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Infectious disease, development, and climate change: a scenario analysis

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ABSTRACT. We study the effects of development and climate change on infectious diseases in Sub-Saharan Africa. Infant mortality and infectious disease are closely related, but there are better data for the former. In an international cross-section, per capita income, literacy, and absolute poverty significantly affect infant mortality. We use scenarios of these three determinants and of climate change to project the future incidence of malaria, assuming it to change proportionally to infant mortality. Malaria deaths will first increase, because of population growth and climate change, but then fall, because of development. This pattern is robust to the choice of scenario, parameters, and starting conditions; and it holds for diarrhoea, schistosomiasis, and dengue fever as well. However, the timing and level of the mortality peak is very sensitive to assumptions. Climate change is important in the medium term, but dominated in the long term by development. As climate can only be changed with a substantial delay, development is the preferred strategy to reduce infectious diseases even if they are exacerbated by climate change. Development can, in particular, support the needed strengthening of disease control programs in the short run and thereby increase the capacity to cope with projected increases in infectious diseases over the medium to long term. This conclusion must, however, be viewed with caution,

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because development, even of the sort envisioned in the underlying socio-economic scenarios, is by no means certain.

1. Introduction

A cursory look at the geography and history of infectious diseases shows that they are prevalent in places where the weather is hot and wet and where the people are poor (e.g., WHO, 2005). Although closer study reveals a multitude of complexity and nuances (e.g., Casman and Dowlatabadi, 2002), climate determines the potential of many infectious diseases to flourish, while health care[1] influences the actual incidence of disease. One would therefore expect that, in a scenario of economic growth, infectious diseases would fall as health care improves (Medlin *et al.*, 2006). Likewise, in a scenario of global warming, one would expect to see infectious diseases spread into new regions and perhaps intensify (McMichael *et al.*, 2001). In a scenario with both growth and warming, it is unclear what to expect, but projections of future disease incidence should take both into account. Indeed, given complex interactions between economic growth and exposure to disease, it is possible that reallocating development aid towards greenhouse gas emission reduction could actually increase the impacts of climate change on infectious diseases.

Previous studies that have looked into this issue (Tol and Dowlatabadi, 2001; Tol, 2005; Tol, forthcoming) suffer from the oversimplification of equating 'development' with 'economic growth'. Here, we address this limitation by driving the evolution of a few of the statistically significant underlying determinants of adaptive capacity (in reducing vulnerability to infectious disease) into the future along economic growth scenarios and tracking the resulting vulnerability to two diseases – malaria and diarrhoea. Previous studies have considered malaria, of course, but none has extended even the simpler approach to a second disease. Moreover, previous work looked only at large regional aggregates, while this paper offers results for individual countries.

In section 2, we report two empirical relationships. One relates vulnerability to infant mortality to three statistically significant determinants of adaptive capacity (per capita income, literacy, and absolute poverty only, because other determinants were statistically insignificant). The second relates vulnerability to under-five mortality to two statistically significant determinants (literacy and absolute poverty). We use these relationships in section 3 to produce alternative scenarios of the incidence of malaria and diarrhoea through 2100 along specific economic development pathways for a sample of developing countries where both diseases are currently a problem. Five different assumptions of the future evolution of incidence, some based on the empirical results from section 2 and others drawn from earlier approaches, produce markedly different temporal profiles. It follows that assessments of the impacts of climate change that ignore the nuances in the relationships between economic development and

[1] Note that we interpret health care in its broadest sense, including hygiene, sanitation, primary health care, and public health infrastructure.

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vulnerability can grossly misrepresent the risks of that change. Concluding remarks in section 4 make this point.

2. Vulnerability to infectious disease

Adaptive capacity

The term 'adaptive capacity' was coined by Smit *et al.* (2001) in the context of impacts of climate change. Impacts follow from the combination of (*i*) being exposed to a particular manifestation of climate change (e.g., an increase in the number of malaria-carrying mosquitoes) and (*ii*) being vulnerable to that (e.g., a lack of access to malaria medicine). This classification of causes has a long tradition in the natural hazard literature (Burton *et al.*, 1993). Adaptive capacity is the ability of a system to adapt to or cope with (climate) change, and is therefore a reflection of the potential to diminish vulnerability. Because neither adaptive capacity nor vulnerability is rigorously defined, we use adaptive capacity loosely as the inverse of vulnerability.

The notion of adaptive capacity has proved useful in the study of the impacts of climate change. Essentially, adaptive capacity measures the ability of a society to respond, either to make the best of new opportunities opened by climate change, or to minimize the negative consequences. Adaptive capacity for climate change is similar to adaptive capacity for any change. Indeed, adaptive capacity is closely linked to development, as a society that cannot cope well with change cannot develop. Vice versa, low development typically implies low adaptive capacity. Again, while these things are true in general, there are important exceptions as well. The impact of Hurricane Katrina on the USA and health care in Cuba demonstrate respectively that rich countries are not invulnerable and that poor countries may do well in reducing specific vulnerabilities.

Yohe and Tol (2002) suggested focusing attention on a list of underlying determinants for adaptive capacity:

1. the range of available technological options for adaptation;
2. the availability of resources and their distribution across the population;
3. the structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed;
4. the stock of human capital, including education and personal security;
5. the stock of social capital, including the definition of property rights;
6. the system's access to risk-spreading processes;
7. the ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers themselves; and
8. the public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

In fact, Yohe and Tol (2002) conjectured that the adaptive capacity of any system would, for all intents and purposes, be limited by the weakest of these underlying determinants; this is the so-called 'weakest link' hypothesis with which they constructed an indexing scheme by which the relative vulnerabilities of wildly different systems could be judged.

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Alberini *et al.* (2006) test the framework of Yohe and Tol (2002) with a panel of experts and with objective data on natural disaster mortality. They find good accordance between experts and data and that the operationalization of adaptive capacity has predictive skill. Tol and Yohe (forthcoming) test the weakest link hypothesis of adaptive capacity by measuring vulnerability, the inverse of adaptive capacity. Statistical representations of the sensitivity of vulnerability to multiple determinants of adaptive capacity supported their tests; we will use their approach here to produce, for the first time, site-specific and (economically) path-dependent trajectories of future vulnerability to two infectious diseases.

Following Tol and Yohe (forthcoming), the vulnerability V of any country C to an external stress, for instance climate change, can be measured as

$$\{1/V_C\} \equiv \{\Sigma \alpha_i \, A_i^{(1-\gamma)}\}^{1/(1-\gamma)} \tag{1}$$

where the A_i are indicators of n distinct determinants of adaptive capacity. The α_i and γ are parameters in the relationship that is motivated by the usual structure of constant elasticity of substitution production functions. In this regard, $(1/\gamma)$ is the 'elasticity of substitution' between any two determinants in supporting the exercise of adaptive capacity in reducing vulnerability to the chosen stress. The substitution elasticity is independent of the level of the determinants of adaptive capacity. Therefore, (1) is known as the constant elasticity of substitution (CES) production function (Arrow *et al.*, 1961). Note that:

- $\gamma \to \infty$ would mean that $\{1/V_C\} \equiv \min\{\alpha_i \, A_i\}$. In this extreme case, the determinants of adaptive capacity would be perfect complements and overall vulnerability would be entirely determined by the 'weakest link' in the sense that strengthening any but the weakest determinant would do nothing to reduce vulnerability.
- $\gamma = 1$ would means that $\{1/V_C\} \equiv \{\prod A_i^{\alpha i}\}$. This is a threshold case because, as γ converges to unity from above, the 'iso-vulnerability' loci do not intersect any of the $A_i = 0$ axis. It follows that vulnerability would be infinite if any single determinant were not present. In all other cases, the determinants can substitute for one another to maintain the same level of vulnerability, but compensation would become increasingly expensive as strength in one or more determinants became weaker. That is, each determinant is essential, but none dominates the others. This is nearly the functional form of the geometric mean employed by Brenkert and Malone (2005), although the geometric mean imposes the condition that all of the α_i coefficients are identical.
- $\gamma < 1$ would mean that the determinants can substitute for one another to maintain the same level of vulnerability and that compensation would become less expensive as strength in one or more determinants became weaker.
- $\gamma = 0$ would mean that $\{1/V_C\} \equiv \{\sum \alpha_i \, A_i\}$. In this case, the determinants of adaptive capacity would be perfect substitutes, regardless of their individual levels. In words, the determinants can substitute for one another at constant rates to maintain the same level of vulnerability.

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Table 1. *Under-5 mortality, infant mortality and malaria mortality in selected African countries*

Country	*Under-5 mortality rate/1000 live births*	*Infant mortality rate/1000 live births*	*Malaria mortality rate/100,000*
Botswana	93	60	8
Ethiopia	179	114	80
Kenya	113	79	67
Lesotho	149	94	65
Madagascar	139	89	138
Mauritania	173	105	103
Niger	255	122	329
Nigeria	183	103	209
Rwanda	182	111	186
Senegal	138	73	71
South Africa	71	49	0
Uganda	147	89	151
Zambia	185	111	158
Zimbabwe	108	71	1

Source: WHO (2004).

Data

Most of our data were taken from WRI (2005), a source that has internal consistency, quality checks, and global coverage. We used two alternative indicators for vulnerability to infectious disease. The first was infant (under-one) mortality. Infant mortality integrates a range of problems of poverty and health. Although disease-specific (infant) mortality would be more informative, data coverage is insufficient, particularly in poorer countries. The second indicator was under-five mortality. We would have preferred to use data on the diseases themselves, particularly malaria and diarrhoea. However, WHO country data omit these diseases for many countries, and crucially so for regions that the WHO regional data suggest are most vulnerable.[2] For those few countries for which there are data, there is a good correlation between all-cause mortality for infants and young children and malaria mortality. See table 1 and figure 1.

We grouped the indicators of adaptive capacity into five categories. Table 1 lists them all. Institutional indicators include the nature of government (democracy etc.), and the nature of government intervention in society (rule of law etc.). Cultural indicators include average attitudes (e.g. to risk). Related to that, we included a list of dummies giving the dominant religion in a country; note that a country may be labelled 'Christian', even though most of its inhabitants are secular. Per capita income, income distribution, and poverty rates were employed as economic indicators.

[2] There are country and disease-specific data for all countries and diseases on http://www.who.int/healthinfo/bodestimates/en/index.html. Unfortunately, these are model results rather than observations.

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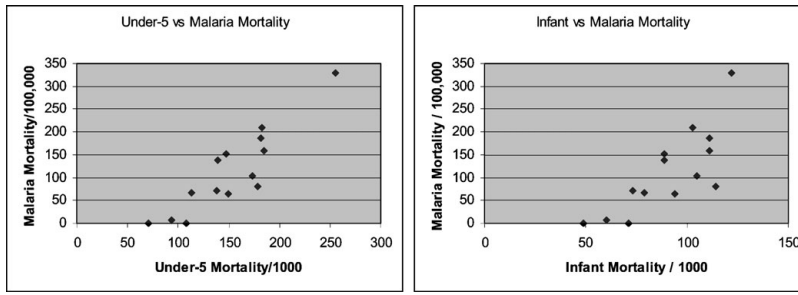


Figure 1. *The relationship between malaria mortality and under-5 mortality (left panel) and infant mortality (right panel).*

Finally, enrolment and literacy reflected education. Note that all data are continuous, except for the religion variables, which are dummies.

Results

We began by trying to explain infant mortality. Two problems with estimating (1) quickly became apparent. The first was model selection. There were many potential indicators of adaptive capacity, each with missing observations for different countries. Furthermore, the regressions were plagued by multicollinearity. One would preferably start with the model that includes all possible explanatory variables. Estimates could then be refined by eliminating variables that are neither individually nor jointly significant in a step-wise process. This procedure was not possible, however, because all of the variables were actually available for only a small number of countries. Indeed, this number was smaller than the number of potential explanatory variables. We were therefore forced to group the explanatory variables; table 2 provides the details. In the first stage of model selection, we regressed infant mortality on the explanatory variables from the same group. We took account of multicollinearity by explicit testing for joint significance. A number of institutional variables had a significant effect on infant mortality: civil liberty (positive),[3] democracy (positive), economic freedom (negative), and political stability (positive). From the religion variables, only Christianity had a significant, positive influence. Individualism and long-term orientation were the only significant cultural variables, both with a positive effect. Secondary education and literacy had significant, positive effects on infant mortality. Absolute poverty, average per capita income, and the Gini coefficient had significant, positive effects on infant mortality. In the second stage of model selection, we put the significant variables of all groups together, and subsequently eliminated those that were neither individually nor jointly significant.

Non-linearity was the second problem in estimating equation (1). Although non-linear estimators are now generally available, CES functions are complicated. We therefore linearly estimated equation (1) for specific γs,

[3] Note that we use 'positive' and 'negative' in the intuitive sense so, for example, increasing civil liberty reducing infant mortality is a positive effect.

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Table 2. *Data used in the regression analysis*

Indicator	*Description*	*Source*
Institutions		
Accountability	Political, civil and human rights	Kaufmann et al. (1999)
Autocracy	Institutionalized autocracy	Marshall and Jaggers (2003)
Civil liberties	Freedom of expression, assembly, association, education and religion	Freedom House (2003)
Executive competition	Extent to which executives are chosen through competitive elections	Marshall and Jaggers (2003)
Corruption	Petty and grand corruption, and state capture	Kaufmann et al. (1999)
Democracy	Institutionalized democracy	Marshall and Jaggers (2003)
Economic freedom	Corruption, barriers to trade, fiscal burden, regulatory burden (health, safety, environment, banking, labour)	Heritage Foundation (2003)
Government effectiveness	Competence of bureaucracy and quality of public service	Kaufmann et al. (1999)
Government quality	Quality of public institutions	Gallup and Sachs (1999)
Rule of law	Contract enforcement, quality of policy and judiciary, and crime	Kaufmann et al. (1999)
Political rights	Free and fair elections, competitive politics, opposition power, minority protection	Freedom House (2003)
Executive recruitment	Institutionalized procedure for the transfer of executive power	Marshall and Jaggers (2003)
Extent of regulation	Incidence of market-unfriendly policies	Kaufmann et al. (1999)
Political stability	Violent threats or changes in government	Kaufmann et al. (1999)
Religion		
Buddhism	Predominantly Buddhist	Adherents.com (2003)
Christianity	Predominantly Christian	Adherents.com (2003)
Hinduism	Predominantly Hindu	Adherents.com (2003)
Islam	Predominantly Moslem	Adherents.com (2003)
Yorubaism	Predominantly Yoruba	Adherents.com (2003)
Animalism and spiritism	Predominantly Animist	Adherents.com (2003)

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Table 2. *Continued*

Indicator	*Description*	*Source*
Culture		
Individualism	Reinforcement of individual achievement and interpersonal relationships	Hofstede (2001)
Masculinity	Degree of gender differentiation and male dominance	Hofstede (2001)
Uncertainty avoidance	Tolerance of uncertainty and ambiguity	Hofstede (2001)
Power distance	Degree of inequality in power and wealth	Hofstede (2001)
Long-term orientation	Degree of orientation on the future	Hofstede (2001)
Trust	Degree of trust of others	WVS (2003)
Economics		
Gini coefficient	Degree of income inequality	WRI (2005)
Absolute poverty	Percentage of population living on less than \$1/day	WRI (2005)
Relative poverty	Percentage of population below national poverty line	WRI (2005)
Per capita income	Per capita GDP, purchasing power parity exchange rate	WRI (2005)
Education		
Primary	Total enrolment relative to school-age population, primary education	WRI (2005)
Secondary	Total enrolment relative to school-age population, primary education	WRI (2005)
Tertiary	Total enrolment relative to school-age population, primary education	WRI (2005)
Literacy	Percentage of the population over 15 able to read and write	WRI (2005)

and then conducted a grid search to produce both a maximum likelihood estimate for γ and the maximum likelihood function as well. The estimated function is

$$V_c^{M1} = (1-\gamma)^{1-\gamma}\left(\underset{(2.1)}{20.6} - \underset{(0.04)}{0.15}\,Y^{1-\gamma} - \underset{(0.37)}{1.52}\,L^{1-\gamma} + \underset{(0.19)}{0.91}\,P^{1-\gamma}\right)^{1/1-\gamma}$$

$$\gamma = \underset{(0.11)}{0.60};\ R^2 = 0.84;\ N = 49 \tag{2}$$

where Y is per capita income, L is literacy, and P is absolute poverty. A modest version of the weakest link hypothesis is somewhat supported in that perfect substitution is rejected, but none of the indicators is essential (as would be the case if $\gamma > 1$).

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We followed the same procedure for under-five mortality. Of the institutional variables, only the rule of law and political stability had a positive, significant influence. Christianity, individualism, and a long-term orientation had a positive, significant effect. Both absolute and relative poverty significantly increase under-five mortality. Literacy and secondary education have a significant, positive effect.

Including all explanatory variables together in a single regression model, only literacy and absolute poverty were statistically significant at the 5 per cent level. The estimated function is

$$V_c^{M5} = (1-\gamma)^{1-\gamma}\left(\underset{(2.4)}{21.8} - \underset{(0.60)}{4.55}\, L^{1-\gamma} + \underset{(0.27)}{1.92}\, P^{1-\gamma}\right)^{1/1-\gamma}$$

$$\gamma = \underset{(0.10)}{0.28};\ R^2 = 0.81;\ N = 55 \qquad (3)$$

Even weaker support for a weakest link assumption was found.

3. Scenarios

Our empirical analysis highlighted three significant indicators of adaptive capacity: per capita income, literacy, and absolute poverty. Standard scenarios for climate change analysis – particularly those in the Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart, 2001) of the Intergovernmental Panel on Climate Change (IPCC) – do not project these variables.[4] In fact, the SRES scenarios only have per capita income, measured in market exchange rates (MER). We measured income in purchasing power exchange rates (PPP), as this better reflects the true standard of living. Following Tol (2006), we assumed that the ratio of PPP to MER falls by 0.28 (0.02) per cent for every 1 per cent increase in per capita income (in MER).[5] The data used in Section 2 show that literacy increases by 0.27 (0.03) per cent for every 1 per cent increase in per capita income (in PPP), and that absolute poverty falls by 1.11 (0.13) per cent with the same 1 per cent increase in per capita income (again in PPP). With these income elasticities in hand, it is easy to show that per capita income has to increase by a factor 1.9 to meet the Millennium Development Goal (MDG) of halving poverty in 2025; this is equal to a 3.2 per cent growth rate over 20 years. Given equation (2), infant mortality would fall by 14.6 per cent (for a per capita income of $530, and a literacy rate of 56 per cent, as in Nigeria).

Figure 2 shows scenario results for Nigeria. We use Nigeria in this initial discussion to represent a large and not untypical country in Sub-Saharan Africa, but we will report results for other countries below. Income per capita (MER) rises by a factor 120 over the course of the twenty-first century in West Africa for the SRES A1B scenario (IMAGE Team, 2002), but only by a

[4] Emissions of greenhouse gases were the focus of the SRES scenarios. Therefore, the models used to build these scenarios pay considerable attention to energy demand and supply. In developing the SRES scenarios, much less attention was paid to population and economy. Nonetheless, the SRES scenarios are now standard in analyses of climate change, climate impacts, and climate policy.

[5] Numbers in brackets are standard deviations.

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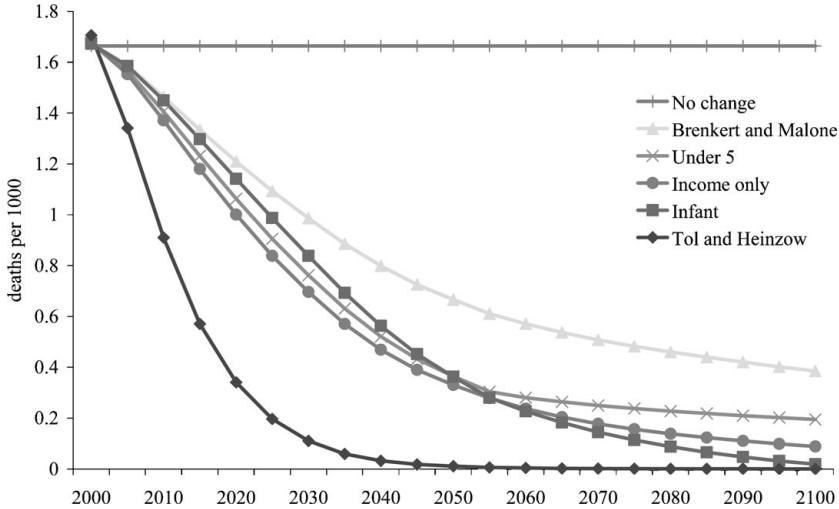


Figure 2. *Malaria incidence (deaths per thousand) in Nigeria according to the SRES A1B scenario of development, with six alternative models of adaptive capacity.*

factor 30 when measured in PPP. Five alternative projections, driven by this lower rate of change in income, are shown for malaria mortality. First, we assumed that the incidence of malaria is proportional to infant mortality and that future infant mortality is driven by per capita income, literacy, and absolute poverty according to equation (2). Second, we assumed that the incidence of malaria is proportional to under-five mortality, where under-five mortality is driven by literacy and absolute poverty according to equation (3). Third, we assumed that the incidence of malaria is proportional to infant mortality and that infant mortality is driven by income only; this implies that the income elasticity of malaria is −0.85 (0.04).[6] Fourth, we followed Tol and Heinzow (2003) who estimated an income elasticity of malaria of −2.65 (0.69) for the 14 WHO regions. Fifth, following Brenkert and Malone (2005), we assumed that changes in malaria are proportional to changes in the geometric mean of per capita income, literacy, and one minus the fraction of people in absolute poverty. For comparison, we also show the case in which malaria stays constant (relative to the population), as assumed by Martens *et al.* (1995, 1997) and van Lieshout *et al.* (2004).

So, we contrast six scenarios. In one scenario, vulnerability does not change. In two scenarios, development is equated with economic growth, and vulnerability follows per capita income. The two scenarios differ in parameter value. In three scenarios, we have a richer specification of development and adaptive capacity; indeed, in one of the scenarios, economic growth only has an indirect effect. The three scenarios differ in terms of parameter choice.

[6] The income elasticity for under-five mortality is –0.90 (0.04), leading to practically the same projections.

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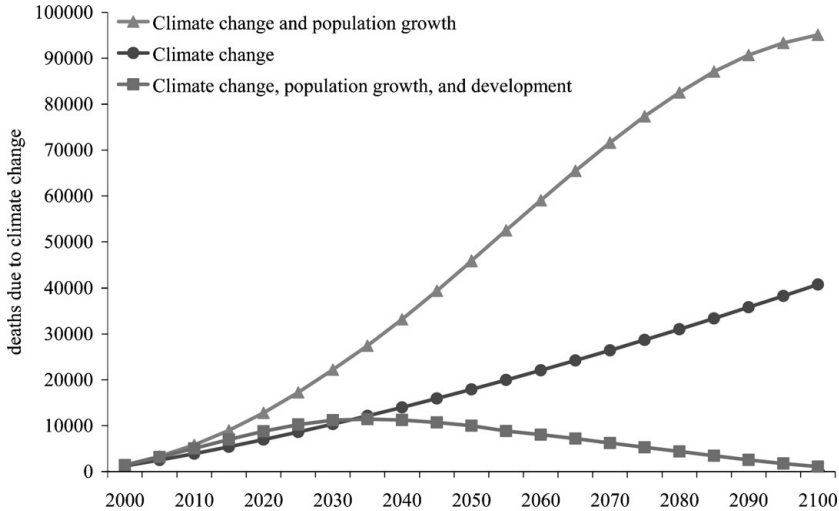


Figure 3. *Number of climate-change-induced malaria deaths in Nigeria according to the three main components of the SRES A1B scenario.*

Note that the six scenarios present different models. In principle, these models should be tested against data, and most or all rejected. However, the lack of data on malaria incidence (see above) prevents this. At the same time, the empirical analysis above clearly shows (a) that infant and under-five mortality are not constant; (b) that infant and under-five mortality are driven by more than per capita income alone; and (c) that the different indicators have different weights. Therefore, the models estimated here are probably closest to the truth, while the empirical evidence casts doubt on the models taken from the literature. The latter are therefore used for comparison only.

The results are strikingly different across the various scenarios. In all, malaria mortality falls from the present 1.7 deaths per thousand per year, the rate reported by WHO for the poorest region of Africa. However, using the geometric mean as suggested by Brenkert and Malone (2005), malaria falls by a factor 4, while malaria disappears under the assumptions of Tol and Heinzow (2003). Incidence driven by the infant mortality and under-five mortality relationships reported in equations (2) and (3), respectively, behave similarly until 2050. After 2050, poverty is eradicated and literacy is universal, so malaria projected with under-five mortality stabilizes. Finally, the trajectory supported by the alternative model that drives infant mortality by a single determinant (income alone) lies somewhere in between 'under five' and 'infant'.

Figure 3 shows the implications for climate change impacts, again using Nigeria as an example with vulnerability driven by infant mortality per equation (2). We assumed that malaria mortality increases by 8 per cent (6 per cent) for every degree of global warming (Tol, 2002); 8 per cent is the average over various malaria and climate models (e.g., Martens *et al.*, 1995,

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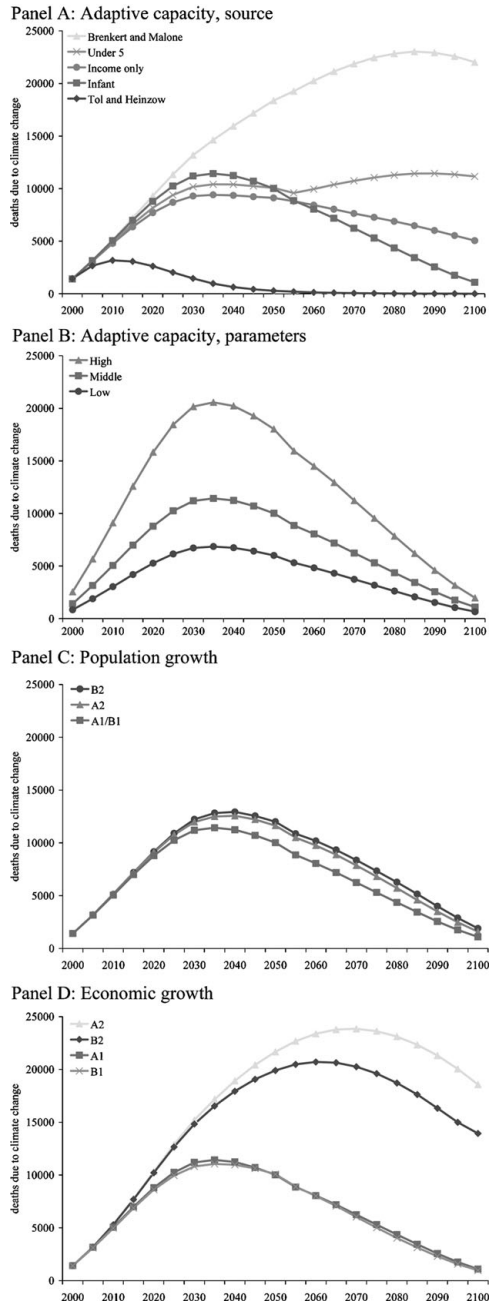
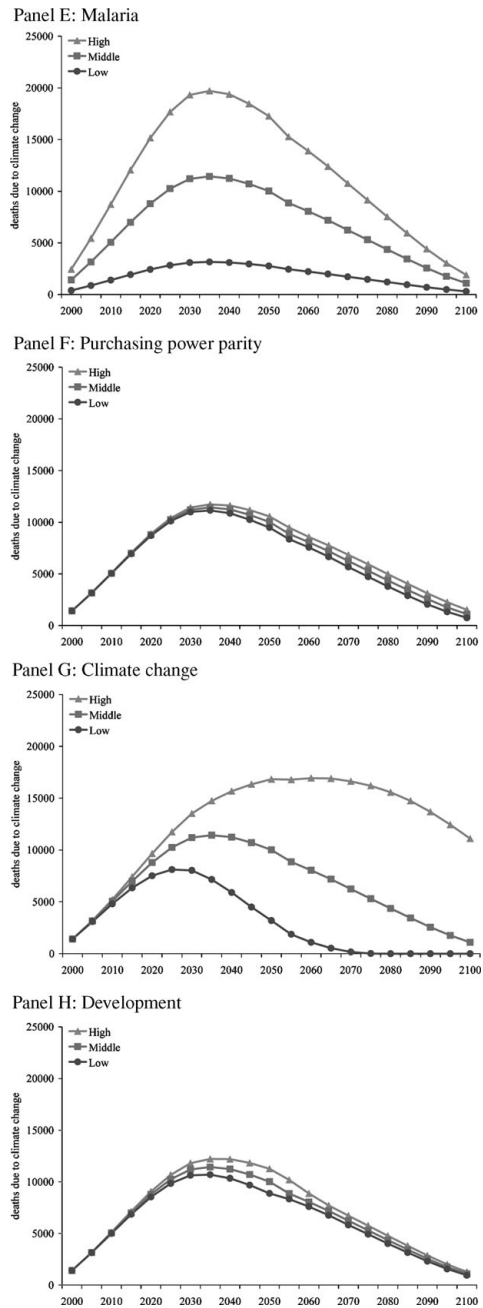


Figure 4. *Number of climate-change-induced malaria deaths in Nigeria for a range of sensitivity analyses: in 'adaptive capacity, source', five alternative models are used (see text), with 'infant mortality' as the base case; in 'adaptive capacity, parameters', the parameters of infant mortality are varied between their mean plus and minus their standard deviation; in 'population', three alternative projections of population growth are used; in 'economic growth', four alternative projections of economic growth are used,*

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with 'A1' as the base case; in 'malaria', the malaria sensitivity is varied between the mean plus and minus the standard deviation; in 'purchasing power parity', the income elasticity of purchasing power parity is varied between its mean plus or minus its standard deviation; in 'climate change', the climate sensitivity is varied between 1.5°C, 2.5°C (the base case) and 4.5°C; and in 'development', the income elasticities of literacy and poverty are varied between the mean plus and minus the standard deviation.

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1997; van Lieshout *et al.*, 2004); 6 per cent is the standard deviation; as the model used is similar in structure and calibrated to the same data, and as parameter and scenario uncertainties are ignored, the range of best guesses is an underestimate of the true uncertainty. The middle trajectory shows that climate change alone would add some 40,000 malaria cases in 2100. If we add population growth,[7] then (as shown in the highest path), this estimate increases to almost 100,000. However, adding economic growth as described above, the number falls to slightly more than 1,000 excess deaths along the lowest path.

Figure 3 was constructed under that assumption that malaria follows infant mortality. Figure 4 offers the results of sensitivity studies designed to examine the robustness of the qualitative results portrayed there. Panel A of figure 4 shows, for example, that the maximum number of climate-change induced malaria deaths over the next century could fall to only 22,000 cases per year even with Brenkert and Malone's (2005) pessimistic assumptions about adaptive capacity (after rising for a period of time early in the century). In a world described accurately by Tol and Heinzow (2003), there will be no malaria in 2100. Panel A shows malaria incidence stabilizing by the middle of the century under the assumption that malaria follows under-five mortality because literacy becomes universal and poverty is eradicated. It must be emphasized, though, that the Millennium Development Goal of cutting under-five mortality by two-thirds is never met, let alone in 2025.

The other panels of figure 4 depict the results of other sensitivity analyses for Nigeria. After the assumptions about adaptive capacity (panels A and B), the rate of economic growth (panel D) and its effect on adaptive capacity are most important for the number of malaria deaths in 2100. The assumed rate of climate change (panel G) and the assumed sensitivity of malaria to climate change (panel E) are most important in the medium run, but dominated by development and economic growth in the long run. The assumptions on population growth (panel C) have little effect, just like assumptions about income elasticities of purchasing power parity (panel F), literacy, and poverty (panel H).

Figure 5 shows the results for Nigeria, Botswana, and Niger when climate change is cast against vulnerability calculated from the infant–mortality relationship of equation (2). The peak of climate-change-induced malaria is lowest and comes earliest in Botswana, and the disease is eradicated soonest. The peak is highest and comes latest in Niger, and is highest in 2100. Nonetheless, the qualitative pattern depicted here is typical of all countries in our sample. Table 3 offers some summary statistics for a selection of countries in Sub-Saharan countries. These are the only countries for which we have observations on infant mortality, per capita income, literacy, and absolute poverty with which to inform equation (2). In both table 3 and figure 5, we vary only the starting point from country to country (i.e., per capita income, literacy, and absolute poverty). The scenario assumptions

[7] Population is assumed to increase by 2.2 per cent per year in the first quarter century, 1.0 per cent in the second quarter, 0.2 per cent in the third, and −0.6 per cent in the fourth. With these assumption, population doubles between 2000 and 2100. These assumptions are from IMAGE Team (2002).

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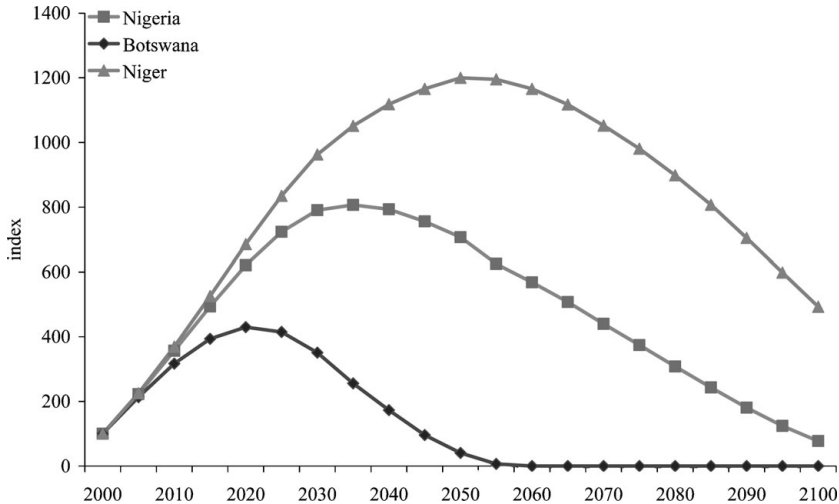


Figure 5. *Index (2000=100) of climate-change-induced malaria deaths in Botswana, Niger, and Nigeria according to the SRES A1B scenario.*

are otherwise the same as described above for Nigeria. The numbers are indexed to the year 2000, normalizing for differences in baseline mortality and population size.

So far, we have focussed on malaria. Tol (2002) postulates the same functional specification for dengue fever and schistosomiasis as for malaria. With that hypothesis, the qualitative behaviour is the same, although both diseases have many fewer victims than does malaria. Moreover, there is a weakly supported hypothesis that schistosomiasis may decrease with climate change. Diarrhoea is different, particularly since it increases with temperature to the power 1.14 (0.51); recall that we assume malaria to be proportional to warming. Figure 6 compares the evolution of malaria and diarrhoea for Nigeria for the A1B scenario. The number of diarrhoea deaths is an order of magnitude larger, but the pattern is much the same, with diarrhoea deaths peaking only slightly later. For completeness, we also show the results for the models of Link and Tol (2004) and Tol and Heinzow (2003). For both diseases, our projections based on infant mortality are much higher than their projections using simple income elasticities.

4. Discussion and conclusion

We show the impact of climate change and development on malaria in Sub-Saharan Africa for a range of scenarios and sensitivity analyses. In the short term, climate change is likely to increase the burden of malaria, but we can expect to see 'tipping points' at which the burden begins to decline. In the medium term, the extent of climate change, the sensitivity of malaria to climate change, the initial conditions, development, and the relationship between development and health care are all important variables in determining the timing of this tipping point. In the long term, however, only the speed of development and how that affects health care

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Table 3. *Summary results for climate-change induced malaria and initial conditions for various countries*

Country	*Infant mortality*[a]	*Income per capita*[b]	*Literacy*[c]	*Poverty*[d]	*Peak level*[e]	*Peak year*[f]	*2100 level*[g]
Nigeria	81	986	56	31	807	2035	77
Botswana	56	6,440	73	33	430	2020	2,060*
Ethiopia	113	435	33	46	1,153	2050	459
Kenya	74	1,128	77	50	743	2040	55
Lesotho	96	1,685	81	49	671	2035	2,100*
Madagascar	96	1,641	39	31	766	2035	127
Mauritania	97	1,641	39	31	795	2035	2,100*
Niger	121	825	14	61	1,200	2030	493
Rwanda	134	770	60	46	814	2050	169
Senegal	73	1,595	33	54	817	2035	11
South Africa	51	6,789	83	24	398	2020	2,060*
Uganda	98	973	62	69	752	2035	90
Zambia	111	853	73	85	763	2045	145
Zimbabwe	61	2,025	85	41	654	2030	2,090*

Notes:
[a]Measured in number per 1,000 people.
[b]Per capita GDP measured in PPP$.
[c]Measured as percentage of people over 15 years of age who can read and write.
[d]Measured in percentage of people living on less than $1 per day.
[e]Peak incidence of climate-change-induced malaria indexed so that year 2000 levels = 100.
[f]Year when peak incidence of climate-change-induced malaria is felt.
[g]Incidence of climate-change-induced malaria in the year 2100 (indexed so that year 2000 levels = 100) or (given $*$) the year when incidence goes to zero.

matter – at least, under the range of assumptions used here. Climate change and its impact on malaria are important only, in the long run, if there is hardly any development over the twenty-first century. Other infectious diseases behave similarly.

As climate change can only be affected in the long term but adaptive capacity can be improved in both the short and long term, this implies that development is a better response to climate-change-induced infectious disease than is greenhouse gas emission reduction. Tol and Dowlatabadi (2001) and Tol (2005) reach the same conclusion, but based on malaria only, using crude spatial aggregation and, most importantly, simplified relationships between infectious disease and development.

Our results show that development will reduce the burden of infectious disease. Progress is slow, however, and for the first few decades the effect of climate change dominates. Moreover, assumptions about economic development embedded in the underlying scenarios, like those articulated in Nakicenovic and Swart (2001), for example, may be over optimistic

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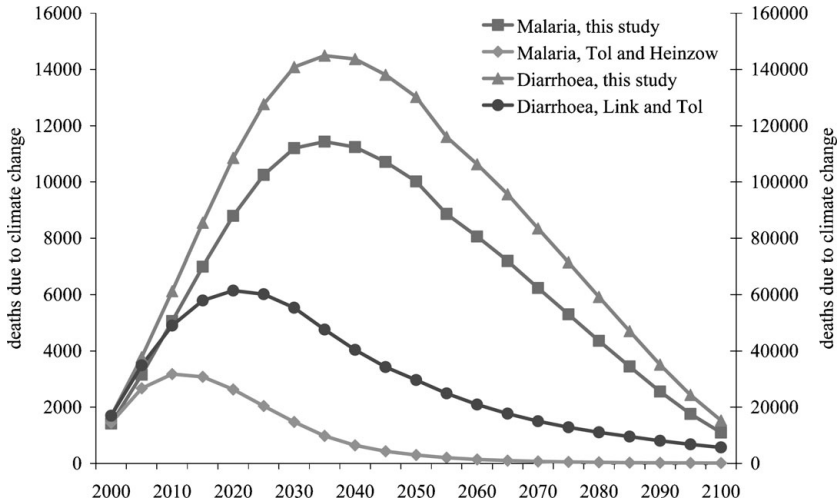


Figure 6. *Number of climate-change-induced deaths due to malaria (left axis) and diarrhoea (right axis) in Nigeria according to the SRES A1B scenario and two alternative scenarios of adaptive capacity.*

for many regions of the world. This suggests that a policy that only focuses on development, assuming that improved health care would follow automatically, may not be advisable. Interventions specifically aimed at infectious diseases (e.g., bed nets and indoor spraying for malaria, see Breman *et al.*, 2006; breast-feeding and oral rehydration therapy for diarrhoea, see Keusch *et al.*, 2006) could save a substantial number of lives.

Of course, policy makers do not need to choose between either investing in development or investing in greenhouse gas emission reduction. Both require investment, and this can be done at the same time. However, policy makers do need to choose how much to invest in either, and resources invested in one cannot also be invested in the other. Indeed, the OECD (2004) counts as Official Development Aid the money spent[8] on greenhouse gas emission reduction through the Clean Development Mechanism of the United Nations Framework Convention on Climate Change.

The most important caveat to our results is that we limit ourselves to the effect of development on infectious disease, ignoring the impact of infectious disease on development – through labour productivity, health care expenditures, education, and fertility. See Sachs (2005). Tol (forthcoming) shows that this is a minor error when considering climate-change-induced malaria, but the impact may be larger when all infectious diseases are included. We ignore the effect of climate change on development (cf. Fankhauser and Tol, 2005), including multiple climate-change induced health stress (e.g., malaria and malnutrition).

[8] Net of the value of the Certified Emission Reductions from the CDM project; as there have been no emissions trade under the Kyoto Protocol, the value of CERs are zero.

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An implicit assumption is that control of infectious disease in developing countries is analogous to control of infectious diseases in developed countries. This is unlikely to be true, as infectious disease in the tropics is not the same as infectious disease in the temperate zone. The burden of malaria in Sub-Saharan Africa is higher than the burden ever was in Europe or North America. Much effort and money has been spent trying to control malaria and diarrhoea but with limited and mixed success.

The results presented here do not carry over to other health impacts of climate change. Particularly, carbon dioxide emission reduction would be more effective for diseases related to air pollution, as both climate and air quality would improve. The effect of development on cardiovascular disease is ambiguous. Development would improve health care and therefore perhaps extend longevity, but it could also promote obesity. The effect of climate change on development is also ambiguous, as both heat stress and cold stress affect people with cardiovascular disorders.

Our results are based on cross-sections between countries. As a result, we ignore the dynamics of the problem – even though health and education are stock variables. The analysis presented here should be repeated with a dynamic panel analysis, as soon as data allow. The findings should be complemented with studies of these effects within countries.

These caveats show the need and direction for further research. However, for now, our strong conclusion is that climate change is of subordinate importance for infectious disease, while development is crucial. Our more cautious conclusion warns that development pathways are difficult to project, and so it is a little risky to count entirely on development to abate the effects of climate change, especially since mitigation will not substantially alter temperature trajectories for decades to come. Targeted interventions designed to promote disease control programs are essential now, and they will be essential for some time to come.

References

Adherents.com (2003), 'Nationally Predominant Religions', available at www.adherents.com/adh_predom.html

Alberini, A., A. Chiabai, and L. Muehlenbachs (2006), 'Using expert judgment to assess adaptive capacity to climate change: evidence from a conjoint choice survey', *Global Environmental Change* **16:** 123–144.

Arrow, K.J., H.B. Chenery, B.S. Minhas, and R.M. Solow (1961), 'Capital–labor substitution and economic efficiency', *Review of Economic Studies* **43**: 225–250.

Breman, J.G., A. Mills, R.W. Snow, J.-O. Mulligan, C. Lengeler, K. Mendis, B. Sharp, C. Morel, P. Marchesini, N.J. White, R.W. Steketee, and O.K. Duombo (2006), 'Conquering malaria', in D.T. Jamison, J.G. Breman, A.R. Measham, G. Alleyne, M. Claeson, D.B. Evans, P. Jha, A. Mills, and P. Musgrove (eds), *Disease Control Priorities in Developing Countries*, 2nd edn, Oxford: Oxford University Press.

Brenkert, A.L. and E.L. Malone (2005), 'Modeling vulnerability and resilience to climate change: a case study of India and Indian States', *Climatic Change* **72**: 57–102.

Burton, I., R.W. Kates, and G.F. White (1993), *The Environment as a Hazard*, New York: Guilford Press.

Casman, E.A. and H. Dowlatabadi (2002), *Contextual Determinants of Malaria*, Washington, DC: Resources for the Future Press.

https://doi.org/10.1017/S1355770X07003841 Published online by Cambridge University Press

Fankhauser, S. and R.S.J. Tol (2005), 'On climate change and economic growth', *Resource and Energy Economics* **27:** 1–17.
Freedom House (2003), 'Freedom in the world – Annual Survey of Political Rights and Civil Liberties', available at www.freedomhouse.org/
Gallup, J.L. and J.D. Sachs (1999), 'Geography and economic development', Center for International Development, Harvard University, Cambridge, MA, available at www.cid.harvard.edu/ciddata.html
Heritage Foundation (2003), 'Index of economic freedom', available at www.heritage.org/Research/TradeandForeignAid/
Hofstede, G. (2001), *Culture's Consequences – Comparing Values, Behaviors, Institutions, and Organizations across Nations*, London: Sage Publications, available at www.geert-hofstede.com/
IMAGE Team (2002), 'The IMAGE 2.2 implementation of the SRES scenarios', RIVM CD-ROM Publication 481508018, RIVM, Bilthoven.
Kaufmann, D., A. Kraay, and P. Zoido-Lobaton (1999), 'Governance matters', Policy Research Working Paper 2196, World Bank, Washington, DC, available at www.worldbank.org/wbi/governance/data.html
Keusch, G.T., O. Fontaine, A. Bhargava, C. Boschi-Pinto, Z.A. Bhutta, E. Gotuzzo, J. Rivera, J. Chow, S.A. Shahid-Salles, and R. Laxminarayan (2006), 'Diarrheal diseases', in D.T. Jamison, J.G. Breman, A.R. Measham, G. Alleyne, M. Claeson, D.B. Evans, P. Jha, A. Mills, and P. Musgrove (eds), *Disease Control Priorities in Developing Countries*, 2nd edn, Oxford: Oxford University Press.
Link, P.M. and R.S.J. Tol (2004), 'Possible economic impacts of a shutdown of the thermohaline circulation: an application of *FUND*', *Portuguese Economic Journal* **3:** 99–114.
Marshall, M.G. and K. Jaggers (2003), 'Polity IV project: political regime characteristics and transitions, 1800–2002', Center for International Development and Conflict Management, University of Maryland, College Park, available at www.cidm.umd.edu/inscr/polity/
Martens, W.J.M., T.H.Jetten, J.Rotmans, and L.W.Niessen (1995), 'Climate change and vector-borne diseases – a global modelling perspective', *Global Environmental Change* **5**: 195–209.
Martens, W.J.M., T.H.Jetten, and D.A. Focks (1997), 'Sensitivity of malaria, schistosomiasis and dengue to global warming', *Climatic Change* **35:** 145–156.
McMichael, A., A. Githeko, R. Akhtar, P. Carcavallo, D. Gubler, A. Haines, R.S. Kovats, P. Martens, J. Patz, and A. Sasaki (2001), 'Human health', in J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds), *Climate Change 2001: Impacts, Adaptation, and Vulnerability – Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press.
Medlin, C.A., M. Chowdhury, D.T. Jamison, and A.R. Measham (2006), 'Improving the health of populations: lessons of experience', in D.T. Jamison, J.G. Breman, A.R. Measham, G. Alleyne, M. Claeson, D.B. Evans, P. Jha, A. Mills, and P. Musgrove (eds), *Disease Control Priorities in Developing Countries*, 2nd edn, Oxford: Oxford University Press.
Nakicenovic, N. and R.J. Swart (eds) (2001), *IPCC Special Report on Emissions Scenarios*, Cambridge: Cambridge University Press.
OECD (2004), *ODA Eligibility Issues for Expenditures under the Clean Development Mechanism*, DAC/CHAIR(2004)4/FINAL, Paris: Organization for Economic Cooperation and Development.
Sachs, J.D. (2005), *The End of Poverty – Economic Possibilities for Our Time*, New York: Penguin.
Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R.J.T. Klein, and G. Yohe (2001), 'Adaptation to climate change in the context of sustainable development

https://doi.org/10.1017/S1355770X07003841 Published online by Cambridge University Press

and equity', in J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds), *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press.

Tol, R.S.J. (2002), 'New estimates of the damage costs of climate change. Part II: dynamic estimates', *Environmental and Resource Economics* **21**: 135–160.

Tol, R.S.J. (2005), 'Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of *FUND*', *Environment and Development Economics* **10:** 615–629.

Tol, R.S.J. (2006), 'Exchange rates and climate change: an application of *FUND*', *Climatic Change* **75**, 59–80.

Tol, R.S.J. (forthcoming), 'Climate, development and malaria: an application of *FUND*', *Climatic Change*.

Tol, R.S.J. and H. Dowlatabadi (2001), 'Vector-borne diseases, climate change, and economic growth', *Integrated Assessment* **2**: 173–181.

Tol, R.S.J. and T. Heinzow (2003), 'Estimates of the external and sustainability costs of climate change', FNU-32, Centre for Marine and Climate Research, Hamburg University, Hamburg.

Tol, R.S.J. and G.W. Yohe (forthcoming), 'The weakest link hypothesis for adaptive capacity: an empirical test', *Global Environmental Change*.

van Lieshout, M., R.S. Kovats, M.T.J. Livermore, and P. Martens (2004), 'Climate change and malaria: analysis of the SRES climate and socio-economic scenarios', *Global Environmental Change* **14**: 87–99.

WHO (2005), 'Malaria cases (per 100,000) by country', *Global Health Atlas*, World Health Organization, available at gamapserver.who.int/mapLibrary/Files/Maps/global_cases.jpg

WRI (2005): *EarthTrends – The Environmental Information Portal*, Washington, DC: World Resource Institute, available at earthtrends.wri.org/

WVS (2003), *World Values Survey*, available at www.worldvaluessurvey.org/

Yohe, G. and R.S.J. Tol (2002), 'Indicators for social and economic coping capacity – moving toward a working definition of adaptive capacity', *Global Environmental Change* **12**: 25–40.

https://doi.org/10.1017/S1355770X07003841 Published online by Cambridge University Press