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The Health Impacts of Climate Change: A Study of Cholera in Tanzania

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Increased temperatures and changes in patterns of rainfall as a result of climate change are widely recognized to entail serious consequences for human health, including the risk of diarrheal diseases. Indeed, there is strong evidence that temperature and rainfall patterns affect the disease pattern. This paper presents the first study that links the incidence of cholera to environmental and socioeconomic factors and uses that relationship to predict how climate change will affect the incidence of cholera. Specifically, the paper integrates historical data on temperature and rainfall with the burden of disease from cholera in Tanzania, and uses socioeconomic data to control for impacts of general development on the risk of cholera. Based on these results we estimate the number and costs of additional cholera cases and deaths that can be attributed to climate change by year 2030 in Tanzania. The analyses are based on primary data collected from the Ministry of Health, Tanzania, and the Tanzania Meteorological Agency. The result shows a significant relationship between cholera cases and temperature and predicts an increase in the initial risk ratio for cholera in Tanzania in the range of 23 to 51 percent for a 1 degree Celsius increase in annual mean temperature. The cost of reactive adaptation to cholera attributed to climate change impacts by year 2030 in Tanzania is projected to be in the range of 0.02 to 0.09 percent of GDP for the lower and upper bounds respectively. Total costs, including loss of lives are estimated in the range of 1.4 to 7.8 percent of GDP by year 2030. Lastly, costs of additional cholera cases and deaths attributed to climate change impacts in Tanzania by the year 2030 largely exceed the costs of preventive measures such as household chlorination.

Keywords: climate change; health impacts; adaptation costs; Tanzania

JEL Classification: I18, O21, Q54

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1. Introduction

With continuous and increasing rates of morbidity associated with waterborne diseases, especially in Sub-Saharan Africa (Kosek et al., 2003), this group of diseases is potentially an enormous economic burden leading to significant direct costs to the health sector and to households, and indirectly by means of lost time allocated to work, school and other productive activities, to the economy and society at large.

Water-related diarrheal diseases, including cholera, are widespread in areas where water resources are scarce and the majority of diarrheal diseases can be attributed to environmental factors such as unsafe drinking water, poor hygiene and lack of sanitation (Prüss-Üstün and Corvalán, 2006). Floods caused by heavy monsoons can contaminate drinking water with the bacterium. In droughts, the bacterium can grow more easily in stagnating water in ponds and rivers. Cholera has been found to vary with climate fluctuations over long time periods (Pascual et al. 2002) and recent studies have associated temperatures and rainfall anomalies with diarrhea and cholera, and these stress the role of climate variability in transmission of diarrheal diseases. (Singh et al. 2001; Koelle et al., 2005; Checkley et al., 2000; Fernández et al., 2009). Furthermore, there is a rising emphasis on quantifying health impacts from climate change (Campbell-Lendrum and Woodruf, 2007; McMichael et al., 2004). The projected climate change impacts for Sub-Saharan Africa indicate increased rainfall variability, increased temperatures as well as prolonged droughts (Christensen et al., 2007). Therefore, the magnitude of climate change related health impacts over the next few decades will largely depend on the effectiveness and timing of adaptation measures. For this purpose, decision makers and national governments need information on the extent of damages attributed to climate change, the financial resources needed for adaptation, and on what damages can be avoided through proposed adaptation measures. Also, the World Health Organization (WHO) has examined the global burden of disease attributable to climate change up to year 2000, and on this background it has emphasized that planning health adaptation to climate change impacts will require detailed assessments of national vulnerabilities to specific health risks (WHO, 2002).

There are two main types of adaptation measures to climate change: *reactive*, which are measures taken in response to climate change, and *preventive* measures taken in advance of climate change to minimize or offset adverse impacts. Suggested adaptation strategies for diarrheal diseases concentrate on the reduction of vulnerability to current climatic events, as well as the inclusion of adaptation policies in planning for long-term sustainable development. Measures for the prevention of cholera mostly consist of providing clean water and proper sanitation to populations who do not yet have access to basic services. Health education and good food hygiene are equally important. Also, strengthening surveillance and early warning greatly help in detecting the first cases and put in place control measures. Reactive measures include treatment of the disease to reduce the negative impacts.

There exist several reviews and studies of costs of health intervention programmes which address the prevention of climate-related diarrhea and cholera (Clasen et al., 2007; Banerjee et al., 2007; Jeuland and Whittington, 2009; Hutton and Haller, 2004; Markandya and Chiabai, 2009). These studies focus on planned interventions (undertaken in a non-climate change related context) and provide indicators and cost estimates that can be applied in a climate change context, since interventions in principle are the same. However, the figures provided must be considered as a lower bound of total costs of adaptation since indirect costs such as loss of earnings, life years lost and disability are not included in these estimates. Recently, studies have therefore turned to focus on the costs of specific interventions for preventive and reactive adaptation measures, including those for diarrheal diseases, related to future climate change (Ebi, 2008; UNFCCC, 2007). There remains, nevertheless, very little information from the literature on the costs of health adaptation in different climate change scenarios, especially for developing countries. This could be accredited to adaptation being a relatively new field, and the difficulties with quantification of costs, especially in developing countries, due to lack of data and long-term reporting on disease and climate variables.

According to WHO, improvements in water supply and sanitation are the most sustainable approach for prevention against cholera and other waterborne epidemic diarrheal diseases (WHO, 2008b). A pressing challenge is therefore the need for improved water supply. A general main development objective is to increase access to clean, affordable and safe water and sanitation and to reduce vulnerability from environmental risk. Nonetheless, the WHO projections of health burden attributable to diarrheal diseases for 2030 predict, for sub-Saharan Africa, an increase in relative number of incidences. This is despite socio-economic development and increased coverage of water and sanitation (WHO, 2008a). The WHO estimations considered a number of environmental and socio-economic variables with a mix of country and regional level inputs.

This paper provides new evidence on the health impacts from climate change on the incidence of cholera as complimentary information to previous estimates of burden of disease attributed to diarrheal diseases in sub-Saharan Africa. The analysis draws on primary data sources to estimate the relationship between climate variables and cholera in Tanzania, and uses these results for projections of future burden of cholera attributed to climate change by year 2030 in Tanzania. These results provide a basis for estimating costs of residual cases of cholera attributed to climate change, including information on the expected future cases and loss of lives, and on the consequences to public health expenditures as well as the additional costs related to loss of lives. The results draw attention to the fact that neglecting climate variables will result in a serious underestimation of the projected number of cholera cases which can be expected by 2030. In addition, economic costs of climate change impacts on burden of cholera will be greatly underestimated by ignoring such changes in environmental factors.

The analysis in this paper is divided into two main elements. Firstly, to quantify the extent of impact from climate change on cholera incidences, the paper starts by analyzing the relationship between temperatures and precipitation and cases of cholera. These results are then used to establish scenarios as indicative measures of potential climate change impacts to cholera distribution in Tanzania by 2030. The number of cases, deaths and burden of disease in terms of disability-adjusted life-years (DALY) are computed. Finally, the second part of the paper estimates the costs associated with residual health impacts attributed to climate change by year 2030.

2. Methodological Issues

In order to analyze the magnitude of burden of cholera attributable to climate change, it is useful to decide on different scenarios that the analysis will build upon. For this purpose, climate change predictions for the specific locality as well as population growth and economic development will need to be considered. The following two scenarios are suggested:

Scenario C_0, year 2030, is the baseline scenario where implications from climate change to disease patterns are not integrated in the analysis. The scenario includes assumptions of economic development and hence implicitly assumes an improved health care sector as a result of increasing GDP and other socio-economic developments which are expected to positively influence on the health sector performance. Socio-economic development is also assumed to include preventive measures such as water and sanitation programmes. As for Tanzania, the strategy for the water sector includes a long- term target of nearly universal access to clean and safe water by 2025 (URT, 2000). The relative burden of disease attributed to cholera in 2030 compared to year 2008 is expected to be lower due to improvements in health sector performance and increased water and sanitation coverage (basic preventive adaptation measures).

Scenario C_1, year 2030, builds on *Scenario* C_0 and estimates the number of cholera cases and deaths considering projected climate change impacts on cholera cases and deaths based on the results of an econometric analysis of the relationship between environmental and socioeconomic variables. The additional number, N_{2030cc}, of incidences of cholera attributed to climate change impacts by year 2030 are hence estimated as

$$N_{2030cc} = Scenario_{C_1} - Scenario_{C_0} \tag{1}$$

The estimations are based on the same main assumptions. The predicted exposure to climate change in Tanzania by year 2030 is carried out for a 1 and 2 degree Celsius temperature increase, respectively, based on the IPCC (2007) predictions. Secondly, socio-economic development is assumed to increase water and sanitation coverage and, thirdly, it is assumed that population projections for year 2030 will be in line with the UN projected population (UN, 2008) for Tanzania and increase from 37,600,000 year 2004 to 75,498,000 people by year 2030. Lastly, projected number of cases and deaths without considering climate change impacts are estimated from WHO Global Burden of Disease (GBD) study (WHO, 2008) which includes projections for diarrheal diseases for Sub-Saharan Africa by 2030.

In the following, *Scenario* C_0 and *Scenario* C_1 form the basis for estimating the incidence of cholera in Tanzania by year 2030 and the number of residual cases attributed to climate change. The costs of reactive adaptation, which in the case of cholera is treatment, are equal to the costs of treatment of the additional number of cases attributed to climate change.

3. Analysis of Health Impacts

3.1 Quantification of the Health Impacts

To assess the burden of cholera attributed to climate change, the magnitude of climate change for the specific location is required. This is both in term of present climate, its variability and how climate variables potentially are expected to change over time. For this matter, an emphasis on time perspective and geographical position are important to assess local and sectoral impacts. Subsequent work by various international experts including climate modelers has assessed at a relatively detailed level the potential climate change impacts in different parts of Africa (Christensen et al., 2007). Among the conclusions that emerge is an agreement across most models to the effect that there will be a tendency to increased precipitation in the winter months in East Africa with future climate change, but that this may also be combined with an increased intensity of rain in shorter periods and drought in other periods. Moreover, temperatures in Tanzania are predicted to increase within the range of 1-2 C^o by year 2030.

3.1.2 Health Outcome for Cholera Attributed to Climate Change

Cholera, which is a diarrheal disease, is primarily waterborne and epidemics may be boosted by extreme climate conditions that enable the waterborne bacterium *Vibrio cholerae* to be spread more easily. High and mean monthly temperatures are found to be strongly associated with increased episodes of diarrheal disease in adults and children (Checkley et al., 2000; Speelmon et al., 2000; Lama et al., 2004; Singh et al., 2001). Evidence is also found that both droughts and floods increase the spread of the cholera (Koelle et al, 2005). In order to investigate a potential relationship between climate variability and cholera cases and deaths we used Poisson regression analysis (similar to others in the field – see e.g. Singh et al., 2001; Kuhn et al., 1994; Tango, 1994). A Poisson regression is used to fit models of the number of occurrences or counts of an event (dependent variable) assuming they follow a Poisson distribution (where the mean and variance are identical). The model estimates the expected value of the dependent variable as a log-linear function of a set of independent variables and regression parameters (Kuhn et al., 1994).

Historical data on burden of disease attributed to cholera were collected from the Ministry of Health, Dar es Salaam. Cholera cases in the whole country were available per month between January 1998 and December 2004, while cholera cases and deaths were available annually for all of Tanzania (1977 to 2004) and for 21 regions of the country (1998 to 2004). The climate variables – rainfall and temperatures – represent the average of 19 weather stations throughout the country. In addition to climate and health variables, socioeconomic data were gathered for the datasets containing data per year. The models are of the general form:

$$\ln(\text{health variable}_t) = \alpha + \beta_1.(\text{climate variable}_t) + \beta_2.X_t + \varepsilon \qquad (2)$$

Where health variable is the incidence of cholera cases or deaths in period t; climate variable represents rainfall or temperature; and X is a vector of socioeconomic factors that may explain the health variable (population growth[4], GDP[1], water and sanitation coverage[5], literacy rate[2] and cassava production per capita[6]). For each dataset several different model have been tested with specifications combining the regressors. The preferred models are chosen according to the level of significance of regressors in each model and the results of a previous correlation analysis of all variables in our datasets. Details of our preferred models are given in Annex 1.

The results using the dataset gathered per month showed a positive and significant association between cholera cases and temperature. A time trend variable was integrated in the model as a proxy to other socioeconomic variables that were absent in this dataset. The relative risk, which represents the relative change in the dependent variable given a one-unit change in the explanatory variable, was estimated to be equal to 1.51. In other words, an increase in temperature equal to 1 degree Celsius would increase the risk ratio for cholera cases in Tanzania by 51 percent. Using the annual data for all Tanzania, temperature also better explained cholera cases when GDP per capita was introduced as a control variable. In this model, an increase in temperature equal to 1 degree Celsius would increase the risk ratio for cholera cases in Tanzania by 23 percent. These results were confirmed when using the panel of

[4] IMF (2008)
[5] URT (1992, 1996, 1999, 2005)
[6] FAO (2005)

regions dataset, in which case a 1 degree Celsius increase in temperature was found to increase the risk ratio for cholera cases by 51 percent.

When fitting models for cholera deaths, literacy rates and access to water and sanitation were individually significant in explaining cholera deaths. The number of observations (15) did not allow enough degrees of freedom to fit a model with all climate and socioeconomic variables, but it is certainly worth gathering a longer series of those variables for future analyses. It was also found that cholera deaths are dependent on the number of cholera cases, that is, the higher the number of cases the higher the number of deaths (i.e. the exposure variable is number of cases). The results were statistically significant and exhibited the expected sign for GDP per capita (negative), but also a negative relationship between rainfall (or temperature) and cholera deaths. It may be the case that climate variables have an impact on cholera cases, but do not affect the case fatality rate; the latter might be more related to socioeconomic health conditions.

In order to investigate such claim a linear regression analysis was developed associating deaths with cholera cases while controlling by real income per capita and percentage of the population with water cover. These models presented the expected signs and statistical significance. Cholera deaths increase with cholera cases and decrease when income and the percentage of the population covered with safe water increase. One extra case of cholera in Tanzania is associated with an extra 0.081 deaths when controlling for income and 0.077 when controlling for safe water cover.

These models allow us to forecast the number of cholera deaths associated with estimates of income as well as the number of cholera cases in a scenario where temperatures increase due to climate change. The number of cholera cases can be predicted using the Poisson models associating cholera cases with marginal increases in temperature.

3.1.3 Morbidity and Mortality Related to Cholera Attributable to Climate Change

In this section we analyze the impacts of a temperature increase of 1 to 2 degree Celsius on the burden of cholera, with focus on cases and deaths, in Tanzania by year 2030.

The number of cases attributable to climate change by 2030, $Cases_{2030cc}$, is equal to the number of cases in Scenario C_1 minus the number of cases in Scenario C_0. The scenarios are characterized as outlined in section 2 on methodology.

$$Cases_{2030cc} = cases_{C_1} - cases_{C_0} \tag{3}$$

The number of cases in each of the scenarios is estimated from the number of projected population year 2030 multiplied by the risk ratio of cholera. The risk ratio varies between the scenarios. For the Scenario C_0 an initial risk ratio of 0.0019 is estimated, based on the WHO projected burden of disease, and for Scenario C_1, an additional risk ratio attributed to climate change is added to the initial risk ratio. The additional risk ratio is estimated from the relative risk ratio calculated based on the econometric estimations presented in section 2.1.3. The risk ratio of having cholera for each of the scenarios is presented in Table 1, including for 1 and 2 degree Celsius increase in temperatures by year 2030, respectively.

Table 1. Risk ratios

Scenario year (2030)		Risk ratio
Scenario C_0		
		0.0019
Scenario C_1 (1^oC 2030)		
	Lower	0.0024
	Upper	0.0029
Scenario C_1 (2^oC 2030)		
	Lower	0.0029
	Upper	0.0044

The table presents the risk ratios for each of the scenarios. For 2 degree Celsius increase in temperature by 2030, the risk ratio = initial risk ratio (Scenario C_0) * additional risk ratio^2

The figures for the respective risk ratios are relatively low, but since the risk ratio in Scenario C_0 is somewhat small with a baseline risk of getting cholera only on 0.19 percent, the risk ratio is also small for a 1 degree Celsius temperature increase with an increase of 0.05 to 0.1 percentage point for the lower and upper bound. Nonetheless, the upper bound estimates for Scenario C_1 with a 2 degree Celsius temperature increase is more than twice as much as the estimated risk in the baseline Scenario C_0.

The number of additional cholera deaths attributed to climate change by year 2030, $Deaths_{2030cc}$, is equal to the number of deaths estimated for *Scenario* C_1 minus the number of deaths projected for *Scenario* C_0.

$$Deaths_{2030cc} = deaths_{C_1} - deaths_{C_0} \qquad (4)$$

The number of cholera deaths for *Scenario* C_0 is based on the projections in the WHO GBD study, while the number of deaths in *Scenario* C_1 are calculated from the estimated number of cases in *Scenario* C_1, as estimated above, multiplied by a case fatality rate of 0.81 based on the econometric results in section 2.1.3. The results of computed cases and deaths are presented in Table 2 for each of the scenarios. The Table also includes estimates of DALYs, which are explained further below.

Table 2. Projected and estimated burden of cholera disease for the different scenarios

	Scenario C_0 2030[7]	Scenario C_1 (1^oC 2030)		Scenario C_1 (2^oC 2030)	
		Lower	Upper	Lower	Upper
cholera cases	145,174	178,564	219,213	219,634	331,011
additional cases		33,390	74,039	74,460	185,837
cholera deaths	11,759	14,464	17,756	17,790	26,812
additional deaths		2,705	5,997	6,031	15,053
DALYs	554,691	682,275	837,590	839,199	1,264,761
additional DALYs		127,584	282,899	284,507	710,070

[7] Based on global burden of disease studies, the WHO predicts an increase in diarrheal incidences of 5 percent per degree Celsius increase in temperatures (Campbell-Lendrum and Woodruf 2007). This would result in a number of 7,259 additional cases and 588 additional deaths from cholera attributed to climate change in Tanzania by year 2030. These much lower estimates are, however, based on case studies from Peru (Checkley et al. 2000) and Fiji (Singh et al. 2001) and for diarrheal diseases as an aggregate estimate.

Scenario C_0 is based on the WHO projection for Sub-Saharan Africa. For Scenario C_1, results are presented for the lower and upper bounds and for a 1 and 2 degree Celsius temperature increase, respectively.

The total number of cases will consequently increase from the projected 145,174 cases to 331,011 with an additional number of 185,837 cases for the upper bound scenario and with a 2 degree Celsius temperature increase by year 2030. For the more moderate scenario with only 1 degree Celsius increase in temperature, still with the upper bound scenario, the additional number of cases will be 74,039. For the most moderate scenario, lower bound and 1 degree Celsius increase in temperature, the additional number of cases attributed to climate change will be 33,390. In regard of deaths, the numbers will increase from the projected 11,759 deaths to 26,812 for the upper bound scenario with a 2 degree Celsius temperature increase. This is equal to an additional 15,053 deaths attributable to climate change. For the most moderate scenario, the additional number of deaths is limited to 2,705.

3.1.4 Disability from Cholera Attributed to Climate Change

Studies that examine associations between climate variables and human health often use additional cases and/or deaths as the main indicator of impact to health. However, in some cases the fatality rate is low or even decreasing with time although the risk ratio is constant or increasing. This is especially true for a developed country but also for developing countries with increasing GDP and thereby increasing health sector development. It may be that incidence rate is dependent on climate variables while case fatality rate is mainly dependent on socio-economic variables (which are also evident from the econometric results above). Therefore, it is considered appropriate to use estimates of DALY to supplement the comparison of estimated deaths and illness in the different scenarios. DALY combines years of life lost (YLL) from premature death, and years of life lived with disabilities (YLD), and is commonly used as an index for comparison of health in studies of disease (Mathers and Loncar, 2005). DALY is calculated as the sum of YLL and YLD:

$$DALY = YLL + YLD \tag{5}$$

where $YLL = N_D * E_X$, N_D is number of deaths, and E_X is life expectancy at age of death. *YLD* is estimated as $YLD = I * DW * L$, where I is total number of episodes, *DW* is disability weight, and *L* is duration of each episode.

To estimate the disease burden, data are needed on number of cases, the demographic distribution of deaths, and duration of episodes, life expectancy, and the disability weight for cholera. The number of cases is available for each scenario as presented in Table 2. WHO estimate the distribution of diarrhea between age groups in sub-Saharan Africa. We assumed that this distribution is the same for Tanzania, and that the age distribution for cholera is equal to that of diarrhea. For each age group, average YLL are calculated for a life expectancy at birth of 63.8 years (both sexes combined) by year 2030 (UN 2008). Disability weight captures valuation of time lived in a non-optimal health state viewed from societal preferences. The disability weight ranges between 0 (health condition is equivalent to full health) and 1 (health condition is equivalent to death) and the disability weight associated with each health condition is fixed across all social, cultural and environmental contexts (Lopez et al., 2006). The use of disability weight for diarrhea range between 0.02–0.12 (WHO, 2008) and an average 0.07 is used for the estimations in this paper assuming that it would be in the same range for cholera. The estimated DALY's lost from cholera attributed to climate change are presented in Table 2 and the additional number of DALYs ranges between 127,584 and 710,070.

DALY estimates can be valuable for estimating the mean costs of preventive measures per DALY avoided by following the cost-effectiveness approach and reporting the results in terms of DALYs averted for each dollar invested for various interventions.

3.2 Estimation of Health Adaptation Costs

Preventive measures, which in the case of cholera are considered mainly as hygiene, water and sanitation programmes, are assumed to be initiated and implemented in line with general socio-economic development in Tanzania and the national goals of nearly universal water and sanitation coverage by year 2025. These programmes are established outside the health sector, but nevertheless bring large health benefits along with other domestic and productivity benefits in terms of time savings for water collection, increased time for education and leisure activities, and benefits to agricultural and income generating activities (Sanctuary et al., 2005). The impact from climate change on health will lead to increasing benefits from such programmes and, likely, there will be an increase of benefits in terms of saved lives and reduced morbidity, with more rapid implementation of preventive measures which are already planned. Based on these considerations, the following section outlines the computation of the costs of the residual cholera incidences attributable to climate change which remains after preventive measures are in place. Two valuation metrics are used: cost of treatment, as a reactive adaptation measure, and a value attached to the increased mortality. Costs are calculated using constant 2006 US$.

3.2.1 Reactive Adaptation Cost Estimation

The residual impacts are treated with reactive measures and for this purpose cost estimates of managing a cholera patient admitted in a hospital have been collected at the Ministry of Health, Tanzania. Cholera patients are not treated as outpatients, they are isolated in a special cholera ward or unit during treatment. Treatment is on average 5 days per case and includes infusions, oral rehydration salt, and antiseptics. In addition to treatment of the cholera patient, people who had contact with cholera patients are under surveillance for 5 days and given preventive treatment/therapy, and are thereby treated as outpatients. The total cost per case of managing a cholera admitted patient including treatment, cost of bed, personnel, and outpatient surveillance is 98 US$(2006). It is assumed that all residual cases are treated with reactive measures. The total costs of reactive measures represent the residual costs of climate change impacts in terms of treatment costs. Ideally, the estimates do not represent the total value of the additional costs of climate change since loss of productivity should be included to estimate direct total cost of illness (costs of treatment, plus loss of productivity).

The estimated residual economic costs of treatment of cholera attributed to climate change are presented in Table 3. The results show that the ratio of additional costs of reactive adaptation to GDP is relatively small with a share of less than 0.1 percent for the upper bound scenario and 2 degree Celsius temperature increase. These estimates, however, only take into account morbidity, and therefore the next section provides estimates of the economic losses from loss of lives due to cholera attributed to climate change impacts.

Table 3. Costs of projected morbidity impacts by year 2030

Scenario		Additional cases	Cost per case, US$	Total cost of reactive measures, US$	Total cost of reactive measures/GDP, %
Scenario C_1 (1^{o}C 2030)					
	Lower	33,390	98	3,272,221	0.02
	Upper	74,039	98	7,255,795	0.04
Scenario C_1 (2^{o}C 2030)					
	Lower	74,460	98	7,297,054	0.04
	Upper	185,837	98	18,212,046	0.09

The share of total cost of reactive measures of GDP in Tanzania by year 2030 has been calculated on the basis of GDP projections for annual GDP growth rates for Sub-Saharan Africa (Mathers and Loncar, 2005).

3.2.3 Cost of lost short term productivity

For estimating cost of cholera in Tanzania, the cost of productivity losses is calculated from wages and days out of work. For wages, a weighted average is estimated from the Integrated Labor Force Survey 2006 (URT 2007), including average wages for self employed and employees. Nearly 90 percent of the population is employed, where of 87.7 percent of this work force are self-employed, while the remaining share of the employed population are formal employees. Even people not formally employed would still contribute to economic activities and therefore a wage corresponding to an agricultural workers wage is applied as a proxy to estimate losses of the unemployed population share. Also for the cases among children it is most likely that an adult will spend time away from work to take care of the sick child and hence withdraw time from productive activities. Therefore, it is assumed in the following estimations that all cases of cholera will result in lost productivity corresponding to weighted wages from five working days, equal to the average number of days of hospitalization for a cholera case. The calculated weighted average productivity loss per case is hence 9.7 US$.

Table 4. Lost productivity per case and for additional cholera cases attributed to climate change by year 2030 in Tanzania for each scenario respectively

Scenario		Additional cases	Productivity loss per case, US$	Total cost of productivity losses, US$
Scenario C_1 (1^{o}C 2030)				
	Lower	33,390	9.7	325,264
	Upper	74,039	9.7	721,241
Scenario C_1 (2^{o}C 2030)				
	Lower	74,460	9.7	725,342
	Upper	185,837	9.7	1,810,307

Table 4 present the results of productivity losses for the respective scenarios. The productivity losses account for approximately 9 percent of total cost of illness for each of the scenarios. This result corresponds to previous estimates for malaria in South Africa which show loss of productivity to account for 8 percent of cost of illness (Turpie et al., 2002).

3.2.3 Cost of Mortality

Efficient treatment of cholera reduces risk of mortality with 80 percent (WHO, 2008b). In previous sections, the effect from treatment of cholera is included in the estimations of number deaths caused by cholera since the WHO baseline, Scenario C_0, includes a variable on impacts of technological change on health status. This variable captures the effect of knowledge and technological development on the implementation of more cost-effective health interventions, including both preventive measures (Mathers and Loncar, 2005). Therefore, in order to estimate incremental costs of mortality, number of deaths and the value of statistical life (VOSL) of 103,344 US$ are included in the estimation of total cost of cholera attributed to climate change. This VOSL is based on the ratio of real per capita GDP, in this case for Tanzania, and adjusted to GDP in the US. By using real GDP it will take into account the purchasing power of the country, in this particular case Tanzania. The VOSL method broadly measures the individual willingness-to-pay to reduce the risk of death and have been used widely in the environmental economics literature to value mortality impacts (Markandya, 1998). The total additional cost of cholera deaths attributed to climate change can be measured from

$$Cost_d = deaths_{2030cc} * VOSL \ , \qquad (6)$$

where $Cost_d$ is total residual cost of cholera deaths attributable to climate change. $deaths_{2030cc}$ is the additional number of deaths from cholera attributable to climate change by year 2030 as estimated in section 3.1.4 based on the econometric analysis, and lastly, VOSL is assumed equal to 103,344 US$ as described above. There exist a number of ways to calculate the value of mortality (and morbidity estimated as DALY in previous section). Nonetheless, there is no agreement on these values, and some have argued for much higher figures than the VOSL applied above. Bosello et al. (2006) for example, take a value per life lost of 200 times per capita income, which would give a value of life around US$1 million for South Africa. This value is almost ten times the estimate which Turpie et al. (2002) calculated for South Africa and in comparison to the VOSL applied above for Tanzania.

Table 5. Costs of projected mortality impacts by year 2030

Scenario	no. of additional deaths	VOSL, US$	total costs of residual deaths, US$	total cost of residual deaths/GDP, %
Scenario C_1 (1°C 2030)				
Lower	2,705	103,344	279,503,272	1.38
Upper	5,997	103,344	619,768,124	3.06
Scenario C_1 (2°C 2030)				
Lower	6,031	103,344	623,292,296	3.08
Upper	15,053	103,344	1,555,617,991	7.68

The share of total cost of residual deaths of GDP in Tanzania by year 2030 has been calculated on the basis of GDP projections for annual GDP growth rates for Sub-Saharan Africa (Mathers and Loncar, 2005).

Table 5 display the results of costs attributed to deaths caused by the increasing number of cholera cases. The share of total cost of residual deaths relative to GDP is considerably larger than the burden of morbidity as estimated in previous section and evidence of a large health cost of deaths attributed to climate change impacts.

3.3.3 Total Cost of Cholera Attributed to Climate Change by 2030

The total additional economic costs of cholera attributed to climate change are calculated as the sum of total cost of treatment of residual cases, loss of productivity and the total cost of residual deaths from cholera attributed to climate change. The results are presented in Table 6.

Table 6. Total costs of cholera attributed to climate change by year 2030

Scenario	Total cost of reactive measures, US$	Total costs of productivity loss, US$	Total cost of residual deaths, US$	Total cost of cholera attributed to climate change, US$	Total cost of cholera attributed to climate change/GDP, %
Scenario C_1 (1°C 2030)					
Lower	3,272,221	325,264	279,503,272	283,100,757	1.40
Upper	7,255,795	721,241	619,768,124	627,745,160	3.10
Scenario C_1 (2°C 2030)					
Lower	7,297,054	725,342	623,292,296	631,314,692	3.12
Upper	18,212,046	1,810,307	1,555,617,991	1,575,640,344	7.78

The share of total cost of GDP in Tanzania by year 2030 has been calculated on the basis of GDP projections for annual GDP growth rates for Sub-Saharan Africa (Mathers and Loncar, 2005).

The costs of cholera attributed to climate change ranges between 1.4 and 7.8 percent of GDP by 2030. The upper bound for the 1 degree Celsius scenario and the lower bound estimate for the 2 degrees Celsius scenario lie around 3.1 percent of GDP. This is a considerable share of GDP, bearing in mind that the full health costs of climate change would be much larger if taking into account other health variables affected by climate change such as other water-borne diseases besides cholera (e.g. diarrhea, typhoid), malnutrition, food-borne (e.g. Salmonella) and vector-borne diseases (e.g. malaria, dengue).

In order to compare these costs with the costs of prevention we look at the number of DALYs avoided as an estimate of the cost per DALY avoided is available in the literature (Clasen et al, 2007). Table 7 displays the cost ranges of water quality interventions for preventing cholera. These estimates are evidence of considerable benefits of preventive measures in comparison to the total costs of cholera attributed to climate change in Tanzania in year 2030 as reflected in Table 6.

Table 7. Costs of preventive adaptation measures in terms of cost per DALY averted and the total cost estimates of averted DALY's attributed to climate change impacts in Tanzania by year 2030

Scenario	Additional number of DALY's	Cost per DALY averted, US$	Total cost range to avoided DALY, US$
Scenario C_1 (1°C 2030)			
Lower	127,584	59 -137	7,544,042 - 17,507,076
Upper	282,899	59 -137	16,727,818 - 38,819,401
Scenario C_1 (2°C 2030)			
Lower	284,507	59 -137	16,822,899 - 39,040,051
Upper	710,070	59 -137	41,986,439 - 97,435,805

The cost range per DALY averted is based on Clasen et al. (2007) where a cost of 59 US$ is for household chlorination and 137 US$ is for improvements of the water source such as dug wells, boreholes and stand posts.

4. Discussion

This paper is the first study to link cholera incidences to environmental and socioeconomic factors and using it for predicting climate change impacts to cholera. Climate variables have a significant impact on the occurrence of cholera and will significantly affect the burden of cholera attributable to climate change. The results presented in this paper are in accordance to what would be expected given the previous evidence on linkages between environmental risk factors and health indicators, including diarrheal diseases. Other studies have analysed the relationship between cholera and environmental factors (Fernández et al., 2009) and linkages between incidence of diarrheal diseases as an aggregate measure and environmental and socio-economic factors (Singh et al., 2001; Koelle et al., 2005; Checkley et al., 2000; Wang et al., 2009). For a waterborne disease, the figures presented in this paper look quite high in comparison to the 8 to 16 percent increase in the initial risk of diarrheal diseases by year 2030, as predicted by WHO (2008a) for Sub-Saharan Africa. However, Wang et al. (2009) predict an increase in diarrheal incidences in the range of 0.6 percentage point for a 1 degree Celsius increase in temperatures for South Arica. The estimates presented in this paper predict an increase of 0.05 – 0.1 percentage point for a 1 degree Celsius increase in temperatures for Tanzania.

The cost estimates used for reactive adaptation are based on unpublished data from Ministry of Health in Tanzania. These costs are considerably higher than the costs of treating diarrhea since diarrheal patients can be treated as outpatients while treatment of cholera has to include hospitalization for an average of 5 days per case and also include cost of surveillance of other people than the patient. In Zambia, inpatient average costs for diarrhea are estimated as 78 US$(2006) per bed day (Chola and Robberstad, 2009), while for Tanzania, inpatient costs are estimated in the range of 3.40 – 11.86 US$(2006) per day (Flessa, 1998). The latter figures correspond well to the cost figures provided by

Ministry of Health in Tanzania on 98 US$(2006) for 5 days of hospitalization. For South Africa, the additional treatment cost of diarrheal cases attributed to climate change by year 2020 is estimated to be equivalent to a 0.2 – 0.52 percent share of GDP (Wang et al. 2009). On this basis, the reactive costs of additional cases of cholera in Tanzania by year 2030 in the range of 0.02 – 0.09 percent share of GDP do not seem unreasonably high.

The results presented in this study have two main limitations. Firstly, the econometric data analysis is based on aggregate monthly and annual measures, and therefore it is likely that with more time-specific data available on health and climate variables, the result could show even stronger impacts. The impacts from climate variability on burden of disease from cholera are complex and dependent on a number of risk factors from local socio-environmental conditions. Nevertheless, the results still provide robust evidence on the implications of climate variability to cholera and to the health sector in terms of costs of additional cases and related deaths. The second limitation is related to the projected number of cases and deaths for the baseline, which are estimated from WHO Global Burden of Disease study (WHO, 2008a). This projection includes projections for diarrheal diseases as an aggregate measure for Sub-Saharan Africa by 2030. The WHO projections are not released at country levels but, nonetheless, the regional projections should provide a reasonable guide to future trends for countries in the respective regions. Based on this, the share of cholera deaths from diarrheal deaths is calculated using Tanzania average share of deaths caused by cholera in respect to diarrheal deaths from WHO epidemiological reports 2003-2009 (WHO, 2003-09).

The implications of the results presented in this paper for future studies suggest that climate change will cause large additional economic burdens to societies and to households. Consequently, it is vital to quantify the burden of disease attributable to climate change at national and local levels opposed to regional levels since the human health vulnerability to climate change, in terms of exposure (environmental variables) and capacity to cope (socioeconomic variables), may vary considerably between time and place. Therefore more and improved projections of future risks are necessary for local (national) decision making in addition to further efforts to refine national costs of preventive and reactive adaptation measures in the health sector.

5. Concluding Remarks

The association of temperatures and cholera cases and deaths remains significant also when controlling for socioeconomic factors. The risk ratio showed to increase with rising temperatures, while the case fatality rate proves to be more related to socioeconomic health conditions than to climate variables. Integrating both climate variables and socioeconomic variables in one model confirm that human health conditions are influenced by many factors and cannot be addressed in isolation. Increase in income and access to safe water proved to reduce the cholera case fatality rate. The results of these effects in relation to the impacts of climate change suggest that it would turn out very beneficial to improve socioeconomic indicators, including access to water and sanitation, even more quickly than originally planned. There is unquestionably a wide array of other benefits for improving performance on these indicators, since they influence on a number of other development objectives such as nutrition and education. Also, the estimates of costs of preventive measures evidence of considerable benefits of water quality improvements programmes such as household chlorination in comparison to the costs of reactive adaptation measures.

The estimations, based on assumptions of climate change projections, suggest that the cholera health cost of increased temperatures of 1 to 2 degree Celsius by year 2030 will be in the range of 0.02 to 0.09 percent of GDP for treatment cost alone (cost of reactive adaptation), while total additional cost attributed to climate change, including the value of loss of lives, would likely be around 3.1 percent, but possibly as much as 7.78 percent of GDP by 2030 for the upper bound. The magnitude of these cost estimates of additional cases of illness resulting from climate change are substantial, and considerably higher than the current budgets allocated for diarrheal diseases in most developing countries. Thus budgetary increases will be needed if treatment is to be provided to deal with the additional cases which are not avoided through preventive adaptation measures.

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Annex 1: Econometric results

A1) Poisson model – monthly data: cholera cases

```
Poisson regression                                Number of obs   =         84
                                                  Wald chi2(2)    =      17.18
                                                  Prob > chi2     =     0.0002
Log pseudolikelihood =  -22523.21                 Pseudo R2       =     0.2418
------------------------------------------------------------------------------
             |               Robust
    chocases |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     maxtemp |   .4146464   .1010562     4.10   0.000       .21658    .6127129
       trend |   .0081052   .0059336     1.37   0.172    -.0035244    .0197349
       _cons |  -23.54482   3.030775    -7.77   0.000    -29.48503   -17.60461
  population | (exposure)
------------------------------------------------------------------------------
Poisson regression                                Number of obs   =         84
                                                  Wald chi2(2)    =      17.18
                                                  Prob > chi2     =     0.0002
Log pseudolikelihood =  -22523.21                 Pseudo R2       =     0.2418
------------------------------------------------------------------------------
             |               Robust
    chocases |        IRR   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     maxtemp |   1.513835   .1529824     4.10   0.000     1.241822    1.845431
       trend |   1.008138   .0059819     1.37   0.172     .9964818    1.019931
  population | (exposure)
-------------+----------------------------------------------------------------
```

A2) Poisson model – annual data: cholera cases

```
Poisson regression                                Number of obs   =         28
```

```
                                                  Wald chi2(3)    =   13124.16
Log pseudolikelihood = -538.40245                 Prob > chi2     =     0.0000

------------------------------------------------------------------------------
             |               Robust
   chodeaths |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     maxtemp |   .2093469   .0057727    36.27   0.000     .1980327    .2206611
  realgdpcap |  -.0017584   .0002964    -5.93   0.000    -.0023393   -.0011776
    chocases |   .0001334   5.83e-06    22.86   0.000      .000122    .0001448
------------------------------------------------------------------------------

Poisson regression                                Number of obs   =         28
                                                  Wald chi2(3)    =   13124.16
Log pseudolikelihood = -538.40245                 Prob > chi2     =     0.0000

------------------------------------------------------------------------------
             |               Robust
   chodeaths |        IRR   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     maxtemp |   1.232873   .0071169    36.27   0.000     1.219002    1.246901
  realgdpcap |   .9982431   .0002958    -5.93   0.000     .9976635    .9988231
    chocases |   1.000133   5.83e-06    22.86   0.000     1.000122    1.000145
------------------------------------------------------------------------------
```

A3) Poisson model – annual data (panel of regions): cholera cases

```
Random-effects Poisson regression               Number of obs      =       119
Group variable: geocode                         Number of groups   =        17
Random effects u_i ~ Gamma                      Obs per group: min =         7
                                                               avg =       7.0
                                                               max =         7
```

```
                                                Wald chi2(2)      =   3436.88
Log likelihood  =  -25843.85                    Prob > chi2       =    0.0000
------------------------------------------------------------------------------
    chocases |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     maxtemp |   .4160645   .0148765    27.97   0.000      .386907     .445222
        year |   .1060606   .0028807    36.82   0.000     .1004146    .1117065
       _cons |  -218.0686   5.634782   -38.70   0.000    -229.1126   -207.0246
-------------+----------------------------------------------------------------
    /lnalpha |   .4582582   .2914785                     -.1130292    1.029546
-------------+----------------------------------------------------------------
       alpha |   1.581317     .46092                      .8931246    2.799793
------------------------------------------------------------------------------
Likelihood-ratio test of alpha=0: chibar2(01) =  2.5e+04 Prob>=chibar2 = 0.000

Random-effects Poisson regression               Number of obs      =       119
Group variable: geocode                         Number of groups   =        17
Random effects u_i ~ Gamma                      Obs per group: min =         7
                                                               avg =       7.0
                                                               max =         7
                                                Wald chi2(2)      =   3436.88
Log likelihood  =  -25843.85                    Prob > chi2       =    0.0000
------------------------------------------------------------------------------
    chocases |        IRR   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     maxtemp |   1.515984   .0225526    27.97   0.000      1.47242    1.560837
        year |   1.111889    .003203    36.82   0.000     1.105629    1.118185
-------------+----------------------------------------------------------------
    /lnalpha |   .4582582   .2914785                     -.1130292    1.029546
-------------+----------------------------------------------------------------
```

```
       alpha |   1.581317     .46092                      .8931246    2.799793
------------------------------------------------------------------------------
Likelihood-ratio test of alpha=0: chibar2(01) =  2.5e+04 Prob>=chibar2 = 0.000
```

A4) Linear (OLS) models – annual data: cholera deaths

```
Linear regression                                      Number of obs =      28
                                                       F(  2,    25) =   12.89
                                                       Prob > F      =  0.0001
                                                       R-squared     =  0.8099
                                                       Root MSE      =  192.98
------------------------------------------------------------------------------
             |               Robust
   chodeaths |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    chocases |   .0815743   .0175598     4.65   0.000     .0454093    .1177394
  realgdpcap |  -.7438819    .204264    -3.64   0.001    -1.164572   -.3231923
       _cons |   381.4173   91.52764     4.17   0.000     192.9126     569.922
------------------------------------------------------------------------------

Linear regression                                      Number of obs =      15
                                                       F(  2,    12) =    9.57
                                                       Prob > F      =  0.0033
                                                       R-squared     =  0.8295
                                                       Root MSE      =   234.4
------------------------------------------------------------------------------
             |               Robust
   chodeaths |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    chocases |   .0779042   .0193398     4.03   0.002     .0357665    .1200418
```

```
  watercover |  -4925.379    1516.12    -3.25   0.007     -8228.72   -1622.038

       _cons |    2628.87    790.597     3.33   0.006      906.307    4351.433

------------------------------------------------------------------------------
```

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