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Keywords: Climate Change Costs, Adaptation, Computable General Equilibrium Models
JEL Classification: C68, Q54

This research project has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under the grant agreement n°266992 (Global IQ).

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Climate change impacts and market driven adaptation: The costs of inaction including market rigidities[1]

Francesco Bosello[1,2,3] and Ramiro Parrado[1,2]

Abstract

This paper presents a first exercise comparing the cost of climate change stemming from integrated assessment models using reduced-form climate change damage functions with that performed by a CGE model. Furthermore, it investigates the role of market driven adaptation, which CGE models explicitly capture through their endogenous price setting mechanism, in determining these estimates. It is shown that world GDP losses computed by the CGE model are not significantly different from that used by some well-established hard-linked integrated assessment models when they consider the same impact categories. Specifically, the major driver of impacts is the modelling of catastrophic outcomes. Then, rigidities in market adjustments, differently said, in market-driven adaptation, are introduced. This is done restricting the elasticity of input substitution in the production function, the substitutability of domestic and imported inputs, and finally sectoral workforce mobility. We demonstrate that notwithstanding these frictions do increase the cost of climate change impacts they do not change substantively neither the qualitative nor the quantitative picture.

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1. Introduction and background

To manage the complexity of economic assessments of climate change impacts, climate change research saw an increasing development and application of integrated assessment models (IAMs). Their distinctive feature is to describe in a controlled environment the "climate-change issue" in its entirety, i.e. connecting the climatic, the environmental and the social components.

Two broad approaches can be identified in the economic quantification of climate change damages with IAMs. One makes ample use of reduced-form climate change damage functions (CCDFs). Basically, a more or less sophisticated functional form translates temperature increases into GDP losses (see e.g.: Nordhaus, 1991; Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000; Popp, 2004; Manne and Richels, 2004; Edenhofer et al. 2005; Bosetti et al., 2006; Gerlagh, 2007; Ortiz et al 2011). Parameterization of these functions derives from extrapolation of the impact literature or expert opinions. A different approach, often coupled with the use of Computable General Equilibrium (CGE) models, consists in translating climate change pressures into changes in quantity/quality of factors of production and/or in agents' preferences driving demand and supply behaviour in the models. GDP losses (climate change costs) are thus the direct outcome of the simulation and do not stem from an explicit function and its ad hoc parameterization (see e.g. Tsigas et al., 1997; Darwin and Tol 2001; Deke et al. 2001; Bosello et al. 2007, 2008, 2012; Eboli et al. 2010; Aaheim et al. 2009; Ciscar et al. 2011).

More than twenty years of IA research produced a vast literature on the cost of climate change (see e.g.: IPCC, 1996, 2001, 2007, 2014; Stern 2007; Tol 2008, 2009, 2011). Trying to summarize: climate change impacts on world GDP seem to be moderately negative (reaching at the maximum the 2% of GDP (IPCC, 2007)) or, according to some studies (Tol, 2002b; Mendelsohn et al., 2000), even slightly positive, for temperature increases below the 2°C. They become unambiguously negative in response to a (roughly) 3°C warming to then increase more than proportionally in temperature. Variability of estimates expands greatly increasing the reference warming. For instance, the latest available summary estimates from Tol (2014) reports the range of damages stemming from 21 studies presenting a gross world product (GWP) loss between basically 2.5 and 16% for 5.5°C warming.[2]

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[2] The literature also stresses relevant regional asymmetries in impacts with developing countries incurring in GDP losses even at low levels of warming and when net benefits can still be observed for the world as a whole. For instance Tol (2002b) and Mendelsohn et al, (2000) report positive or no impact

This variability affects the assessment of the marginal cost of carbon emissions, also referred to, in the literature, as the social cost of carbon. This, ranges from negative figures (implying gains from climate change), to values higher than 800 $/tC. The majority of available estimates reports anyway values lower than 100 $/tC (Tol, 2008, 2009).

Also due to their obvious policy relevance,[3] these estimates are surrounded by a heated debate, and many authors suggest that they are likely to underestimate climate change costs. Namely: many features of climate change, environmental and social responses are still uncertain and/or not well captured by IAMs. For instance, relatively small changes in climate sensitivity can greatly change the cost estimates from these models (Ackermann and Stanton, 2012; Anthoff and Tol, 2013). In this vein, a higher emphasis on seasonal and extreme-weather short-term effects lead Hanemann (2008) to quadruple Nordhaus damage estimates for the US in response to a 2.5°C warming. Quantitative modelling frameworks are also ill suited to measure important social phenomena like conflicts, mass migrations, disruption of knowledge, learning and social capital potentially triggered by climate change (Anthoff and Tol, 2013; Stern, 2013). IAMs emphasize impacts on GDP, which even disregarding its deficiency as a welfare measure, captures flow and tend to overlook stock losses (Stern 2013). Risk and irreversibility associated to high damage low probability events is usually left out of the analysis which can seriously bias downward damage estimates (Weitzman, 2007, 2008, 2009, 2010; Ackerman and Stanton 2012). Finally, IAMs tend to be overly optimistic in describing timing and scale of adaptation processes, disregarding the fact that, while adapting, agents may not use perfect information and for technological, economic, psychological and cultural characteristics may resist to some changes (Patt et al., 2010). All these critiques are particularly relevant when climate change impact assessments are conducted with CGE models.

They provide a peculiar richness in the analysis of climate change costs, highlighting sectoral effects and, above all, tracking endogenous market adjustments and rebounds triggered by climate change shocks. But, at the same time, they are grounded on GDP, account just for marketable relations, typically model instantaneous and frictionless adjustments. Against this background, the assessments performed with CGE models

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from climate change on world GDP (namely 2.3%, and 0% of GDP for temperature increases of 1°C, and 2.5°C respectively), with estimated losses of the 4.1% and 3.6% of GDP both in Africa.

[3] For instance US governmental agencies are supported on cost-benefit analyses of regulatory actions that impact cumulative global emissions by periodically updated interagency reports (see e.g. IWGSCC 2010, 2013) where the social benefits of reducing carbon dioxide emissions stem from analyses conducted with the DICE, FUND and PAGE IA models. Mc Callum et al. (2013) is an extended report released in support to the EU adaptation strategy.

tend to fall somewhat in the lower end of cost estimates. For instance according to Ciscar et al. 2009 the highest welfare loss in the EU for a quite high 5.4°C increase in temperature is -1.25% experienced by the Southern EU region; according to Aaheim et al (2009), for a 4°C warming, the highest GDP looser in the EU is the Iberic peninsula with its -0.5%. The picture is similar for world-level assessments. For instance McCallum et al. (2013) highlights a world GDP contraction of the 1.9% for a 4°C temperature increase, while for Roson and van der Mensbrugghe (2010) the reduction is about 1.8% for a temperature increase of roughly 2.5°C.

In this paper we present a simple exercise to address the following research questions. Do climate change impact assessments performed with CGE models estimate lower GDP losses than reduced-form climate change damage based assessments? What is the role of market driven adaptation in determining these estimates?

We do this first running a standard climate change impact assessment exercise with a recursive-dynamic CGE model using updated estimates of an extended set of climate change impacts for different temperature increase scenarios. Then we use this information to extrapolate a reduced-form climate change damage function. We show that, at the global level, this is not significantly different from that produced by some established hard-linked integrated assessment models when the comparison is even, i.e. when the same impact categories are included.

Furthermore, we perform the same exercise reducing what can be defined "market driven adaptation". In practice, we restrict the elasticity of input substitution in the production function, the substitutability of domestic and imported inputs, and finally sectoral workforce mobility. We demonstrate that, notwithstanding these frictions increase the cost of climate change impacts, they do not change substantively neither the qualitative nor the quantitative picture.

In what follows, section 2 describes the ICES CGE model and its benchmark, section 3 the derivation and implementation of climate change impacts, section 4 presents the impact estimates for different temperature increase scenarios, extrapolates a reduced-form climate change damage function with full market-driven adaptation and compares it with the results from reduced forms used in other well established IA models, section 5 analyses the effects of introducing rigidities in adaptation processes, finally section 6 concludes.

2. The ICES CGE model and benchmark

ICES is a recursive-dynamic computable general equilibrium (CGE) model based on the GTAP 8 database (Narayanan et al. 2012). ICES simulation period is 2007-2050 resolved in one-year time steps, with 2007 as the calibration year. Compared to the standard GTAP database and model, in addition to the dynamic in capital stock, it includes renewable energy production. Different versions of the ICES model have been extensively used in past exercises to economically assess many different kinds of climate change impacts for different climatic scenarios and regional aggregations (see e.g. Bosello and Zhang, 2006; Bosello et al., 2006, 2007, 2008; Eboli et. al 2010; Bosello et. al. 2012).[4] For the sake of the present analysis, the world economic system has been specified into 25 regions and 19 representative industries (see Table 1).

Table 1: Regional and sectoral detail of the ICES model applied in this study

Regional detail				
Europe	***Africa/Middle East***	***Americas***	***Asia***	***Oceania***
North Europe	North Africa	USA	Japan	Australia
North_EU15	Sub-Saharan Africa	Canada	South Korea	New Zealand
Med_EU15	South Africa	Rest of LACA	South Asia	
Med_EU12	Middle East	Brazil	India	
East_EU12		Mexico	China	
Rest of Europe			East Asia	
Russia				
Rest of FSU				

Sectoral detail	
Sectors	***Energy sectors***
Agriculture	Coal
Forestry	Oil
Fishing	Gas
Energy sectors (see right column) →	NuclearFuel
Energy Intensive industries	Oil_Pcts
Other industries	Ely_Nuclear
Transport	Ely_Biomass
Market Services	Ely_Hydro
Public Services	Ely_Solar
	Ely_Wind
	Ely_Other

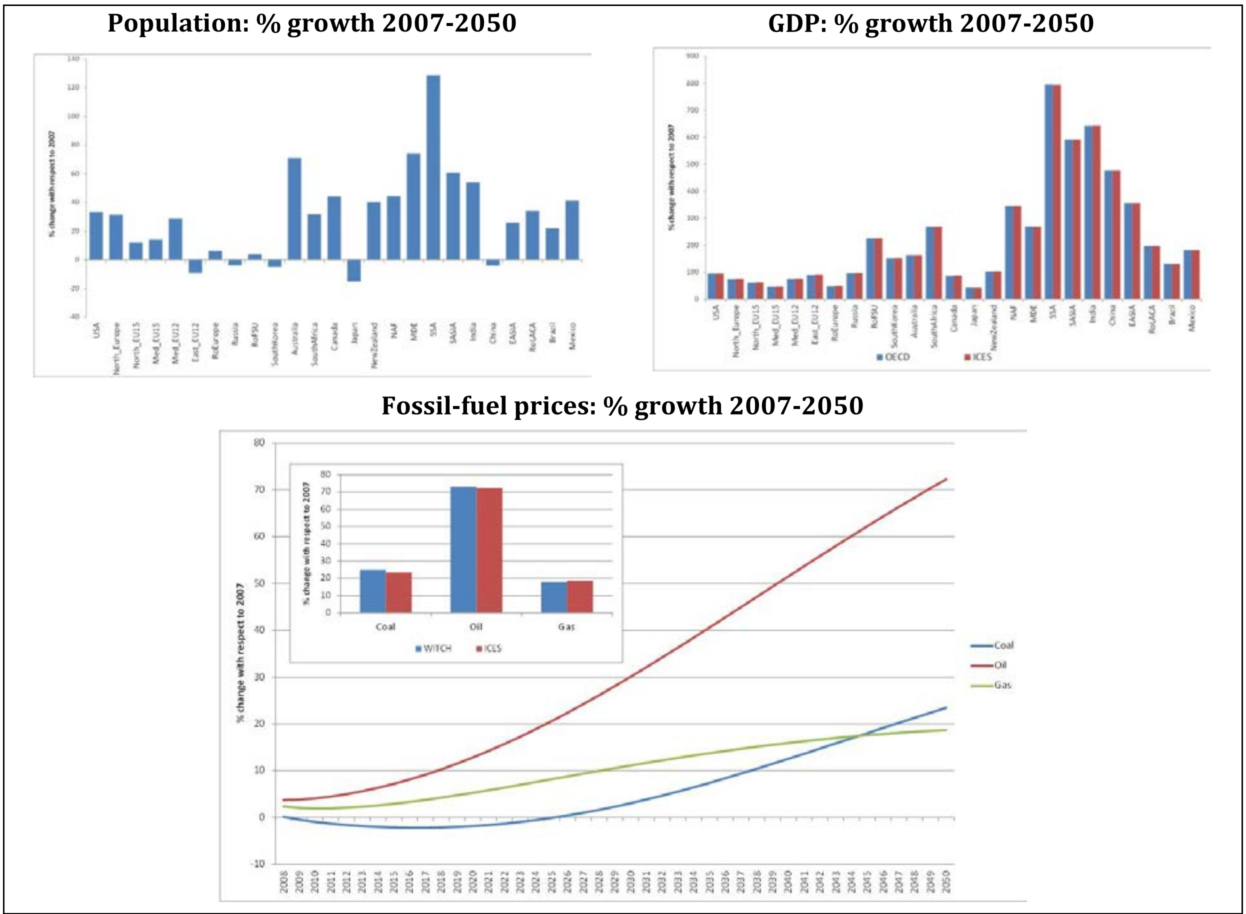
The social-economic reference for the analysis is the SSP2 – "Middle of the Road or Dynamics as Usual" scenario of the Shared Social Economic Pathways (O'Neill et al., 2014). This scenario assumes a socio economic development in line with that of recent decades, with reductions in resource and energy intensity at historic rates and a slowly decreasing fossil fuel dependency. Quantitatively, the ICES reference baseline assumes (see Figure 1):

- GDP and population growths as those reported for the SSP2 in the "OECD version".[5]
- Labour force growth the same as that of population.

[4] A more detailed description of the core of the model can be found in Parrado and De Cian (2013) and in the ICES website at http://www.feem-web.it/ices/.
[5] The SSPs database is available at: https://secure.iiasa.ac.at/web-apps/ene/SspDb/

- Fossil fuel prices growth trends of the 25%, 73% and 18% for coal, oil and gas respectively within the period 2007 to 2050.[6]
- Energy efficiency yearly increases between 0.28% and 0.56% in developed countries and 0.63 % in developing countries.[7]

Figure 1. Population, GDP and fossil-fuel prices trends for the ICES baseline



3. Economic assessment of climate change impacts

This exercise considers an extended set of climate change impacts. They refer to the consequences of changes in sea level, in fish stock productivity, in land productivity, in tourism flows, in energy demand, in health status and in ecosystem services. Source information are bottom-up partial-equilibrium exercises performed within the

[6] These price trends are derived from simulations performed with the WITCH integrated assessment dynamic optimization model (Bosetti, et .al. 2009) applied to the SSP2. WITCH, among other features, offers a detailed description of the energy system and therefore an endogenous energy price formation.

[7] We set these average growth rates for energy efficiency based on information from IEA (2011, 2012). For 2011 the World Energy Outlook 2011 shows an annual average reduction of energy intensity about 1.3% and almost 1.5 % for OECD and Non-OECD countries in the period 1985-2009. In the following edition of the WEO 2012, the annual average percentage change of world energy intensity is reported to be only -0.5% for the period 2000-2010. Accordingly, we impose higher growth rates of energy efficiency for developing countries (0.63%) and lower rates for developed countries (between 0.28% and 0.56%)

framework of recently concluded and ongoing EU Sixth and Seventh Framework Program (FP6 and FP7) research projects: ClimateCost, SESAME and Global-IQ. The impact literature and the methodology applied by dynamic optimization hard linked integrated assessment models supported the computations of impacts on health and ecosystem services. Table 2 provides a summary of the impacts considered as well as their sources. All studies have a global coverage and, in their majority - come from grid-based data sets and models - report data with a high spatial resolution. When necessary, results have been aggregated to match the geographical resolution of the CGE model.

Impacts are computed for temperature increases consistent with the Representative Concentration Pathways (RCPs) 2.6, 6.0, and 8.5 (Van Vuuren et al., 2012). Nonetheless only crop yield changes are explicitly related to those scenarios. The other source studies quantify impacts in the A1B and/or B2 IPCC SRES scenarios (Nakicenovic and Swart, 2000). This introduces a relatively minor approximation problem in specifying the RCP 8.5 reference as until 2050 its temperature profile and that of A1B are reasonably close. Larger differences characterize RCP 8.5, RCP 6.0, and RCP 2.6. Thus, when necessary, impacts consistent with the RCP 6.0 and RCP 2.6 have been reconstructed mapping the temperature of A1B and B2 scenarios to that of RCP 6.0 following Rogelj et al. (2012) and the average trend of temperature changes for each RCP. Then, impacts have been translated from a temperature increase scenario to the other proportionally. They have not been obtained by direct re-running of the sectoral/bottom-up impact models. The outcomes of our elaborations are reported in the next subsections.

Table 2. Summary of climate change impacts

#	CC Impact	Source	Project	Time frame	Scenarios / Reduced form	
					AR5	SRES
1	Sea level Rise	DIVA model - Vafeidis et. al (2008)	ClimateCost	2001-2100		A1B,E1
2	Fisheries	Cheung et. al (2010)	SESAME	2000-2060		A1
3	Agriculture	PIK – LPJmL model ISIP-MIP runs	GLOBAL-IQ	2007-2100	RCP8.5 RCP6.0 RCP2.6	
4	Ecosystem	Warren et al (2006), Manne et al (1995)		2000-2060	***Reduced form***	
5	Tourism	Tol (2002a) - HTM Bigano et. al (2007)	ClimateCost	2005-2100		A1, B2
6	Energy demand	POLES - Criqui (2001) Criqui et. al (2009)	ClimateCost	2000-2050		A1
7	Health	Tol (2002a)	-	2008-2060	***Reduced form***	

3.1 Sea-level rise

Estimates of coastal land lost to *sea-level rise* are based upon the Dynamic Integrated Vulnerability Assessment (DIVA) model outputs (Vafeidis *et al.*, 2008) applied in the FP7 ClimateCost project (Brown et al. 2011). DIVA is an engineering model designed to address the vulnerability of coastal areas to sea-level rise. The model is based on a world database of natural system and socioeconomic factors for world coastal areas reported with a spatial resolution of 5°. The temporal resolution is 5-year time steps until 2100 and 100-year time steps from 2100 to 2500. Changes in natural as well as socio-economic conditions of possible future scenarios are implemented through a set of impact-adaptation algorithms. Impacts are then assessed both in physical (i.e. sq. Km of land lost) and economic (i.e. value of land lost and adaptation costs) terms. The Met Office Hadley Centre generated the sea-level rise scenarios for Climate-Cost.

3.2 Fisheries

Climate-change induced changes in global catch potential derive from the FP6 SESAME project and are based upon Cheung et al. (2010). Basically the changes in future changes in catch potential are calculated considering i) species distribution, and ii) the primary production of oceans.

1. Species distribution depends on species' maximum and minimum depth limits, northern and southern latitudinal range limits, an index of association with major habitat types.
2. Primary production has been predicted following published algorithms and empirical models, according to two climate scenarios.

By combining this kind of information for each spatial cell the empirical model (Cheung et. al, 2008a) computes the maximum catch potential. The specific details are described in Cheung et. al, (2010). They applied an empirical model (Cheung et al. 2008a) that predicts maximum catch potential depending upon primary production and distribution range of 1066 species of exploited fish and invertebrates. Distribution of each species on a 30' latitude 30' longitude grid is derived from an algorithm (Close et al. 2006) including the species' maximum and minimum depth limits, northern and southern latitudinal range limits, an index of association with major habitat types and known occurrence boundaries as input parameters. Future changes in species distribution are simulated by using a dynamic bio climate envelope model (Cheung et al., 2008b, 2010). The model associate species' preference profiles with environmental conditions: seawater temperature (bottom and surface), salinity, distance from sea-ice and habitat types (coral reef, estuaries, seamounts, coastal upwelling and a category that include all other habitat types). Preference profiles consider the suitability of environmental conditions to each species. Then, these are linked to the expected carrying capacity in a population dynamic model. The model assumes that carrying capacity varies positively with habitat suitability of each spatial cell. Finally, aggregating spatially and across species, the related change in total catch potential can be determined.

3.3 Agriculture

Climate change impacts on crop yield (physical production per hectare) derive from the output of the LPJmL Dynamic Global Vegetation Model (Bondeau *et al.*, 2007) developed at PIK and applied within the FP7 Global-IQ project. The LPJ model, endogenously determines spatially explicit transient vegetation composition and the associated carbon and water budgets for different land-uses. It can estimate potential yield and its changes for many crops with a global resolution of 0.5 degree grid cells. In Global-IQ yield data for the different crops have been aggregated into just one weighted average value for the agricultural sector as a whole. The data hereby estimated does not consider the carbon fertilization effects on vegetation.

3.4 Ecosystems

To estimate losses in ecosystem services, a modified Willingness To Pay (WTP) approach has been used. The starting assumption is that these services are largely non marketed and non-directly marketable. Accordingly, their value can be only extracted through elicitation of preferences. In particular the WTP to avoid a given loss in ecosystems is used to approximate the lost value in case they are not protected. This is for instance the methodology applied in the MERGE model (Manne et al., 1995) where the monetized ecosystem losses related to a 2.5°C temperature increase above pre-industrial levels is set equal to the 2% of GDP when per capita income is above $ 40,000. The 2% figure is the US EPA expenditure on environmental protection in 1995. The implicit assumptions are that what actually paid is reasonably close to the WTP, and also roughly sufficient to preserve ecosystems and their services in a world warming moderately.

This approach has been applied here, but rescaling all to the more recent data of the EU 2007 expenditure on environmental protection by the public sector (0.62% of GDP, EUROSTAT, 2013), and assuming more conservatively than Manne et al., (1995) that the observed expenditure allows protection against 2°C warming. Then, to derive WTP in non EU countries the logistic function proposed by Manne et al., (1995) is used (see also Warren et al., 2006):

$$WTP_{n,t|t=2.°C} = \gamma \Delta T^{\varepsilon}{}_{n,t|t=2°C} \frac{1}{1+100e^{(-0.23*GDPn,t|t=2°C/POPn,t|t=2°C)}} \quad (1)$$

The parameter calibration derives from EU data thus γ is set to give exactly 0.62% of GDP when per capita income is the 2007 EU average ($34,262), and ΔT=2°C. The last step is that to use the WTP to measure the direct cost of losses in ecosystem and their services.

3.5 Tourism

Changes in *tourism flows* induced by climate change are derived from simulations based on the Hamburg Tourism Model (HTM, Bigano *et al.*, 2006, 2007) amply used in EU research projects like: FP6 CIRCE, ClimChalp, and more recently the FP7 ClimateCost project. HTM is an econometric simulation model, estimating the number of domestic and international tourists by country, the share of international tourists in total tourists, and tourism flows between countries. The model runs in time steps of 5 years. First, it estimates the total tourists in each country, depending on the size of the population and of average income per capita. Then, it divides tourists between those that travel abroad and those that stay within the country of origin. In this way, the model provides the total number of holidays as well as the trade-off between holidays at home and abroad. The share of domestic tourists in total tourism depends on the climate in the home country and on per capita income. International tourists are then allocated to all other countries based on a general attractiveness index, climatic characteristics, per capita income in the destination countries, and the distance between origin and destination. Climate is proxied by the annual mean temperature which enters among the explanatory variables with a quadratic form. This to capture the fact that warmer climate can be indeed more attractive, but just up to a given "optimal level". Then further increases are negative for tourism.

The model is calibrated to 1995 data., and as in Berrittella et al., (2006) and Bigano et al. (2008) estimations of tourism flows by region are obtained from version 1.2 of the Hamburg Tourism Model (HTM).

3.6 Residential energy demand

Responses of *residential energy demand* to increasing temperatures derive from the POLES model (Criqui, 2001; Criqui *et al.*, 2009) which was also used in FP7 ClimateCost project. Poles is a bottom-up partial-equilibrium model of the world energy system. It determines future energy demand and supply for different energy vectors (coal, oil, natural gas, electricity) according to energy prices trend, technological innovation and climate impacts through their effects on heating and cooling degree-days.

3.7 Health

Impacts on human health are expressed by changes in mortality and morbidity associated to malaria, schistosomiasis, dengue, diarrhoea, cardiovascular and respiratory diseases applying the same methodology of Bosello et al. (2006). Estimates of the change in mortality due to vector-borne diseases (malaria, schistosomiasis, dengue fever) as the result of a one degree increase in the global mean temperature are taken from Tol (2002a). To account for changes in vulnerability possibly induced by improved access to health care facilities associated to improvement in living standards (read GDP growth) Tol (2002a) applies the relationship between per capita income and disease incidence developed by Tol and Dowlatabadi (2001).[8] We use the same relationship applying the projected per capita regional income growth of the ICES model.

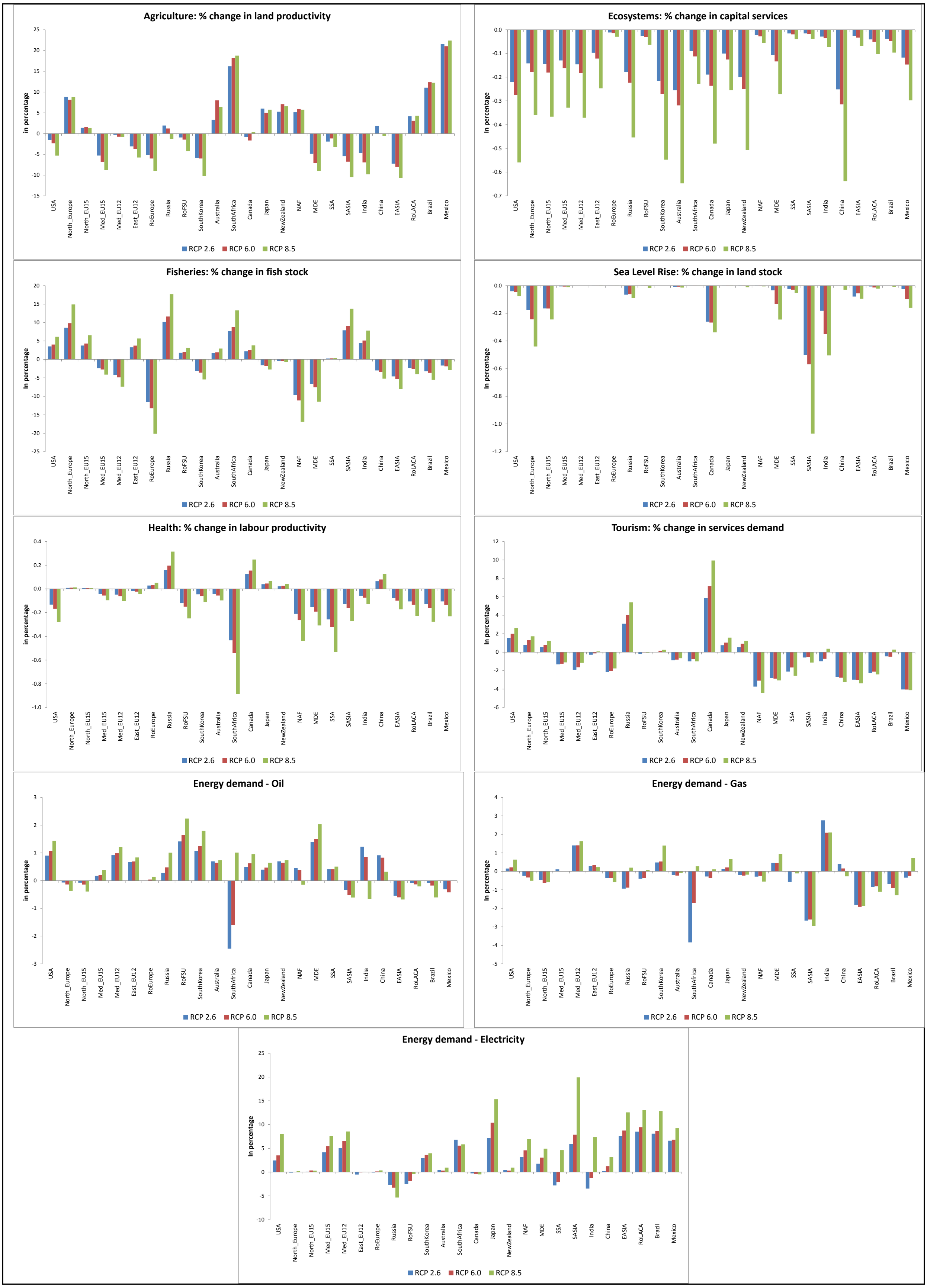
For diarrhoea, we follow Link and Tol (2004), who report the estimated relationship between mortality and morbidity on the one hand and temperature and per capita income on the other hand, using the WHO Global Burden of Disease data (Murray and Lopez, 1996). Martens (1998) report the results of a meta-analysis of the change in cardiovascular and respiratory mortality for 17 countries. Tol (2002a) extrapolates these findings to all other countries, using the current climate as the main predictor. Cold-related cardiovascular, heat-related cardiovascular, and (heat-related) respiratory mortality are specified separately, as are the cardiovascular impacts on the population below 65 and above. Heat-related mortality is assumed to only affect the urban population. We use this model directly on a country basis, before aggregating to the ICES regions

Changes in health care expenditures are also estimated. The literature on the costs of diseases is thin and few papers can be used as reference. The costs of vector borne diseases are taken from Chima et al. (2003), who report the expenditure on prevention and treatment costs per person per month.

Figure 2 reports the data computation for 2050 referring to the RCP 2.6, 6.0 and 8.5 (respectively associated to a temperature increase of 1.76°C, 1.91°C and 2.52°C with respect to preindustrial level)

[8] Vulnerability to vector-borne diseases strongly depends on basic health care and the ability to purchase medicine. Tol and Dowlatabadi (2001) suggest a linear relationship between per capita income and health. In this analysis, vector-borne diseases have an income elasticity of −2.7.

Figure 2. Direct impacts of climate change, inputs to the ICES CGE model (ref. year 2050)



Source: Our elaborations from quoted studies reported in section 3

3.8 Including climate change impacts in the CGE model

Once the impacts have been quantified, they need to be translated into a format compatible with that of the ICES model, accordingly, into changes of those factors driving demand and supply patterns inside the model.

Two broad categories of impacts can be distinguished in Table 3. The first affects the supply-side of the economic system, and concerns variables that are typically exogenous in CGE models, namely: quantity or productivity of primary factors. Changes in these variables can be thus easily accommodated. Impacts on sea-level rise, agriculture, and human health belong to this category and they do not require any substantial change in the basic structure of the model to be implemented.

The second affects changes in the demand side. Impacts on tourism and on energy consumption are of this kind. This implies to intervene on variables which are endogenous to, or output of, the model. The technicality involved is more complex than in the case of exogenous variables and the following procedure has been adopted. The computed percentage variations in the demands are imposed as exogenous shifts in the respective demand equations. The implicit assumption is that the starting information refers to partial equilibrium assessments, thus with *all prices and income levels held ideally constant*. The model is then left free to determine the *final* demand adjustments. Modification in demand structure imposes however to comply with the budget constraint, so the changed consumption of energy and tourism services are compensated by opposite changes in expenditure for all the other commodities.

Table 3: Climate-change impacts modelled in ICES

Supply- side impacts
Impacts on land quantity (land loss due to sea level rise)
Impacts on capital stock (assumed to be equal in % to land loss due to sea level rise)
Impacts on fisheries (changes in fish stock available to the fishing industry)
Impacts on land productivity (Yield changes due to temperature changes)
Impacts on ecosystem services (assumed to reduce capital stock according to the willingness to pay to avoid the impacts due to an increase in temperature)
Impact on labour productivity (changes in morbidity and mortality – health effect of climate change)
Demand-side impacts
Impacts on energy demand (change in households energy consumption patterns for heating and cooling purposes)
Impacts on recreational services demand (change in tourism flows induced by changes in climatic conditions)
Impacts on health care expenditure

In what follows we briefly discuss the procedures adopted to implement each of the impacts considered inside the ICES model.

Land losses to sea-level rise have been modelled as percent decreases in the stock of productive land and capital by region. Both modifications concern land and capital stocks variables, which are exogenous to the model and therefore can be straightforwardly implemented. As information on capital losses is not readily available, in the ICES simulations it is assumed that they exactly match land losses.[9]

Changes in *potential fish catches* have been modelled as per cent reductions in the natural resource stock (primary factor of production) available to the countries' fishing sectors.

Changes in *crops' yields* have been modelled through exogenous changes in land productivity. Due to the nature of source data, land productivity varies by region, but is uniform across all crop types present in ICES.

Impacts on *ecosystems* have been modelled as a loss of physical capital stock. In ICES the capital stock does not enter directly in the production function, rather capital services do. Nonetheless in the model there is a one on one relation between capital stock and capital services as any change in the former implies an equal change in the latter. The assumption made thus, is that ecosystems offer a set of support services to the production activity which are all embedded in capital services. When ecosystem deteriorates, its production support services deteriorates and thus (through deterioration of the capital stock) capital services deteriorate. The amount of the deterioration corresponds to the WTP assessed following the procedure in section 3.4.

Changes in *tourists' flows* have been modelled as changes in (re-scaled) households' demand addressing the market services sector, which includes recreational services. In addition, changes in monetary flows due to variations in tourism demand are simulated through a direct correction of the regional income of each region.

Changes in regional *households' demand for oil, gas and electricity* have been modelled as changes in households' demand for the output of the respective industries.

Changes in labour productivity are also considered as the channel to account for *health* impacts. Lower mortality translates in an increased labour productivity which is one on one proportional to the change in the total population. The underlying assumption is that health impacts affect active population, disregarding the age characteristic of cardiovascular and respiratory diseases. This information is complemented with health expenditures as percentage of GDP.

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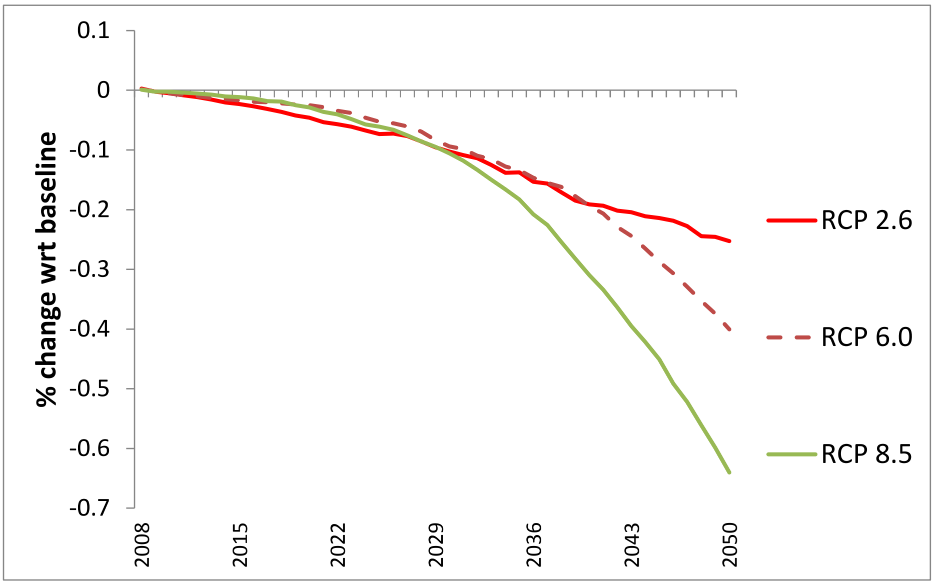
[9] We could have avoided including capital losses, however they are an important part of sea-level rise costs therefore we prefer to have a rough even though arbitrary estimation of this component rather than none. We are not including displacement costs.

4 Climate change impacts in a context of full market adaptation

Results refer to the economic effects of all the impacts above mentioned when they are jointly imposed over the model baseline. These could be referred as market impacts or damages given that they do not consider any other kind of damage estimation such as catastrophic ones. Figure 3 reports climate change impacts on GWP. As expected, RCP 2.6, which is a stabilization scenario, produces the lower costs, while RCP 6.0 is in the middle of the range. In 2050 total costs remain small even in RCP 8.5 reporting the higher CO_2 concentrations. In that year, temperature increase is just slightly beyond the 2.5°C increase. In this context, impacts are still manageable and roughly amount to 0.64% of GDP.

Figure 3. Climate change impacts on Gross World Product (GWP)



These aggregate figures however hide important regional asymmetries revealed by Figure 4.[10] This highlights on the one hand the huge differentiation in regional exposure, sensitivity and adaptive capacity and on the other hand the usefulness of a disaggregated assessment. The clear insight emerging is the higher vulnerability of developing countries to climate change impacts, particularly regions like South Asia and India losing more than 4% of their GDP, and Eastern Asia and Sub Saharan Africa losing roughly 2% of their GDP in 2050 in the RCP 8.5 scenario.

[10] The trend of impacts from 2007 to 2050 for each region and each RCP scenario is in Figure 12 of Annex I.

Figure 4: Climate change impacts on regional GDP in 2050 (RCP 8.5)

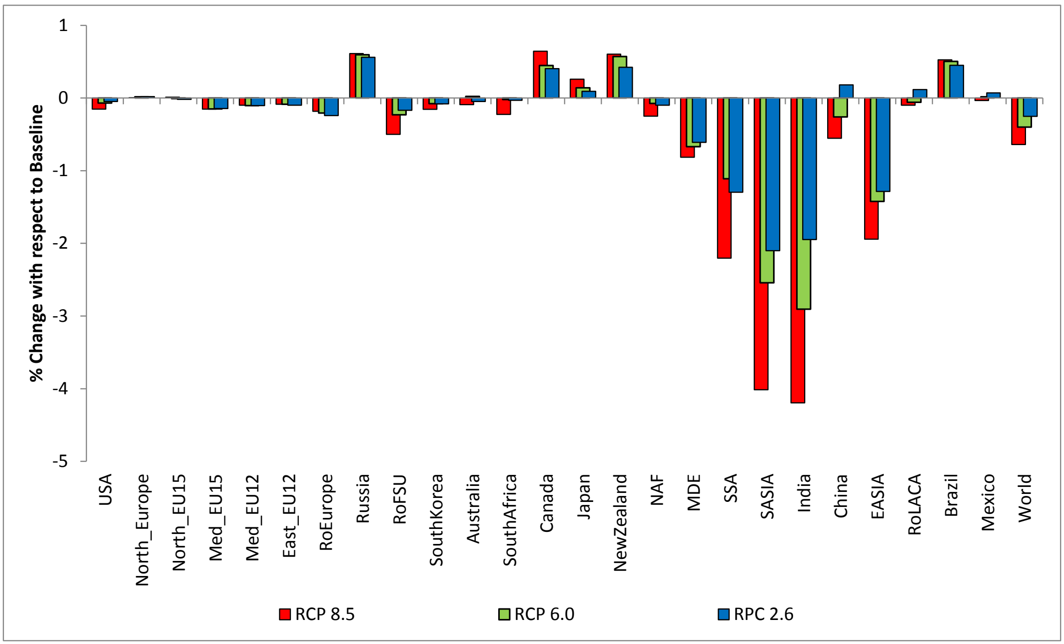
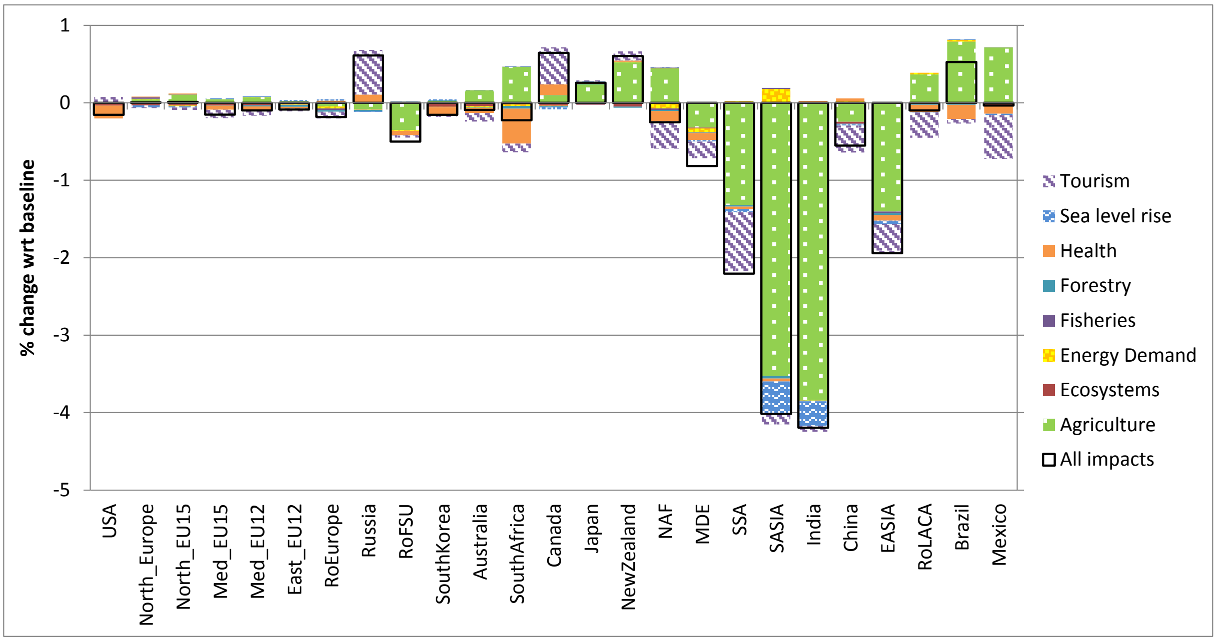


Figure 5 disentangles the different drivers of GDP impacts at the regional level.[11] It highlights two main points: i) The final effect (All impacts) results from the interaction of pressures exerted by several single impacts which could be either positive or negative, and that may compensate each other up to a certain extent; and ii) vulnerability is not the same across countries and it depends on economic and geographical characteristics. The most significant effects come from agriculture, tourism, sea-level rise and health. Impacts on agriculture and sea-level rise reveal a higher vulnerability in developing countries, whilst tourism affects also developed countries but mostly in a positive way. An interesting outcome for most of the world, including most developed regions, is the vulnerability arising from health impacts from climate change, which for instance is very important in USA as well as in other Annex I countries.

[11] This is done for RCP 8.5, the other concentration scenarios are qualitatively similar.

Figure 5. Decomposition of climate change effects on regional GDP by type of impact (ref. RCP 8.5)



These results are quite well established in the literature.

Taken as they are, they may convey the following implications: climate change is of concern just in the longer term; it can be a relevant issue for developing and much less for developed countries; without "low probability catastrophic losses", it remains basically a distributional/equity rather than a "scale " issue.

Which kind of reduced-form climate change damage functions could these results produce? Would they differ substantively from the functions existing in the literature?

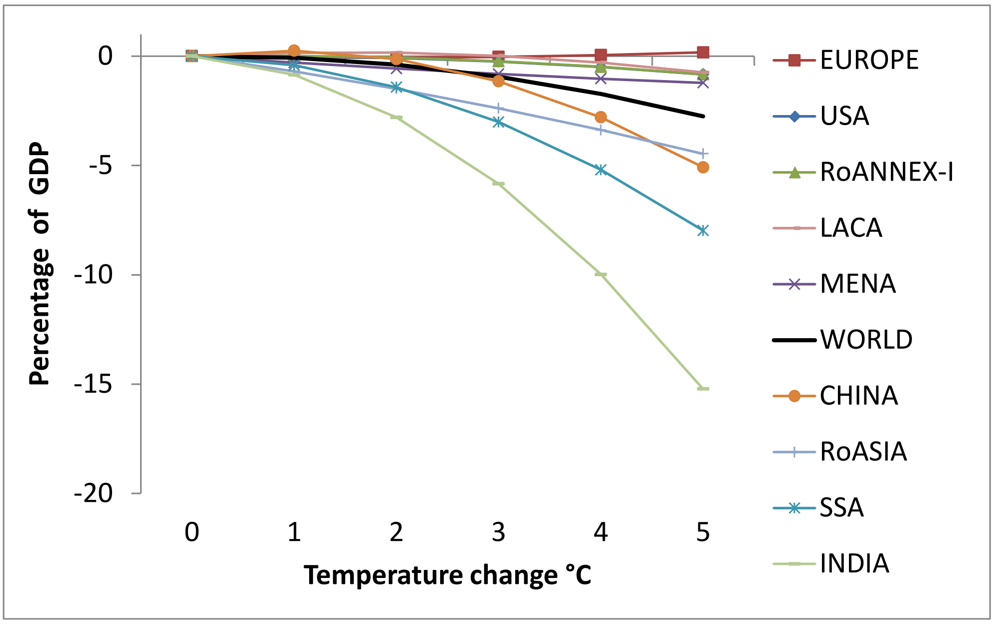
4.1 Reduced-form climate change damage functions

The GDP losses quantified in section 4 can offer a basis for estimating a reduced-form CCDF for each of the ICES region. This reduced-form damage function embeds the effect of market-driven adaptation (or said differently the "endogenous price effect") that the CGE model can capture. The procedure is the following. For each year, the different RCPs produce three set of impacts linked to three different temperature increases and consequently three GDP effects. We selected as reference one single year, specifically 2050, which is the year with the stronger temperature-GDP signals (we recall that impacts are defined for a temperature increase of 1.76°C, 1.91°C and 2.52°C with respect to preindustrial level). Then we apply exactly the same functional form used by Nordhaus and Boyer (2000) and Nordhaus (2007) in the RICE model to extrapolate the damage-temperature trend out of sample:

$$D_r(t) = \theta_{1,r}T(t) + \theta_{2,r}T(t)^2$$

where D_r is the regional damage at time t, T is the change in temperature, while $\theta_{1,r}$, and $\theta_{2,r}$. are fitted parameters for each region. The outcome of the procedure for the world and some representative regional aggregates is represented in Figure 6.

Figure 6. Regional reduced form damage functions for market impacts



At the world level, a temperature increase of 5°C would produce a GDP loss of roughly 2.75%. This value is close to what reported for similar temperature increases for instance by the FUND model (roughly 3% of global GDP loss) but lower than in the PAGE (5% world GDP loss) and DICE (7% world GDP loss) models according to the values used in IWG SCC (2010).[12,13]

However these figures computed by ICES do not account for some important damage components. One that for instance in the Nordhaus work is a major driver of economic losses refers to "catastrophic events". These are defined as severe events such as sharp

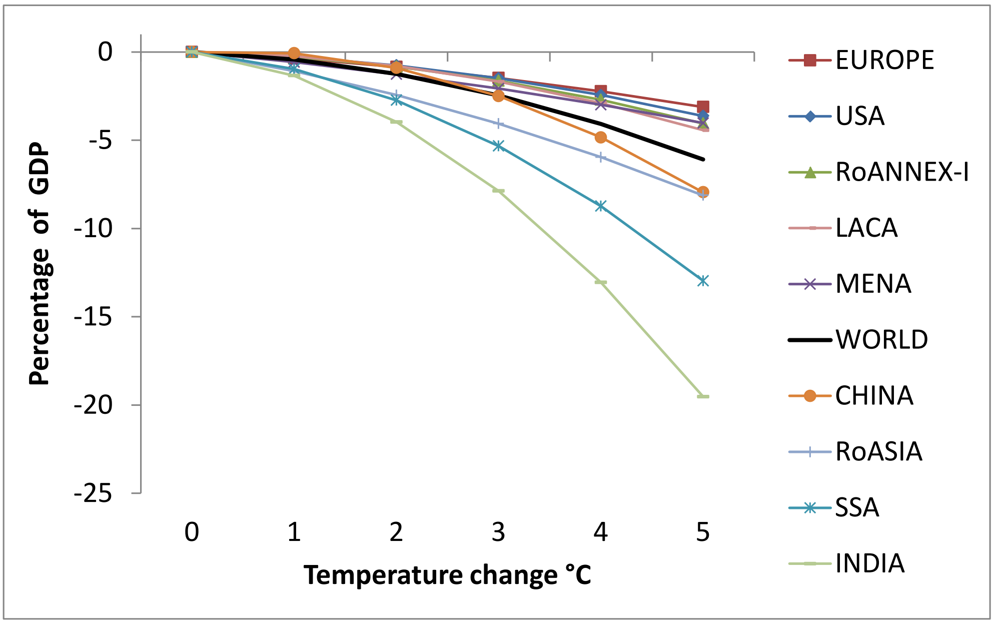
[12] To be precise, this document reports GDP losses referred in fact to 2100.

[13] Incidentally, it is worth to note the huge GDP losses in India and the Sub-Saharan Africa, both larger than the 7%.

sea level rise, a shutdown of the thermohaline circulation, a runaway greenhouse effect, shifting monsoons, a collapse of the West Antarctic Ice Sheet, and are quantified in terms of percentage of GDP following an approach of willingness to pay to avoid catastrophic risk Nordhaus and Boyer (2000).

To allow a more even comparison, we include thus a catastrophic damage component in our reduced-form CCDF following the same methodology and quantification of Nordhaus (2007).[14] The total damages that we are finally able to extrapolate are represented in Figure 7.

Figure 7. Regional reduced form damage functions for market impacts corrected with catastrophic losses



As shown by Figure 7, the reduced-form climate change damage function enhanced with catastrophic damages reports GWP losses of 6.09 % for a 5°C, comparable with those of DICE 2007.[15] This points out, once again, the particular relevance of low probability high damage events, and of their modelling, in determining the final economic impact. Given the few points available for the extrapolation, also the choice of the particular functional form for the damage function is crucial in determining the economic losses for high temperature increases.

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[14] In fact, the regional detail between ICES and Nordhaus (2007) is slightly different. When the regions do not perfectly match, we used simple averaging techniques to derive the appropriated catastrophic losses.

[15] And stresses a particular vulnerability for India, the Sub-Saharan Africa, the Rest of Asia and China, all with losses higher than 7% of GDP for a 5°C temperature increase.

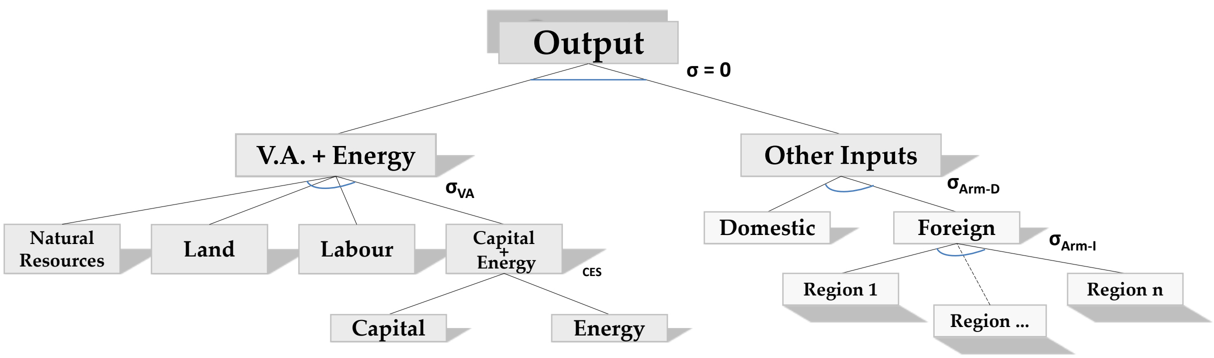
In summary, when the comparison is even, damage information extracted from CGE models do not originate CCDFs sensibly different from those obtained with other methodologies, even though the first, differently from the latter, incorporate explicitly endogenous market reactions.

Anyway, the objection moved to CGE models concerning their potentially overly optimistic view of market-driven adaptation due to the absence of frictions and instantaneous adjustments after a shock still applies. What is the role of these features in the final determination of climate change costs? This question is addressed in the next sections.

5 Introducing rigidities in market-driven adaptation

As standard in CGE models, ICES adopts the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modelled through representative firms, minimizing costs while taking prices as given. The production functions are specified via a series of nested CES functions as shown in Figure 8. Final output is the result of the combination of a Value Added-Energy composite with other intermediate inputs in a Leontief technology production function. The value added nest is a particularly important node as it governs the substitutability across primary factors, in order to produce the final output. The key parameter is the elasticity of substitution σ_{VA}. Furthermore, intermediate inputs can be produced domestically or imported. Domestic and foreign inputs are imperfect substitutes according to the so-called "Armington" assumption, which accounts for - amongst others - product heterogeneity. Armington elasticities (σ_{Arm-D}, σ_{Arm-I}) specify this substitutability.

Figure 8: A reduced representation of the production functions in ICES



Sectoral mobility of primary inputs within a region, can be perfect or sluggish. In the standard ICES version labour and capital, are perfectly mobile across sectors within a region and accordingly there is just one wage economy-wide.

We model a more difficult market-driven adaptation working on these three different "stages" of the production activity. We reduce by ¼ the degree of substitutability between primary factors (σ_{VA}); between domestic and imported intermediates ($\sigma_{Arm\text{-}D}$ and $\sigma_{Arm\text{-}I}$); then we reduce the labour mobility across sectors transforming labour into a sluggish factor of production.

The idea behind the first experiment is to explore the effect of a less optimistic assumption on the technological options available to substitute inputs. The 25% reduction of the initial calibrated value is inspired by Jomini et al. (1991), according to who in the short term substitution elasticities are roughly 60% of the long-term ones. We thus used the slightly higher estimate of 75% to represent a more rigid system.

The rationale of the second experiment is to simulate a more difficult substitutability of domestic with foreign inputs. In principle this could be driven by both technological reasons or by a more difficult trade. The 25% reduction derives from comparing the GTAP 8 Armington elasticities (on average 7) with the old GTAP 5 elasticity (on average 5.3).

The third experiment aims to remove the particularly unrealistic assumption of frictionless and instantaneous labour mobility form a shrinking to an expanding sector. Sluggishness implies that labour is an imperfect substitute across sectors. It can still move from one sector to another depending on wage differentials, but now its allocation depends upon a constant elasticity of transformation (CET) function. The elasticity of transformation is changed from -1 to -0.5.

In a final experiment, we combine all these three rigidities in a worst-case scenario. The climate change impacts are those calculated for the RCP 8.5.

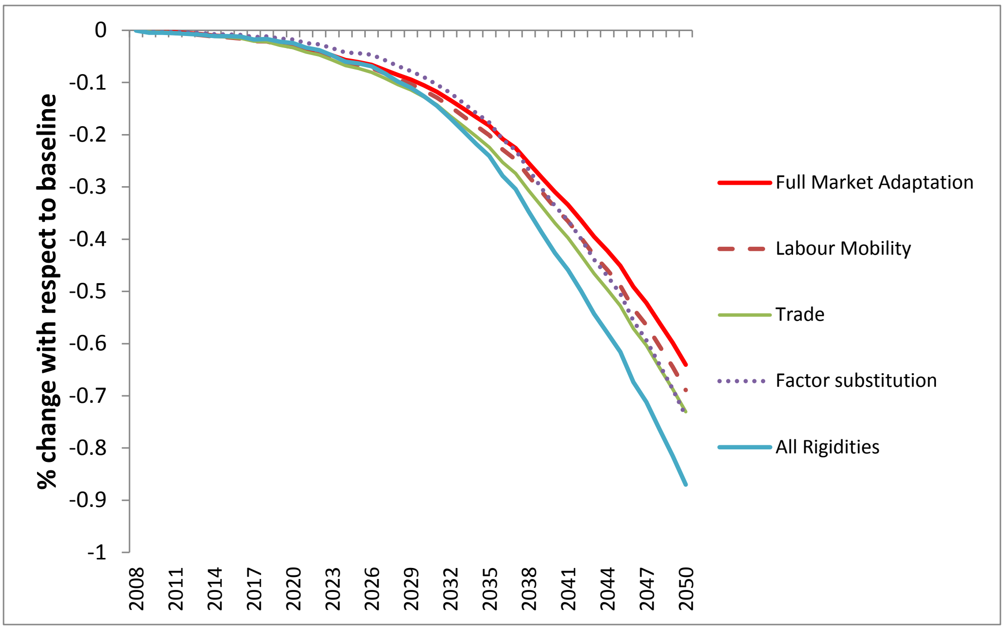
5.1 Results

The inclusion of the rigidities above mentioned in the production process induces an increase of the costs of climate change as shown in Figure 9. GWP losses rise from roughly 0.64% to almost 0.87%.[16]

[16] Note that in this comparison we are not using the values corrected with catastrophic losses, but those stemming from smooth climate change.

The major drivers of these higher costs are the lower degree of substitution across primary factors, and the reduced Armington elasticity. The first pushes losses to more than 0.73% of Global GDP in 2050. Facing a reduced ability to recombine primary factors intensifies the initial negative impact on the supply side of the economy. For instance, reduced land productivity can be only partly compensated by using more of the remaining primary factors. Limiting the model's flexibility related to international trade increases climate change costs also to 0.73% of Global GDP in 2050, showing a very similar impact as reducing primary factor substitution, but has a stronger effect in the initial simulation years. A reduced labour mobility seems a minor determinant: it increases costs just by 0.04 percentage points of global GWP in 2050.

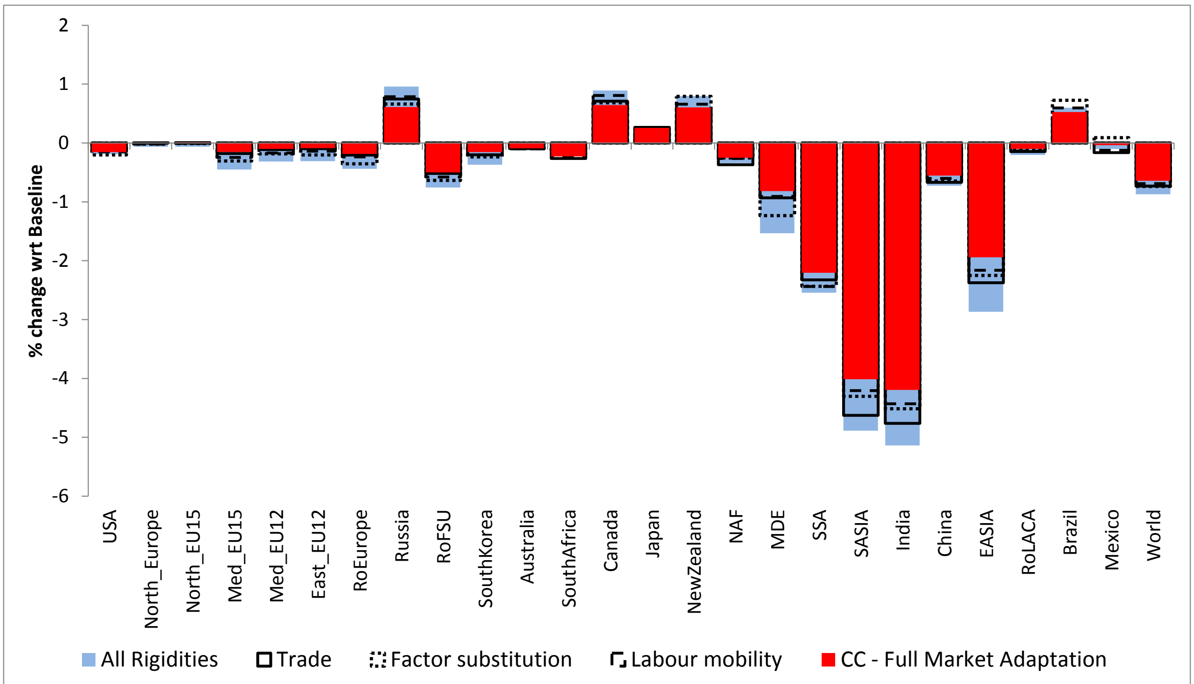
Figure 9: Climate change impacts on global GDP with market rigidities (RCP 8.5)



A quick inspection of the regional detail (Figure 10) confirms the asymmetric distribution of negative impacts which are much higher in developing countries. South Asia and India show losses of around 5% of GDP. Developed countries, albeit increasing their losses, are much less adversely affected: USA loose roughly 0.2% of GDP by "limited market adaptation"; GDP losses in European countries remain negligible. Worth to note that rigidities in primary factor substitution and labour mobility turn the initial slight gains from climate change into a slight loss for northern European countries. Interestingly, some of the countries that in the case of full adaptation experienced net benefits from a changing climate (i.e. Russia, Canada, Japan, Russia and Brazil) increase these gains in the limited adaptation scenarios. This last result depends upon two facts: firstly, the different elasticities produce a slightly different structural composition of the economic system. Therefore, notwithstanding the GDP is the same across the full and limited adaptation case, macro sectors weight differently and this can amplify/smooth positive/negative effects. Secondly, there are interaction effects trough international trade. Higher losses in some countries can induce higher gains in their competitors.

All in all, the exercise shows somewhat mixed results: on the one hand relatively minor deviations from the basic parameterization of the model concerning input substitutability/intersectoral mobility, are able to increase impacts by roughly 30% at the global level. In this sense the modelling of market adjustments play an important role in the determination of the final impacts. On the other hand, the main messages conveyed by the assessment do not change: without including catastrophic events, at least at the world level, and considering the limited range of temperature increase analysed, GDP impacts of climate change remain limited. This seems to point out that the "apparently" low climate change costs emphasized by CGE models only marginally depend on autonomous market adaptation mechanisms. In fact, this seems mostly due to other impacts which are usually omitted due to their proven difficulty to be included in a regular CGE assessment such as: extreme events, damages due to ecosystem services' losses, as well as major disruptions due to the existence of tipping points.

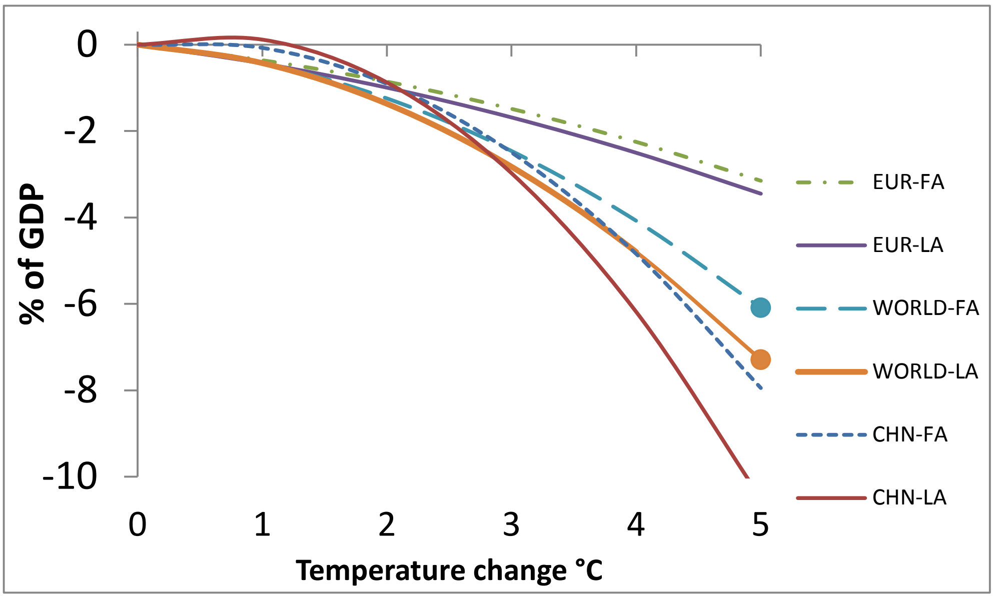
Figure 10: Climate change impacts on regional GDP with market rigidities (RCP 8.5)



5.2 Reduced-form climate change damage functions with “limited adaptation”

For completeness, in this section we extrapolate a reduced-form climate change damage function for the case of limited adaptation. The methodology followed is the same of section 4.1. For the sake of comparability, we also include in the damage component catastrophic impacts from Nordhaus and Boyer, (2000) and Nordhaus, (2007). Figure 11 compares full and limited adaptation damage functions for the World, Europe and China. As expected, limited adaptation results in a higher damage for the world. Due to the quadratic specification of the damage function the divergence of the two settings is particularly notable for higher temperatures: GWP losses are the 20% higher than with full adaptation at a temperature of 5°C. Different regions also present different sensitivity to limits to adaptation. Europe is among the regions that register lower damages even in the presence of market rigidities. Damages with limited adaptation increase only by 10% with respect to full adaptation at the same temperature increase. China provides instead a striking example of a much higher damage in a scenario with limited adaptation: total impacts of climate change would increase by 32% at a temperature of 5°C.

Figure 11: Reduced form damage functions with full and limited adaptation



6 Conclusions

The IA literature proposes two broad approaches for the economic quantification of climate change damages. One makes ample use of reduced-form climate change damage functions which translate temperature increases into GDP losses. Parameterization of these functions are extrapolations from the impact literature or are directly taken from experts' opinion. The other, extensively used in impact assessments conducted with Computable General Equilibrium (CGE) models, consists in translating climate change pressures into changes in quantity/quality of factors of production and/or in agents' preferences driving demand and supply behaviour in the models. GDP losses (climate change costs) are thus the direct outcome of the model simulation and do not derive from an explicit function and its ad hoc parameterization.

In this paper we present a simple exercise comparing these two methodologies and testing in particular if the assessments performed with CGE models produce lower climate-change cost estimates than IA models using reduced-form damage functions. Furthermore, we investigate the role of market driven adaptation, that CGE models explicitly capture through their endogenous price setting mechanism, in determining these estimates.

We show that in fact when the same impact categories are considered across the two methodologies, damage estimates do not differ significantly at the global level. In particular, the major driver of differences in costs is the modelling of the catastrophic component. When this is introduced to correct the CGE driven estimates, these are not significantly different from that used by some well-established hard-linked integrated assessment models.

Then, we repeat the exercise, but introducing rigidities in market adjustments, differently said, in market-driven adaptation. This is done restricting the elasticity of input substitution in the production function, the substitutability of domestic and imported inputs, and finally sectoral workforce mobility. We find that, on the one hand these frictions do increase the cost of climate change impacts (from 0.6% to 0.87% of GWP). The most important driver of cost increases in the long term is the elasticity of input substitution while, in the short term, it is the restriction in domestic and imported input substitution. On the other hand, without including catastrophic events, at the global level, GDP impacts of climate change remain limited.

The autonomous market adaptation mechanisms embedded in CGE models explain only marginally low climate change costs. This is due to the fact that these assessments omit other impacts because of their proven difficulty to be modelled, such as: extreme events, damages due to ecosystem services' losses, as well as major disruptions due to the existence of tipping points.

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Nevertheless please consider that the values reported in this document are our elaborations based on these data and accordingly ours is the only responsibility for any mistake or imprecision.

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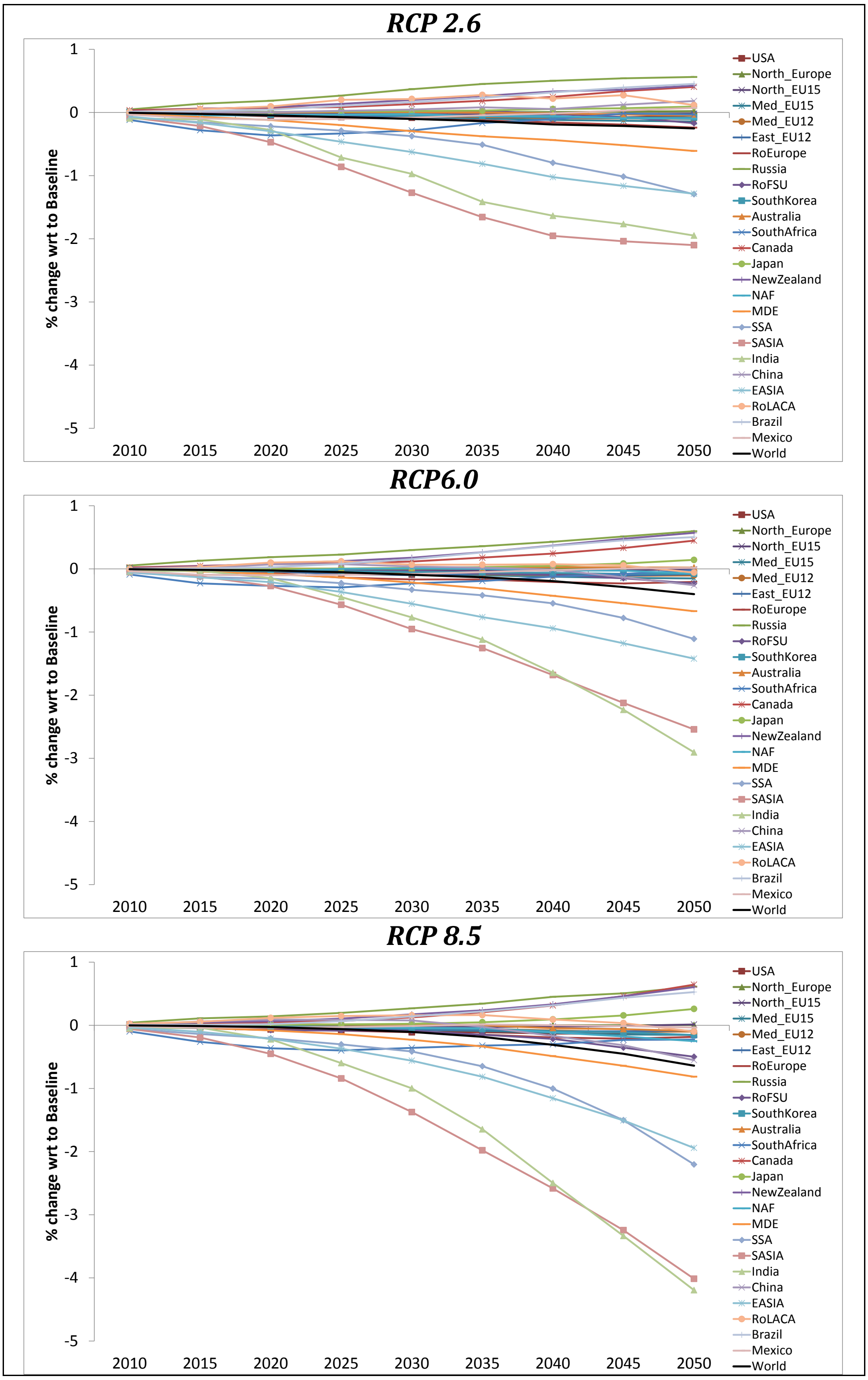
Annex I

Figure 12: Climate change impacts on regional GDP by RCP

(RCP 2.6.0 top; RCP6.0 medium; RCP 8.5 bottom)



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