitic diseases in terms of latitude and altitude, with vector-borne diseases particularly prone to change. However, although a significant rise in temperature occurred over the past century, there is little empirical evidence whether climate change has indeed favoured infectious diseases. This might be explained by the complex relationship between climate change and the frequency and the transmission dynamics of infectious diseases, which is characterised by nonlinear associations and countless other complex factors governing the distribution of infectious diseases. Here, we explore whether and how climate change might impact on diseases targeted by the Regional Network for Asian Schistosomiasis and Other Helminth Zoonoses (RNAS^{+}). We start our review with a short summary of the current evidence-base how climate change affects the distribution of infectious diseases. Next, we introduce biology-based models for predicting the distribution of infectious diseases in a future, warmer world. Two case studies are presented: the classical RNAS^{+} disease schistosomiasis and an emerging disease, angiostrongyliasis, focussing on their occurrences in the People's Republic of China. Strengths and limitations of current models for predicting the impact of climate change on infectious diseases are discussed, and we propose model extensions to include social and ecological factors. Finally, we recommend that mitigation and adaptation strategies to diminish potential negative effects of climate change need to be developed in concert with key stakeholders so that surveillance and early-warning systems can be strengthened and the most vulnerable population groups protected.

5.1. INTRODUCTION

During his Nobel Lecture delivered in Oslo, Norway on 10 December 2007, Al Gore, the former vice-president of the United States of America, said: ''[...] the earth has a fever. And the fever is rising. The experts have told us it is not a passing affliction that will heal by itself. [...] Now comes the threat of climate crisis – a threat that is real, rising, imminent, and universal. [. . .] For now we still have the power to choose our fate, and the remaining question is only this: have we the will to act vigorously and in time, or will we remain imprisoned by a dangerous illusion?''

Is Mr. Gore telling us an inconvenient truth? Indeed, there is burgeoning consensus that climate change (see Glossary) is real and that it is an increasing and evolving threat imposing negative biotic impact, including biodiversity loss (Amano et al., 2010; Potts et al., 2010) and a risk for public health on a local, regional and global scale (Haines et al., 2009; Klausmeyer and Shaw, 2009; Lafferty, 2009; Pickett et al., 2010; St Louis and Hess, 2008). With regard to infectious diseases, particularly vector-transmitted tropical diseases such as malaria and dengue, the conventional wisdom is that climate change will result in an expansion throughout temperate areas (Epstein, 2000). It has also been speculated that malaria will climb into higher altitudes at the margins of its current distribution, but there is an ongoing debate with regard to highland malaria in East Africa (Chaves and Koenraadt, 2010). Since hosts other than humans are also subject to infectious diseases, there is considerable concern that climate change will not only impact public health, but also conservation biology, as well as agriculture, aquaculture, fishery and livestock production (Crabbe, 2009; Forman et al., 2008; Harvell et al., 2002; Lafferty, 2009; Mas-Coma et al., 2009; McMichael et al., 2007; Miraglia et al., 2009; Solomon et al., 2007).

The aim of this review is to explore whether climate change will have an effect on the major helminth infections in Southeast Asia, which largely coincide with the target diseases of the Regional Network for Asian Schistosomiasis and Other Helminth Zoonoses (RNAS^{+}; see Glossary). First, we provide a summary of the current evidence-base regarding climate change and the spatial and temporal distribution of infectious diseases emphasising that climate change is only one among many contributing factors that govern the transmission of infectious diseases. Second, we introduce biology-based models (see Glossary) that are widely used for predicting the distribution of infectious diseases in a future, warmer world. Third, we present two case studies from the People's Republic of China (P.R. China) that exemplifies how biology-based and statistical models can be utilised to predict the distribution of infectious diseases in the future. The first study focuses on the classical RNAS^{+} disease (i.e. schistosomiasis), whereas the second deals with an emerging disease (i.e. angiostrongyliasis). We highlight the importance of biology-based models, which require an in-depth understanding of relationships between climate variables and vital data. Strengths and weaknesses of current model specifications for predicting a potential impact of climate change on schistosomiasis and angiostrongyliasis are discussed, along with a proposal of how these models could be further extended, hence including not only biological, but also ecological and social factors. Finally, we discuss mitigation and adaptation strategies that need to be developed, validated and applied to diminish the potential negative effects of climate change on RNAS$^+$ target diseases. Issuing from this discussion, a set of recommendations arises with respect to research needs for surveillance and early-warning systems.

5.2. CLIMATE CHANGE

5.2.1. Definition and general considerations

In 2002, at the World Summit on Sustainable Development in Johannesburg, South Africa, the World Health Organization (WHO) initiated a broad action plan on health and the environment. Further specificity was added to this action plan in 2008 when WHO called on its member states to 'Protect health from climate change', the selected theme of the World Health Day 2008. Justification of this theme came from a previously published report, suggesting that climate change might already be responsible for over 150,000 deaths annually, including the loss of approximately 5 million disability-adjusted life years (DALYs; see Glossary) globally (Ebi et al., 2005). Originally developed by Murray and Lopez (1996), the DALY metric is widely used in public health, but it has important shortcomings (King, 2010; King and Bertino, 2008). Human beings are exposed to climate change directly through changing weather patterns (e.g. more extreme and more frequent events) and indirectly through changes in water, air and food quality/quantity, ecosystems, agriculture, livelihoods and infrastructure (McMichael et al., 2007).

What exactly does climate change mean? As defined in the Glossary, climate change denotes a long-term process, characterised by statistical change of weather distribution (spatially) and significant temporal fluctuations that range from short-term periods to millions of years. The drivers of climate change include both natural variability and anthropogenic transformations, with the latter of growing importance since the beginning of the industrial revolution (Crowley, 2000; Huang et al., 2000). Solar radiation, volcanism, deviations in the Earth's orbit, continental drift and changes in greenhouse gases and tropospheric aerosols are the key factors of climate change. Of note, a variety of climate change feedbacks can further exacerbate or reduce the initial forcing. Moreover, the oceans and ice caps represent important parts of the climate system that, because of their large masses, respond only slowly to climate change. Therefore, the climate system can take many decades to fully respond to new external forcing. There is growing consensus that the combustion of fossil fuels for energy production and transportation is the key driver of the recent global warming due to anthropogenic activities (IPCC, 2007). Carbon dioxide (CO_2) is the predominant, long-lived greenhouse gas, and its atmospheric concentration has increased from approximately 280 ppm in the pre-industrialised period (around the year 1750) to 379 ppm in the year 2005 (IPCC, 2007). Methane (CH_4), nitrous oxide (N_2O) and halocarbons (a group of gases containing bromine, chlorine or fluorine) are another three long-lived greenhouse gases. The global atmospheric concentrations of CH_4 and N_2O have increased from 715 and 270 ppb in the pre-industrial era, respectively, to 1774 and 319 ppb in 2005 (IPCC, 2007).

The Earth's average temperature has increased by 0.74°C (95% confidence interval: 0.56–0.92°C) over the past 100 years (1906–2005), with an unusually steep rise over the past 30 years (IPCC, 2007). However, there is considerable spatial and temporal variation. Indeed, increased temperatures were particularly marked at high latitudes of the northern hemisphere (Murphy et al., 2004), and larger differences were recorded for monthly average minimum and maximum temperatures during winter rather than summer (Easterling et al., 1997). Given these spatial and temporal heterogeneities, new research is needed to more readily capture local climate changes, and hence models must be further developed so that they can assign meteorological parameters also at relatively small scales (Haines et al., 2006; Knowlton et al., 2004; Patz et al., 2005).

In the fourth assessment report, put forward by the Intergovernmental Panel of Climate Change (IPCC; see Glossary) in 2007, the average temperature is predicted to rise with 0.2°C per decade over the next 20 years. These predictions seem plausible, as the initial predictions made by IPCC for the first decade of the new millennium have now been validated with real data. It is exceedingly difficult to make longer-term predictions because of the growing level of uncertainty and strong dependence of model scenarios, most importantly on emissions of long-lived greenhouse gases. Yet, the initial predictions from IPCC that our world might be between 1.4 and 5.8°C warmer in 2100 as compared to 1990 are still reported in the latest assessment report (IPCC, 2001, 2007).

Besides rises in surface air temperature, climate change also alters free atmospheric temperature, sea level pressure, height of tropopause, ocean heat content and precipitation at local, regional and global scales. Among these factors, the most difficult one to assess and quantify is precipitation (Zhang et al., 2007). Temperature rise leads to increases in the moisture-holding capacity of the atmosphere at a rate of approximately 7% per centigrade.

5.2.2. Impact of climate change on different sectors, including health

Table 5.1 summarises projected impacts of climate change on different sectors and ecosystems such as agriculture, forestry, water resources and, most importantly for the current review, human health. Data for this table have been derived from the latest available assessment report put forth by IPCC. Of note, the headline conclusion regarding health reads as follows: "The health status of millions of people is projected to be affected

TABLE 5.1 Predicted impacts of climate change on different sectors, including public health

	Examples of major projected impacts by sector		
Phenomenon	Agriculture, forestry and ecosystems	Water resources	Public health
Warmer days and nights	Increased risk of insect outbreaks	Effects on water resources relying on snow melt	Reduced human mortality from decreased cold exposure
Warm spells/ heat waves	Increased danger of wildfire; decreased yields due to heat stress	Increased water demand; water quality problems (e.g. algal blooms)	Increased risk of heat-related mortality, especially for the elderly and chronically sick people
Heavy precipitation	Damage to crops; soil erosion and inability to cultivate land due to water logging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply	Increased risk of deaths, injuries and infectious, respiratory and skin diseases
Drought	Land degradation; lower yields and crop damage; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases
Tropical cyclone	Damage to crops, trees and coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders
Extreme high sea level	Salinisation of irrigation water	Decreased freshwater availability	Increased risk of deaths and injuries by drowning in floods; migration-related health effects

Note: All examples are based on projections for the mid- to late 21st century. These do not take into account any changes or developments in adaptive capacity (Solomon et al., 2007).

through, for example, increases in malnutrition; increased deaths, diseases and injury due to extreme weather events; increased burden of diarrhoeal diseases; increased diseases due to higher concentrations of ground-level ozone related to climate change; and the altered spatial distribution of some infectious diseases'' (Parry et al., 2007). Naturally, space limits us to provide only a few examples from the large and rapidly growing body of literature documenting the impact of climate change on health, but it should suffice to convince our readers that we cannot but live with change (Ebi et al., 2005; Epstein, 2000, 2001; Haines and Patz, 2004; Haines et al., 2006, 2009; Knowlton et al., 2004; McMichael et al., 2007; Patz et al., 2000, 2005).

5.2.3. Climate change and vector-borne diseases

A line of scientific inquiry that has received special attention to date is the potential impact of climate change on shifts in the spatio-temporal distribution of disease vectors, and hence the frequency and transmission dynamics of vector-borne diseases (Chaves and Koenraadt, 2010; Gething et al., 2010; Hunter, 2003; Lafferty, 2009; Ready, 2008; Reiter, 2001; Semenza and Menne, 2009; Sutherst, 2004; Zhang et al., 2008). Interestingly, most studies assessing a potential impact of climate change are focussed on malaria (Gething et al., 2010; Sutherst, 2004; Tanser et al., 2003). An early attempt to estimate the excess risk of malaria due to climate change suggests that the distribution of the disease may increase by 12–27% as a direct consequence of higher average temperatures (Martens et al., 1997). These estimates are further supported by mathematical modelling, coupled with a geographical information system (GIS; see Glossary) and remote sensing (see Glossary) approach. Indeed, an increase of the at-risk population is predicted with regard to malaria transmission due to climate change, particularly at higher altitudes (e.g. the highlands of East Africa) and to some degree also at higher latitudes (Lindsay and Martens, 1998; Tanser et al., 2003). However, conflicting results have been reported, and there is a heated debate with regard to the real impact of climate change on highland malaria in East Africa (Chaves and Koenraadt, 2010; Hay et al., 2002; Pascual et al., 2006).

Table 5.2 summarises key findings obtained from studies focussing on climate change and vector-borne diseases, including diseases other than malaria, that is, lymphatic filariasis, schistosomiasis, leishmaniasis, onchocerciasis, human African trypanosomiasis and arboviral diseases (e.g. dengue, yellow fever and Japanese encephalitis).

The particular interest to assess the potential impact of climate change on vector-borne diseases can be explained by the fact that vectors (as well as other pathogens such as bacteria, parasites and viruses) survive and reproduce within certain optimal, climatic conditions, with temperature playing a particularly important role. Changes in climate therefore alter

TABLE 5.2 Global status of major vector-borne diseases and the likely change in their distribution due to climate change

Disease	At-risk population (million)	Prevalence of infection (million)	Present distribution	Likelihood of change of disease distribution due to climate change[a]
Parasitic disease				
Malaria	2211[b]	515[b]	Tropics and subtropics	+++
Lymphatic filariasis	>1000[b]	120[b]	Tropics and subtropics	+
Schistosomiasis	779[b]	207[b]	Tropics and subtropics	++
Leishmaniasis	350[b]	12[b] (+400,000 new cases/year)	Asia, Africa, South America and South Europe	n.k.
Onchocerciasis	120[b]	18[b]	Africa and Latin America	+
Human African trypanosomiasis	>60[b]	0.5[b] (+25,000 new cases/year)	Africa	+
Arboviral diseases				
Dengue	n.k.	n.k.	Tropics and subtropics	++
Yellow fever	n.k.	n.k.	Africa and Latin America	+
Japanese encephalitis	n.k.	n.k.	East Asia and Southeast Asia	+

[a] Likelihood of change stratified as follows: 0, unlikely; +, likely; ++, very likely; +++, almost certain; n.k., not known.
[b] Source: Brooker and Utzinger (2007).

the transmission of vector-borne diseases in different ways, such as changing the survival and reproduction rate of the vector and of the pathogen, as well as changing vector activities (Hunter, 2003; Patz et al., 2000). The following three main lines of investigation have been pursued. The first issue pertains to the relationship between climate parameters and transmission of vector-borne diseases, and hence assessing whether transmission is likely to change in a warmer, future world. The second line of inquiry focuses on methodologies used in statistical models to simulate the potential increase in transmission intensity. Third, advances have been made with biology-based models, with key biological parameters derived from experimental studies and field observations, and inference derived from extrapolations. It is important to note that very few studies have been carried out thus far that looked at adaptation and mitigation strategies related to vector-borne diseases in the face of climate change (for a notable exception, see Beebe et al., 2009).

5.3. RNAS+ AND ITS TARGET DISEASES

Currently, there are five helminthic diseases forming the primary focus of RNAS+, namely schistosomiasis, cysticercosis/taeniasis and the three main food-borne trematode infections (i.e. clonorchiasis, fascioliasis and opisthorchiasis; Olveda et al., 2010; Zhou et al., 2008a). However, other parasitic diseases that are endemic in Southeast Asia and neighbourhood countries (e.g. echinococcosis; McManus, 2010) and emerging parasitic diseases such as angiostrongyliasis receive growing interest from the network (Lv et al., 2010b; Odermatt et al., 2010).

Climate change, particularly the rise in temperature, has been linked to altered geographical distributions in major trematode infections, including those forming the primary emphasis of RNAS+ (Moodley et al., 2003; Yang et al., 2005; Yilma and Malone, 1998; Zhou et al., 2008b), and temperature is believed to have a direct effect on the transmission of these diseases. Theoretically, the consequence of climate change could not only alter the geographical distribution of transmission areas, but transmission intensity would also increase. Even a small increase in the average temperature might result in a growing burden of the disease.

Mollusks (generally snails) serve as the first (or only) intermediate host for all trematodes. The asexual stage of these parasites develop within this intermediate host, eventually producing large numbers of free-swimming cercariae, which either directly infect the vertebrate definitive host (as in schistosomiasis; Muth et al., 2010; Zhou et al., 2010) or a second intermediate host (fish or a shellfish as in the major food-borne trematodiases; Keiser and Utzinger, 2009; Sripa et al., 2010). The parasite's use of the snail for the production of cercariae is the most important of the processes governing the overall transmission success. The temperature is the key factor since it directly influences this part of the life cycle, and the survival of both the snail and the parasite is restricted by threshold temperatures that vary from one parasite species to another. Thus, it is always coupled with an increase of cercarial development speed and output (Ataev, 1991; Lo and Lee, 1996; Mouritsen, 2002; Umadevi and Madhavi, 1997; Yang et al., 2007).

5.4. CASE STUDIES

In order to assess a potential impact of climate change on infectious diseases, particularly the effect of rising temperature on the distribution and transmission of parasitic diseases, a detailed understanding of the life cycle and thermal thresholds at critical stages of the life cycle are necessary. The use of biology-based models holds promise to determine how temperature and its dynamics influence host–parasite interactions (Malone, 2005). In previous studies, biology-based models have been utilised to determine the potential impact of climate change and other anthropogenic disturbances on the distribution of malaria and other tropical parasitic diseases (Kutz et al., 2009; Pascual et al., 2006; Ready, 2008; Reiter, 2008).

Here, we present two case studies that employed biology-based models to predict the distribution of schistosomiasis japonica and angiostrongyliasis cantonensis in a future, warmer P.R. China. Table 5.3 summarises key determinants that were utilised to construct biology-based models for schistosomiasis japonica and angiostronyliasis cantonensis. While some of the determinants were readily available from the literature, additional experiments were conducted in the laboratory and under semi-natural field conditions to obtain additional information on the remaining determinants. Table 5.4 contains comparable information on key biological features of the transmission of schistosomiasis japonica and angiostrongyliasis cantonensis.

5.4.1. Climate change and schistosomiasis japonica

Detailed accounts of the epidemiology and control of schistosomiasis japonica in P.R. China, including the schistosome life cycle, are available (McManus et al., 2010; Utzinger et al., 2005; Zhou et al., 2005, 2010). Additionally, the development and use of a biology-based model, in connection with major water resources development projects, to predict a potential impact of climate change on the distribution of schistosomiasis in P.R. China, have been presented (Yang et al., 2005, 2006; Zhou et al., 2008b). The key issues governing the biology-based model are summarised here.

TABLE 5.3 Biological determinants considered in schistosomiasis japonica and angiostrongyliasis cantonensis transmission models

Host/parasite	Determinant	Parameter	Value: Schistosomiasis	Value: Angiostrongyliasis
Parasite[a]	Developmental period	DTTp (°C)	15.4	15.0
		GDDp (degree days)	852.6	262.5
	Transmission period	Period above DTTp (day)	[b]	212[c]
	Extreme temperature tolerance	Upper threshold (°C)	[b]	[b]
		Lower threshold (°C)	[b]	[d]
	Longevity in hosts	Life span (day)	[b]	414.2
Intermediate host[e]	Reproduction intensity	DTTs (°C)	5.8	11.7
		GDDs (degree days)	3846.3	1404.1
	Extreme temperature tolerance	Highest (°C)	42.1	[b]
		Lowest (°C)	−2.7	5.43[c]
			0[c]	3.62[c]
	Dormancy	Upper threshold (°C)	40.0	[b]
		Lower threshold (°C)	5.8	17.0
Definitive host[f]	Longevity of infected individuals	Life span (day)	[b]	173.2

DTTs and DTTp denote developmental threshold temperature of snail and parasite, respectively; GDDs and GDDp are growing degree days of snail and parasite, respectively.

[a] *S. japonicum* in schistosomiasis transmission model, *A. cantonensis* in angiostrongyliasis transmission model.

[b] Denotes that these parameters have not been considered.

[c] Denotes fitting to currently known distribution. In angiostrongyliasis transmission model, 5.43 for 'spread' region and 4.62 for 'establishment' region.

[d] Indicates that there are no specific data available, but cold tolerance of nematode considered equal or greater than that of their host, as supported by previous experiments.

[e] *O. hupensis* in schistosomiasis transmission model, *P. canaliculata* in angiostrongyliasis transmission model.

[f] Not considered in schistosomiasis transmission model, rat in angiostrongyliasis transmission model.

TABLE 5.4 Biological feature in schistosomiasis japonica and angiostrongyliasis cantonensis transmission dynamics, characteristic for P.R. China

Risk factor	Schistosomiasis japonica transmission model		Angiostrongyliasis cantonensis transmission model	
Internal factors	Species	Biological features	Species	Biological features
Parasite	*Schistosoma japonicum*	Trematode High specificity to intermediate host and low specificity to definitive host Asexual multiplication in snail Cercariae shed from snail Infection via skin of definitive host Adult worms parasitising intestinal vessels	*Angiostrongylus cantonensis*	Nematode High specificity to definitive host and low specificity to intermediate host Non-multiplication mode Larvae harboured within snail Infection via mouth of definitive host Adult worms parasitising pulmonary arteries
Intermediate host	*Oncomelania hupensis*	Pomatiopsidae Native freshwater snail species Small size (6.09–9.73 mm in length, 2.57–4.24 mm in width) Tropical and subtropical Amphibious, mainly on wet soil	*Pomacea canaliculata*	Ampullariidae Invasive freshwater snail species Large size (up to 170 mm in length) Tropics and subtropics Amphibious, mainly in shallow water

Definitive hosts	Human, domestic and wild mammals	Longevity (>2 years) Longevity somewhat shortened by infection	Rats	Longevity (<2 years) Longevity significantly shortened by infection
External factors	**Item**	**Potential impact**	**Item**	**Potential impact**
Environmental change	Land use	Confirmed	Land use	n.a.
	Biological diversity	n.a.	Biological diversity	n.a.
	Pollution	n.a.	Pollution	n.a.
	Water projects	Potential, not confirmed	Water projects	Not confirmed
Climate change	Rising temperature	Potential, not confirmed	Rising temperature	Potential, not confirmed
	Flooding	Confirmed	Flooding	n.a.
	Annual fluctuation of climatic factors	n.a.	Annual fluctuation of climatic factors	n.a.
Social factors	Political will	Confirmed	Political will	n.a.
	Financial support	Confirmed	Financial support	n.a.
	Technical support	Confirmed	Technical support	n.a.
	Human behaviour	Human–water contact patterns	Human behaviour	Eating freshwater or terrestrial snails and slugs, or paratenic hosts
	Farming mode	Confirmed	Farming mode	n.a.
	Control strategy	Under control	Control strategy	Without control

n.a., not assessed.

Studies carried out at Jiangsu Institute of Parasitic Diseases in Wuxi have found that the minimum thermal limit of *S. japonicum* harboured in its intermediate snail host *O. hupensis* is 15.3°C (Yang et al., 2007). The temperature at which half of the snails were hibernating (ET_{50}) was shown to be 6.4°C, while the lower lethal temperature for *O. hupensis* is 0°C in a dry environment and 1°C under wet conditions (Sun et al., 2003). A detailed time-series analysis of two 30-year temperature data sets (1961–1990 and 1971–2000) revealed an overall increase in the average January temperature in P.R. China of 0.96°C from 1971 to 2000. This observation resonates well with the global and regional picture. Although the estimated temperature increase is considerably higher than that predicted by the IPCC report (Solomon et al., 2007), it has been noted that a large portion of the global warming occurred after the mid-1970s, that temperature rises were more pronounced at northern latitudes and that the increased temperatures were particularly pronounced during the winter months (Easterling et al., 1997; Huang et al., 2000). Another study forecasted that the mean January temperatures in P.R. China would increase by 0.9°C in 2030 and 1.6°C in 2050 (Zhou et al., 2008b).

Based on our biology-based model, these temperature increases would clearly result in an altered transmission of schistosomiasis japonica, with disease transmission extending northwards into currently non-endemic areas. A detailed time-series analysis of temperature records and probing on a GIS platform, facilitated by simple spatial statistics, estimates that, a surface area of 41,335 km^2 could potentially become schistosome-endemic, putting an additional 21 million people at risk for an infection with *S. japonicum* (Yang et al., 2005). In view of current estimates that 779 million people are at risk of schistosomiasis worldwide (Steinmann et al., 2006), this finding translates to a 2.7% increase globally (Fig. 5.1). No doubt such a result would have a profound public health impact and be of considerable economic significance.

The study by Zhou et al. (2008b) applied three key factors to infer risk maps for schistosomiasis transmission in P.R. China by 2030 and 2050. The most important findings can be summarises as follows: (i) the mean January temperature can be utilised to delineate a 'freezing line' north of which *O. hupensis* cannot survive, hence transmission of *S. japonicum* would not be possible; (ii) the mean growing degree days (GDD; see Glossary) for the development of *S. japonicum* in its intermediate host snail is 852.6 degree-days; and (iii) the mean GDD for the development of a generation of *O. hupensis* is 3846 degree-days. This model is useful in this connection and based on the assumption that a plant or a poikilothermal animal only develops when the environmental temperature is higher than a specific minimal threshold, and that the total thermal energy required for development is constant (Higley and Haskell, 2001). These results, coupled with the predicted temperature increases, predict that a large surface area

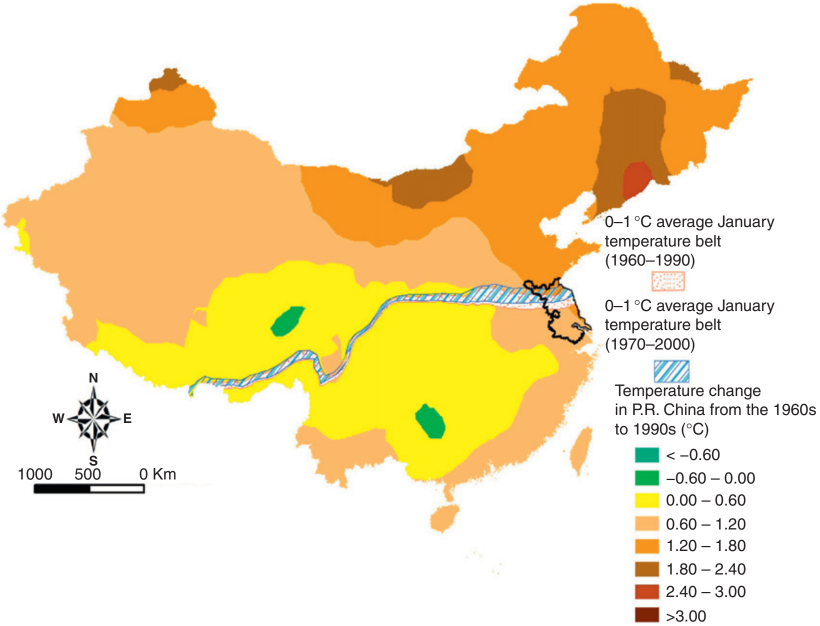

FIGURE 5.1 Smoothed map of P.R. China exhibiting the average January temperature difference between the 1960s and 1990s, including the new potential transmission area of *S. japonicum* due to climate change. The black lines in the mid-eastern part of P.R. China delineate the Jiangsu province (Source: Yang et al., 2005).

(i.e. 783,883 km^2) might become additional risk areas for schistosomiasis by 2050, which translates to 8.1% of the total surface area of P.R. China. It is also conceivable that the situation would be exacerbated as transmission intensity increases in the current endemic areas. Recently, by using the results from PRECIS on reference years (1961–1990), A2 (2010–2020) scenario and B2 (2010–2020) scenario, which were developed in the IPCC Special Report on Emissions Scenarios (SRES), the biology-based model is used to calculate the corresponding risk areas and potential transmission index in P.R. China in response to different climate scenarios (Fig. 5.2). Two project maps were created (Fig. 5.3). Figure 5.3 showed that under the A2 and B2 scenarios in 2020, the transmission areas for schistosomiasis are located in green areas, the potential risk transmission areas are distributed in red areas and reduced transmission areas are in purple. The figure also showed that the transmission areas of schistosomiasis are located up to north altitude about 33°15′ inside Jiangsu province in 2005, and extended to northern Jiangsu in 2020 under both A2 and B2, but the extended areas in B2 are larger than that in A2.

The intimate connection of water resources development and managements, such as irrigation systems and large dams, on the transmission

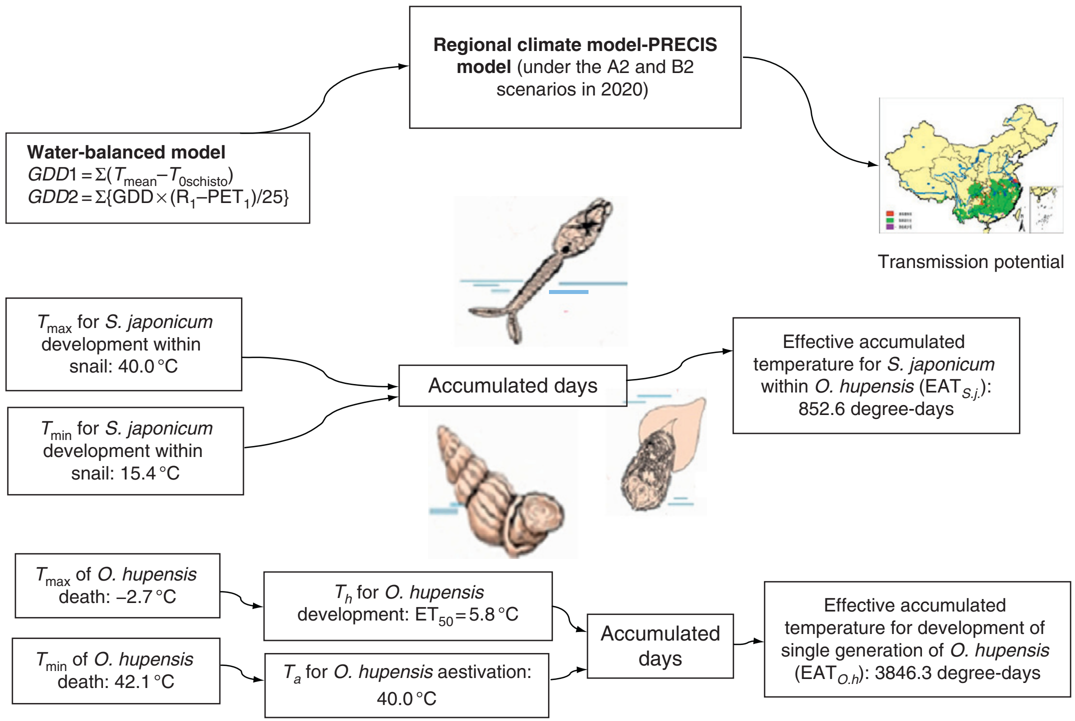

FIGURE 5.2 Biology-based model on the basis of daily outputs from Regional Climate Modeling System (RCM)-PRECIS to assess the effect of temperature on critical stages of *S. japonicum* within *Oncomelania* snail intermediate host. The climate data (1961–1990) is used as quasi-observed boundary conditions to drive RCM-PRECIS, then the data set is employed to test the effects of feeding biology-based model of schistosomiasis transmission. The biology-based model was divided into two parts, one is the growing degree model to predict the risk distribution areas of schistosomiasis, and the other is the water-balanced model to predict the transmission potential measured by potential transmission index. Both the growing degree model and water-balanced model were using RCM daily outputs directly via comparing the simulated results and the station observation.

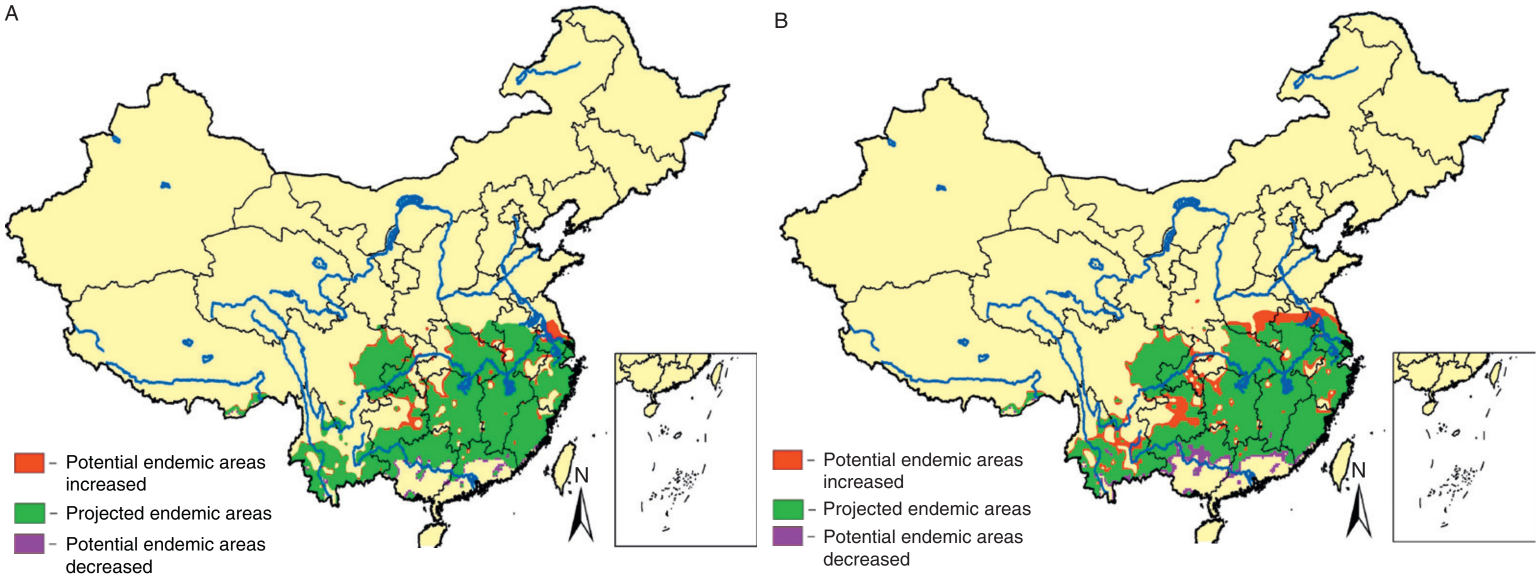

FIGURE 5.3 The predicted risk map of schistosomiasis transmission in P.R. China in 2005 and 2020 under A2 scenarios (A) and B2 scenarios (B). Green colour denotes potential risk areas for schistosomiasis transmission in 2000, red colour denotes predicted additional risk areas and purple colour denotes deceasing risk areas, under the A2 and B2 scenarios in 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this chapter.)

dynamics of schistosomiasis has been documented for myriad ecological and epidemiological settings across Africa (Hunter, 2003; Mott et al., 1995; Southgate, 1997; Steinmann et al., 2006). There is therefore considerable concern that the construction and operation of large-scale water projects in close proximity to schistosome-endemic areas of P.R. China would result in negative health effects (Li et al., 2007; McManus et al., 2010; Xu et al., 2000). The South-North Water Transfer (SNWT) project (see Glossary), a major infrastructure development project aiming at social and economic development of the water-deprived northern part of P.R. China through improved waterways, must be mentioned in this connection. Two lakes, Hongze and Baima, both located in the current risk areas for *S. japonicum* transmission and both planned to be connected with the SNWT project have been identified as risk-prone areas (Yang et al., 2005). There is concern that schistosomiasis might become a public health problem in this area when the construction has been finalised (Liang et al., 1996), and implementation of the SNWT project could result in a wider distribution of intermediate host snails by enlarging the wetlands and enabling direct snail transfers from the infested Yangtze River, not only to the Baima and Hongze lakes, but also to another lake, the Gaoyou Lake (Yang et al., 2005, 2006; Fig. 5.4).

It needs to be re-emphasised that climate change does not only signify a rise in temperature. Additionally, climate change also contributes to an increased frequency of extreme climate events that can, for example, result in high winds, increased rainfall and widespread flooding (Easterling et al., 2000). The flooding along the lower reaches of the Yangtze River that occurred in the late 1990s, might, at least partially, be explained by extreme weather events due to climate change. This flooding, in turn, was a key driver for increased transmission of *S. japonicum* locally and resulted in a larger number of infected humans than had been previously predicted (Fig. 5.5). It is noteworthy that the use of a GIS approach proved useful in predicting the distribution of *O. hupensis* in the face of the temporarily changed environmental conditions (Zhou et al., 2002). Hence, it is not surprising that GIS and remote sensing find increased application to further out understanding of the epidemiology and control of schistosomiasis (Simoonga et al., 2009; Yang et al., 2005).

5.4.2. Climate change and angiostrongyliasis cantonensis

Angiostrongyliasis, or eosinophilic meningitis, is caused by the rat lungworm *A. cantonensis*, which is prevalent in Southeast Asia, the Pacific islands and the Caribbean (Graeff-Teixeira et al., 2009; Wang et al., 2008). Crabs, frogs, lizards, shrimps, snails and slugs play the role as paratenic hosts, and humans become infected when they consume these foodstuffs raw or insufficiently cooked. Consumption of insufficiently cooked freshwater or contaminated vegetables

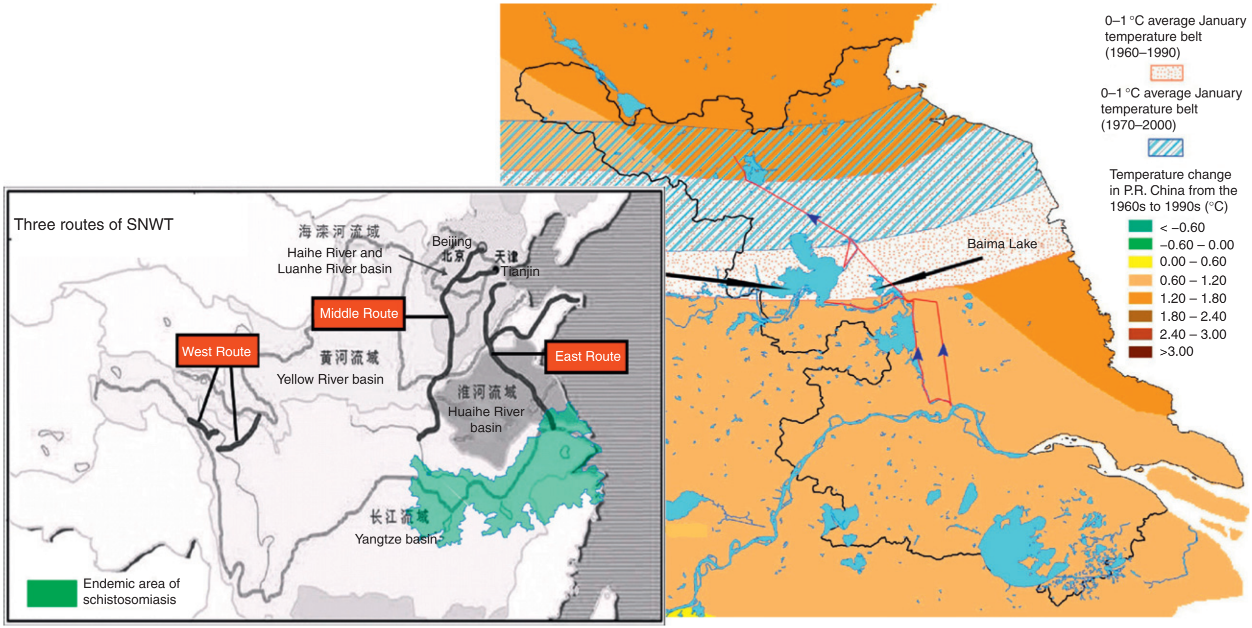

FIGURE 5.4 Potential transmission area of *S. japonicum* in Jiangsu province, P.R. China, due to higher average January temperatures (right). Red line indicates part of the Eastern route of the planned South-North Water Transfer project (left and right). The blue arrows show the water flow direction (Source: Yang et al., 2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this chapter.)

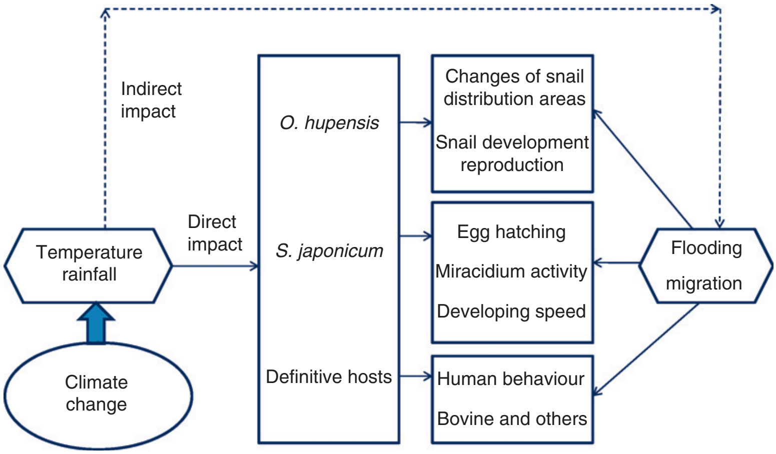

FIGURE 5.5 The proposed mechanism of the impact of climate change on schistosomiasis transmission.

is another route of infection. A series of studies have confirmed that an invasive freshwater snail species, that is, *P. canaliculata*, is responsible for the emergence of angiostrongyliasis in the mainland of P.R. China (Lv et al., 2008, 2009). *P. canaliculata* is widely distributed in 11 provinces of the southern parts of P.R. China according to a recent national sampling survey and several more isolated populations have been recently reported from Jiangsu, Zhejiang, Hubei and Sichuan provinces (Lv et al., 2010a).

The distribution of *A. cantonensis* is well matched with that of *P. canaliculata*, except in Yunnan province where this parasite was previously common. However, the parasite was not found when the recent national sampling survey was carried out (Lv et al., 2009). Although *A. cantonensis* has a low specificity with regard to intermediate hosts, *P. canaliculata* could become the leading driver of expansion of the endemic area due to its unique biological features (Table 5.4).

Climate change would facilitate the spread of *P. canaliculata* if it led to sustained, rising temperatures. Hence, the expansion of *A. cantonensis* in a warmer, future P.R. China would be assured. A recent study has been conducted in order to assess the potential impact of climate change on the invasive snail species and *A. cantonensis* (Lv et al., 2010a). In brief, the biology-based model was built around three key assumptions for the transmission of *A. cantonensis*, namely (i) *P. canaliculata* is the only intermediate host considered; (ii) the current distribution of *P. canaliculata* will reach the maximal range under the present climate conditions after which the known distribution was stratified into 'spread' and 'establishment' regions according to the general law of biological invasion

(Jeschke and Strayer, 2005); and (iii) *A. cantonensis* transmission is interrupted if snails do not ingest infective rat faeces for a period equal or longer than the mean longevity of the infected rats.

As seen in Table 5.3, all parameters considered in the modelling pertained to environmental temperature. Notably, two relevant factors, that is, longevity of the *A. cantonensis*-infected rats and the dormancy of *P. canaliculata*, were taken into account and played key roles in this model. Another important factor was the developmental period of *A. cantonensis* within *P. canaliculata*, which was determined by a GDD model (Lv et al., 2006). Other factors, such as longevity of *A. cantonensis* within definitive hosts, transmission season and the tolerance of the parasite against cold temperatures within the snail, were considered, but resulted in less meaningful predictions.

According to the assumption of this model, the distribution of *P. canaliculata* is the prerequisite of further expansion of *A. cantonensis*-endemic area. The potential distribution and change of *P. canaliculata* has been separately predicted. The first factor pertained to the *P. canaliculata* population density, which was directly related to the annual number of generation. A GDD model was employed to determine the parameter. The January temperature was considered as another important factor to determine the distribution range of *P. canaliculata*. Both factors were obtained by fitting to the known distribution.

Like the schistosomiasis japonica transmission model presented in the first case study, no comprehensive index was constructed for the angiostrongyliasis cantonensis transmission model. The current distributions of *P. canaliculata* and *A. cantonensis* were determined by overlapping the separate maps determined by different parameters. Similarly, the potential changes of distribution range in a future, warmer P.R. China (the 2020s and the 2030s) were determined. The results show that there would be significant expansion of the endemic areas of both the parasite *P. canaliculata* and the snail *A. cantonensis* (Fig. 5.6).

5.4.3. Common features and specificities

The transmission models utilised for schistosomiasis japonica and angiostrongyliasis cantonensis share a host of similar features, both with regard to internal and external factors (see Table 5.4). However, there are a number of specific features for the individual transmission models, which were readily incorporated into the biology-based models and parameterisation. For example, *S. japonicum* is highly specific to intermediate hosts; indeed there is only one intermediate host snail (i.e. *Oncomelania* spp.) that is amphibious. The distribution of this snail species in P.R. China is well known. With regard to *A. cantonensis*, thus far, over 30

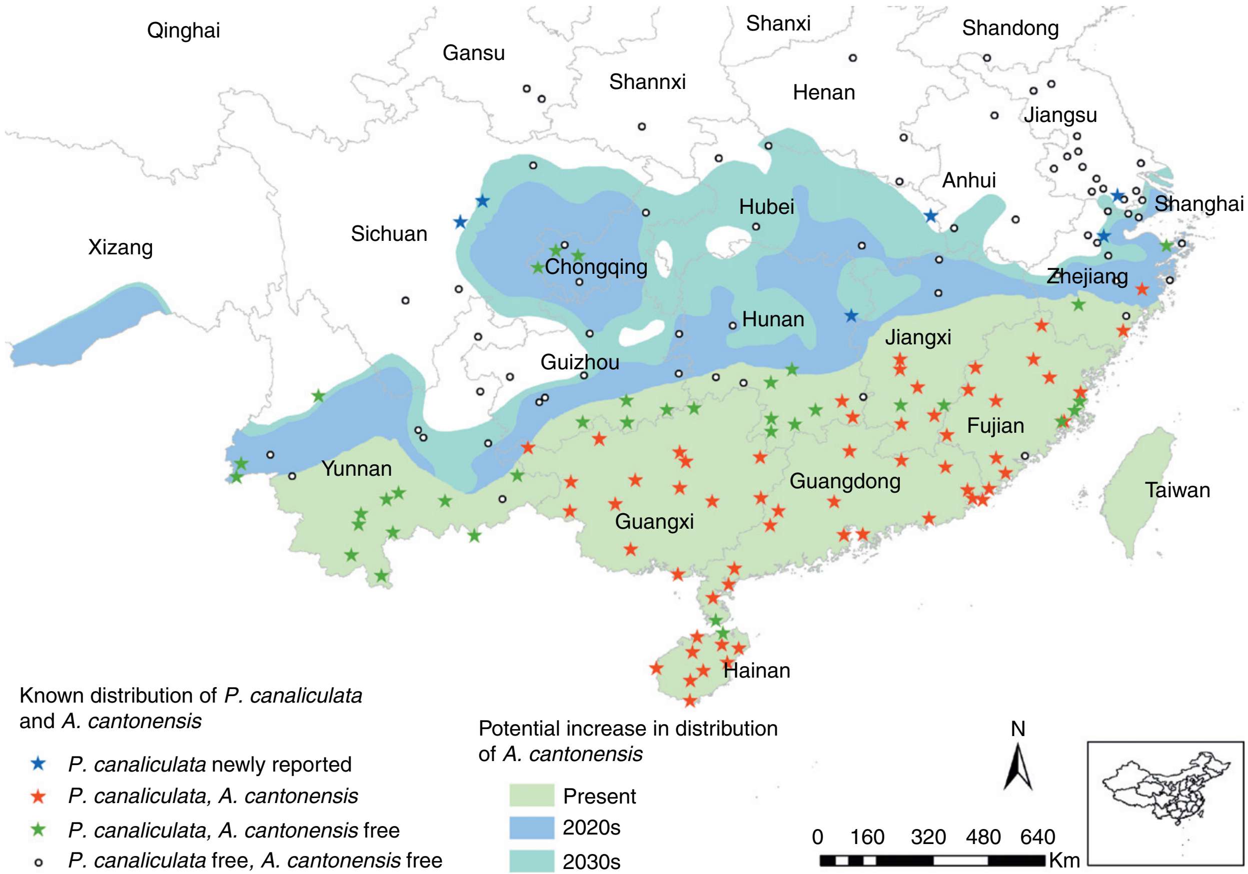

FIGURE 5.6 The current distribution of *A. cantonensis* and potential changes in the 2020s and 2030s in P.R. China. This figure integrates a series of maps that have been presented elsewhere (Lv et al., 2010a). The present distributions of *A. cantonensis* and the predicted distribution in the 2020s and 2030s, respectively, were determined by overlapping the predicted distributions of *P. canaliculata* and *A. cantonensis*. The current distribution is fitted based on the data from 740 observing stations and the potential distributions in the 2020s and the 2030s are based on predicted data of over 10,000 grid points derived from the so-called PRECIS model.

mollusc species identified in P.R. China are permissive for transmission (Lv et al., 2008). In the current model, *P. canaliculata* is considered the only intermediate host according to the results of the recent national survey supplemented with in-depth epidemiological studies (Lv et al., 2008, 2009), although other mollusc species may play a role in transmission of *A. cantonensis*. It should be noted that *P. canaliculata* is an exotic freshwater snail that spreads along waterways. Although the first nationwide survey on *A. cantonensis* and its vectors reveal the current distribution of *P. canaliculata* (Lv et al., 2009), further expansion of its range at the current climate condition was not confirmed. Therefore, different strata, that is, spread area and establishment area, were considered according to the general law of biological invasion (Lv et al., 2010a). Our model evaluates the impact of climate change on these two strata, respectively.

Rodents, especially rats, are the definitive host of *A. cantonensis*. Experimental findings show that the longevity of infected rats is significantly affected by *A. cantonensis* infection (Kino, 1984). Heavy infection intensities can result in death of rats and the time span is usually less than 1 year. As a result, longevity of infected rats and molluscan dormancy in winter must be taken into consideration for transmission modelling. With regard to the transmission of *S. japonicum*, the longevity of human and domestic animals attributed to schistosome infection is seldom less than 1 year, although it may be significantly affected by infection. Hence, dormancy of *Oncomelania* spp. has not been considered in the biology-based model to predict a potential impact of climate change on schistosomiasis in P.R. China (Zhou et al. 2008b).

External factors, including environmental transformations, climate change and social factors, may affect the distribution of *S. japonicum* and *A. cantonensis*, and thus the frequency and transmission dynamics of schistosomiasis and angiostrongyliasis. In the current models, demographic, ecological and socio-economic factors were not taken into account. For schistosomiasis in P.R. China, concerted efforts are underway to control the disease, including morbidity control using large-scale administration of praziquantel and management of infection sources to interrupt transmission (Utzinger et al., 2005; Wang et al., 2009a; Xiao et al., 2010; Zhou et al., 2005, 2010). Transmission has already been interrupted in five provinces. In contrast, angiostrongyliasis is emerging, along with biological invasion of the exotic snail species *P. canaliculata* (Lv et al., 2008, 2009, 2010b). To date, there is no nationwide strategy targeting this disease and its leading vectors. Unlike schistosomiasis, angiostrongyliasis can be acquired beyond endemic areas because of convenient food transportation, which renders spatial-temporal predictions of *A. cantonensis* infection particularly challenging.

5.5. RESPONSE TO CLIMATE CHANGE

Climate change is likely to have pervasive effects, which will be felt in some way by every person and every organisation, public or private, and at all levels, from strategic management to operational activities. The impact will be felt across environmental issues, economic performance, social behaviour, infrastructure and other aspects of human existence. Changes are likely to develop gradually, but could also be sudden. It is therefore important to begin planning for predicted changes sooner rather than later.

5.5.1. Mitigation and adaptation

Mitigation (see Glossary) and adaptation (see Glossary) are two important terms that are fundamental in the current climate change discussion (IPCC, 2001). Mitigation aims to limit the risk factors. Adaptation is adjustment in natural or human systems in response to actual or expected climatic changes or their effects. Mitigation tackles the causes of climate change, while adaptation tackles the effects. Climate mitigation and adaptation should not be seen as alternatives to each other, as they are not discrete activities but rather a combined set of actions in an overall strategy to reduce greenhouse gas emissions. In general, the more mitigation, the smaller the potential effects of climate change. However, even the most rigorous mitigation efforts cannot avoid further impacts of climate change because of historically committed emissions, which make adaptation to climate change essential.

5.5.2. Adaptation strategy of schistosomiasis in P.R. China

The studies carried out by Yang et al. (2005) and Zhou et al. (2008b) revealed the impact of climate change on the transmission of schistosomiasis japonica in P.R. China from 1960s to 1990s and predicted such an impact for the coming 20–40 years. In view of the authors' predictions made for the year 2030, adaptation measures have been proposed and indeed, three countermeasures have been implemented in three pilot studies located in different endemic zones: (i) a potentially endemic area; (ii) a non-epidemic but sensitive area; and (iii) a hyper-endemic area (Fig. 5.7 and Table 5.5).

Snail and population surveys were carried out to ensure accreditation of situation in the study areas. In the potentially endemic region, no snail-infected areas or *S. japonicum*-positive cases were detected. In the sensitive zone, snail retention tanks were constructed to prevent the spread of the intermediate hosts. Meanwhile, local environmental management

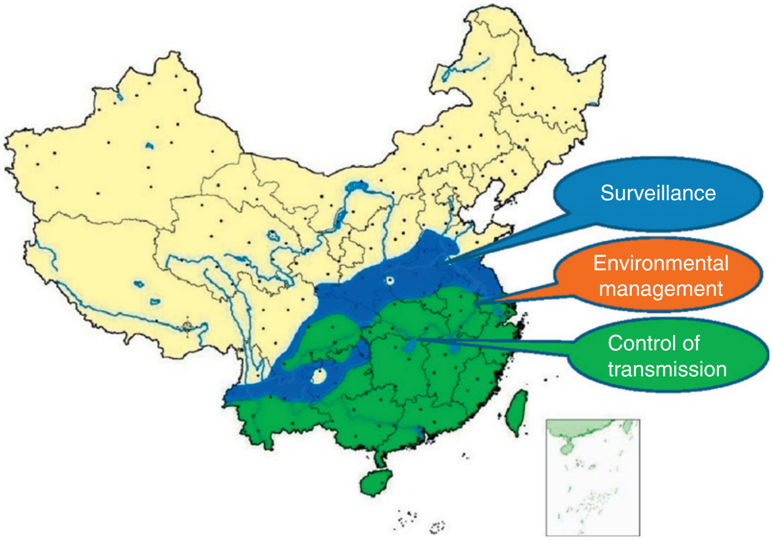

FIGURE 5.7 The three adaptation approaches applied in the higher risk areas (green colour), northern border line of transmission areas (between green and blue colours) and potential risk areas (blue colour) of schistosomiasis transmission in P.R. China. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this chapter.)

TABLE 5.5 Adaptation measures implemented in response of a potential impact of climate change on schistosomiasis in P.R. China

Zone	Counter measure	Pilot study site
Potential endemic zones	Surveillance of snail/ population, health education	Gaoyou city, Jiangsu province
Sensitive zones	Prohibition of snail spreading	Hanjiang district, Jiangsu province
Hyper-endemic zones	Control of infection sources	Jiangling county, Hubei province

interventions were implemented to eliminate possible snail habitats. Within the hyper-endemic zone, an integrated control strategy was implemented with the aim of stopping contamination by schistosome eggs to the environment. The control tools employed included fencing of the water buffaloes (since water buffaloes act as reservoir host of schistosomiasis japonica), chemotherapy using praziquantel, access to clean water and improved sanitation and snail control. Implementation of this package of interventions dramatically reduced the infection rate among humans and snails, and hence it was concluded that the transmission interruption could be achieved within a couple of years (Wang et al., 2009a). Importantly, this strategy has an impact beyond the target disease, since significant drops in the prevalence of soil-transmitted helminth infections were noted (Wang et al., 2009b).

5.5.3. Research priorities

We have highlighted some approaches to study the potential impacts of climate change on zoonotic helminths, placing special emphasis on schistosomiasis and angiostrongyliasis in P.R. China. Table 5.6 summarises

TABLE 5.6 Gap analysis and identified research priorities with regard to climate change, including adaptation and mitigation measures of RNAS^{+} target diseases

RNAS^{+} target disease	Biological variables for threshold determinants	Assessment	Adaptation	Mitigation
Schistosomiasis	Lowest and highest developing temperature of *S. japonicum* and *O. hupensis*; GDD of *S. japonicum* and *O. hupensis*	Only in P.R. China	Only in P.R. China	Only in P.R. China
Cysticercosis/ taeniasis	n.a.	None	None	None
Food-borne trematodiasis				
Clonorchiasis	n.a.	None	None	None
Opisthorchiasis	n.a.	None	None	None
Fascioliasis	GDD of *Fasciola hepatica* and *F. gigantica*	None	None	None

n.a., not available.

research gaps identified with regard to RNAS$^+$ target diseases in face of climate change, including adaptation, and mitigation measures and strategies. We suggest that the following approaches be given priority:

- Effective adaptation requires an awareness of the risks posed by climate change and importantly, an understanding of the relative significance of those risks. Hence, there is a pressing need to make knowledge more widely available to the public.
- New research is warranted to assess the potential impact of the distribution and transmission patterns of the main helminthiasis in Southeast Asia and neighbourhood countries with respect to climate change and other demographic, ecological and social transformations.
- The following issues need detailed scientific inquiry: how should we respond to climate change in terms of strategic development and with regard to exploration of mitigation and adaptation? Hence, our understanding of the impact of climate change needs to be well supported, including the variability at the regional level. The consequences of responses to these factors with respect to the environment and human communities need to be addressed.
- Finally, can we evaluate an adaptation strategy in terms of cost-effectiveness and cost–benefit approaches? A thorough evaluation would help humans to understand how to adapt responses to climate change implementing the assessed strategy into increasingly wider scales.

As prediction cannot be much more than 'guestimates' at this point and only limited resources are currently available, we are still a long way from being able to examine these complex questions analytically with a low level of uncertainty. However, prognoses based on the 'balance of evidence' from a range of approaches might eventually enable some generalisations to be made, just as they have been in relation to climatic change itself. Progress would be made if research groups using a particular methodology would view alternative approaches as complementary rather than competitive. International collaboration facilitates the work, and it is important to stress the need for maintenance of long-term meteorological and ground epidemiological data sets to 'ground-truth' and validate predictions.

5.6. CONCLUSIONS

Climate change is already showing an effect on the frequency and transmission dynamics and the distribution of many infectious diseases. It will continue to do so if the trend of global warming does not abate. Research on the RNAS$^+$ target diseases is currently limited to schistosomiasis, but biological experiments with respect to other RNAS$^+$ target diseases are also warranted, for example, general research on threshold determinants. Climate change may asymmetrically affect transmission of the RNAS$^+$ target diseases due to special transmission features in each disease, which call for different consideration in selection of model parameters. Mitigation and adaptation strategies to reduce the potential impacts of climate change on infectious diseases are recommended to be listed in the agenda of high-level discussion. Surveillance and early-warning system to strengthen the adaptation strategy need to be initiated as soon as possible. More intra- and international collaboration and interdisciplinary research are encouraged to foster a sense of unity.

GLOSSARY: IMPORTANT TERMS AND CONCEPTS INTRODUCED IN THE CURRENT REVIEW

Adaptation According to the third assessment report of IPCC, published in 2001, adaptation has been defined as follows: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.

Biology-based model Key features of the biological requirements of a disease are known from laboratory investigations and field studies, and hence meaningful inference on environmental preferences, limits of tolerance (e.g. temperature) and behaviour of an organism, its vector, intermediate host and definitive host can be drawn. Biology-based models are also known as process-based or mechanistic models and allow estimates to be made how habitat suitability of an organism changes with the environment.

Climate change A change in the statistical distribution of weather (e.g. a change in the average weather or a change in the distribution of weather events around an average, such as extreme weather events), including natural changes that occurred over millions of years, recurring, often cyclical climate patterns such as El Niño-Southern Oscillation and the unusually rapid rise in temperature observed since 1860, which has become particularly pronounced since the 1970s due to anthropogenic combustion of greenhouse gases. Climate change may be limited to a specific region, or may occur across the whole Earth.

Disability-adjusted life year (DALY) The DALY is a measure of disease burden, originally developed in the 1990s. The DALY represents a single common metric combining potential years of life lost due to premature death (YLL) with years of 'healthy' life lost by virtue of being in a state of poor health or disability (YLD). Hence, the DALY combines mortality and morbidity, which allows comparison across different diseases, injuries and risk factors. Although the DALY is extensively used in the field of public health, this metric has important shortcomings and the burden of the so-called neglected tropical diseases has most likely been underestimated. A new concerted effort is underway to (re-)estimate the global burden of over 150 diseases, injuries and risk factors for the year 2005, and hence it will be interesting to see the new global DALY estimates for the neglected tropical diseases.

Geographical information system (GIS) According to the Environmental System Research Institute (ESRI), a GIS is defined as 'an organised collection of computer hardware, software, geographical data, and personnel designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information' GIS is particularly well suited for disease epidemiology at an exploratory level, as it can readily display associations between location, disease, vector/intermediate host and the environment.

Growing degree days (GDD) Also known as the degree-day model, the concept of GDD is based on the assumption that a plant or a poikilothermal animal only develops when the environmental temperature is higher than a specific minimal threshold, and that the total thermal energy required for development is constant. The specific minimal threshold temperature is called developmental threshold temperature (DTT) and the constant termed GDD.

Intergovernmental Panel on Climate Change (IPCC) The IPCC is a scientific intergovernmental body tasked with evaluating the risk of climate change caused by human activity. The panel was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The IPCC shared the 2007 Nobel Peace Prize with Mr. Al Gore, the former vice-president of the United States of America. A main activity of IPCC is publishing special reports on topics relevant to the implementation of the United Nations framework convention on climate change (UNFCCC), an international treaty that acknowledges the possibility of harmful climate change. The IPCC assesses the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change. The IPCC published its first assessment report in 1990, a supplementary report in 1992, a second assessment report in 1995 and a third assessment report in 2001. The fourth and most recent assessment report was released in 2007. Each assessment report consists of three volumes, corresponding to separate working groups.

Mitigation According to the fourth assessment report of IPCC, published in 2007, mitigation has been defined as follows: 'Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce GHG emissions and enhance sinks'.

Regional Network for Asian Schistosomiasis and Other Helminth Zoonoses (RNAS$^+$) In 1998, UNICEF/UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases (TDR) initiated the idea of creating a regional network for Asian schistosomiasis. Over the years, the exclusive focus on schistosomiasis has been expanded to include other neglected tropical diseases, such as cysticercosis/taeniasis, echinococcosis and food-borne trematodiasis (e.g. clonorchiasis, fascioliasis, opisthorchiasis and paragonimiasis), and additional countries have joined the six Asian founding states. RNAS$^+$ provides a platform for exchange for scientists, public health experts and disease control managers pursuing multidisciplinary research and integrated control activities. At present, Cambodia, Indonesia, Japan, Lao PDR, P.R. China, South Korea, Thailand, The Philippines and Vietnam are active member states, and there is a strong network of partners based in different countries across Europe.

Remote sensing A broad definition of remote sensing is 'the acquisition of information of an object or phenomenon, employing either a real-time sensing device that is not in physical or intimate contact with the object itself, e.g. by means of an aircraft or a satellite'. In the current review, remote sensing primarily refers to the use of imaging sensor technologies aboard satellites for the acquisition of environmental data.

South-North Water Transfer (SNWT) project The SNWT project in P.R. China is a massive inter-basin water transfer project, which will not only solve water shortage problems, promote regional economic development and improve living conditions in northern P.R. China, but also facilitate ecological environmental restoration of the region. Of its three routes (i.e. East, Middle and West), the Eastern route diverts water from the lower reach of the Yangtze River to the north along roughly the ancient Beijing-Hangzhou Grand Canal. The first phase of the Eastern route was initiated in 2003 and will divert approximately 9 billion m^3 of water per year. The Middle route will transfer an estimated 14 billion m^3 of water annually from the Han River, a tributary of the Yangtze River and the water supplying area, to Beijing by 2030. The Western route is in the design stage, which will divert water from three upper-reach tributaries of the Yangtze River to the upper reaches of the Huanghe (http://nsbd.mwr.gov.cn/).

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