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Article *in* Parassitologia · April 2005

Source: PubMed

Parassitologia 47: 127-134, 2005

A potential impact of climate change and water resource development on the transmission of *Schistosoma japonicum* in China

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Abstract. There is growing consensus among climate modellers that the unusual global warming observed in the last decades of the 20th century is primarily forced by human activities, namely greenhouse gas increases in the atmosphere. Global warming will trigger alterations in physical and biological systems, including shifts in the spatio-temporal distribution of disease vectors, but the nature and extent of these changes are poorly understood. The purpose of the present study was to assess the potential impact of climate change and water resource development on the distribution of *Oncomelania hupensis*, the intermediate host snail of *Schistosoma japonicum*. We employed two 30-year composite datasets comprising average monthly temperatures collected at 623 observing stations throughout China, spanning the periods 1961-1990 and 1971-2000. Temperature changes were assessed spatially between the 1960s and 1990s for January, as this is the critical month for survival of *O. hupensis*. Our database shows that January temperatures increased at 590 stations (94.7%), and that China's average January temperature in the 1990s was 0.96°C higher than 30 years earlier. The historical 0-1°C January isotherm, which was considered the approximate northern limit of *S. japonicum* transmission, has shifted from 33°15' N to 33°41' N, expanding the potential transmission area by 41,335 km^2. This translates to an additional 20.7 million people at risk of schistosomiasis. Two lakes are located in this new transmission area that form part of the proposed South-North water transfer project. Climate change, coupled with water resource developments in China, may pose additional challenges for the control of schistosomiasis.

Key words: China, climate change, geographical information system, *Oncomelania hupensis*, *Schistosoma japonicum*, spatial analysis, water resource development.

Temperatures in the northern hemisphere have been reconstructed over the past 1,000 years, with particular consideration of the effects of natural variability and anthropogenic influence (Crowley, 2000; Huang *et al.*, 2000). The main causes of climate change include (i) solar variability, (ii) volcanism, and (iii) changes in greenhouse gases and (iv) tropospheric aerosols. Since the early decades of the 18th century, the world climate has been in a warming phase (Reiter, 2001). Instrumental records, available for the past 150 years, suggest that the Earth has warmed by approximately 0.6°C over the past 100 years (IPCC, 2001b). This unusual warming of the 20th century has been particularly pronounced during the last three decades (Easterling *et al.*, 1997; Crowley, 2000; IPCC, 2001b; Haines and Patz, 2004). Human activity, most notably the increase in greenhouse gases due to large-scale combustion of fossil fuels for energy production and transportation, is the most likely driver of forced global warming (Crowley, 2000; IPCC, 2001b; Diaz, 2004). The predominant greenhouse gas is carbon dioxide (CO_2); its atmospheric concentration has increased from 290 parts per million (ppm) in 1890 to 373 ppm in 2002 (Reiter, 2001; Beggs, 2004). In their 2001 report, the 'Intergovernmental Panel of Climate Change' (IPCC) predicted that the mean global temperature will increase by between 1.4°C and 5.8°C from 1990 to 2100 (IPCC, 2001a). Recent model simulations over a wide range of parameterization under the scenario of a doubling CO_2 concentration predict a global warming of 2.4-5.4°C in the same time frame (Murphy *et al.*, 2004).

Climate change is characterized by considerable spatial and temporal heterogeneity. For example, warming is particularly pronounced at high latitudes of the northern hemisphere (Murphy *et al.*, 2004; Stocker, 2004). Larger differences have been found for monthly average maximum and minimum temperatures during winter months when compared to the summer (Easterling *et al.*, 1997). To capture localized climate changes, models are needed that can assign meteorological parameters at relatively small scales (Knowlton *et al.*, 2004).

There is a growing body of literature documenting the impacts of climate change on physical and biological systems, including human health (Patz *et al.*, 2000; Epstein, 2001; Beggs, 2004; Diaz, 2004; Haines and Patz, 2004; Knowlton *et al.*, 2004). An area that has received particular attention is the potential impact of global warming on shifts in the spatio-temporal distri-

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bution of disease vectors, and hence the frequency and transmission dynamics of vector-borne diseases (Reiter, 2001; Hunter, 2003; Sutherst, 2004). Most studies have focused on malaria (Sutherst, 2004). An early estimate suggested that its epidemic potential may increase by 12-27% as a direct consequence of higher temperatures (Martens *et al.*, 1997). The use of mathematical models, coupled with geographical information system (GIS) and remote sensing techniques, revealed an increase of the population at risk of malaria transmission due to climate change, particularly at higher altitudes and to some degree also at higher latitudes (Lindsay and Martens, 1998; Tanser *et al.*, 2003).

Climate change will also impact the distribution of snails that act as intermediate hosts for schistosomiasis, but the nature and extent of these effects are poorly understood (Morgan *et al.*, 2001). While some models of global warming predicted an extension of the area conducive for schistosomiasis transmission (Martens *et al.*, 1995), other models forecasted a decrease in the epidemic potential of the disease (Martens *et al.*, 1997). It is generally agreed that the transmission dynamics is most sensitive to climate change around the boundaries of endemic areas (Sutherst, 2004). Implementation and operation of water resource development projects, which have a history of facilitating the spread and intensification of schistosomiasis (Hunter *et al.*, 1993; Jobin, 1999; Chitsulo *et al.*, 2000), could further amplify the negative effects of climate change.

The objective of this study was to assess the potential impact of climate change on the spatial distribution of *Oncomelania hupensis*, which is the intermediate host snail of *Schistosoma japonicum*. The geographical focus is on China, particularly around the 33°15' N latitude, as historical records suggest that this was the approximate northern limit where *O. hupensis* occurred (Mao, 1990). Preliminary work put forth that the distribution of *O. hupensis* might expand northwards as a consequence of climate change (Zhou *et al.*, 2002b). We extracted average January temperatures from two 30-year composite datasets to assess and quantify localized temperature changes over the past 30 years, and used an integrated GIS approach to estimate areas and people at risk of schistosomiasis transmission.

Materials and methods

Digital map of China and meteorological data

A digital map of China, produced by the National Bureau of Surveying and Mapping, was purchased from the Chinese Center for Geographic Science (Beijing, China). It contains layers of administrative units from the provincial to the county level, and the hydrological network consisting of rivers and lakes.

Two datasets, each comprising 30-year composite average monthly temperatures collected at 623 meteorological stations throughout China, were obtained from the Climate Data Center, Chinese Meteorological Center (Beijing, China). The two datasets span the periods of 1961-1990 and 1971-2000, respectively. All meteorological stations have been georeferenced (latitude, longitude and altitude). They are depicted on Fig.1.

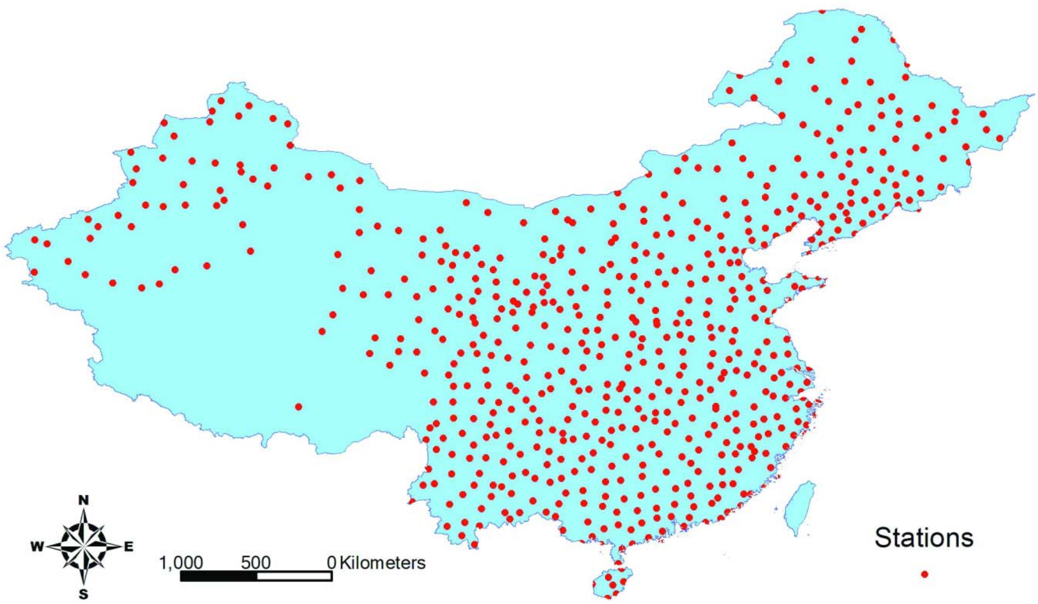

Fig. 1. Spatial distribution of meteorological stations (n = 623) throughout China from which temperature data were derived for the current analysis.

Data management and analysis

A climate dataset, consisting of the average monthly temperatures of the two 30-year composites derived from the 623 meteorological stations, was created on an EXCEL spreadsheet (Microsoft Corporation; Redmond, WA, USA). Data analyses were done with version 8.0 of the STATA software package (Stata Corporation; College Station, TX, USA). The average January temperatures were extracted, as January is the coldest month of the year in China, and hence considered the critical climate factor that determines the distribution of *O. hupensis*, and thus the transmission of *S. japonicum* (Mao, 1990).

Box 1 shows the approach we adopted for calculation of changes in the average January temperature over the past 30 years. In a first step, two temperature datasets, i.e. T1 and T2, were created on the basis of the average January temperatures for the periods 1961-1990 and 1971-2000, respectively. We then generated a temperature difference dataset, i.e. Td, of the average January temperatures during the 10-year periods of 1961-1970 and 1991-2000, respectively, by subtracting T1 from T2 and multiplying this difference with a factor 3. This multiplication factor is necessary to convert the difference of the average temperatures over the two 30-year periods, namely 1961-1990 and 1971-2000, to the difference of the average temperatures over the non-overlapping 10-year-periods of 1961-1970 and 1991-2000, respectively.

Box 1. Calculation of temperature changes from the 1960s to 1990s.

$$Td = 3 * (T2-T1)$$

T1 represents the average January temperature during the period of 1961-1990.

T2 represents the average January temperature during the period of 1971-2000.

In view of historical records, considering the latitude of 33°15’ N as the edge of *O. hupensis* distribution (Mao, 1990), we divided the Td dataset into two parts, representing north and south of the 33°15’ N latitude (i.e. Td_{North} and Td_{South}). Overall, 345 (55.4%) stations were located in Td_{North}, whereas the remaining 278 (44.6%) stations were located in Td_{South}.
We employed a Wilcoxon signed-rank test for paired data to examine whether the differences in the respective Td, Td_{North} and Td_{South} datasets were statistically significant, thus comparing average January temperature between the 1960s and 1990s. Statistical analysis was also performed between the Td_{South} and Td_{North} datasets by using a two-sampled Wilcoxon rank-sum (Mann-Whitney) test.

Geographical information system and risk assessment

We created a GIS using version 8.2 of the ArcGIS software (ESRI; Redlands, CA, USA). The average January temperature differences between the 1960s and 1990s (Td) were attached to each of the 623 meteorological stations. A trend analysis was applied to the Td dataset, using the geostatistic analyst module of ArcGIS, to examine differences in the north-south and east-west dimensions. We employed ordinary kriging (Cressie, 1993) to generate a smoothed surface map of the Td dataset. Three separate models were fitted assuming polynomial forms for the location coordinates of order 1, 2 and 3, respectively. The model with the smallest root-mean-square standardized value, following cross-validation, was used for subsequent spatial analyses.
Finally, we generated surface maps of T1 and T2 that were also based on ordinary kriging models.
We extracted the average January temperature belts of 0-1°C for T1 and T2, as areas within this belt are considered sensitive for survival of *O. hupensis*. We compared the spatial extent of these sensitive intermediate host snail habitats at the two time points and estimated the total surface area of the new potential transmission area of *S. japonicum*. Employing a mean population density of 500 people per km^2 (http://www.hzsin.gov.cn/ReadNews.asp?NewsID=550, 2003), we then estimated the number of people who have potentially become at risk of *S. japonicum* transmission due to climate change.

Results

Changes in average January temperature in China over the past 30 years

Examination of the Td dataset revealed that the average January temperature in China increased at 590 of the 623 meteorological stations (94.7%), whereas only 33 stations (5.3%) recorded lower average January temperatures in the 1990s when compared to those measured three decades previously. Overall, an increase of 0.96°C (95% confidence interval – CI: 0.90, 1.03°C) occurred in the average January temperature from the 1960s to the 1990s. This increase had a high statistical significance (Wilcoxon signed-rank test: z = 19.91; P <0.001).
The mean values of the Td_{South} and Td_{North} datasets were 0.52°C (95% CI: 0.46, 0.59°C) and 1.32°C (95% CI: 1.22, 1.41°C), respectively. Thus, the increase in China’s average January temperature over the past 30 years showed statistical significance both south (z = 12.07, P <0.001) and north of the 33°15’N latitude (z = 15.38, P <0.001). According to the results of the Mann-Whitney test, the Td_{North} dataset was significantly higher than Td_{South} (z=12.95, P <0.001). In other words, over the past 30 years, more pronounced increases in the average January temperatures occurred in the northern rather than in the southern parts of China.

Fig. 2 shows the results from the trend analysis applied to the Td dataset, using the geostatistic analyst module of the ArcGIS software. This trend analysis confirmed that average January temperatures increased with higher latitude, thus temperature increases in the north were larger than in the south (shown by the blue line on the Y-Z-axes surface). From west to east China, a parabolic trend in the change of the average January temperatures were observed between the 1960s and 1990s (shown by the green line on the X-Z-axes surface). It follows that the highest January temperature increases over the past three decades occurred in the north-eastern parts of China.

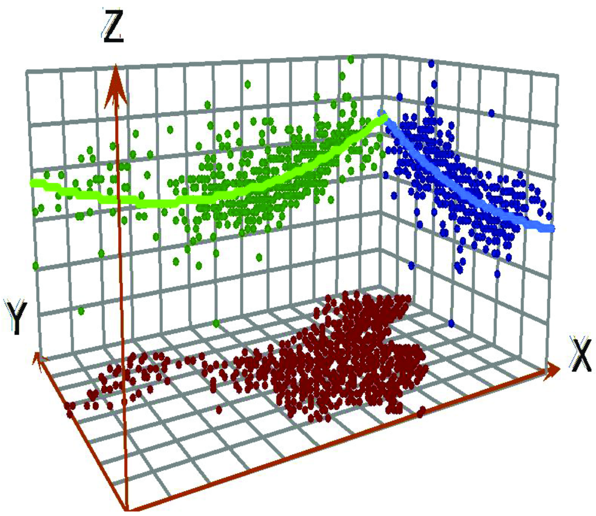

Fig. 2. Trend analysis of climatic datasets (rotation angles: location = 0 degree). The trend of average temperature change in January from south to north China is shown as blue line on the Y-Z-axes surface and that from west to east China is shown as the green line on the X-Z-axes surface.

Smoothed map of average January temperature changes in China

The three kriging models we employed revealed root-mean-square standardized values of 1.101, 1.052 and 1.085, respectively. In view of the lowest root-mean-square standardized value of model 2, subsequent surface analyses were done with this model.

Fig. 3 shows the smoothed changes of the average January temperature that occurred in China over the past 30 years. The map confirms that January temperatures have increased in most parts of China, and that changes were more pronounced in the north than in the south (orange and brown colours). Estimated temperature increases in the month of January in some areas in the northeastern part of China were as high as 3.0°C (dark brown colour). The smallest average January temperature changes were observed in central and south China. In two small areas the average January temperature actually decreased over the past 30 years. At some of the observing stations, the average January temperature rose by more than 3.0°C from the 1960s to the 1990s, with a maximum value of +4.5°C. Temperature declines by more than 0.6°C have also been observed with the lowest value of -3.3°C. However, on the smoothed map these climate change extremes were not apparent due to only few stations with such extreme values and the smoothing procedures.

Potential new transmission area of S. japonicum *and people at risk*

Fig. 3 also shows the two extracted 0-1°C belts of the T1 and T2 datasets that have been overlaid on the Td map described above. The two 0-1°C belts of T1 and T2 are displayed in white stipple and blue-white hatched colours, respectively. They extend in east-west direction across central China. The spatial analysis showed that the 0-1° belt of T2 extended further north when compared with the corresponding T1 belt, particularly in the eastern part of China. The areas within the 0-1°C belt of T1 that are not overlapping with the respective 0-1°C belt of T2 (delineated by white stipple colour only) indicate the new suitable habitats for permanent occurrence with *O. hupensis*, hence areas that have become potentially conducive to the transmission of *S. japonicum*. We found that the historic northern distribution edge of *O. hupensis* (33°15' N) extended some 0°26' further north to 33°41' N. Quantification of this new potential area of schistosomiasis transmission revealed a total surface area of 41,335 km^2. Multiplication of this estimated surface area with a mean population density of 500 people per km^2 in this part of China revealed that an estimated 20.7 million people have potentially become at risk of schistosomiasis. The areas delineated by blue-white hatched colour represent the new potential northern edges of *O. hupensis* distribution in China.

Effect of climate change coupled with water resource development

Fig. 4 shows in greater detail the potential impact elevated January temperatures had on the spatial distribution of *O. hupensis*, and hence the transmission of *S. japonicum*. The focus is on the Jiangsu province, located in east China. As mentioned before, our GIS approach suggested that the areas of the 0-1°C belt of the T1 dataset (exclusively coloured in white stipple) have become suitable habitats for *O. hupensis* year-round. Consequently, the potential transmission area of *S. japonicum* extends further northwards. To better understand the potential impact of climate change in the face of water resource development and management, the hydrological layer (main rivers and lakes) has been added. Within the southern boundary of the 0-1°C band of the T1 dataset, there are two lakes, namely Hongze Lake and Baima Lake. Both lakes are located in the main route of the proposed South-North water transfer project (red lines), which in turn might further aggravate the risk of spreading *O. hupensis* further northwards.

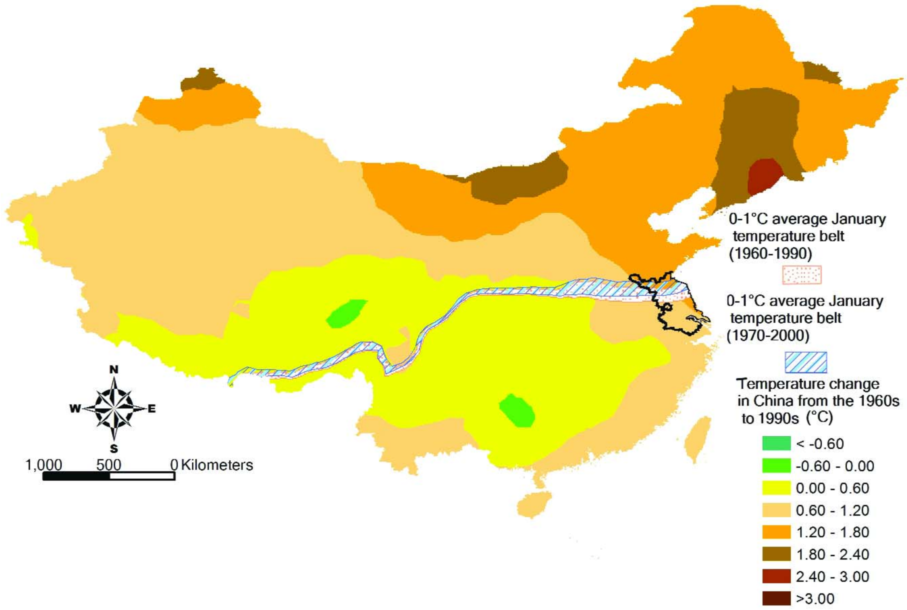

Fig. 3. Smoothed map of China exhibiting the average January temperature difference between the 1960s and 1990s, including the new potential transmission area of *S. japonicum*. The black lines in the middle eastern part of China delineate the Jiangsu province.

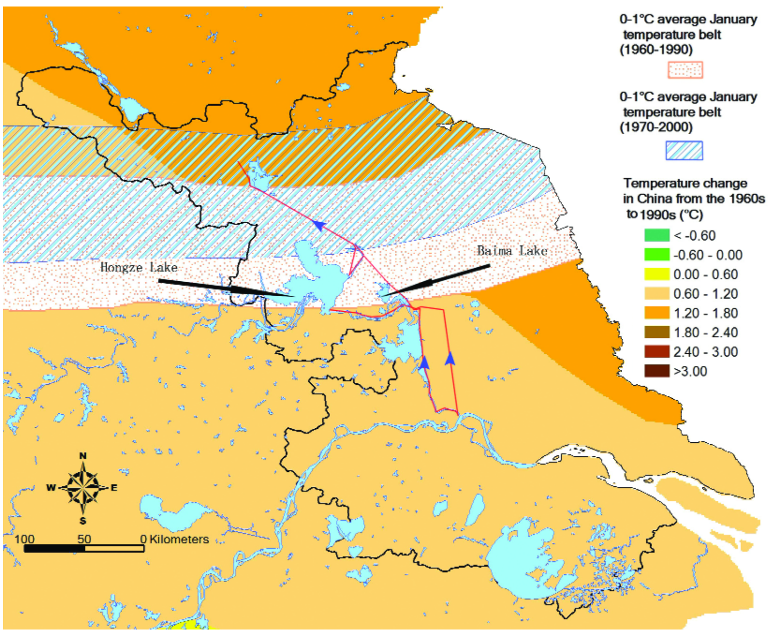

Fig. 4. Potential transmission area of *S. japonicum* in Jiangsu province due to higher average January temperatures. Red lines indicate part of the eastern route of the planned South-North water transfer project. The blue arrows show the water flow direction.

Discussion

The majority of climate change risk assessments carried out thus far have focused on vector-borne diseases, particularly malaria (Sutherst, 2004). Using a modelling approach, often coupled with GIS and remote sensing techniques and appropriate spatial statistics, most of the analyses predicted an increase in the population at risk of malaria. The main underlying reason was the direct effect of increased temperature, thus expanding the geographical distribution of disease transmission into higher altitudes and higher latitudes, with the former more important than the latter (Lindsay and Birley, 1996; Martens *et al.,* 1997; Lindsay and Martens, 1998; Reiter, 2001; Tanser *et al.,* 2003; Sutherst, 2004). Interestingly, one study that employed an alternative statistical approach came to the conclusion that the current distribution of *Plasmodium falciparum* malaria will remain fairly constant in the future under various climate scenarios, including the most extreme ones (Rogers and Randolph, 2000). However, outcomes of this model have been challenged on various grounds, including (i) lack of specificity in the current distribution of malaria due to *P. falciparum,* (ii) inherent uncertainties in modelling moisture-related climate changes, (iii) vulnerability of adaptation mechanisms to cope with malaria in the face of social unrest and economic decline, and (iv) unsuitability of statistical models to take into account setting-specific idiosyncrasies in parasite-vector-host interactions (Sutherst, 2004). Despite these differences, there is consensus that malaria transmission is most sensitive to climate change in areas around the current distribution edges, and that small increases at low temperatures can change risk profiles disproportionately (Lindsay and Birley, 1996; Martens *et al.,* 1997; Sutherst, 2004).

Only a few attempts have been made to assess the potential impact of climate change on the frequency and transmission dynamics of diseases other than malaria, including schistosomiasis. Analogous to malaria, it is acknowledged that the transmission potential of schistosomiasis is most sensitive on the periphery of current areas of endemicity (Martens *et al.,* 1997; Sutherst, 2004). However, two previous studies identified in the literature reported conflicting results on the potential impact climate change has on the extent of the area conducive for schistosomiasis transmission, and hence on the population at risk (Martens *et al.,* 1995, 1997). We have now used a detailed time series of instrumental records in combination with an integrated GIS approach and spatial statistics. We estimate that 41,335 km^2 and 20.7 million people have become at risk of *S. japonicum* transmission in central China. These estimates are based on the direct effect of localized climate warming. In fact, we have found that China's average January temperature has increased by almost 1°C over the past 30 years with considerable spatial variation. In view of recent estimates that 652 million people live in areas at risk of schistosomiasis worldwide (Chitsulo *et al.,* 2000; Utzinger and Keiser, 2004), our finding of 20.7 million Chinese who have potentially become at risk of schistosomiasis due to climate change translates to 3% on a global scale. Such a result may have profound public health and economic significance, hence the strengths and weaknesses of our study warrant further scrutiny.

Regarding the strengths, five issues are offered for discussion. First, instrumental records were obtained from as many as 623 meteorological stations across China. This large ensemble of observing stations facilitates assessment of localized impacts of climate change with a high degree of accuracy at relatively small regional scales. It is important to note that few assessments of health impacts attributable to climate change have been made at a spatial resolution of tens of kilometres (Knowlton *et al.,* 2004). Instead, most of the previous modelling approaches were carried out at the global scale (Easterling *et al.,* 1997; Crowley, 2000; Huang *et al.,* 2000; Atkinson *et al.,* 2004; Murphy *et al.,* 2004; Thomas *et al.,* 2004). For example, maximum and minimum temperature trends over the past 100 years were analyzed on the basis of 5,400 observing stations around the globe (Easterling *et al.,* 1997).

Second, the overall increase in the average January temperature in China over the past 30 years (i.e. 0.96°C) fits well into the global and regional picture. Although this temperature increase is considerably higher than the 0.6°C average surface temperature increase observed worldwide over the past 100 years (IPCC, 2001b), it has been noted that a large portion of the global warming occurred after the mid 1970s, and that temperature increases were more pronounced in the northern hemisphere, particularly at high latitudes, and were highest in winter months (Easterling *et al.,* 1997; Huang *et al.,* 2000; IPCC, 2001b). Analysis of a 10-year time series from Tianjing city in China, for example, indicated that the average annual temperature in this urban setting increased by 0.7° from 1986 to 1995 (Yu *et al.,* 1998).

Third, our study confirmed the strong spatial heterogeneity of climate change within a single country. While we found two small foci where average January temperatures actually decreased slightly over the past 30 years, there were some areas where average January temperatures in the 1990s were more than 2 or even 3°C higher than in the 1960s. In support of item two articulated above, consistently larger temperature increases were observed in the northern part of China rather than in the south. In addition, temperature increases were somewhat more pronounced in east China when compared to the west.

Fourth, an important aspect of our study is that application of ordinary kriging within a GIS framework provides a sound basis for the creation of a smoothed surface map showing the difference of average January temperatures between the 1960s and 1990s. Such a map is a good means for policy discussions, as it highlights the areas that are most significantly affected by climate change; hence can guide subsequent mitigation measures. We have recently developed and applied Bayesian kriging for spatio-temporal modelling of county level data of *S. japonicum* infection prevalence in Jiangsu province, eastern China (Yang *et al.,* 2005) and for assessment and prediction of *S. mansoni* risk among schoolchildren in the region of Man, western Côte d'Ivoire (Raso *et al.,* 2005).

Fifth, we have shown that the GIS approach adapted here facilitated an integrated framework for schistosomiasis risk assessment, as it considered the potential impact of climate change coupled with water resource developments. In fact, we have identified two lakes that are located in contemporary risk areas of *S. japonicum* transmission, as the average January temperatures in the 1990s were above the critical thermal limits for *O. hupensis* survival (Mao, 1990; Liang *et al.,* 1996). The two lakes are in the main route of the proposed South-North water transfer project, which is a large-scale infrastructure development project that aims at social and economic development of the water-deprived northern part for China (Yang *et al.,* 2005). The negative effects of water resource development and management on the frequency and transmission dynamics of schistosomiasis have been documented in different ecological and epidemiological settings across Africa (Abdel-Wahab *et al.,* 1979; Hunter *et al.,* 1993; Mott *et al.,* 1995; N'Goran *et al.,* 1997; Southgate, 1997). There is considerable concern that the implementation and operation of large-scale water projects in schistosome-endemic areas of China may result in negative health effects (Xu *et al.,* 2000).

Regarding the weaknesses of our study, four issues are worth highlighting. First, in the absence of year-by-year average monthly temperatures for each of the 623 observing stations across China covering the period of 1961-2000, we used two 30-year composite measures with an overlap of 20 years. Consequently, the difference in the average January temperatures between the 1960s and 1990s reported in the present study is a gross estimate and, unfortunately, no detailed information was retrievable on a yearly basis.

Second, instrumental records measure ambient temperature; hence the increase in the average January temperature reported here is the observed change in ambient temperature that occurred over the past 30 years. However, empirical relations between schistosomiasis transmission dynamics and temperature have been established with respect to water temperature, because the disease is primarily transmitted in freshwater bodies where intermediate host snails release the infective stages of the parasite (i.e. cercariae) that penetrate the human skin during occupational or recreational activities (Martens *et al.,* 1995). Since thermal conditions of shallow water reflect ambient temperatures quite well, it is conceivable that this measure can serve as a good proxy for shallow water temperature. An important peculiarity of *S. japonicum* transmission is that it can also occur in proximity to freshwater bodies (e.g. in marshland), as its intermediate host snail, namely *O. hupensis*, is amphibious. In contrast, intermediate host snails of the four remaining human schistosome species are all aquatic.

Third, our estimates of the potential area and population at risk of *S. japonicum* transmission due to climate change must be juxtaposed to coping mechanisms, which in turn can alter the shape of risk profiles. For example, China's sustained efforts to control schistosomiasis over the past 50 years are exemplary (Yuan *et al.,* 2000; Ross *et al.,* 2001; Chen *et al.,* 2005). In addition, China's rapid and sustained social and economic development that commenced in the late 1970s and, which goes hand-in-hand with environmental sanitation, is a major feature explaining the overall decline in mortality (Banister and Zhang, 2005), and the control of schistosomiasis in particular (Utzinger *et al.,* 2003; Chen *et al.,* 2005).

Finally, climate extremes were not considered in the current analysis. However, it should be noted that climate change not only results in higher temperatures, but it also increases the frequency of extreme climate events, including floods (Easterling *et al.,* 2000). A significant flooding event occurred along the lower reaches of the Yangtze River in 1998, which posed an excess risk of *S. japonicum* transmission. Whether or not this event was due to climate change remains to be investigated, although a GIS approach was earlier shown to be useful in predicting the distribution of *O. hupensis* in the face of such specific environmental conditions (Zhou *et al.,* 2002a).

We conclude that a significant increase has occurred in China's average January temperature over the past 30 years, and that spatial heterogeneity of this change was considerable. Development and application of an integrated GIS framework provides an excellent platform to assess the potential impact of climate change and an array of other factors – e.g. major water resource development projects – on the spatial distribution of *O. hupensis*, and hence on the frequency and transmission dynamics of *S. japonicum*. Such an integrated framework can serve as a powerful tool for policy makers and disease control personnel; hence it can further inspire and guide schistosomiasis control efforts in China and in other countries where the disease continues to be a major public health problem.

Acknowledgements

We thank Prof. G. Cringoli and Prof. J. B. Malone for inviting us to prepare this paper for a special theme issue on GIS and remote sensing in *Parassitologia*. This work received financial support from the UNICEF/UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases (TDR), project M8/181/4/Y.88 (ID-A10775) and the Chinese National Science Foundation (No. 300070684). P. Vounatsou and J. Utzinger are grateful to the Swiss National Science Foundation (SNF) for sustained financial support through Project No. 3252B0-102136 and an "SNF-Förderungsprofessur" (Project No. PP00B-102883), respectively.

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