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CLIMATE CHANGE

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Climate Change

THE ECONOMIC IMPACT OF CLIMATE CHANGE IN THE 20TH AND 21ST CENTURIES

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Abstract

The national version of FUND3.6 is used to infrapolate the impacts of climate change to the 20th century and extrapolate to the 21st century. Carbon dioxide fertilization of crops and reduced energy demand for heating are the main positive impacts. Climate change had a negative effect on water resources and, in most years, human health. Most countries benefitted from climate change until 1980, but after that the trend is negative for poor countries and positive for rich countries. The global average impact was positive in the 20th century. In the 21st century, impacts turn negative in most countries, rich and poor. Energy demand, water resources, biodiversity and sea level rise are the main negative impacts; the impacts of climate change on human health and agriculture remain positive until 2100.

Key words

economic impact; climate change; 20th century; 21st century; backcast; forecast

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1. Introduction

There is a substantial literature about the future impacts of climate change (Cline 1992b;Fankhauser 1995;Mendelsohn et al. 2000;Nordhaus 1991;Tol 2002a); see (Tol 2009b) for an overview. Less is known, however, about the impacts of climate change in the past. While there is no immediate policy relevance of estimates of past effects – as liability is yet to be established (Tol and Verheyen 2004) – such estimates would serve to validate models of future impacts – and thus help to improve these models and build confidence. In this paper, I turn this question on its head. I use a model to backcast past impacts, thus generating hypotheses to be tested against observations.

Unfortunately, there are no direct observations of the economic impact of past climate change. Note that the cause of climate change, past or future, is irrelevant for its impacts. There are, however, some studies that estimate particular aspects of the impact of past climate change, typically focussing on biophysical impacts.

The literature on natural disasters is perhaps most advanced (Barredo 2009;Changnon and Changnon, Jr. 1998;Changnon 2003;Changnon and Changnon 1992;Neumayer and Barthel 2011;Pielke 2005;Pielke et al. 2008;Ryan 2011). These studies typically conclude that trends in the damage done by natural disasters are largely, if not entirely, the result of increases in the number of people and their wealth. It should be noted, though, that these studies rely on ad hoc normalisation rather than multiple regression (Toya and Skidmore 2007).

Estimates of the impact of past climate change on crop yields generally find a significant effect, but one that is small relative to other trends in agriculture; impacts are positive or negative depending on crop and location (Holmer 2008;Lobell et al. 2005;Lobell et al. 2011;Lobell and Asner 2003;Lobell and Field 2007;Myneni et al. 1997;Nicholls 1997;Tao et al. 2006;Tao et al. 2008;Twine and Kucharik 2009;Zhang et al. 2010). Carbon dioxide concentrations vary little over space and only slowly over time, so there is little statistical evidence of its impact on crop yields. Experimental evidence, however, points to a positive impact (Long et al. 2006).

The impact of past climate change on malaria has also been the subject of intense debate (Byass 2008;Chaves and Koenraadt 2010;Craig et al. 2004;Gething et al. 2010;Hay et al. 2002a;Hay et al. 2002b;Loevinsohn 1994;Small et al. 2003;Thomas 2004). Overall, there is agreement that climate change is not the main driver of the spread of malaria; some people argue it has a small effect while others argue the effect is negligible. The story is the same for diarrhoea – another big killer that is sensitive to weather and climate – but there is less evidence (Lloyd et al. 2007). There is empirical evidence for negative health impacts of both heat and cold stress (D'Ippoliti et al. 2010;Martens 1998;McMichael and Dear 2010). The net impact is different across space (EUROWINTER Group 1997) and over time (Carson et al. 2006;Davis et al. 2002;Davis et al. 2003).

Empirical research into the effect of climate change on energy demand resembles that of heat and cold stress: There are many case studies (Giannakopoulos and Psiloglou 2006;Henley and Peirson 1998;Moral-Carcedo and Vicens-Otero 2005;Pardo et al. 2002;Sailor and Munoz 1997), but few multi-country studies (Bessec and Fouquau 2008) and few studies that cover a longer time-period (Considine 2000;Hekkenberg et al. 2009). The latter studies are, of course, best suited for the detection of structural patterns that would allow extrapolation into the future. These studies find that warming would lead to a decrease of energy demand in winter and an increase of energy demand in summer. The relative magnitude of these two opposite effects depends on socio-economic circumstances and the climatic starting point.

Statistical analyses of climate and water resources are typically done for single river basins. There are a few studies that cover a wider area (Kundzewicz et al. 2005;Lindstroem and Bergstroem 2004;Lins and Slack 1999;Svensson et al. 2005). These studies typically conclude that every river responds differently to changes in precipitation and temperature.

In sum, the empirical literature on the impacts of climate change finds mixed effects. Unfortunately, none of these studies aggregates the impacts, so that it is difficult to say whether past climate change was positive or negative. Below, I will use a model, FUND, to answer that question.

The paper proceeds as follows. Section 2 presents the data and the model. Section 3 discusses the results. Section 4 concludes, paying particular attention to the testable hypotheses that emerge from this paper.

2. Data and model

2.1. Data

National data on population and income for 1960-2000 are taken from EarthTrends by the World Resources Institute.[1] For 1900-1960, regional data are from (Maddison 1995). I assumed equal national growth rates within regions. I used HadCRUT3 for the global mean temperature[2] and carbon dioxide concentration from CDIAC[3].

2.2. Model

I use the *Climate Framework for Uncertainty, Negotiation, and Distribution* (*FUND*), version 3.6 in its national resolution. The continental version of *FUND* is a fully integrated model, including scenarios of population, economy, energy use, and emissions; a carbon cycle and simple climate model; and a range of impact models. The national version of *FUND* (Link and Tol 2011) only covers the impacts of climate change – while population etc are as observed for the 20th century and exogenous for the 21st century.

Version 3.6n of *FUND* corresponds to version 1.6 (Tol et al. 1999;Tol 2001;Tol 2002c) except for the impact module described in (Link and Tol 2004;Narita et al. 2009;Narita et al. 2010;Tol 2002a;Tol 2002b) and carbon cycle feedbacks taken from (Tol 2009a). A full list of papers and the technical documentation for the model can be found online at http://www.fund-model.org/. The model code for this paper is at: http://dvn.iq.harvard.edu/dvn/dv/rtol.

The model runs from 1900 to 2100 in time steps of five years. The model is initialised for 1895.

[1] http://earthtrends.wri.org/
[2] http://www.cru.uea.ac.uk/cru/data/temperature/
[3] http://cdiac.ornl.gov/trends/co2/contents.htm

The climate impact module (Tol 2002a;Tol 2002b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, unmanaged ecosystems, and tropical and extra tropical storms. This list of impacts is not exhaustive, but other impacts have yet to be consistently quantified and monetized at the global scale. Climate change related damages can be attributed to either the rate of change (i.e., the annual change in temperature, benchmarked at 0.04°C/yr) or the level of change (i.e., the temperature change since pre-industrial times, benchmarked at 1.0°C). Sectors impacted by climate change also change for other reasons, but the impacts shown below are the impacts of climate change only. Impacts are impacts on welfare, expressed in dollars at market-exchange rates. Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol 2002b).

People can die prematurely due to climate change, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (Cline 1992a). The value of emigration is set to be 3 times the per capita income (Tol 1995). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (Fankhauser 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (Fankhauser 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (Tol 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, in which welfare is maximum. The location of the optimum is determined by a variety of factors, including physiology, infrastructure and behaviour. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from the optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (Tol 2002b).

The impacts of climate change on coastal zones, forestry, tropical and extratropical storm damage, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (Tol 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress (Yohe and Tol 2002). Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term (Tol 2002b). The income elasticities (Tol 2002b) are estimated from cross-sectional data or taken from the literature.

Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population (because of the urban heat island effect and the combination of poverty, isolation and crime). The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per capita income, which are estimated from a cross-section of countries in 1995.

3. Results

Figure 1 shows the global mean surface air temperature and the rate of change. Temperature is averaged over five years, that is, the value for, say, 1900 is the average of 1898-1902. Averaging is needed because the impact model is designed with smooth trajectories of warming in mind. The model does not estimate the impact of annual weather variability; rather, it estimates the impact of secular climate change. The first decade of the 20th century saw cooling, followed by three decades of warming, three decades of volatility, and three decades of warming. The projected warming for the 21st century is smooth.

Figure 1.The level of the (five-year running average) global mean surface air temperature (left axis) and the rate of change (right axis) in the 20th and 21st century.

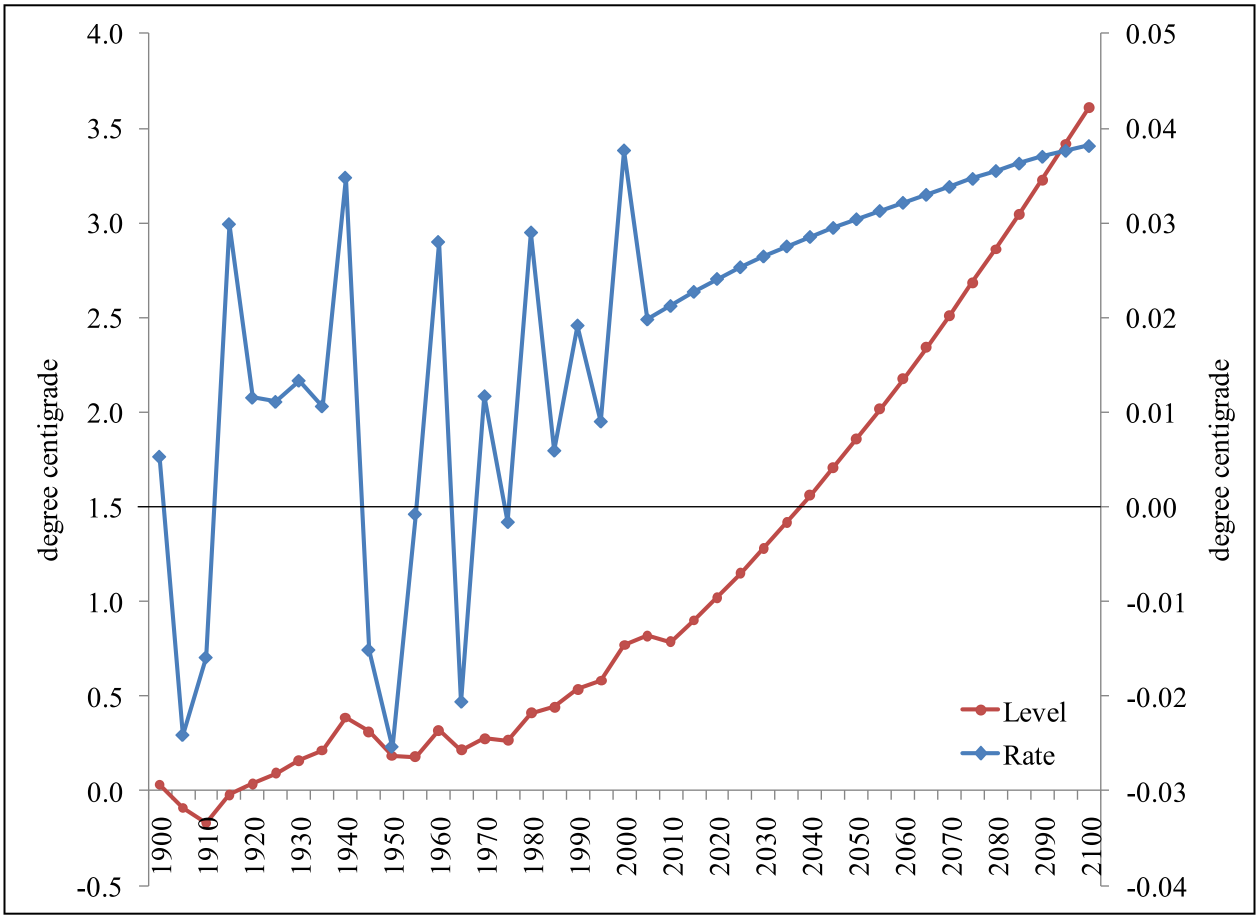


Figure 2 shows the economic impact of climate change, aggregated over countries and over sectors. Note that the results are welfare impacts, rather than changes in economic activity. In the 20th century, the impact is small but positive. Climate change increased welfare by the equivalent of a 0.5% increase in income for the first half of the 20th century. After 1950, impacts became more positive, edging up to 1.4% of GDP by 2000. However, impacts roughly stabilize after that, reaching their maximum at 1.5% of GDP in 2025 and then precipitously fall to reach -1.2% of GDP in 2100.

Figure 2. The global average, minimum and maximum total economic impact of climate change in the 20th and 21st century.

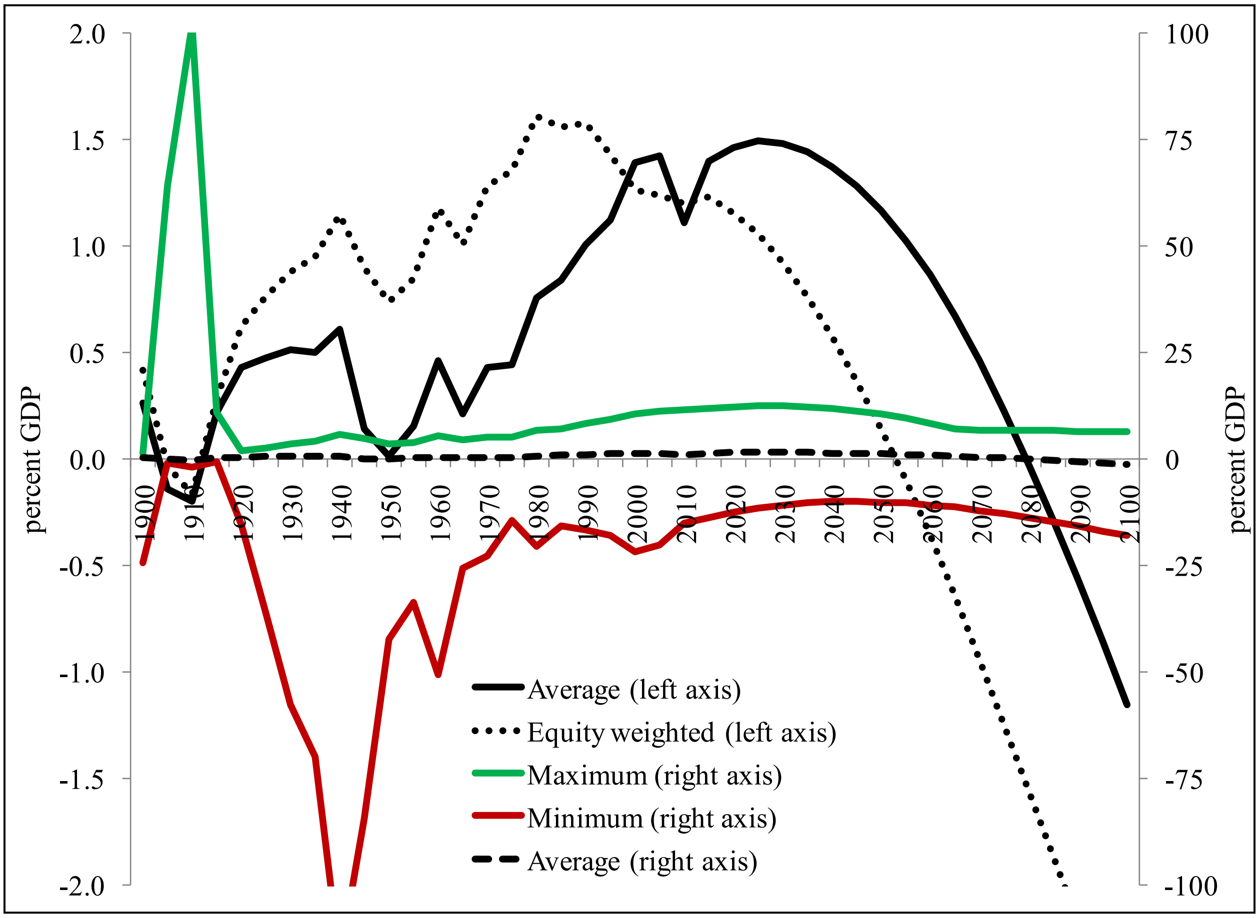
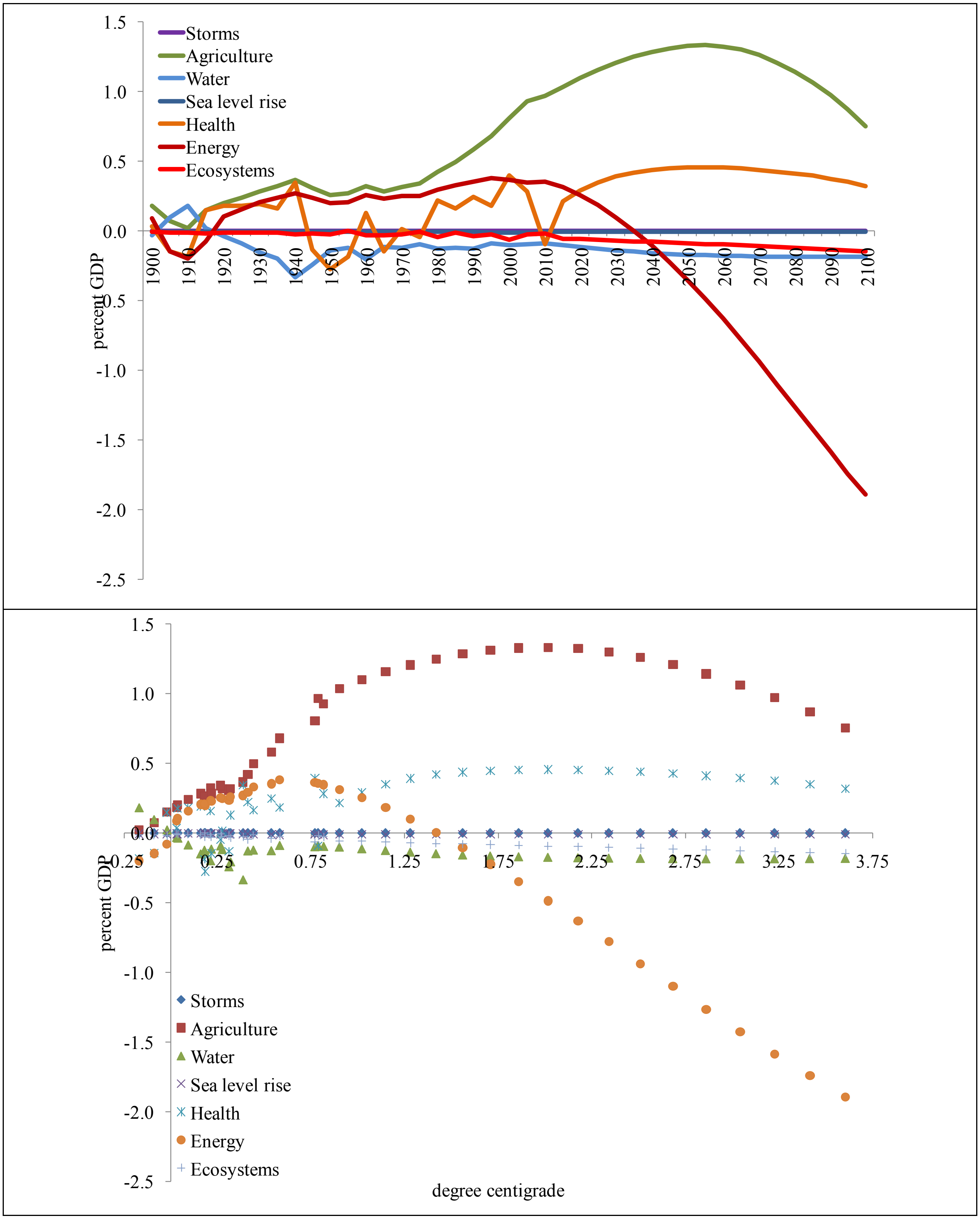


Figure 3 shows the global economic impact of climate change by sector (see Figure 2 for the total). The top panel shows the impact over time, the bottom panel shows the impact as a function of temperature (cf. Figure 1). The impact of climate change through tropical storms is small, in line with the statistical analyses referred to in the introduction. The impact of sea level rise is small too, because sea level rose by only 12 cm over the course of the 20th century. In the 21st century, sea level rise is 61 cm but coastal protection keeps the impacts in check.

Figure 3. The global average sectoral economic impact of climate change in the 20th and 21st century as a function of time (top panel) and temperature (bottom panel).



The aggregate impact of global warming on water resources is negative. The relationship to accumulative warming is roughly linear in temperature in the first half of the 20th century, but the negative effect is alleviated by improved water use efficiency and economic growth[4] in the second half of the 20th century and the 21st century. Impacts are about -0.1% of GDP in 2000 and edge up to -0.2% of GDP. Although the overall impact is negative, national impacts are mixed with some countries benefitting in some periods. Qualitatively, therefore, the model is not inconsistent with the empirical literature reviewed in the introduction.

The health impact of climate change is mixed. Generally speaking, cooling brings net benefits, moderate warming brings both benefits and damages, while larger warming brings net damages. This is because FUND has a number of health impacts, some related to cold and some to heat – see below – and some related to the level of climate change and others to its rate. Furthermore, health impacts depend on the age structure of the population and income (a proxy for health care), while the value also depends on income. The result is the complex pattern shown in Figure 3. By the end of the 20th century, the impact is clearly positive, equivalent to an income gain of 0.4%. Impacts continue to increase slightly till 2055 and then begin to fall to reach 0.3% in 2100.

The impact of global warming on energy consumption is positive during the 20th century. While the demand for cooling in summer increased, this is more than offset by the reduction in the demand for heating in winter. Towards the end of the 20th century, the annual savings on energy amount to almost 0.4% of GDP. The national impacts are mixed, with losses and gains in different places and times, qualitatively corresponding to the literature surveyed above. After 2010, however, the demand for cooling starts to rise rapidly while the reduction in demand for heating levels off. The result is a large negative impact, reaching -1.9% of GDP by 2100.

Agriculture is the biggest positive impact in the 20th century, approaching 0.8% of GDP by 2000. This is entirely due to carbon dioxide fertilization, which makes crops grow faster and more water efficient. The impact of climate change (temperature, precipitation, cloud cover, wind, etc) is actually negative, reaching -0.3% in 2000. Because carbon dioxide fertilization is the dominant effect, impacts are positive for all countries and periods. This is in contrast to the empirical literature reviewed in the introduction – although it should be noted that that literature is limited to crop yields while the results here are for agricultural production. Impacts continue to increase to 1.3% in 2055. After that, impacts begin to fall as carbon dioxide fertilization begins to saturate and the negative impacts of warming grow larger. By 2100, however, impacts are still positive (0.8% of GDP).

Figure 2 shows world aggregate economic impact, which ranges between -0.2 and 1.4% of GDP in the 20th century and between -1.2% and 1.4% of GDP in the 21st century. Figure 2 also shows the maximum and minimum impact across countries.[5] The range is large with high positive impacts (~100%) for the rapid cooling around 1910 and high negative impacts (~-120%) for the

[4] Water is a necessary good. The assumed income elasticity is 0.85, that is, a 10% increase in per capita income leads to an 8.5% increase in the per capita value of water.
[5] Note that Figure 2 shows the worst off and best off countries at each point in time, rather than the worst off and best off countries averaged over the centuries.

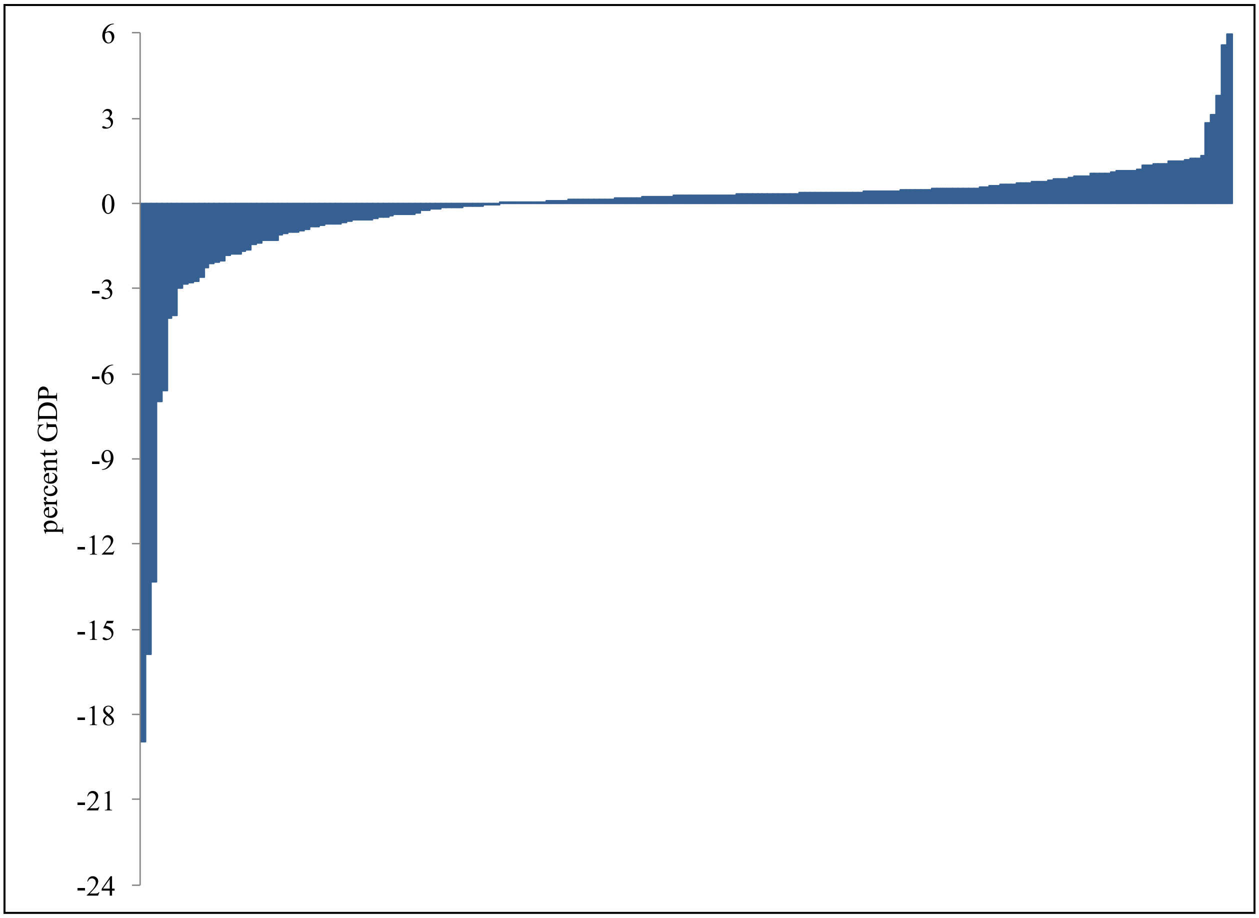
rapid warming around 1940 – health is the main driver of these large impacts (see below). Overall, the maximum and minimum are two orders of magnitude larger (in absolute terms) than the average. In the 21st century, the range of impacts is much narrower. Nonetheless, a lot of variation is hidden by the mean. In 2100, for instance, impacts range from -18% to +6% of GDP – roughly an order of magnitude larger than the mean. This suggests that the variability of the climate in the 20th century drives the distribution of impacts across countries.

Figure 2 further shows the equity-weighted impacts.[6] These are more positive in the 20th century than the non-weighted average, indicating that poorer countries see greater benefits than richer countries – primarily due to carbon dioxide fertilization of agriculture. However, the gap begins to close in 1980 – the maximum impact of climate change occurs 45 years earlier when equity weighted. The equity-weighted impacts fall rapidly to reach -2.8% in 2100.

Figure 4 highlights the differences between countries. It shows the average impact over the century for each of the 207 countries in the model, which ranges from a negative 19% (Timor Leste) to a positive 6.0% (China). Figure 5 shows the same information on the map. Figure 5 also shows the impact for the years 1900, 1950, 2000, 2050 and 2100.

[6] National impacts are weighted with the ratio of world average per capita income and national per capita income. This corresponds to a logarithmic function for individual utility and utilitarian social welfare (Fankhauser et al. 1997).

Figure 4. The net total economic impact of climate change by nation averaged over the 20th century (ranked from highest to lowest).



A number of countries stand out. China benefits most from climate change on average across the 20th century. Agriculture is a big positive, followed by energy use and water resources. Haiti is the second biggest beneficiary. This is entirely due to the positive effects of carbon dioxide fertilization on agriculture. Averaged over the 20th century, each African nation loses out. In the first half of the century, however, there are both winners and losers. The main positive factor is the large impact on agriculture. Negative impacts on health outweigh agriculture in the second half of the 20th century.

Timor Leste is hurt most by climate change on average across the 20th century. This is largely due to the impacts of climate change on poverty-related health problems, particularly diarrhoea and malaria. Bangladesh is the most vulnerable country outside of Africa. It sees relatively large negative impacts on its health, coastal zone, and water resources – which are larger than the positive impacts on agriculture and energy use. Russia also stands out. Although there are large damages due to a climate-change-induced increase in water scarcity, this is more than offset by benefits for energy use, agriculture and human health.

Figure 5. The national total economic impact of climate change in three selected years and averaged over the 20th century; purple: impact > 1% GDP; blue: impact > 0% GDP; yellow: impact < 0% GDP; red: impact < -1% GDP; green: no data.

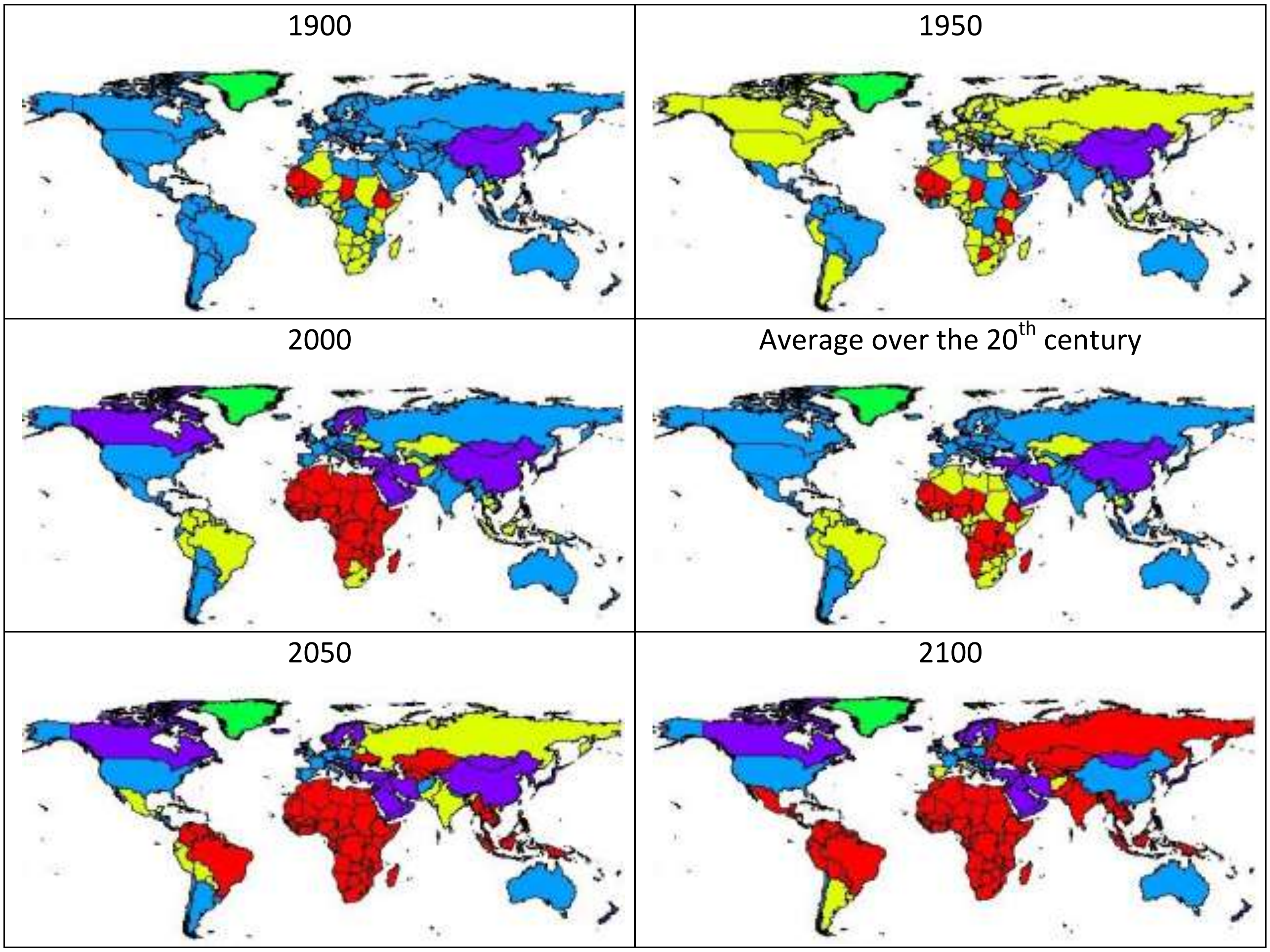


Figure 6 shows the world aggregate health impacts per disease. The total number of premature deaths roughly traces the global mean temperature (cf. Figure 1). The temperature impact on cardiovascular deaths is modelled as a process of acclimatisation, so that the effect does not manifest itself during cooling-after-warming (1945, 1975, 2010). Winter cold dominates summer heat as a health problem. Warming has a negative (positive) impact on respiratory disorders, malaria, dengue fever and diarrhoea (schistomiasis), and the pattern in Figure 6 follows (mirrors) that in Figure 1. Climate change has caused the premature deaths of a substantial number of people over the 20th century – on average 7.5 per million per year. In 2000, according to FUND, 90,000 people died because of climate change. This estimate is roughly equal to the one by (Campbell-Lendrum and Woodruff 2006). In the 21st century, avoided cold-related cardiovascular deaths increase steadily whereas heat-related cardiovascular deaths increase rapidly. Respiratory deaths increase too, but malaria and diarrhoea fall with economic growth and the concomitant improvement in health care.

Figure 6. The global average impact of climate change on mortality by cause of death; the white insets denote total mortality.

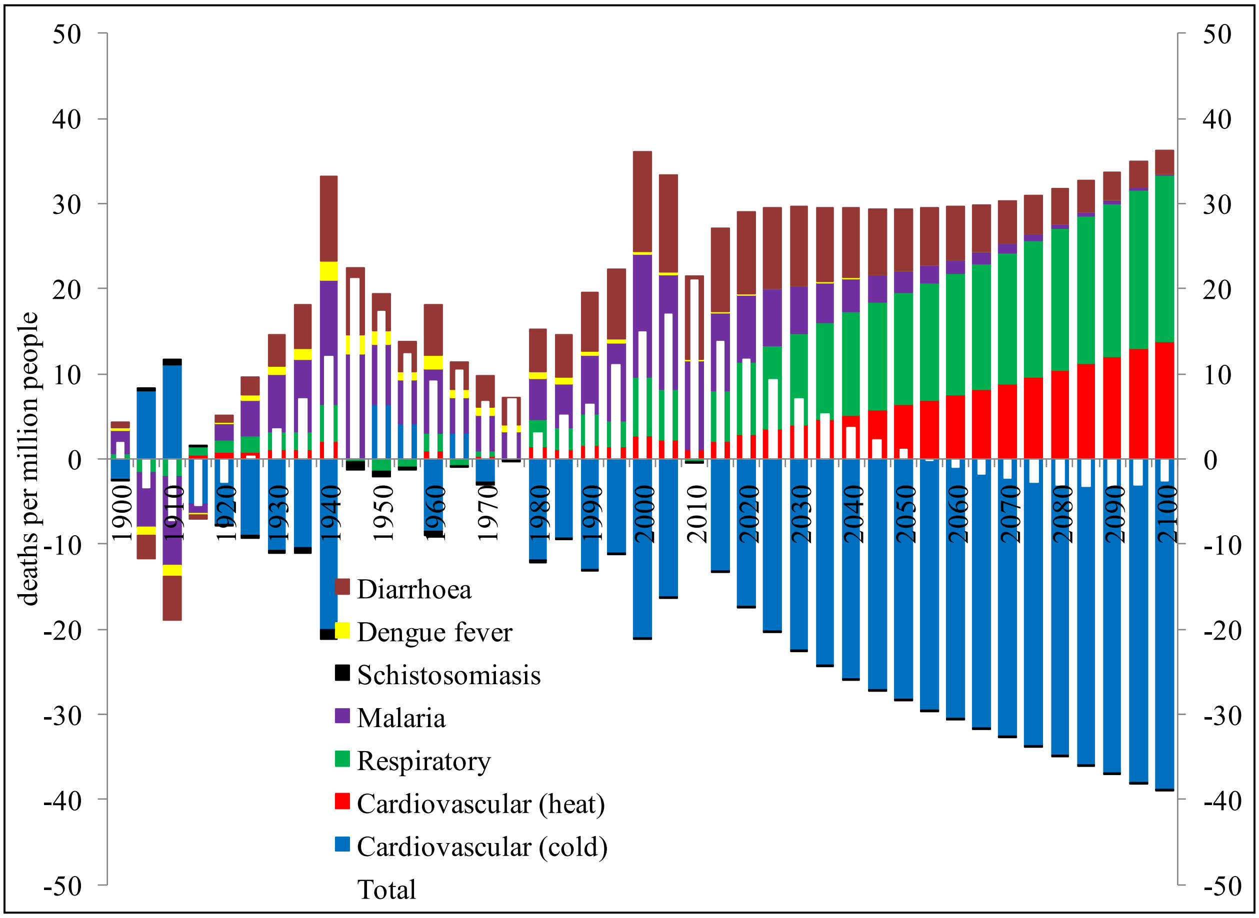
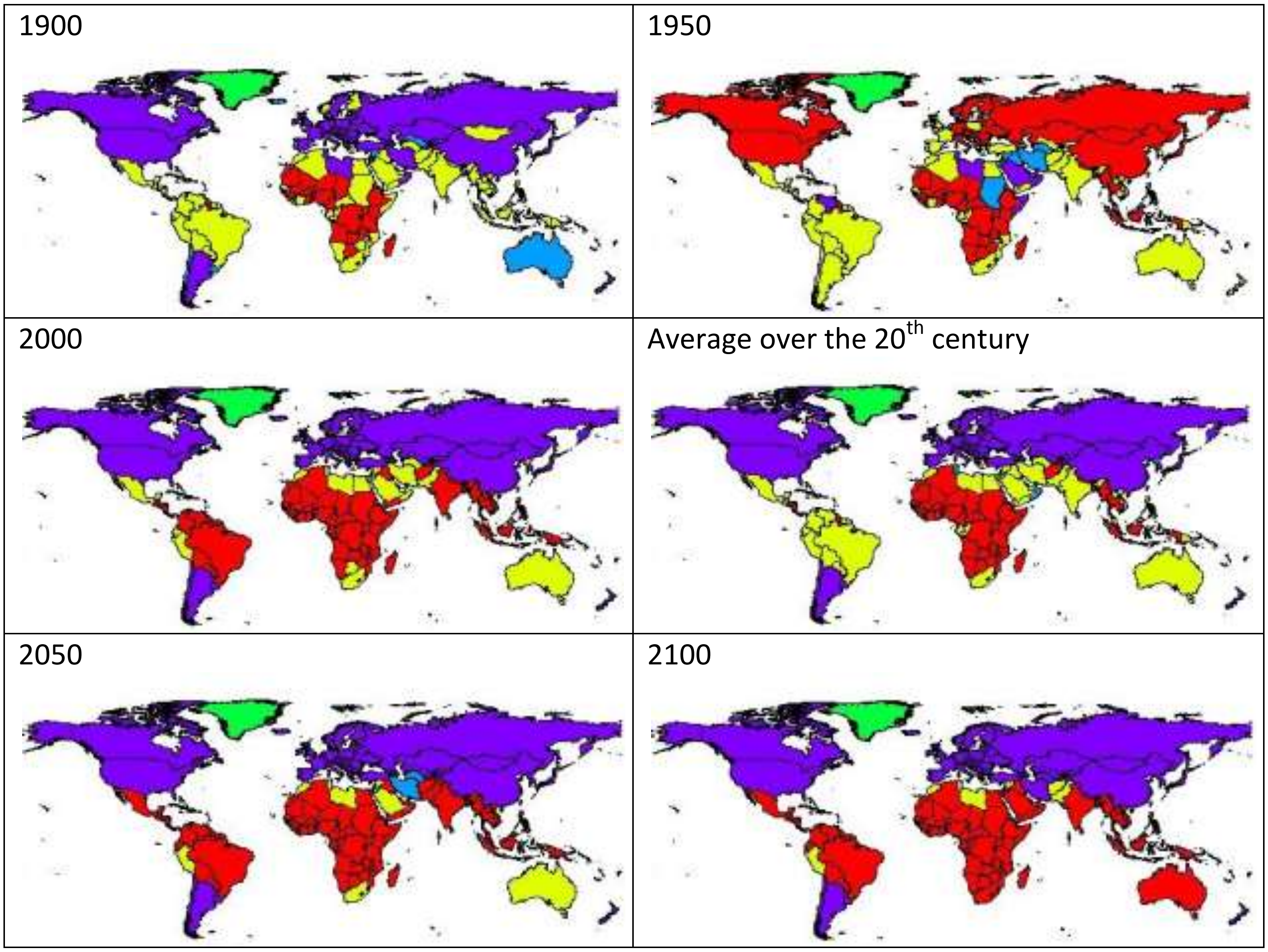


Figure 7 shows the aggregate health impact per country for selected years and averaged over the century. In 1900 and 2000, there are positive impacts in the richer and cooler countries, and negative impacts in poorer and hotter countries. In 1950, negative impacts are widespread. Averaged over the century, there is a clear divide. Rich countries with temperate climates see positive impacts of climate change on health; other countries see negative impacts. This pattern becomes more entrenched in the 21st century.

Figure 7. The national total number of premature deaths due to climate change in three selected years and averaged over the 20th century; purple: impact < -1 per million; blue: impact < 0; yellow: impact > 0; red: impact > 10 per million; green: no data.



4. Discussion and conclusion

Previous studies have found that moderate, future climate change would bring net benefits (Tol 2009b). This study finds that past, moderate climate change brought net benefits. This is no surprise as the current study infrapolates from previous work. Carbon dioxide fertilization of crops and reduced energy demand for heating are the main positive impacts. Climate change had a negative effect on water resources and (by and large) human health. Most rich and most poor countries benefitted from climate change until 1980, but after that the trend is negative for poor countries and positive for rich countries. In the 21st century, impacts turn negative in most countries, rich and poor. Future climate change is a reason for concern.

A number of testable hypotheses arise from these results. Energy demand and agricultural production are relatively well-understood. While statistical analyses have focussed on recent decades for which data are excellent, it should be feasible to use older data to test the impact of climate change. The same should be possible for water resources in at least some parts of the world. For health, data availability would allow for selected case studies only. Care should be taken that like is compared with like. For example, FUND considers agricultural production while empirical studies tend to focus on crop yields.

I briefly reviewed the empirical literature in Section 1. Not surprisingly as FUND is calibrated to that literature, the model backcasts are roughly in line with the data. The impact of climate change on tropical cyclone damages is small in both model and observations. The impact on human health varies but is more often negative than positive in both model and observations. The impact on water resources is predominantly negative in the model, while the observations suggest a mixed impact. The impact on agriculture is predominantly positive in the model, while the observations suggest a mixed impact. The impact on energy use is positive is both model and observations. Note, however, that a direct comparison between the model results and the empirical results is not possible, because coverage and scope are different, and the empirical studies focus on different indicators.

The results for the 20th and 21st century were derived with the same model, and impact patterns are therefore similar. However, the spread of impacts is larger in the 20th century than in the 21st century. This is because climate variability is considered in the 20th century but not in the 21st. This would suggest that the spread of the impacts is underestimated for the 21st century. This result affects not only FUND, but all models of the economic impact of climate change.

The exercise presented here should be repeated with other models of the impact of climate change. Surveys and meta-analyses of the empirical literature on the impact of climate change should be conducted to created indicators that can be directly compared to the model results. This is needed to build confidence in the models that are used to assess the magnitude of the problem of climate change.

References

Barredo, J.I. (2009), 'Normalised flood losses in Europe: 1970-2006', *Natural Hazards and Earth System Science*, **9**, (1), pp. 97-104.

Bessec, M. and J.Fouquau (2008), 'The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach', *Energy Economics*, **30**, (5), pp. 2705-2721.

Byass, P. (2008), 'Making sense of long-term changes in malaria', *The Lancet*, **372**, (9649), pp. 1523-1525.

Campbell-Lendrum, D. and R.Woodruff (2006), 'Comparative risk assessment of the burden of disease from climate change', *Environmental Health Perspectives*, **114**, (12), pp. 1935-1941.

Carson, C., S.Hajat, B.Armstrong, and P.Wilkinson (2006), 'Declining vulnerability to temperature-related mortality in London over the 20th century', *American Journal of Epidemiology*, **164**, (1), pp. 77-84.

Changnon, D. and S.A.Changnon, Jr. (1998), 'Evaluation of Weather Catastophe Data for Use in Climate Change Investigations', *Climatic Change*, **38**, 435-445.

Changnon, S.A. (2003), 'Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming', *Natural Hazards*, **29**, (2), pp. 273-290.

Changnon, S.A. and J.M.Changnon (1992), 'Temporal Fluctuations in Weather Disasters: 1950-1989', *Climatic Change*, **22**, 191-208.

Chaves, L.F. and C.J.M.Koenraadt (2010), 'Climate change and highland malaria: Fresh air for a hot debate', *Quarterly Review of Biology*, **85**, (1), pp. 27-55.

Cline, W.R. (1992a), *Global Warming - The Benefits of Emission Abatement* ,OECD, Paris.

Cline, W.R. (1992b), *The Economics of Global Warming* Institute for International Economics, Washington, D.C.

Considine, T.J. (2000), 'The impacts of weather variations on energy demand and carbon emissions', *Resource and Energy Economics*, **22**, (4), pp. 295-314.

Craig, M.H., I.Kleinschmidt, J.B.Nawn, D.le Sueur, and B.L.Sharp (2004), 'Exploring 30 years of malaria case data in KwaZulu-Natal, South Africa: Part I. The impact of climatic factors', *Tropical Medicine and International Health*, **9**, (12), pp. 1247-1257.

D'Ippoliti, D., P.Michelozzi, C.Marino, F.De'Donato, B.Menne, K.Katsouyanni, U.Kirchmayer, A.Analitis, M.Medina-RamÃ³n, A.Paldy, R.Atkinson, S.Kovats, L.Bisanti, A.Schneider, A.Lefranc, C.IÃ±iguez, and C.A.Perucci (2010), 'The impact of heat waves on mortality in 9 European cities: Results from the EuroHEAT project', *Environmental Health: A Global Access Science Source*, **9**, (1).

Davis, R.E., P.C.Knappenberger, W.M.Novicoff, and P.J.Michaels (2002), 'Decadal changes in heat-related human mortality in the eastern United States', *Climate Research*, **22**, (2), pp. 175-184.

Davis, R.E., P.C.Knappenberger, W.M.Novicoff, and P.J.Michaels (2003), 'Decadal changes in summer mortality in U.S. cities', *International Journal of Biometeorology*, **47**, (3), pp. 166-175.

EUROWINTER Group (1997), 'Cold Exposure and Winter Mortality from Ischaemic Heart Disease, Cerebrovascular Disease, Respiratory Disease, and All Causes in Warm and Cold Regions of Europe', *Lancet*, **349**, 1341-1346.

Fankhauser, S. (1994), 'Protection vs. Retreat -- The Economic Costs of Sea Level Rise', *Environment and Planning A*, **27**, 299-319.

Fankhauser, S. (1995), *Valuing Climate Change - The Economics of the Greenhouse*, 1 edn, EarthScan, London.

Fankhauser, S., R.S.J.Tol, and D.W.Pearce (1997), 'The Aggregation of Climate Change Damages: A Welfare Theoretic Approach', *Environmental and Resource Economics*, **10**, (3), 249-266.

Gething, P.W., D.L.Smith, A.P.Patil, A.J.Tatem, R.W.Snow, and S.I.Hay (2010), 'Climate change and the global malaria recession', *Nature*, **465**, (7296), pp. 342-345.

Giannakopoulos, C. and B.E.Psiloglou (2006), 'Trends in energy load demand for Athens, Greece: Weather and non-weather related factors', *Climate Research*, **31**, (1), pp. 97-108.

Hay, S.I., J.Cox, D.J.Rogers, S.E.Randolph, D.I.Stern, G.D.Shanks, M.F.Myers, and R.W.Snow (2002a), 'Climate change and the resurgence of malaria in the East African highlands', *Nature*, **415**, 905-909.

Hay, S.I., D.J.Rogers, S.E.Randolph, D.I.Stern, J.Cox, G.D.Shanks, and R.W.Snow (2002b), 'Hot topic or hot air? Climate change and malaria resurgence in East African highlands', *TRENDS in Parasitology*, 1-5.

Hekkenberg, M., R.M.J.Benders, H.C.Moll, and A.J.M.Schoot Uiterkamp (2009), 'Indications for a changing electricity demand pattern: The temperature dependence of electricity demand in the Netherlands', *Energy Policy*, **37**, (4), pp. 1542-1551.

Henley, A. and J.Peirson (1998), 'Residential energy demand and the interaction of price and temperature: British experimental evidence', *Energy Economics*, **20**, (2-6), pp. 157-171.

Holmer, B. (2008), 'Fluctuations of winter wheat yields in relation to length of winter in Sweden 1866 to 2006', *Climate Research*, **36**, (3), pp. 241-252.

Kundzewicz, Z.W., D.Graczyk, T.Maurer, I.Pinkswar, M.Radziejeswki, C.Svensson, and M.Szwed (2005), 'Trend detection in river flow series: 1. Annual maximum flow', *Hydrological Sciences Journal*, **50**, (5), pp. 797-810.

Lindstroem, G. and S.Bergstroem (2004), 'Runoff trends in Sweden 1807-2002', *Hydrological Sciences Journal*, **49**, (1), pp. 69-84.

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**, (2), 99-114.

Link, P.M. and R.S.J.Tol (2011), 'The Economic Impact of a Shutdown of the Thermohaline Circulation: An Application of FUND', *Climatic Change*, **104**, (2), 287-304.

Lins, H.F. and J.R.Slack (1999), 'Streamflow trends in the United States', *Geophysical Research Letters*, **26**, (2), pp. 227-230.

Lloyd, S.J., R.S.Kovats, and B.G.Armstrong (2007), 'Global diarrhoea morbidity, weather and climate', *Climate Research*, **34**, (2), pp. 119-127.

Lobell, D.B. and G.P.Asner (2003), 'Climate and management contributions to recent trends in U.S. agricultural yields', *Science*, **299**, (5609), p. 1032.

Lobell, D.B. and C.B.Field (2007), 'Global scale climate-crop yield relationships and the impacts of recent warming', *Environmental Research Letters*, **2**, (1).

Lobell, D.B., J.I.Ortiz-Monasterio, G.P.Asner, P.A.Matson, R.L.Naylor, and W.P.Falcon (2005), 'Analysis of wheat yield and climatic trends in Mexico', *Field Crops Research*, **94**, (2-3), pp. 250-256.

Lobell, D.B., W.Schlenker, and J.Costa-Roberts (2011), 'Climate Trends and Global Crop Production Since 1980', *Science*.

Loevinsohn, M.E. (1994), 'Climatic warming and increased malaria incidence in Rwanda', *Lancet*, **343**, (8899), pp. 714-718.

Long, S.P., E.A.Ainsworth, A.D.B.Leakey, J.Noesberger, and D.R.Ort (2006), 'Food for Thought: Lower-than-Expected Crop Yield Stimulation with Rising CO2 Concentrations', *Science*, **312**, (5811), 1918-1921.

Maddison, A. (1995), *Monitoring the World Economy 1820-1992* OECD Publications, Paris.

Martens, W.J.M. (1998), 'Climate change, thermal stress and mortality changes', *Social Science and Medicine*, **46**, (3), pp. 331-344.

McMichael, A.J. and K.B.G.Dear (2010), 'Climate change: Heat, health, and longer horizons', *Proceedings of the National Academy of Sciences of the United States of America*, **107**, (21), pp. 9483-9484.

Mendelsohn, R.O., W.N.Morrison, M.E.Schlesinger, and N.G.Andronova (2000), 'Country-specific market impacts of climate change', *Climatic Change*, **45**, (3-4), 553-569.

Moral-Carcedo, J. and J.Vicens-Otero (2005), 'Modelling the non-linear response of Spanish electricity demand to temperature variations', *Energy Economics*, **27**, (3), pp. 477-494.

Myneni, R.B., C.D.Keeling, C.J.Tucker, G.Asrar, and R.R.Nemani (1997), 'Increased plant growth in the northern high latitudes from 1981 to 1991', *Nature*, **386**, (6626), pp. 698-702.

Narita, D., D.Anthoff, and R.S.J.Tol (2009), 'Damage Costs of Climate Change through Intensification of Tropical Cyclone Activities: An Application of FUND', *Climate Research*, **39**, pp. 87-97.

Narita, D., D.Anthoff, and R.S.J.Tol (2010), 'Economic Costs of Extratropical Storms under Climate Change: An Application of FUND', *Journal of Environmental Planning and Management*, **53**, (3), pp. 371-384.

Neumayer, E. and F.Barthel (2011), 'Normalizing economic loss from natural disasters: A global analysis', *Global Environmental Change*, **21**, (1), pp. 13-24.

Nicholls, N. (1997), 'Increased Australian wheat yield due to recent climate trends', *Nature*, **387**, (6632), pp. 484-485.

Nordhaus, W.D. (1991), 'To Slow or Not to Slow: The Economics of the Greenhouse Effect', *Economic Journal*, **101**, (444), 920-937.

Pardo, A., V.Meneu, and E.Valor (2002), 'Temperature and seasonality influences on Spanish electricity load', *Energy Economics*, **24**, (1), pp. 55-70.

Pielke, J. (2005), 'Are there trends in hurricane destruction?', *Nature*, **438**, (7071).

Pielke, R.A., J.Gratz, C.W.Landsea, D.Collins, M.A.Saunders, and R.Musulin (2008), 'Normalized hurricane damage in the United States: 1900-2005', *Natural Hazards Review*, **9**, (1), pp. 29-42.

Ryan, P. C. e. a. Emergence timescales for detection of anthropogenic climate change in US tropical cyclone loss data. Environmental Research Letters 6[1], 014003. 2011.
Ref Type: Abstract

Sailor, D.J. and J.R.Munoz (1997), 'Sensitivity of electricity and natural gas consumption to climate in the U.S.A. - Methodology and results for eight states', *Energy*, **22**, (10), pp. 987-998.

Small, J., S.J.Goetz, and S.I.Hay (2003), 'Climatic suitability for malaria transmission in Africa, 1911-1995', *Proceedings of the National Academy of Sciences of the United States of America*, **100**, (26), pp. 15341-15345.

Svensson, C., Z.W.Kundzewicz, and T.Maurer (2005), 'Trend detection in river flow series: 2. Flood and low-flow index series', *Hydrological Sciences Journal*, **50**, (5), pp. 811-824.

Tao, F., M.Yokozawa, J.Liu, and Z.Zhang (2008), 'Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends', *Climate Research*, **38**, (1), pp. 83-94.

Tao, F., M.Yokozawa, Y.Xu, Y.Hayashi, and Z.Zhang (2006), 'Climate changes and trends in phenology and yields of field crops in China, 1981-2000', *Agricultural and Forest Meteorology*, **138**, (1-4), pp. 82-92.

Thomas, C. (2004), 'A changed climate in Africa?', *Nature*, **427**, (6976), pp. 690-691.

Tol, R.S.J. (1995), 'The Damage Costs of Climate Change Toward More Comprehensive Calculations', *Environmental and Resource Economics*, **5**, (4), 353-374.

Tol, R.S.J. (2001), 'Equitable Cost-Benefit Analysis of Climate Change', *Ecological Economics*, **36**, (1), 71-85.

Tol, R.S.J. (2002a), 'Estimates of the Damage Costs of Climate Change - Part 1: Benchmark Estimates', *Environmental and Resource Economics*, **21**, (1), 47-73.

Tol, R.S.J. (2002b), 'Estimates of the Damage Costs of Climate Change - Part II: Dynamic Estimates', *Environmental and Resource Economics*, **21**, (2), 135-160.

Tol, R.S.J. (2002c), 'Welfare Specifications and Optimal Control of Climate Change: an Application of *FUND*', *Energy Economics*, **24**, 367-376.

Tol, R.S.J. (2009a), *Climate Feedbakcs on the Terrestrial Biosphere and the Economics of Climate Policy: An Application of FUND*, Working Paper **288** ,Economic and Social Research Institute, Dublin.

Tol, R.S.J. (2009b), 'The Economic Effects of Climate Change', *Journal of Economic Perspectives*, **23**, (2), 29-51.

Tol, R.S.J., T.E.Downing, and N.Eyre (1999), *The Marginal Costs of Radiatively-Active Gases* **W99/32** ,Institute for Environmental Studies, Vrije Universiteit, Amsterdam.

Tol, R.S.J. and R.Verheyen (2004), 'State responsibility and compensation for climate change damages - a legal and economic assessment', *Energy Policy*, **32**, 1109-1130.

Toya, H. and M.Skidmore (2007), 'Economic Development and the Impacts of Natural Disasters', *Economics Letters*, **94**, 20-25.

Twine, T.E. and C.J.Kucharik (2009), 'Climate impacts on net primary productivity trends in natural and managed ecosystems of the central and eastern United States', *Agricultural and Forest Meteorology*, **149**, (12), pp. 2143-2161.

Yohe, G.W. and R.S.J.Tol (2002), 'Indicators for Social and Economic Coping Capacity -- Moving Towards a Working Definition of Adaptive Capacity', *Global Environmental Change*, **12**, (1), 25-40.

Zhang, T., J.Zhu, and R.Wassmann (2010), 'Responses of rice yields to recent climate change in China: An empirical assessment based on long-term observations at different spatial scales (1981-2005)', *Agricultural and Forest Meteorology*, **150**, (7-8), pp. 1128-1137.