Journal of Global Economic Analysis, Volume 1 (2016), No. 2, pp. 78-115.

Estimation of Climate Change Damage Functions for 140 Regions in the GTAP 9 Database

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Climate change damage (or, more correctly, impact) functions relate variations in temperature (or other climate variables) to economic impacts in various dimensions, and are at the basis of quantitative modeling exercises for the assessment of climate change policies. This document provides a summary of results from a series of meta-analyses aimed at estimating parameters for six specific damage functions, referring to: sea level rise, agricultural productivity, heat effects on labor productivity, human health, tourism flows, and households' energy demand. All parameters of the damage functions are estimated for each of the 140 countries and regions in version 9 of the Global Trade Analysis Project (GTAP 9) Data Base. To illustrate the salient characteristics of the estimates, the change in real gross domestic product is approximated for the different effects, in all regions, corresponding to an increase in average temperature of +3°C. After considering the overall impact, the paper highlights which factor is the most significant one in each country, and elaborates on the distributional consequences of climate change.

JEL codes: C68, C82, D58, Q51, Q54.

Keywords: Climate change, integrated assessment, computable general equilibrium, damage function, climate impacts.

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1. Introduction

Understanding how the ongoing climate change could ultimately affect our society and the well-being of current and future generations requires an evaluation of the complex interplay between human and natural systems.

The human or anthropogenic influence on the Earth's climate is mainly associated with the emissions of greenhouse gases (GHGs) in the atmosphere, which is in turn related to the level of several economic activities. To forecast the future climate, physical scientists need to know the expected level of GHG emissions, which depend on scenarios of economic growth as well as on the possible implementation of climate mitigation policies. On the other hand, economic growth itself is influenced by the climate change, through its manifold impacts. As Tol (2015, p. 1) puts it: "There are so many and so different effects: crops hit by worsening drought, crops growing faster because of carbon dioxide (CO_2) fertilization, heat stress increasing, cold stress decreasing, sea levels rising, cooling energy demand going up, heating energy demand going down, infectious disease spreading, and species going extinct. It is hard to make sense of this. Therefore, aggregate indicators are needed to assess whether climate change is, on balance, a good thing or a bad thing and whether the climate problem is small or large relative to the many other problems that we have".

Damage functions have been introduced to this purpose, that is to "translate" physical impacts in terms of economic variables inside Computable General Equilibrium (CGE) models, Integrated Assessment Models (IAMs) and other numerical economic models. Therefore, damage functions are one or more relationships between climate variables (typically average temperature, but sometimes also humidity or "heating days") and economic variables (potential income, productivity, resource endowments, etc.). It is generally acknowledged that damage functions constitute a weak link in the economics of climate change (Weitzman, 2010). Pindick (2013) goes as far as saying that "When it comes to the damage function (...) we know almost nothing, so developers of IAMs can do little more than make up functional forms and corresponding parameter values."

In line with Revesz et al. (2014), we rather take a more positive stance, as we think it is possible to achieve a better parametrization of damage functions if the different mechanisms bringing about economic effects are clearly distinguished, and if information from non-economic studies is properly exploited and filtered. Nonetheless, even if our damage function estimates are based on peer-reviewed empirical studies, several shortcomings in the underlying estimates remain and this work is being made available to push the community to improve on the estimates.

Various other methodologies have been employed for the estimation of damage function parameters, from subjective expert assessment (Nordhaus, 1994) to panel methods (Dell et al., 2014) to meta-analyses (Tol, 2002). Also, the functions may be built by summing up different effects into a single aggregate, or they may retain some sectoral detail. The first approach is typical of earlier models like RICE (Nordhaus and Yang, 1996, Nordhaus and Boyer, 1999), MERGE (Manne et al., 1995) and CETA (Peck and Teisberg, 1992), where a relationship is posited between loss of potential income (GDP) and temperature. More recent contributions, based on multi-sectoral models like DART (Deke et al., 2001), GTEM (Pant, 2002), ICES (Eboli et al., 2010) and ENVISAGE (Roson and van der Mensbrugghe, 2012) keep the sectoral detail and attribute the various impacts to different variables and parameters in a disaggregated macroeconomic model, which typically has a general equilibrium structure.

The main advantage of holding distinct the different economic effects of climate change, despite the cost of higher data collection and computational complexity, is that it is possible to trace the various mechanisms through which the climate can affect the economic system. Furthermore, in a general equilibrium formulation, it is possible to account for second-order effects linked to variations in relative prices, which are often very relevant.

This document illustrates the methodology and presents some results for the estimation of damage functions parameters, for all 140 countries and regions in the version 9 of the Global Trade Analysis Project (GTAP 9) Data Base (Aguiar et al., 2016), and for six climate impacts: sea level rise, variation in crop yields, heat effects on labor productivity, human health, tourism and household energy demand. Effects from 1°C up to 5°C average temperature increments are separately considered, as most impacts are non-linear.

The GTAP social accounting matrix has become a de-facto standard for the calibration and implementation of computable general equilibrium models, or integrated assessment models with a CGE core, so our set of estimates can be seen as a "ready-to-use" information source for the realization of climate-related numerical experiments with a general equilibrium structure.

Our parameters are obtained by processing information coming from many diverse studies, based on different approaches and methodologies, as we are undertaking an interdisciplinary assessment of climate change impacts. This means that, although we are trying to build a standardized data set, the original information remains intrinsically heterogeneous. Consequently, our results have the same strengths and weaknesses as their primary references, which are difficult to judge, except for the fact that most of them are from published sources. Due to uncertainty in climate damage estimates, the supplementary files published with this article include a spreadsheet that allows users to modify key input parameters used in our calculations.

The paper is structured as follows. Section 2 clarifies the scope of the work and illustrates the overall estimation strategy. Sections 3 to 8 are devoted to presenting the methodology and some estimates for the six impact typologies, whereas detailed numerical results (Tables S1-S9) are available in a separate, downloadable "Supplementary Material" document. Section 9 provides a synthesis of the findings by showing first-order approximations of the change in national GDPs triggered by the various effects, when the average temperature is assumed to increase by three Celsius degrees (estimates at the national level are presented in the Appendix). Finally, the results are discussed in a concluding section.

2. Scope and estimation strategy

Despite the fact that the choice of functional forms and parameters of damage functions is critical in determining the results in all integrated assessment models, an account of this delicate task can be typically found concealed only inside the technical description of the various models.[1] To the best of our knowledge, this is the first paper that almost exclusively focuses on damage function estimation.

This is because our aim is providing a key ingredient to other researchers, to help them developing better models for climate change impact and policy assessment, through the provision of a framework for moving from diffuse empirical estimates to a consistent set of shocks (mainly for CGE analysis). Results can be adapted and tailored to their specific needs, and useful evaluations, possibly including some systematic sensitivity analysis on parameter values, could be undertaken. We also supply a complementary spreadsheet, where all impact parameters, global or regional, can be modified.

The typical model we have in mind is a global computable general equilibrium model, and this explains why we are providing parameters in a format consistent with the latest GTAP database. However, our estimates could well fit other types of models, for example partial equilibrium, regional ones.

The choice of a CGE background has some important implications, inducing us to provide information only about economic impacts that are expected to

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[1] A synthetic description of estimation procedures for some popular IAM models can be found in Bosello and Roson (2007).

affect resource endowments, productivity, technology, etc. for factors and goods having explicit, formal markets. This deliberately leaves out some important economic impacts, which cannot be easily captured by means of CGE-like models, e.g.: non-market public goods, ecosystem services and option values, health status of persons outside the labor force, etc..

For each of the impact categories we are considering, we start by reviewing the recent, mostly non-economic literature on the specific subject. We typically select one or a few articles that we believe convey useful information for our purposes. The selection criteria are: (a) the article has to be published in a refereed, scientific journal or similar kind of publication; (b) it has to be sufficiently recent; (c) it should provide, at least in principle, global coverage. Especially this last criterion leaves out some important contributions, having the nature of case studies. However, whenever new or better quality information would become available in the future, we encourage the interested researchers to modify our parameters and impact estimates, using the accompanying data spreadsheet.

After the identification of our primary source of information, we elaborate the results so that parameter values can be expressed in terms of variables that can be found inside an economic model (e.g., factor productivity), with the desired degree of regional disaggregation. For instance, epidemiological studies could provide information about "people at risk" and "mortality" for a given disease. Neither variable can be typically found in a CGE model, so one should first convert the information in terms of "lost labour days", then "labour productivity", and so on. This conversion process is quite tricky and working assumptions are introduced all along the way, which are subjective and based — at best — on educated guesses.[2]

Another potential problem is that most sectoral studies evaluate the impacts not only in terms of climatic variables, but also as a function of other "scenario" hypotheses, including economic ones. Here, epidemiological studies provide again a good example, since the actual impact of diseases depends, and quite importantly so, on the level of economic development. We want to single out the contribution of the changing climate in affecting the diffusion of some diseases, net of the economic growth effect. Some studies, based on econometric or similar

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[2] On the other hand, the modifiable spreadsheet we provide allows changing several parameter values, whenever better data becomes available or alternative assumptions are adopted. For example: temperature thresholds for heat stress effects on labor productivity, elasticity parameters for international tourism flows, and many others.

techniques, actually allow for such an analysis. However, when our impact parameters are plugged back into an economic model, are the endogenous income levels generated by the model consistent with the assumed parameter values?

This last point highlights a more general issue: we are (deliberately) not considering adaptation behavior. This means that we are implicitly presuming that: no defensive infrastructure is built to prevent sea level rise, no changes are introduced to crop varieties and cultivation methods, no acclimatization to higher temperatures takes place, no new disease prevention measures are taken, no new tourism marketing strategies are adopted, etc. Are these assumptions realistic? Of course not! We are not aiming at producing "realistic" impact forecasts. Indeed, adaptation could effectively curb some negative effects of climate change, but it does not come without a cost. The careful modeler should then introduce adaptation costs alongside lower values for impact parameters.

We provide central values (or best estimates) of climate change impacts in the various categories, but we refrain from tackling any analysis of uncertainty, or from evaluating the overall robustness of our findings. Actually, some of the original studies do not supply information like standard errors of the parameters, whereas for those in which such information is available (in some way), converting it to a different spatial and temporal scale would be a rather complicated process.

We understand that assessing uncertainty in climate change impacts is essential from both a scientific and a practical policy perspective, but we leave the issue for further future research. The full impact of climate change is a slowly unfolding event, and data continue to be gathered by experts in great efforts such as the Inter-governmental Panel on Climate Change (IPCC). New evidence will be available, and confidence on data and parameters will improve over time. Nonetheless, climate change impacts are and will remain differentiated among sectors and regions, which requires both a continuous interdisciplinary cooperation and the development of modeling platforms for the simultaneous appraisal of multiple impacts.

All in all, there are important caveats to be kept in mind to appreciate, on one hand, the limitations of our study and, on the other hand, how our estimates should be properly utilized in subsequent modeling exercises.

3. Climate change impact #1: Sea Level Rise

A large number of studies reviewed by the Fifth IPCC Assessment Report (IPCC, 2014) have shown that the increase in global temperature brings about an increase in the level of the sea. Sea level rise (hereafter SLR) affects the land stock through the erosion, inundation or salt intrusion along the coastline. This phenomenon is in turn generated by (i) the thermal expansion of water bodies and (ii) glaciers' melting.

The share of land which may be lost (in terms of economic production factor) depends on several country-specific characteristics, like: (i) the composition of the shoreline (cliffs and rocky coasts are less subject to erosion than sandy coasts and wetlands); (ii) the total length of the country coast; (iii) the share of the coast which is suitable for productive purposes (i.e. in agriculture); (iv) the vertical land movement (VLM). The latter is a generic term for all processes affecting the elevation at a given location (tectonic movements, subsidence, ground water extraction), causing the land to move up or down. This is typically a slow process with values commonly between -10 mm/year (sinking) and +10 mm/year (rising). Local vertical land movement becomes relevant when looking at the local effects of sea level rise. The orders of magnitude are comparable, and VLM can thus either exacerbate or dampen the SLR.

The literature offers several studies dealing with the SLR, but they are mainly local and country-level studies or macro-level studies, where countries are aggregated into large macro-regions. Perhaps the most employed model is DIVA (Vafeidis et al., 2008), which is an integrated model of coastal systems that assesses biophysical and socio-economic consequences of SLR.

In our estimates, we focus on losses of land (which is almost exclusively used as a production factor in agriculture), disregarding other potential negative impacts, for example on the infrastructural capital stock, located nearby the coast. We do this for a number of reasons. First, climate-induced sea level rise is a very slow process, so it should not be confused with floods, storm surges, and other extreme events. Therefore, it can be safely assumed that important economic activities, urban settlements and infrastructure can and will be relocated inwards. Second, despite what is commonly believed, there is simply not enough solid scientific evidence (and explanations in terms of physical processes) linking climate change to a possible increase in the frequency of some extreme events.[3] For instance, DIVA does not consider an increase in storm surges frequency and intensity. On the other hand, Losada et al. (2013) actually detect an increase in storm intensity associated with sea level rise, for Latin

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[3] This argument applies to impacts of extreme events on the human health as well (Bosello et al., 2008). For a modeling effort on the economic implications of extreme events, see Calzadilla et al. (2007).

America and the Caribbean. A similar claim is made by Reguero et al. (2015), assessing the population and physical capital exposure to future, climate-induced flooding in the same region. However, these studies do not provide useful evidence for our purposes, for two main reasons. First, statistical correlation (based on a limited time span and referring to a specific region) does not prove causality. Second, "exposure" is not a synonym of "damage".[4]

3.1 Methodology

The latest IPCC Assessment Report (IPCC AR5) reports the global mean SLR (in meters) associated with the global mean surface temperature change (in °C), at the time intervals [2046-2065] and [2080-2100]. These estimates, plotted in Figure 1, suggest that there exist a positive relationship between SLR and the increase in global mean surface temperature, but also a time component, related to the substantial inertia of the physical processes involved.

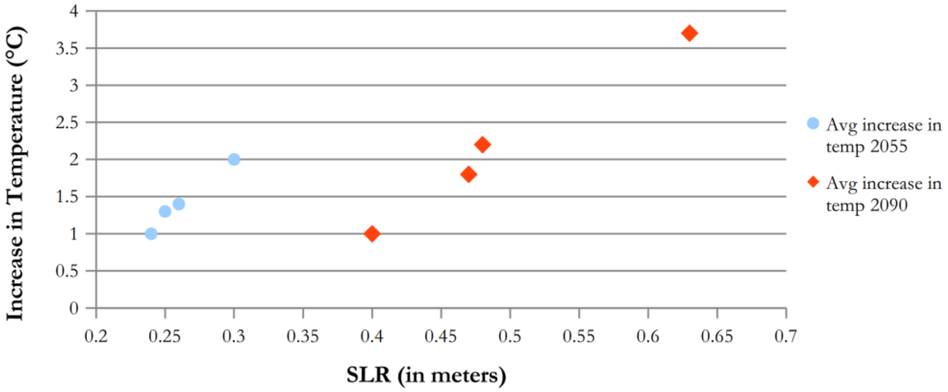

Figure 1. Global mean surface temperature change (°C) and mean sea level rise (m).

Source: Authors' elaboration from IPCC (2014).

To better understand the nature of the relationship between the global mean SLR, the increase in the mean global temperature and time, we ran a series of regressions, finding that the following equation provides a satisfactory fit for the relationship:

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[4] Furthermore, the estimates of impacts on infrastructure by Reguero et al. (2015) are based on weak and questionable assumptions. They assume, for instance, that the ratio of capital to total national income is a time-invariant constant. Also, they assume that the physical capital location is the same as that of population. Both hypotheses are patently unrealistic.

$$SLR = [(\alpha + \beta \Delta t)(T - 2000)] \quad (1)$$

where Δt is the change in average global temperature with respect to the baseline [1985-2005], and T is the year period. A panel estimation of equation (1) gives a value for the α coefficient of 0.000954281, whereas the corresponding value for β is 0.003421296.

To account for the vertical land movement (V), equation (1) can be modified as follows:

$$aSLR = [(\alpha + \beta \Delta t - V)(T - 2000)] \quad (2)$$

where $aSLR$ is the *adjusted* sea level rise. Data on VLM by country have been retrieved from the SONEL database (www.sonel.org).

For example, the adjusted SLR associated with an increase in temperature of +1°C and VLM of +0.001 m/yr (rising) at the year 2050 is:

$$0.16878 = [(0.000954281 + 0.003421296x1 - 0.001)(2050 - 2000)]$$

that is, about 0.17 meters.

Using the DIVA v2.04 model, Arnell et al. (2014) provide estimates of the percentage loss in the coastal wetland for 16 macro-regions and 3 single countries. These estimates, reported in Table 1, are associated with a future global mean SLR of 0.16 m, predicted by the HadCM3 climate model under the A1b SRES scenario.

Table 1. Changes in coastal wetland at 0.16 m of SLR by macro-region, %.

Region/country	% change in coastal wetland by 0.16 m of SLR	Region/country	% change in coastal wetland by 0.16 m of SLR
West Africa	-0.07	Australasia	-0.12
Central Africa	-0.13	North Africa	-0.21
East Africa	-0.12	West Asia	-0.22
South Africa	-0.17	West Europe	-0.17
South Asia	-0.1	Central Europe	-0.2
South-East Asia	-0.12	East Europe	-0.19
East Asia	-0.22	Canada	-0.06
Central Asia	0	USA	-0.24
Meso-America	-0.18	South America	-0.19
Brazil	-0.09	-	-

Source: Arnell et al. (2014).

Each of the 140 GTAP 9 database regions has been associated to one macro-region of Table 1. The percentage loss in coastal wetland (Table 1) has been multiplied by the percentage of erodible coast and applied to the whole coast. For the European regions, the shares of erodible coast have been obtained from the Eurosion project (http://www.eurosion.org/) while for the remaining countries we have adopted the 70% value suggested by Bird (1987, 2010). Considering which fraction of total coast is suitable for agricultural and other productive activities we have estimated the fraction of agricultural land which is lost when SLR equals 0.16 meters. Scaling up, we got the share of productive land which is lost for one meter of SLR, labelled L_R. Data on coastline length are provided by the CIA database (www.cia.gov); data on the fraction of coast suitable for agricultural activities have been obtained from UNEP (2005).

The percentage change in the land stock by year and country, L_{RT}, is computed by multiplying the percentage of effective land change by meter of SLR, L_R, and the predicted adjusted SLR, as follows:

$$L_{RT} = L_R[(\alpha + \beta\Delta t - V_R)(T - 2000)] \tag{3}$$

Notice that the impact function (3) has four parameters. Two parameters (α, β) are common across all regions, two other parameters (L_R and V_R) are country/region specific.

Table S1 shows, for each GTAP 9 region, the percentage loss of land by meter of SLR, corresponding to the parameter L_R in (3), and the vertical land motion (VLM), corresponding to the parameter V_R.

Table S2 illustrates the percentage losses of productive land endowments for +1, +2, +3, +4 and +5 °C increases in average temperature, at the years 2050 and 2100, for all 140 countries and regions. As one can see, relevant physical effects of SLR are concentrated in a few countries, in particular: small island states of Oceania, Central America and Asia, Hong Kong SAR, China, Japan, Singapore, Jamaica, Puerto Rico, Trinidad and Tobago, Cyprus, Croatia, Bahrain, Kuwait, Qatar, United Arab Emirates and Mauritius.

4. Climate change impact #2: Variation in crop yields (agricultural productivity)

Climate change is expected to bring about higher temperatures, a higher concentration of CO_2 in the atmosphere, and a different regional patterns of precipitation. These are all factors affecting crop yields and agricultural productivity. Not surprisingly, effects of climate change on agricultural production volumes are perhaps the most studied area of sectoral impacts.

Despite the many studies realized and the extensive empirical evidence produced, however, it is still difficult to identify some sort of “consensus” for the most likely impacts of climate change on agricultural productivity, especially for all world regions. This is because the issue is intrinsically complex and the eventual effect depends on several factors, which are difficult to evaluate ex-ante, for example: (i) the role of adaptation behavior by farmers, firms and organizations, including variety selection, crop rotation, sowing times, etc.; (ii) the amount of fertilization due to higher CO_2 concentration; (iii) the actual level of water available for irrigation, and irrigation techniques.

Some studies in this area are based on controlled experiments. Others are based on crop models applied to different crops in different regions and on the basis of different climate scenarios. This heterogenous information is summarized in the latest IPCC Assessment Report (2014), while efforts are under way to standardize the process of agronomic experiments and modeling (AgMIP, 2014).

Because of the heterogeneity of the underlying available information, we follow here two distinct approaches. The first approach, similar to the one adopted by Roson and Sartori (2010), relies on a meta-analysis provided in the Fifth IPCC Assessment Report (2014), providing central estimates for variations in the yields of maize, wheat and rice. We elaborate on these results to get estimates of productivity changes for these three crops, in all 140 regions and for the five levels of temperature increase, from +1°C to +5°C.

The second approach is similar to that of Cline (2007), and brings about an estimate of productivity changes for the whole agricultural sector in the various regions. The decision about which estimates to use in a general equilibrium simulation depends on the level of industrial disaggregation of the model. We suggest to use the first set of parameters if maize, wheat and rice are considered as separate industries, and the second set for the rest, or for the whole agricultural sector if this is regarded as a single aggregate industry.

4.1 Methodology

The IPCC AR5, similarly to the previous one, provides a graphical summary (Figure 7-4 in IPCC (2014)) for estimates of changes in productivity of maize, wheat and rice obtained by several studies. It distinguishes between tropical and temperate regions and identifies a non-linear interpolation function for the two cases, with and without simple agronomic adaptation. The figure is reproduced here below (Figure 2).

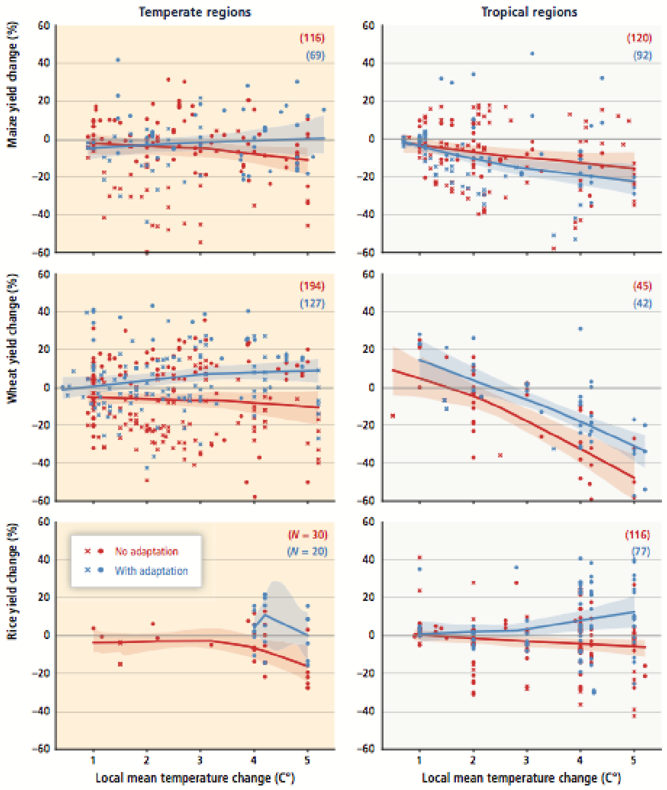

Figure 2. Percentage simulated yield change as a function of local temperature change.

Source: IPCC (2014).

We first express the central values (without adaptation) of Figure 2 as percentage variations in the following table:

Table 2. Central values of the percentage simulated yield change as a function of local temperature change.

	Temperate					*Tropical*				
	+1°C	**+2°C**	**+3°C**	**+4°C**	**+5°C**	**+1°C**	**+2°C**	**+3°C**	**+4°C**	**+5°C**
Maize	-1%	-3%	-4%	-7%	-11%	-4%	-8%	-10%	-12%	-14%
Wheat	-5%	-6%	-7%	-8%	-9%	4%	-4%	-20%	-34%	-44%
Rice	-4%	-3%	-2%	-7%	-16%	0%	-2%	-4%	-6%	-8%

Source: IPCC (2014).

We then associate the type of region (temperate or tropical) to its latitude, assuming that the reference tropical region has a central latitude of 0° (the equator) and the reference temperate region has a central latitude of 40° (North or South). We compute the percentage variation VY in the yield of crop C in a region with latitude L as:

$$VY(C,L) = VY(C,0) + \left(VY(C,40) - VY(C,0)\right) * L/40 \qquad (4)$$

Therefore, we assume that the variation in the crop yield ranges linearly from its baseline value at the equator up (or down) to its value at 40° latitude and beyond. Considering the central latitude of all countries and regions in the GTAP 9 dataset, we get the parameters shown in Table S3.

A second and different methodology is based on the Mendelsohn and Schlesinger (1999) reduced form Agricultural Response Functions in the formulation proposed by Cline (2007), where the variation (DY) in output per hectare is expressed as a function of temperature T, precipitation P and CO_2 concentration K:

$$DY = 115.992DT - 9.936DT^2 + 0.4752DP + 7.884\,DK/K \qquad (5)$$

We need to link changes in yield to variations in average temperature only. To this purpose, we rely on temperature and precipitation data from the United States Geological Survey (USGS) Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Change Viewer (GCCV), averaging results from many Global Circulation Models[5]. We collected information on baseline levels and variation in average annual temperature and annual precipitation, by country, comparing the period 1980-2004 (central year 1992) with the period 2050-2074 (central year 2062) under the RCP 8.5 scenario. We also assume that from 1992 to 2062 (70 years) the concentration of CO_2 rises (from a baseline level of 365 ppm) at an annual rate of 2.11 ppm.

We use the variation in temperature as an indicator, expressing how much the climate has changed. By dividing the country-specific variation in precipitation with the one of temperature we get a precipitation to temperature coefficient, p. In the same way, we get a CO_2 concentration to temperature coefficient k, so that we can write:

$$DY = (115.992 + 0.4752p + 7.884\,k/365)DT - 9.936DT^2 \qquad (6)$$

Finally, we need to transform DY to percentage changes DY/Y, which can be done by dividing DY by the output per hectare Y, in millions of dollars. Cline (2007) uses estimated values for the year 2003 which, unfortunately, vary widely

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[5] http://regclim.coas.oregonstate.edu/visualization/gccv/cmip5-global-climate-change-viewer/

(for example, from 29 in Australia to 8707 in the Republic of Korea), ultimately producing unrealistically volatile percentage changes for agricultural productivity.

Here we follow a different strategy, which is based on the "calibration" of the output per hectare Y. The latter is chosen so that the percentage change for +3°C is "in line" with a simple mathematical average of estimated variations in the yield of the three crops maize, wheat and rice, for the same temperature change. "In line" means in the range +/-1%, but conditional on a minimum level for Y of 500 and a maximum level of 10,000.

After calibrating the output per hectare, the percentage variation of agricultural output for 1, 2, 3, 4 and 5°C increases in temperature can be computed for each of the 140 GTAP 9 countries and regions. The results are shown in Table S4.

The variation in temperature refers to the average annual temperature specific to each country or region, which may differ from the variation in the global average temperature. On the basis of actual global and regional temperature variations, we estimated for each region a correction factor, which can be used to get an approximated regional variation in temperature through multiplication from the global change. These correction factors are displayed in Table S5. When only information on the change in global temperature is available, one could therefore estimate the corresponding change in regional temperature using the correction factors.

A quick inspection of the table reveals that variations in regional temperature are typically wider at a higher latitude and whenever the region has limited or no access to the sea or ocean.

5. Climate change impact #3: Heat stress and labor productivity

Labor productivity is affected by working conditions. Heat stress, determined by high temperature and humidity, implies more frequent pauses, interruptions, lower speed and higher probability of injury (Tawasupa et al., 2013). Even if acclimatization, on one hand, and protective measures like air conditioning, on the other hand, can help curbing the negative effects of heat stress, the effectiveness and applicability of any adaptation mean is limited and dependent on the context.

Previous work with the ENVISAGE model (Roson and van der Mensbrugghe, 2012), has shown that the impact of increased heat on average labor productivity can be substantial and, furthermore, very much differentiated between developing and developed countries.

To our knowledge, Kjellström et al. (2009) is the only paper investigating the relationship between climate change, heat stress and labor productivity at a global scale.[6] Other works have considered local impacts, or produced regional maps of occupational heat exposure (Hyatt et al., 2010). Hsiang (2010) finds that variations in surface temperature are more important than the occurrence of cyclones in determining the economic performance of industries in Caribbean states, and attributes this effect to the response of workers to thermal stress. However, this causal association is unwarranted, and not supported by physical or economic evidence.

In this section, we estimate heat damage functions, which are relationships between average temperature and labor productivity. The functions are estimated for three sectors: Agriculture (A), Manufacturing (M) and Services (S) and for 1, 2, 3, 4 and 5 °C increases in average temperature, bringing about a total of 140 x 3 x 5 = 2100 estimated parameter values.

5.1 Methodology

Most quantitative standards to protect workers from heat injury use the "wet bulb globe temperature" (WBGT) to define the percentage of a typical working hour that a person can work assuming the remaining time is rest. The heat exposure index WBGT (unit=°C) is a combination of the natural wet bulb temperature (measured with a wetted thermometer exposed to the wind and heat radiation at the site), the black globe temperature (measured inside a 150 mm diameter black globe), and the air temperature (measured with a "normal" thermometer shaded from direct heat radiation). Lemke and Kjellström (2012) propose a methodology to estimate the WBGT from meteorological data.

In this study, following Kjellström et al. (2009), we compute average monthly WBGT using average temperature and relative humidity, on the basis of the Australian Bureau of Meteorology equations:

$$WBGT = 0.567T + 3.94 + 0.393E \tag{7}$$

$$E = (RH/100) \times 6.105 \times exp(17.27\,T/(237.7 + T)) \tag{8}$$

where T is the average air temperature in °C; E is the average absolute humidity (water vapour pressure) in hPa; and RH is the average relative humidity in %.

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[6] A possible limitation of Kjellström's approach is that it is based on standards prepared for safety, and it is not statistically validated.

Monthly average temperature (and precipitation) by country has been obtained from the Weatherbase website[7]. Unfortunately, data on average relative humidity is not generally available for all countries in our set, but only for specific locations (from http://www.weather-and-climate.com), for example New Delhi (Figure 3).

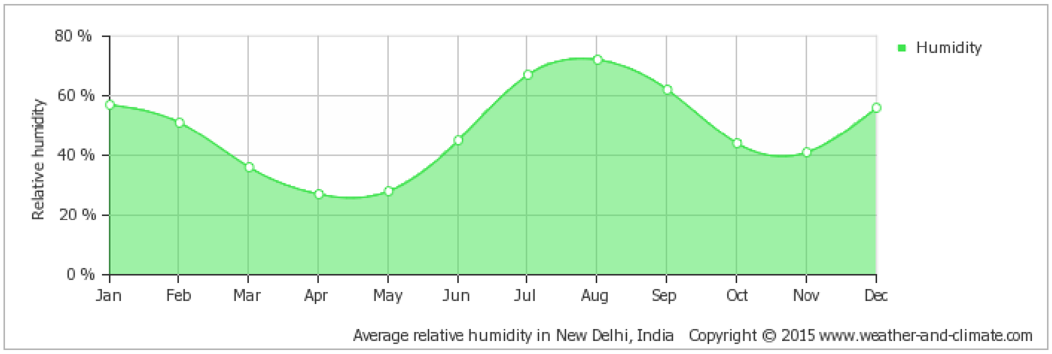

Figure 3. Average relative humidity in New Dehli.

Source: http://www.weather-and-climate.com.

In order to approximate the relative humidity from temperature and precipitation data, we ran a series of regressions, finding that the following equation provides a satisfactory estimation:

$$RH = 67.1082 - 0.8438T + 0.2305P - 0.0005P^2 \tag{9}$$

where P is precipitation in mm.

Therefore, we have computed monthly WBGT for all countries, using temperature and precipitation, in order to assess labor productivity in the three sectors. Kjellström et al. (2009) produced a graph of "work ability" as the maximum percentage of an hour that a worker should be engaged working (Figure 4). The four curves represent four different work intensities. We assume that 200 W corresponds to office desk work and service industries; 300 W to average manufacturing industry work and 500 W to agricultural work.

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[7] http://www.weatherbase.com/weather/countryall.php3

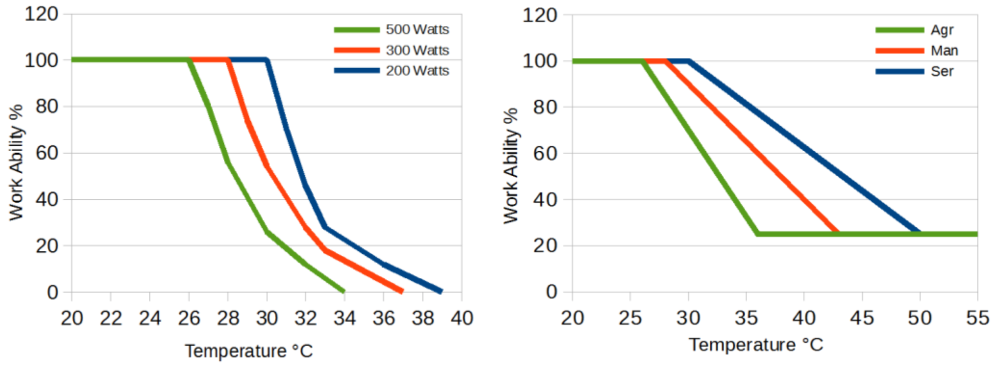

Figure 4. Work ability (productivity) as a function of WBTG (°C) at four work intensities (Watts): acclimatized (left panel) and rescaled (right panel).

Source: Left panel Kjellström et al. (2009); Right panel authors' elaborations.

We found that curves in Figure 4 (left panel) would give rise to a too rapid and unrealistic decline in productivity at high temperature, especially because we are considering here aggregate averages. We have therefore replaced the relationships depicted in the left panel of Figure 4 with the ones shown in the right panel of Figure 4. These are characterized by: (a) a minimum threshold, below which no heat effects are felt (26°C for Agriculture, 28°C for Manufacturing, 30°C for Services), (b) a minimum level of 25% for productivity, reached at 36°C for Agriculture, 43°C for Manufacturing and 50°C for Services.

We computed the percentage level of productivity for all months, sectors and countries. Monthly values have subsequently been aggregated in a yearly average, since economic flows in many CGE and other numerical models are expressed on an annual basis.

We scaled up temperature levels from 1 to 5 Celsius degrees, assuming that the monthly distribution of temperature will be unaffected and relative humidity stays the same. Finally, we computed the relative percentage change in (annual) productivity with respect to the baseline, for all countries and sectors.

5.2 Results Overview

Table S6 presents our estimates for the 140 countries and regions in the GTAP data base. Column headers refer to the sectors (A, M, S) and to the increment in temperature (1, 2, 3, 4 and 5 °C).

The box-plots in Figure 5 display the distribution of impacts on labor productivity for the three sectors, for the various changes in temperature. In the services, impacts are minimal for a +1°C increase, with a mean of -0.17% (maximum impact -1.67% in Thailand), but no impacts for 108 out of 140 regions. At five degrees, some effects are felt in about half of the regions (73), with a mean of -3.71% and maximum impact -18.16% in Singapore. For the manufacturing industries, the effects are more significant, but the distributions are still very much skewed, with 88 regions with no impacts for +1°C, 47 for +5%. The mean percentage variation in labor productivity ranges from -0.90% to -8.12%. The most significant effects are perceived in Singapore, from -5.96% to -31.46%. Agriculture is the sector most significantly affected by higher heat stress. Some effects are felt by about half of the countries (73) already at +1°C, but at +5°C only those countries located at sufficiently high latitudes (32) do not experience reductions in labor productivity. The mean percentage variation ranges from -2.52% to -17.48%.

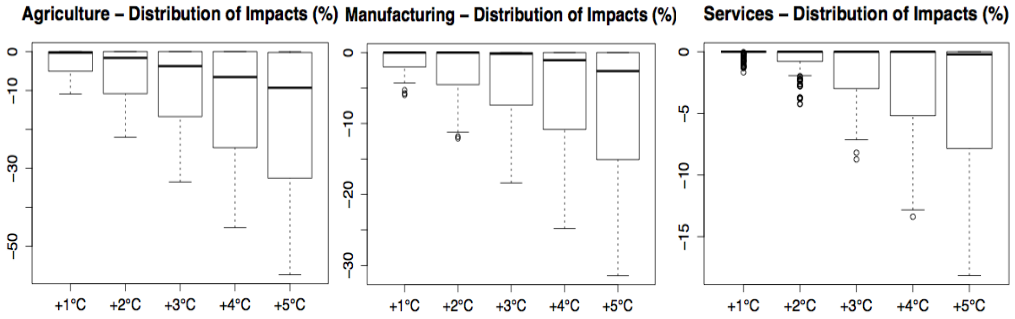

Figure 5. Distribution of impacts on labor productivity in the three sectors, for the various changes in temperature.

Source: Authors' elaborations.

6. Climate change impact #4: Human Health

This section describes the methodology and presents some estimates of the effects of increases in temperature on labor productivity, due to changes in mortality and morbidity incidence of some diseases. Other possible economic impacts, like variations in private or public expenditure on health care services, are not considered, because of lack of data at the desired level of regional and industrial disaggregation. Also, it should be noticed that some effects on human health may well emerge as a consequence of impacts in other categories. We have separately taken into account, for instance, heat exposure, and nutrition-related diseases are clearly linked to agricultural productivity.

The approach follows the one in Bosello et al. (2006) by considering some vector-borne diseases (malaria, dengue, schistomiasis), heat and cold related diseases, and diarrhea.[8] It does not consider other diseases and impacts mentioned in the IPCC AR5 (2014), like effects of extreme events, heat exposure effects on labor productivity (separately considered), hemorrhagic fever with renal syndrome, plague, chikungunya fever, Japanese and tick-borne encephalitis, cholera and other (non-diarrhea) enteric infections, air quality and nutrition related diseases, allergic diseases, mental health. A recent report by WHO (2014) considers other impact categories, but it does not add further evidence for the purposes of this work.[9]

Because of lack of data, it is not possible to ascertain possible non-linear impacts of temperature, so the results are expressed as changes in average labor productivity for a +1°C increase in temperature (implicitly assuming that the relationship is approximately linear). Also, the focus is on impacts on labor productivity, whereas other impacts, like those on private and public expenditure for health services, or non-market impacts (e.g., value of life for retired persons) are not taken into account.

We consider only the direct effect of temperature on the incidence of the various diseases, despite the fact that other variables (most notably economic development expressed through income levels) are very important (especially for vector-borne and diarrhea illnesses). To this end, the projected income levels at the year 2050 are taken as reference values for determining the degree of vulnerability in each region. This method implies that indirect effects on human health are not taken into account. For instance, climate change could bring about a reduction of income and a worsening of living conditions, making a society more vulnerable to the direct effects on health.

6.1 Methodology

The starting point of the analysis presented in Bosello et al. (2006), which is in turn based on Tol (2002), is a survey of the epidemiological, medical and interdisciplinary literature, with the aim of obtaining best estimates for the

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[8] This work has been criticized by Ackerman and Stanton (2008), but their critiques have been forcefully rebutted in Bosello et al. (2008, ibid.).

[9] The report considers: heat-related mortality in elderly people, mortality associated with coastal flooding, mortality associated with diarrhoeal disease in children aged under 15 years, malaria population at risk and mortality, dengue population at risk and mortality, undernutrition (stunting) and associated mortality. For the reasons explained in Section 2, only malaria and dengue data can be usefully exploited in the present study.

number of extra cases of mortality and morbidity (for a set of diseases) associated with a given increase in average temperature. These estimates often specify the distribution of cases in the age/sex structure of a population, as well as the length of the illness period (if applicable).

This information can therefore be combined with data on the structure of the working population, to infer the number of lost working days or other variables. For example, Bosello et al. (2006) present the following Table 3, expressing the "additional years of life diseased in 2050 by region and disease".

Table 3. Additional years of life diseased in 2050 by region and disease.

	Malaria	Schistom.	Dengue	Cardio	Respiratory	Diarrhea	TOT
USA	0	0	0	-167,357	22,257	83,070	-62,030
Europe Un.	0	0	0	-171,908	20,936	25,608	-125,364
E.E.F.S.U.	0	0	0	-259,884	46,884	57,717	-155,283
Japan	0	0	0	-65,353	33,161	912	-31,280
RestAnn.I	0	0	0	-45,232	11,108	1,361	-32,763
EnergyExp.	7,219	-1,088	29	-66,363	1,706,267	112,633	1,758,697
ChinaIndia	632	0	0	-1,119,902	770,340	156,271	-192,659
Rest World	232,737	-154,375	203	-194,383	3,683,042	834,294	44,01,518

Source: Bosello et al. (2006).

In this study, we review the most recent literature on health impacts, and in particular some studies mentioned in IPCC (2014), to modify the figures contained in Table 3 above, with the aim of scaling up or down the variation in labor productivity calculated by Roson and Sartori (2010). For example, the change in labor productivity assumed for Japan, for +1°C, was +0.034%, which corresponds to the -31280 decrease in diseased years in Table 3. Our updated estimates for the number of diseased years in Japan point to an *increase* in the number of years (+57894), corresponding to a change in labor productivity of -0.063%.

The procedure is slightly more complicated if several countries are included in the same macro-region, especially if those estimates of changes in productivity showed in Roson and Sartori (2010) have different sign. In this case, the original estimates are still multiplied by a correction factor, but the magnitude of the factor is determined by a mathematical optimization software, ensuring that the average variation in productivity for the whole group is consistent with the updated figures of diseased years.

For malaria, our primary source is Béguin et al. (2011), who suggest that extra cases of malaria, net of the effect due to income growth, should only be found in

Africa and China/India. Correspondingly, we set to zero the impact for Energy Exporting Countries, while increasing[10] the number of cases (diseased years) in Africa and China/India, since the new estimates appear to be higher than those at the basis of Table 3.

For schistomiasis, it is unclear why in the original estimates by Tol (2002) an increase in temperature should produce a decrease in the number of cases, if the effect of temperature is considered net of the impact of higher income levels. Actually, some studies highlight that climate change is expected to create the conditions for a potential spreading of the disease in some regions, for example in China (Zhou et al., 2008). Therefore, we decide to disregard any impact for schistomiasis, by putting zeros in the corresponding column.

Dengue is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years (WHO, 2013). However, according to Åström et al. (2012) the geographic distribution of dengue is strongly dependent on both climatic and socioeconomic variables. They present a model showing that, under a scenario of constant per capita GDP, global climate change results in a modest but important increase in the global population at risk of dengue. Under scenarios of high GDP growth, this adverse effect of climate change is counteracted by the beneficial effect of socioeconomic development. With higher income sets at projected 2050 levels, the vulnerability to dengue fever is rather low. We accommodate for this information by concentrating all extra cases of dengue in Africa, and by setting the figures of diseased years at 10% of their original levels in the benchmark Table 3.[11]

Among heat-related illnesses we consider, in line with Tol (2002), respiratory and a share of cardiovascular diseases. As the recent literature on heat risks for health (e.g., Honda et al., 2013) does not present very significant changes from earlier estimates, the contribution of heat-related diseases to the overall variation in labor productivity has been kept unchanged.[12] The same reasoning applies to health impacts of changes in diarrhea cases (Kolstad and Johansson, 2011).

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[10] The increasing factor used in this study, approximating the higher vulnerability detected by Béguin et al. (2011) is +33%, or 1/3.

[11] This is again intended to approximate the difference in the results between old and new epidemiological studies.

[12] Heat-related diseased are very important for elderly people (65+), and some differences may be noticed in the literature for this specific population group. In this study, however, we focus on the implied changes in labour productivity, that is on the working population (under 65), for which the differences among the available estimates are quite negligible.

On the contrary, our assumptions about cold-related diseases are dramatically different. In Bosello et al. (2006), consistent with Table 3, a reduction of cold-related cases brings about a reduction of mortality/morbidity in most countries, and an increase in labor productivity. However, the recent epidemiological literature has questioned the finding of a positive effect of higher temperature levels on winter mortality and morbidity. For example, Ebi and Mills (2013) argue that although there is a physiological basis for increased cardiovascular and respiratory disease mortality during winter months, the limited evidence suggests cardiovascular disease mortality is only weakly associated with temperature. This is because several illnesses have a strong seasonal component, in which relative temperature, not absolute temperature, actually matters. Correspondingly, we disregard any effect of climate change on cold-related diseases. This has very important implications for our estimates, because now all health impacts become negative in all countries.

6.2 Results Overview

The estimated percentage variation of labor productivity for 140 regions and for a +1°C increase in temperature is presented in Table S7. The unweighted average is -0.27%, and the range is from -0.75% (India, Nepal and Sri Lanka) to 0% (Canada).

The variations can be grouped in 32 classes. Figure 6 displays the number of countries in each class. The three most numerous classes are: -0.631% (African countries), -0.034% (Western Europe), -0.135% (Central America).

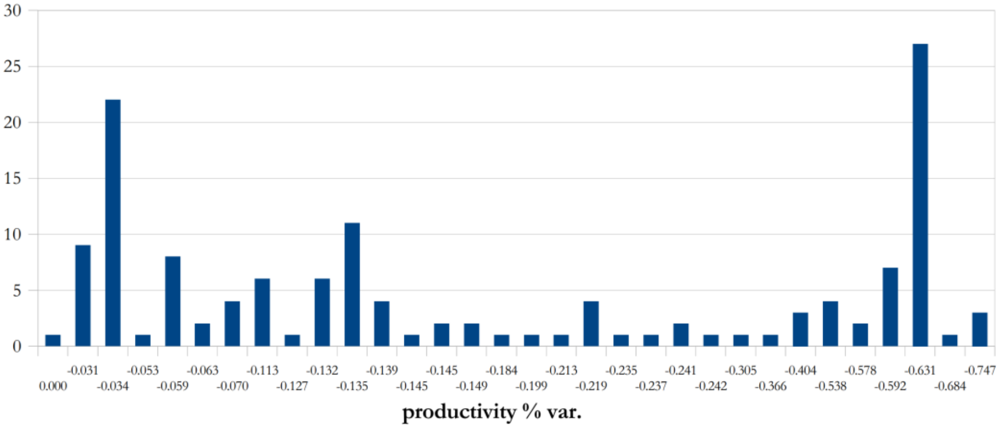

Figure 6. Number of countries in each class.

Source: Authors' calculations.

7. Climate change impact #5: Tourism

Climate is one of the main drivers of international tourism, and tourism revenue is a fundamental pillar of the economy in many countries. It is surprising that the tourism literature pays little attention to climate and climatic change and, when it does so, the analysis is typically based on local case studies.

It is equally surprising that the climate change impact literature pays little attention to tourism. Previous work with the ENVISAGE model (Roson and van der Mensbrugghe, 2012) has shown that the impact of changing tourism attractiveness can be substantial, bringing about a sizable redistribution of income among various countries.

Perhaps the only study conducting a quantitative assessment of climate impacts on international tourism flows, at a global scale, is Hamilton et al. (2005).[13] We start from some functions and parameters computed in this study to elaborate data on arrivals, departures, temperature and expenditure. The ultimate goal is estimating a relationship between average temperature changes and net inflow of foreign currency and expenditure of foreign tourists in the hosting country.

7.1 Methodology

Hamilton et al. (2005) have built an econometric model for the estimation of international tourism flows. They used econometric techniques to estimate parameters of two functions. In the first function, the logarithm of yearly arrivals of tourists in a country is expressed as a function of land area, average temperature, length of coastline and per capita income. In a second function, the logarithm of the ratio of departures over population is expressed as a function of temperature, income, land area and number of countries with shared land borders.

We take these two functional relationships to get equations linking arrivals (A) and departures (D) in a region solely to its average temperature (T), in Celsius degrees:

$$A = K_A \times exp(0.22T - 0.00791T^2) \qquad (10)$$

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[13] This study has some limitations, but we do not believe those invalidate it as a source of information for our analysis (and, in any case, no alternative global estimates are available, to the best of our knowledge). Hamilton et al. (2005), for instance, do not distinguish between tourists and other type of travelers, and they only model international tourism.

$$D = K_D \times exp(-0.18T + 0.00438T^2) \tag{11}$$

where K_A and K_D are country-specific constants, accounting for all other factors different from temperature. We calibrate these parameters on the basis of regional data on yearly arrivals, departures and average temperature.

We can see that both relationships are non-linear. The maximum number of arrivals is obtained at the optimal average temperature of 13.9°C. The minimum number of departures is obtained at 18.6°C. For increases in temperature below the 13.9°C threshold, arrivals increase and departures decrease, therefore a country gets a beneficial net inflow of foreign currency. The opposite is found for increases in temperature above the 18.6°C threshold. For variations between 13.9°C and 18.6°C, effects are ambiguous, not only because arrivals and departures push to different directions, but also because the average expenditure level of an incoming tourist may be different from the expenditure level of an outgoing tourist[14].

We estimated changes in arrivals and departures for 1, 2, 3, 4 and 5 °C increases in average temperature from its baseline level, for all 140 countries and regions. Variations in arrivals multiplied by per capita expenditure minus variations in departures multiplied by per capita expenditure give a first estimate of changes in net foreign currency inflow.

Of course, changes can be both positive and negative. Furthermore, summing up all changes does not typically gives a zero result. However, as it will be made clearer in Sub-section 7.3, if foreign currency flows are interpreted as international income transfers, we would actually need to impose that all variations sum up to one.

To this end, we scaled up or down all our estimates, by subtracting the average net inflow if positive, or adding it if it turns out to be negative. One possible interpretation of this ex-post rescaling is in terms of relative competitiveness, since flows are not only affected by local conditions, but also by conditions in competing destinations.

7.2 Results overview

Our rescaled estimates of changes in net foreign currency inflows, relative to the 2011 GDP level, are displayed in Table S8. These variations follows a rather non-linear path. Limited increases of temperature are beneficial but higher levels are detrimental in China, the Republic of Korea, Italy and Turkey. Vice versa,

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[14] We estimated per capita expenditure data on the basis of IMF data on tourism revenue (IMF, 2014).

initial negative impacts turn positive at +5°C in Mongolia, Estonia, Lithuania, Slovak Republic, Slovenia, Bulgaria, Belarus, Romania and Kazakhstan.

Benefits are concentrated in a few countries. For example, at +3°C only 26 countries get an increase in tourism revenue, whereas as many as 97 countries experience a relative loss. Benefitted countries include North European and North American countries, Japan and the Russian Federation, which are all rich nations: tourism impacts have adverse distributional consequences.

Furthermore, the dispersion of income flows gets larger as temperature rises. The standard deviation of the distribution of net revenue inflows increases progressively from about 1.48 billion US$ at +1°C up to around 5.36 billion US$ at +5°C.

7.3 Inclusion of Tourism Impacts in a CGE Model

Our estimates of net currency inflows are meant to be used as inputs in a CGE model, assessing economic impacts of climate change. The exogenous shock can be inserted as a variation in international income transfers and, possibly, as a shift in the pattern of final consumption.

Most CGE models are based on a "territorial" definition of income. In other words, GDP rather than GNP is taken as the reference value for income and other macroeconomic variables. This implies that there is no distinction between nationals and foreigners when income is spent inside a country boundaries. However, the purchasing power of foreigners comes from income generated abroad. In order to consider this important aspect, Berrittella et al. (2006) and Bigano et al. (2008) simulate the occurrence of some international income transfers, whose magnitude corresponds to the estimated change in net currency inflows.

Since foreign tourists are unlikely to have a structure of consumption similar to that of the representative household in a country, a further step is simulating an exogenous increase (or decrease) in the consumption of tourism (hotels, restaurants, recreation facilities) and domestic transport services, which can be implemented by inserting some shifting parameters in the final demand for these items.

8. Climate change impact #6: Household Energy Demand

Household energy demand is directly affected by variations in temperature. This relationship is rather complex, as the impact on energy consumption depends on the season, the source of energy and the climatic condition of the country.

For instance, an increase in winter temperatures would cause a decrease in energy used for heating purposes, whereas an increase in summer temperatures is likely to cause an increase of energy consumed for cooling purposes, depending on the latitude of the country (i.e., tropical, temperate, cold).

In what follows, the impact of increasing average temperature on energy demand is computed, taking into account all these factors.

8.1 Methodology

Our estimates are based on De Cian et al. (2013), who computed parameters of a model for household energy demand, by energy source and season, using econometric techniques and a global panel database. Energy demand is expressed as dependent, among other factors, on the (natural logarithm of) seasonal average temperature, expressed in °F.

Table 4. Long run temperature elasticities from De Cian et al. (2013).

Season	Climate	Electricity	Gas	Oil Products
Winter	*Cold*	-0.085	-0.422	-0.406
	Mild	-0.085	-0.422	-0.406
	Hot	-0.085	-0.422	-0.406
Spring	*Cold*	0.522	0.686	-0.395
	Mild	-0.077	0.686	-0.395
	Hot	0.263	0.686	-0.395
Summer	*Cold*	-0.321	-1.008	-0.912
	Mild	0.2	-1.008	-0.912
	Hot	0.174	-1.008	-0.912
Fall	*Cold*	-	0.685	0.0002
	Mild	-	0.685	0.0002
	Hot	-	0.685	0.0002

Source: De Cian et al. (2013).

Seasonal long run temperature elasticities by energy source and by climate region (Table 4) are those estimated by De Cian et al. (2013). Since we are interested in the variation of total energy demand, elasticities in Table 4 have been scaled down by considering the share of energy used for heating and cooling purposes (Table 5). The adjusted elasticities are shown in Table 6.

Data on average seasonal temperature by country are obtained from the Weather Database (www.weatherbase.com), whereas each country has been classified as Cold, Mild or Hot, according to its latitude.[15] Applying the model estimated by De Cian et al. (2013), to the percentage variation in temperature corresponding to 1°C (and 2, 3, 4, 5°C) increase in seasonal average temperature has been multiplied by the elasticities reported in Table 6.

Table 5. Share of energy demanded for heating and cooling purposes, by energy source and climate region.

	Electricity		**Gas**	**Oil Products**
Climate	Heating	Cooling	Heating	Heating
Cold	8%	5%	72%	88%
Mild	9%	17%	56%	86%
Hot	7%	28%	48%	86%

Source: U.S. Residential Energy Demand Database (www.eia.gov)

Table 6. Adjusted long run temperature elasticities.

Season	**Climate**	**Electricity**	**Gas**	**Oil Products**
Winter	*Cold*	-0.0111	-0.3053	-0.3558
	Mild	-0.0221	-0.2345	-0.3496
	Hot	-0.0300	-0.2008	-0.3496
Spring	*Cold*	0.0682	0.4962	-0.3462
	Mild	-0.0200	0.3812	-0.3401
	Hot	0.0929	0.3264	-0.3401
Summer	*Cold*	-0.0419	-0.7292	-0.7993
	Mild	0.0519	-0.5602	-0.7853
	Hot	0.0614	-0.4797	-0.7853
Fall	*Cold*	-	0.4955	0.0002
	Mild	-	0.3807	0.0002
	Hot	-	0.3260	0.0002

Source: Authors' calculations.

8.2 Result overview

Table S9 shows our estimates of the percentage variations in household energy demand corresponding to a +1, +2, +3, +4 and +5°C increase in the average seasonal temperature. Estimates are provided for the 140 GTAP 9 regions, but they are available for more countries.

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[15] Hot countries: latitude<27°; mild countries: 27°<latitude<63°; cold countries: latitude>63°. For aggregated regions the latitude has been computed as a weighted sum of the latitude of each single country.

A quick inspection of the table reveals that: (i) household demand for electricity rises, especially in the hot countries, as this source of energy is mainly used for air conditioning. The highest relative growth is expected in the African countries; (ii) household demand for energy from oil products dramatically decreases in all countries, especially in cold countries; (iii) the effect on household demand for energy from gas is positive (negative) in mild and cold (hot) countries.

9. Aggregation of impacts and first-order effects on GDP

The illustration of our estimates for the different impacts of the climate change has made clear that the impacts are different in sign, magnitude and relevance for the various countries and regions. Therefore, it would be interesting to see what is the net aggregate effect, for example in terms of real income or GDP, of the combined impacts.

A fully fledged analysis of this kind would require a global, disaggregated macroeconomic model, in which our estimates would be employed to shock exogenous parameters. For instance, an exogenous reduction in agricultural productivity would reduce the relative competitiveness for the domestic agricultural sector, increasing imports from abroad, inducing a real devaluation, expanding production and exports in manufacturing and services.

Such kind of analysis is beyond the scope of this paper. Nonetheless, we can provide here a first-order approximation of the impact on the real GDP, because most of the impacts affect variables which are components of the Gross Domestic Product, with the exception of the variation in energy demand. Because of that, an approximated impact on the GDP can be readily obtained by multiplying the variation of one GDP component by its share, and in particular:

- impacts of sea level rise on GDP can be gauged by multiplying the estimated changes in available land resources by the share of land rents income on total GDP;
- agricultural productivity variations can be evaluated by multiplying the changes by the share of agricultural value added on total GDP;
- the reduction in labor productivity due to heat stress has an effect on the GDP that can be estimated as the sum of variations in labor productivity in the three sectors (agriculture, manufacturing, services) multiplied by the shares of (sectoral) labor income on total GDP;
- human health effects can be obtained by multiplying the estimated changes by the share of labor income on total GDP;

- the net inflow of foreign currency due to tourism flows can be directly expressed as relative to a baseline GDP level.

Even if the sum of the different impacts on GDP is only limited to first-order effects and does not consider general equilibrium feedbacks, we believe that such an approximation of the composite GDP footprint could reveal important insights about the order of magnitude, relevance, and distribution of the various impacts. Tables A1.1 and A1.2 in the Appendix present our estimates, corresponding to an increase in average temperature of +3°C[16] for the five categories above and their total algebraic sum. We highlight with a green background color the positive net variations in GDP, with a yellow background moderate reductions (from -1% to -5%) and with a red background the large reductions (below -5%). In addition, we identify, for each country, which among the three types of impact is the one contributing the most to the overall effect on GDP.[17]

A quick inspection of Tables A1.1 and A1.2 reveals a number of thought-provoking facts. Only a few countries (Mongolia, Canada, and central-northern European countries, including Russia) are expected to get moderate gains from a +3°C increase in temperature, and these gains are typically due to an increase in tourists' arrivals (and diminished outgoing domestic tourists). Many countries (whose estimates are highlighted in red) are expected to suffer from dramatic reductions in GDP. The most negatively affected countries are Togo in Africa (-18.29%) and Cambodia in South-East Asia (-18.25%), where again Tourism is the most important factor.

In addition to tourism income, variations in agricultural and labor productivity are also very relevant in many countries. Sea level rise, on the other hand, never appears as the primary factor, because of its limited incidence on total land and the relative small share of land income on GDP. Remarkably, Tourism is (possibly with Heat) the least studied effect of climate change, maybe because it causes a redistribution of income and wealth, but it has negligible consequences at the global level.

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[16] This refers to changes in the global average temperature. For agricultural productivity, we consider regional variations, which could be larger or smaller than the global one. Furthermore, sea level rise does not depend only on temperature levels, but on time. For this estimation, we set the year 2100 as the one corresponding to the +3°C temperature increment.

[17] Therefore, it has the same sign of the total variation.

It is also evident that effects are similar among similar countries, that is when they belong to the same region or are characterized by comparable socio-economic conditions. Figure 7 presents a scatter plot of total percentage variations of GDP against per capita income levels. The correlation between these two variables is positive and as large as 0.445, confirming a robust finding from previous studies (e.g. Eboli et al., 2010; Roson and van der Mensbrugghe, 2012) that climate change impacts act like a highly regressive tax, often making poor countries poorer, and rich countries richer.

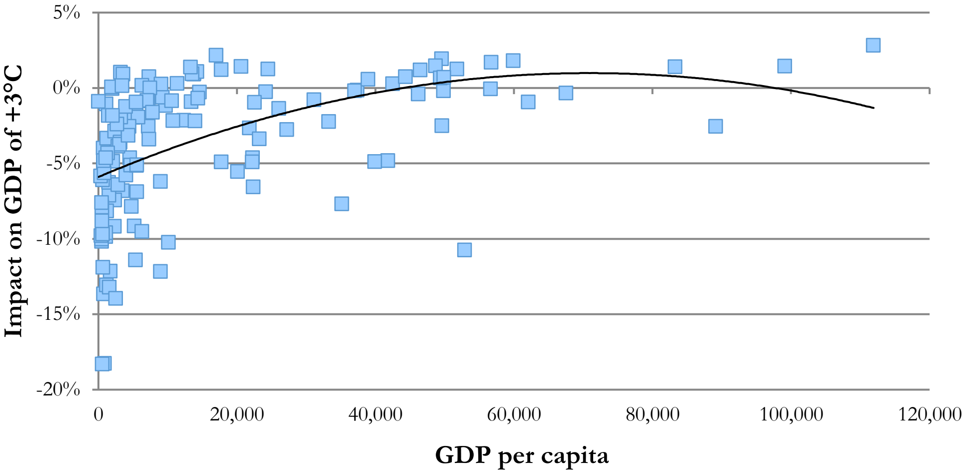

Figure 7. Percentage variation of GDP against per capita income level.

Source: Authors' calculations.

It is known that economic development is itself correlated with geographical location and temperature: in contemporary data, national income falls 8.5% per degree Celsius in the world cross-section (Dell et al., 2009). We do not discuss here any causality or interpretation for this correlation. Rather, we show in Figures 8 and 9 another two scatter plots, this time contrasting GDP variations with average temperature and latitude. The corresponding correlation factors are, respectively, -0.785 and 0.732.

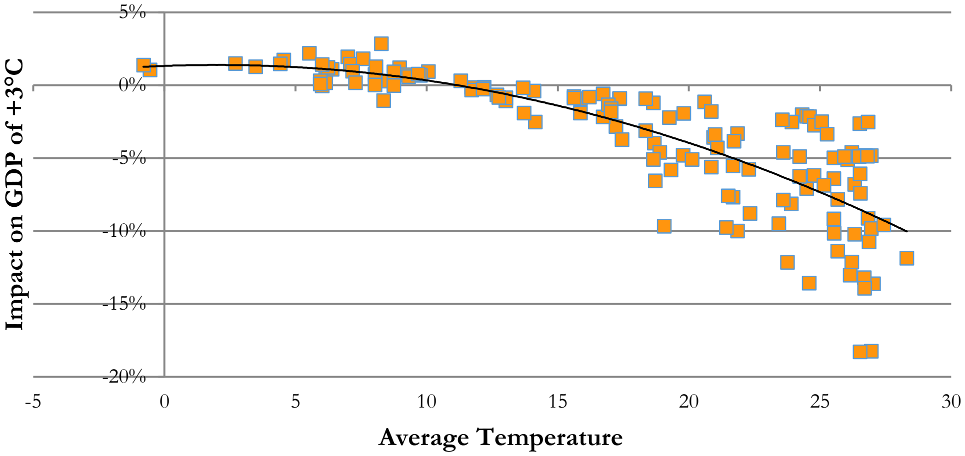

Figure 8. Percentage variation of GDP against average temperature.

Source: Authors' calculations.

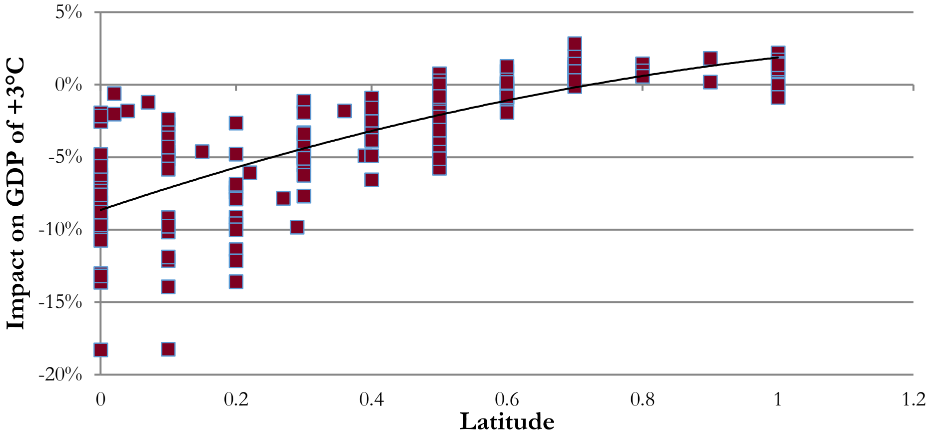

Figure 9. Percentage variation of GDP against latitude.

Source: Authors' calculations.

10. Conclusions

In this paper, a new set of climate change damage functions has been presented, improving earlier estimates in several ways. First, functions and parameters are provided with a large regional disaggregation (140 countries) and in a format which, by referring to the latest GTAP social accounting matrix, makes them easily employable in many general equilibrium and other economic models. Information from new, recently available studies, mostly from the non-economic literature, has been processed in such a way that parameter values for economic variables, like labor productivity, can be estimated. Because of the wealth of primary data utilized in this exercise, it has also been possible to detect non-linearities in many impacts of climate change.

Although our estimates are mostly intended for use in multi-sectoral macroeconomic models, we undertook a simple aggregation procedure to verify the order of magnitude of the various impacts, as well as their distribution. Our findings confirm that the negative effects of climate change will be mainly borne by developing countries, located in tropical regions.

Acknowledgment

The research for this paper was supported by the Knowledge for Change multi-donor trust fund. The views and opinions expressed in this paper are solely those of the authors and do not represent the views of the World Bank Group.

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Appendix

Table A1.1. Impact on GDP of +3°C by country

N	Code	Country Name	SLR	AGR	HEAT	HEALTH	TOURISM	Incidence on GDP of +3°C	Dominant impact
1	AUS	Australia	0.0000%	-0.1686%	-0.0162%	-0.2370%	-0.5029%	**-0.92%**	TOURISM
2	NZL	New Zealand	-0.0005%	-0.0975%	0.0000%	-0.2073%	0.1806%	**-0.12%**	HEALTH
3	XOC	Rest of Oceania	-0.0095%	-0.3135%	-1.3971%	-0.3030%	0.0000%	**-2.02%**	HEAT
4	CHN	China	0.0000%	0.1975%	-0.5449%	-0.8164%	0.0890%	**-1.07%**	HEALTH
5	HKG	Hong Kong SAR, China	-0.0118%	-0.0480%	-1.6329%	-0.7237%	-5.2541%	**-7.67%**	TOURISM
6	JPN	Japan	-0.0005%	-0.0765%	-0.2334%	-0.0967%	0.0205%	**-0.39%**	HEAT
7	KOR	South Korea	-0.0006%	-0.1113%	-0.2600%	-0.0843%	0.2123%	**-0.24%**	HEAT
8	MNG	Mongolia	0.0000%	0.5520%	0.0000%	-0.4409%	0.9466%	**1.06%**	TOURISM
9	TWN	Taiwan, China	-0.0004%	-0.1019%	-2.4258%	-0.9099%	-2.0929%	**-5.53%**	HEAT
10	XEA	Rest of East Asia	-0.0010%	-0.3961%	-4.2472%	-0.1915%	0.0000%	**-4.84%**	HEAT
11	BRN	Brunei Darassalam	-0.0001%	-0.0059%	-2.0021%	-0.1206%	-2.6786%	**-4.81%**	TOURISM
12	KHM	Cambogia	-0.0002%	-2.1774%	-5.2924%	-0.1315%	-10.6492%	**-18.25%**	TOURISM
13	IDN	Indonesia	-0.0010%	-1.1587%	-4.7511%	-0.1790%	-0.7110%	**-6.80%**	HEAT
14	LAO	Lao People's Democratic Republic	0.0000%	-3.5049%	-4.1597%	-0.1425%	-5.7644%	**-13.57%**	TOURISM
15	MYS	Malaysia	-0.0005%	-0.7494%	-4.8378%	-0.1816%	-4.4406%	**-10.21%**	HEAT
16	PHL	Philippines	-0.0028%	-0.9965%	-4.6830%	-0.1445%	-1.5898%	**-7.42%**	HEAT
17	SGP	Singapore	-0.0020%	-0.0200%	-4.4945%	-0.2987%	-5.9202%	**-10.74%**	TOURISM
18	THA	Thailand	-0.0001%	-0.7803%	-3.7029%	-0.1419%	-4.5046%	**-9.13%**	TOURISM
19	VNM	Vietnam	-0.0006%	-1.3580%	-3.3932%	-0.1501%	-2.1889%	**-7.09%**	HEAT
20	XSE	Rest of Southest Asia	-0.0010%	-3.2015%	-6.4740%	-0.1549%	0.0000%	**-9.83%**	HEAT
21	BGD	Bangladesh	-0.0001%	-1.2004%	-3.2480%	-0.2020%	-0.3383%	**-4.99%**	HEAT
22	IND	India	-0.0001%	-1.3077%	-3.3046%	-1.0484%	-0.5829%	**-6.24%**	HEAT
23	NPL	Nepal	0.0000%	-0.0773%	-1.1111%	-0.9108%	-1.8753%	**-3.97%**	TOURISM
24	PAK	Pakistan	0.0000%	-1.7497%	-1.2167%	-0.0985%	-0.2498%	**-3.31%**	AGR
25	LKA	Sri Lanka	-0.0008%	-1.3164%	-2.9340%	-0.8583%	-1.2886%	**-6.40%**	HEAT
26	XSA	Rest of South Asia	0.0000%	-1.9427%	-2.8045%	-0.1434%	0.0000%	**-4.89%**	HEAT
27	CAN	Canada	-0.0001%	0.1723%	0.0000%	0.0000%	1.1003%	**1.27%**	TOURISM
28	USA	United States of America	0.0000%	0.0159%	-0.0048%	-0.2896%	0.1152%	**-0.16%**	HEALTH
29	MEX	Mexico	0.0000%	-0.3420%	-0.1530%	-0.2326%	-0.4177%	**-1.15%**	TOURISM
30	XNA	Rest of North America	-0.0033%	0.0118%	-0.0037%	-0.3277%	0.0000%	**-0.32%**	HEALTH
31	ARG	Argentina	0.0000%	-0.2384%	-0.1037%	-0.3114%	-0.2509%	**-0.90%**	HEALTH
32	BOL	Bolivia	0.0000%	-1.3641%	0.0000%	-0.1476%	-1.3293%	**-2.84%**	AGR
33	BRA	Brazil	0.0000%	-0.5921%	-0.8644%	-0.3432%	-0.3293%	**-2.13%**	HEAT
34	CHL	Chile	-0.0002%	0.0103%	0.0000%	-0.2737%	0.0007%	**-0.26%**	HEALTH
35	COL	Colombia	-0.0001%	-0.7781%	-0.9717%	-0.1258%	-0.6461%	**-2.52%**	HEAT
36	ECU	Ecuador	-0.0004%	-1.0763%	0.0000%	-0.1526%	-0.7002%	**-1.93%**	AGR
37	PRY	Paraguay	0.0000%	-1.9012%	-2.2562%	-0.1768%	-1.4291%	**-5.76%**	HEAT
38	PER	Peru	-0.0002%	-1.4078%	0.0000%	-0.1868%	-0.3127%	**-1.91%**	AGR
39	URY	Uruguay	-0.0001%	-0.4524%	-0.0572%	-0.2972%	-1.3583%	**-2.17%**	TOURISM
40	VEN	Venezuela, RB	-0.0001%	-0.6564%	-0.9783%	-0.1686%	-0.3473%	**-2.15%**	HEAT
41	XSM	Rest of South America	-0.0013%	-0.4069%	-0.0462%	-0.1470%	0.0000%	**-0.60%**	AGR
42	CRI	Costa Rica	-0.0011%	-0.8385%	-1.9108%	-0.2989%	-3.1429%	**-6.19%**	TOURISM
43	GTM	Guatemala	-0.0002%	-1.4468%	-0.3188%	-0.1860%	-1.6208%	**-3.57%**	TOURISM
44	HND	Honduras	-0.0005%	-1.3208%	-4.0728%	-0.1931%	-3.5740%	**-9.16%**	HEAT
45	NIC	Nicaragua	-0.0006%	-1.8717%	-5.0354%	-0.1958%	-5.0277%	**-12.13%**	HEAT
46	PAN	Panama	-0.0012%	-0.6504%	-2.7781%	-0.1926%	-4.9428%	**-8.57%**	TOURISM
47	SLV	El Salvador	-0.0003%	-1.2835%	-0.9629%	-0.1481%	-2.1513%	**-4.55%**	TOURISM
48	XCA	Rest of Central America	-0.0044%	-1.1027%	-3.3145%	-0.1863%	0.0000%	**-4.61%**	HEAT
49	DOM	Dominican Republic	-0.0006%	-0.6860%	-1.8276%	-0.1301%	-4.2142%	**-6.86%**	TOURISM
50	JAM	Jamaica	-0.0006%	-0.3236%	-2.3722%	-0.1938%	-8.4870%	**-11.38%**	TOURISM
51	PRI	Puerto Rico	-0.0006%	-0.1014%	-1.6726%	-0.1793%	-0.7814%	**-2.74%**	HEAT
52	TTO	Trinidad and Tobago	-0.0009%	-0.1245%	-2.4513%	-0.1207%	-2.1839%	**-4.88%**	HEAT
53	XCB	Caribbean	-0.0017%	-0.5995%	-3.3617%	-0.2107%	-3.6624%	**-7.84%**	TOURISM
54	AUT	Austria	0.0000%	0.0197%	0.0000%	-0.0472%	1.9809%	**1.95%**	TOURISM
55	BEL	Belgium	0.0000%	0.0062%	0.0000%	-0.0482%	1.2519%	**1.21%**	TOURISM
56	CYP	Cyprus	-0.0004%	-0.4306%	-0.1406%	-0.0426%	-3.9984%	**-4.61%**	TOURISM
57	CZE	Czech Republic	0.0000%	0.0369%	0.0000%	-0.0383%	1.4414%	**1.44%**	TOURISM
58	DNK	Denmark	0.0000%	0.0271%	0.0000%	-0.0506%	1.8480%	**1.82%**	TOURISM
59	EST	Estonia	0.0000%	0.1165%	0.0000%	-0.0379%	2.1074%	**2.19%**	TOURISM
60	FIN	Finland	0.0000%	0.1317%	0.0000%	-0.0471%	1.3954%	**1.48%**	TOURISM
61	FRA	France	0.0000%	0.0002%	0.0000%	-0.0501%	0.3515%	**0.30%**	TOURISM
62	DEU	Germany	0.0000%	0.0115%	0.0000%	-0.0530%	0.7933%	**0.75%**	TOURISM
63	GRC	Greece	-0.0001%	-0.2039%	-0.0545%	-0.0329%	-1.0597%	**-1.35%**	TOURISM
64	HUN	Hungary	0.0000%	0.0191%	0.0000%	-0.0376%	0.9476%	**0.93%**	TOURISM
65	IRL	Ireland	0.0000%	0.0116%	0.0000%	-0.0404%	0.7150%	**0.69%**	TOURISM
66	ITA	Italy	0.0000%	-0.1355%	0.0000%	-0.0417%	-0.0005%	**-0.18%**	AGR
67	LVA	Latvia	0.0000%	0.1817%	0.0000%	-0.0396%	0.8261%	**0.97%**	TOURISM
68	LTU	Lithuania	0.0000%	0.1642%	0.0000%	-0.0379%	0.9750%	**1.10%**	TOURISM
69	LUX	Luxembourg	0.0000%	0.0057%	0.0000%	-0.0497%	2.8828%	**2.84%**	TOURISM
70	MLT	Malta	-0.0001%	-0.1480%	-0.0711%	-0.0361%	-6.2965%	**-6.55%**	TOURISM

Table A1.2. Impact on GDP of +3°C by country

N	Code	Country Name	SLR	AGR	HEAT	HEALTH	TOURISM	Incidence on GDP of +3°C	Dominant impact
71	NLD	Netherlands	0.0000%	0.0103%	0.0000%	-0.0506%	0.7591%	**0.72%**	TOURISM
72	POL	Poland	0.0000%	0.0511%	0.0000%	-0.0405%	0.9494%	**0.96%**	TOURISM
73	PRT	Portugal	0.0000%	-0.1230%	0.0000%	-0.0486%	-0.7612%	**-0.93%**	TOURISM
74	SVK	Slovak Republic	0.0000%	0.0359%	0.0000%	-0.0392%	1.2305%	**1.23%**	TOURISM
75	SVN	Slovenia	0.0000%	0.0273%	0.0000%	-0.0523%	1.3031%	**1.28%**	TOURISM
76	ESP	Spain	0.0000%	-0.1623%	0.0000%	-0.0521%	-0.5523%	**-0.77%**	TOURISM
77	SWE	Sweden	0.0000%	0.0566%	0.0000%	-0.0516%	1.7159%	**1.72%**	TOURISM
78	GBR	United Kingdom	0.0000%	0.0099%	0.0000%	-0.0551%	0.6373%	**0.59%**	TOURISM
79	CHE	Switzerland	0.0000%	0.0151%	0.0000%	-0.0665%	1.4678%	**1.42%**	TOURISM
80	NOR	Norway	-0.0001%	0.0756%	0.0000%	-0.0487%	1.4445%	**1.47%**	TOURISM
81	XEF	Rest of EFTA	0.0000%	0.0364%	0.0000%	-0.0742%	0.0000%	**-0.04%**	HEALTH
82	ALB	Albania	-0.0002%	-0.5880%	-0.0018%	-0.0837%	-1.8545%	**-2.53%**	TOURISM
83	BGR	Bulgaria	0.0000%	-0.2314%	0.0000%	-0.0836%	1.0793%	**0.76%**	TOURISM
84	BLR	Belarus	0.0000%	0.1365%	0.0000%	-0.1016%	0.1481%	**0.18%**	TOURISM
85	HRV	Croatia	-0.0059%	-0.1818%	0.0000%	-0.0475%	-0.4174%	**-0.65%**	TOURISM
86	ROU	Romania	0.0000%	0.0507%	0.0000%	-0.0406%	0.2620%	**0.27%**	TOURISM
87	RUS	Russian Federation	-0.0001%	0.2438%	0.0000%	-0.0620%	1.2058%	**1.39%**	TOURISM
88	UKR	Ukraine	0.0000%	0.0614%	0.0000%	-0.0829%	0.9421%	**0.92%**	TOURISM
89	XEE	Rest of Eastern Europe	0.0000%	0.0685%	0.0000%	-0.0887%	0.0000%	**-0.02%**	HEALTH
90	XER	Rest of Europe	0.0000%	0.0479%	0.0000%	-0.0396%	0.0000%	**0.01%**	AGR
91	KAZ	Kazakhstan	0.0000%	0.0489%	0.0000%	-0.0843%	0.3404%	**0.31%**	TOURISM
92	KGZ	Kyrgyzstan	0.0000%	0.7822%	0.0000%	-0.0638%	-1.7649%	**-1.05%**	TOURISM
93	XSU	Rest of Former Soviet Union	0.0000%	0.1312%	0.0000%	-0.0568%	0.0000%	**0.07%**	AGR
94	ARM	Armenia	0.0000%	0.2216%	0.0000%	-0.0714%	0.0175%	**0.17%**	AGR
95	AZE	Azerbaijan	0.0000%	-0.5908%	-0.0988%	-0.0414%	-0.1307%	**-0.86%**	AGR
96	GEO	Georgia	-0.0003%	0.1385%	-0.0522%	-0.0843%	-1.9215%	**-1.92%**	TOURISM
97	BHR	Bahrain	-0.0005%	-0.0683%	-1.1748%	-0.4204%	-3.2314%	**-4.90%**	TOURISM
98	IRN	Iran, Islamic Republic of	0.0000%	-0.4277%	-0.1860%	-0.1181%	-0.0843%	**-0.82%**	AGR
99	ISR	Israel	0.0000%	-0.1655%	-0.0400%	-1.2584%	-0.7563%	**-2.22%**	HEALTH
100	JOR	Jordan	0.0000%	-0.3556%	-0.1463%	-0.5373%	-4.0531%	**-5.09%**	TOURISM
101	KWT	Kuwait	0.0000%	-0.0182%	-0.7005%	-0.2407%	-1.5365%	**-2.50%**	TOURISM
102	OMN	Oman	0.0000%	-0.0558%	-0.7102%	-0.3094%	-1.5583%	**-2.63%**	TOURISM
103	QAT	Qatar	-0.0001%	-0.0346%	-1.2702%	-0.3952%	-0.8283%	**-2.53%**	HEAT
104	SAU	Saudi Arabia	0.0000%	-0.0700%	-1.4904%	-0.5016%	-1.2991%	**-3.36%**	HEAT
105	TUR	Turkey	-0.0001%	-0.4687%	0.0000%	-0.3499%	-0.0075%	**-0.83%**	AGR
106	ARE	United Arab Emirates	-0.0002%	-0.1686%	-1.3851%	-0.4344%	-2.8718%	**-4.86%**	TOURISM
107	XWS	Rest of Western Asia	0.0000%	-0.7620%	-0.2868%	-0.1673%	0.0000%	**-1.22%**	AGR
108	EGY	Egypt, Arab Rep.	-0.0005%	-1.1341%	-0.6905%	-0.4656%	-1.5531%	**-3.84%**	TOURISM
109	MAR	Morocco	-0.0001%	-1.1070%	-0.0555%	-0.7353%	-1.8221%	**-3.72%**	TOURISM
110	TUN	Tunisia	-0.0001%	-0.7579%	-0.2464%	-0.5286%	-1.5935%	**-3.13%**	TOURISM
111	XNF	Rest of North Africa	0.0000%	-0.3463%	-0.1242%	-0.4551%	0.0000%	**-0.93%**	HEALTH
112	BEN	Benin	0.0000%	-2.2061%	-5.8667%	-0.7895%	-4.7655%	**-13.63%**	HEAT
113	BFA	Burkina Faso	0.0000%	-2.3843%	-5.8824%	-0.6710%	-2.9330%	**-11.87%**	HEAT
114	CMR	Cameroon	0.0000%	-2.4157%	-2.6122%	-1.0351%	-2.0672%	**-8.13%**	HEAT
115	CIV	Cote d'Ivoire	0.0000%	-2.6715%	-7.3540%	-1.1743%	-1.8351%	**-13.03%**	HEAT
116	GHA	Ghana	0.0000%	-2.5318%	-7.6143%	-1.2015%	-1.8443%	**-13.19%**	HEAT
117	GIN	Guinea	0.0000%	-2.2525%	-2.4491%	-0.5128%	-4.9416%	**-10.16%**	TOURISM
118	NGA	Nigeria	0.0000%	-4.0968%	-8.2096%	-0.9791%	-0.6444%	**-13.93%**	HEAT
119	SEN	Senegal	0.0000%	-1.5615%	-3.6766%	-0.6634%	-3.6789%	**-9.58%**	TOURISM
120	TGO	Togo	0.0000%	-2.9926%	-6.7908%	-0.8777%	-7.6318%	**-18.29%**	TOURISM
121	XWF	Rest of Western Africa	0.0000%	-1.5088%	-3.9966%	-0.5685%	0.0000%	**-6.07%**	HEAT
122	XCF	Rest of Central Africa	0.0000%	-0.4709%	-0.8100%	-0.6294%	-0.4675%	**-2.38%**	HEAT
123	XAC	Rest of South Central Africa	0.0000%	-0.9863%	-0.0461%	-0.7702%	0.0000%	**-1.80%**	AGR
124	ETH	Ethiopia	0.0000%	-3.4512%	0.0000%	-0.8943%	-1.4763%	**-5.82%**	AGR
125	KEN	Kenya	0.0000%	-2.8648%	-0.1698%	-0.9299%	-1.6563%	**-5.62%**	AGR
126	MDG	Madagascar	-0.0002%	-2.9062%	-2.5131%	-0.9861%	-3.5947%	**-10.00%**	TOURISM
127	MWI	Malawi	0.0000%	-2.6408%	-1.5485%	-0.9422%	-4.6332%	**-9.76%**	TOURISM
128	MUS	Mauritius	-0.0009%	-0.7158%	-2.1495%	-0.8996%	-8.3783%	**-12.14%**	TOURISM
129	MOZ	Mozambique	-0.0001%	-1.1773%	-2.7128%	-0.9728%	-3.0178%	**-7.88%**	TOURISM
130	RWA	Rwanda	0.0000%	-3.7427%	0.0000%	-1.0299%	-4.8945%	**-9.67%**	TOURISM
131	TZA	Tanzania	-0.0001%	-2.5945%	-1.4315%	-1.0207%	-3.7480%	**-8.79%**	TOURISM
132	UGA	Uganda	0.0000%	-2.3230%	-0.3320%	-0.8564%	-4.0730%	**-7.58%**	TOURISM
133	ZMB	Zambia	0.0000%	-1.1479%	-0.4776%	-1.1182%	-1.5571%	**-4.30%**	TOURISM
134	ZWE	Zimbabwe	0.0000%	-0.9073%	-0.1290%	-0.7963%	-2.9613%	**-4.79%**	TOURISM
135	XEC	Rest of Eastern Africa	0.0000%	-1.2136%	-2.4070%	-0.9955%	0.0000%	**-4.62%**	HEAT
136	BWA	Botswana	0.0000%	-0.5257%	-0.3916%	-0.7531%	-1.7062%	**-3.38%**	TOURISM
137	NAM	Namibia	0.0000%	-0.9395%	-0.0747%	-0.7110%	-3.3564%	**-5.08%**	TOURISM
138	ZAF	South Africa	0.0000%	-0.2159%	-0.0003%	-0.8577%	-0.5198%	**-1.59%**	HEALTH
139	XSC	Rest of South African Customs Union	0.0000%	-1.0459%	-0.0015%	-0.7656%	0.0000%	**-1.81%**	AGR
140	XTW	Rest of the World	-0.0013%	-0.1252%	0.0000%	-0.7543%	0.0000%	**-0.88%**	HEALTH