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Impact and distribution of climatic damages: a methodological proposal with a dynamic CGE model applied to global climate negotiations

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Impact and distribution of climatic damages: a methodological proposal with a dynamic CGE model applied to global climate negotiations

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Abstract

The UNFCCC Paris Agreement, entered into force on 4 November 2016, represents a step forward in involving all countries in mitigation actions, even though it is based on a voluntary approach and lacks the active participation of some major polluting countries. The underinvestment in mitigation actions depends on market and policy failures and the absence of price signals internalizing the economic losses due to climatic damage. This contributes to underestimating potential benefits from global action. In this paper we discuss how crucial is the assessment of the vulnerability of a country to climate change in defining the threat and action strategies. A dynamic climate-economy CGE model is developed that includes a monetary evaluation of regional damages associated with climate change. By considering alternative damage profiles, results show that internalizing climatic costs might change the bargaining position of countries in climate negotiations. Consequently, damage costs should be given greater importance when defining the implementation of a global climate agreement.

Keywords: Climate change damage costs; Climate negotiations; Burden sharing; Mitigation costs; GTAP; Dynamic CGE.

J.E.L. Codes: C680; H230; O440; Q540.

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Abstract

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1. Climate negotiations and damage costs

The twenty-first Conference of the Parties (COP21) held in Paris in December 2015 under the United Nation Framework Convention on Climate Change (UNFCCC) succeeded in reaching the so-called Paris Agreement. Entered into force on 4th November 2016, it will be effective from 2020. In order to achieve the long-term goal of keeping the global temperature rise this century to well below 2 degrees Celsius above pre-industrial levels, all Parties aim to reach global peaking of greenhouse gas emissions (GHG) as soon as possible. The voluntary approach and the absence of sanctions (Nordhaus, 2015), together with the great country heterogeneity (Brunnée and Streck, 2013; Costantini et al., 2016) make this agreement weak in achieving an inter-generational sustainability goal. Contributions to past GHG patterns reflecting development inequalities create additionally difficulties in designing a burden sharing that exhibits a globally equitable climate mitigation strategy (Matthews, 2016). Such difficulties will increase further if large emitters with historical responsibility do not participate, which is what is happening in the case of the U.S. after the declaration of President Trump in June 2017 to withdraw from the Paris climate accord.

At the same time, the greater vulnerability to negative effects from climate change faced by poor countries is causing an increase in intra-generational inequity at the global level (Roson and van der Mensbrugghe, 2012). According to the outcome of the meeting in Cancun by the Global Platform for Disaster Risk Reduction, at least 87 countries should systematically account for environmental disaster losses by 2020, around 90% of which will result from climate change. A recent report by the World Bank (Hallegatte et al., 2016) provides a broad monetary quantification of the cost of inaction for the underdeveloped world that would force more than 100 million people into extreme poverty by 2030.

The uneven distribution across countries of losses caused by climatic damage is strictly related to how vulnerable a country is to environmental factors. Vulnerability increases the likelihood of natural hazards turning into damages (or disasters). The magnitude of the effect depends in turn on how many people are exposed to the hazard and live in areas lacking prevention actions to reduce the impact on anthropogenic activities (Paul, 2011). Accordingly, expenditure to reduce such vulnerability – broadly known as adaptation – will be greater the larger is a country's likelihood to experience frequent and strong natural hazards, as long as adequate economic resources are available (Neumayer et al., 2014).

While this reasoning can be fully applied to resilience and adaptation measures, the global public bad characteristic of climate change might lead to diverging positions for the polluter and the agent affected by the damage in the bargaining process of sharing mitigation costs. Thus, if countries responsible for a high share of GHG emissions do not correspond to those most vulnerable to climate change, their propensity to mitigate will decrease. Although this heterogeneous regional distribution of climatic damage and GHG emissions can be considered as a barrier to a global action, the internalization of damage costs into market mechanisms could help to reduce this gap and shape a different geography of climate political economy (Kelly and Adger, 2000; Moore and Diaz, 2015).

Several attempts have been made to analyse the physical impacts of climate change and their monetary evaluation (Anderson, 2006; Arndt et al., 2015; Bosello et al., 2012b, EU, 2011; Fussel and Klein, 2006; Fussel, 2010). Better information on where climatic damages occur, combined with a credible quantification of its monetary costs should increase the likelihood of coalitions succeeding in the bargaining process, thus inducing larger coalitions to be more stable (Dellink et al., 2013; Méjean et al., 2015; Verendel et al., 2016).

Furthermore, given the voluntarily approach characterizing the Paris Agreement, awareness of climatic damages can substantially influence the efforts of countries, especially developing ones, in climate actions. Under the Paris framework, all countries are asked to submit their National Determined Contributions (NDCs), formal documents stating the efforts and the targets set by each country in order to contribute to the achievement of the final global goal, together with the means of implementation. So far, despite their poverty conditions, most developing countries have set mitigation actions to be implemented with national resources and with the international support.[1] These actions are also planned by very poor and vulnerable countries, suffering from high climatic costs, as a consequence of the role that the cost of climate change is already playing in influencing bargaining positions. The more a country is aware of the costs induced by climate change, the more this is reflected in the contents of its NDC, with respect to mitigation and adaptation actions, requests for international support and access

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[1] Source: http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.

to resources from climate international financing mechanisms, such as the Green Climate Fund (GCF).[2] This position is fully consistent with what Valentini and Vitale (2018) define as the choice of optimal climate policy in the case of a pessimistic social planner. In the case of low uncertainty on the large damages associated to climate change in one country, the policy maker will be favourable to early adoption of sharp and immediate mitigation efforts. Since NDCs must be revised every five years on the basis of national circumstances and priorities, both effective actions and future positions of developing countries in negotiations are likely to be strongly influenced by their exposure to climate change and by the awareness of climatic damages.

The present paper attempts to evaluate to what extent the introduction of monetary costs of climatic damage into climate policy impact assessment might influence the relative attractiveness of potential mitigation actions debated under the Paris Agreement framework. Section 2 provides a brief review of existing contributions on monetary evaluation of climatic damage. Section 3 describes the long-term dynamic climate-economic computable general equilibrium (CGE) model (GDynEP) used to internalize damage cost and evaluate abatement scenarios. Section 4 provides an interpretation of the results under the lens of a cost-benefit analysis approach, while Section 5 provides brief policy conclusions.

2. Economic losses due to climatic damages

Damage assessment is subject to large uncertainties with respect to: the definition of future emission paths, the related change in GHG concentration in the atmosphere, the effect on temperature increase and the effects of adaptation actions (Markandya, 2014). Furthermore, given that adaptation depends on the interactions between physical climate conditions and socio-economic systems, the climatic economic losses also depend on the projected future socio-economic scenarios.

Applied energy and climate models have been used extensively to measure these economic losses (Markandya et al., 2017) but damage estimations are still quite heterogeneous. For a lower bound temperature increase (around 2-3°C) and a time horizon of 2050, costs range from a low loss of 0.3% of

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[2] The GCF, discussed and approved during the COP16 held in Cancun in 2010 and officially launched the following year at COP17, is explicitly individuated as a key mechanism for international support by several developing and emerging countries in their NDCs, such as China, Gabon, Morocco, Sudan, among the others.

world GDP (Mendelsohn et al., 1998) to a higher impact of 2% (OECD, 2015). Considering a temperature increase between 2.4°C and 5.5°C, the global loss is even greater, on average 3% of global GDP but with a range of 1.5%-6.1% (Dellink et al., 2014; Nordhaus, 2008, 2011, 2013; Roson and van der Mensbrugghe, 2012; Stern, 2007). Although most of the studies agree on the fact that developing countries will bear the highest costs (DARA, 2012a,b; Moore and Diaz, 2015), there is still no complete consensus about the amount and regional distribution of climatic costs. These differences in estimates arise from the heterogeneity of methods applied to calculate the costs (Tol, 2015) and are magnified by the several steps of the climate assessment.

First, monetary evaluation of climate damages varies with the impacts covered (Dellink et al., 2014; Mendelsohn et al., 1998). While some studies only account for market impacts, which are those affecting agriculture, fisheries, tourism or energy sectors (Mendelsohn et al., 2006; OECD, 2015; Roson and Sartori, 2016), others include a wider range of components, considering also non-market impacts related to extreme events, loss of biodiversity or health effects (Bosello et al., 2009; DARA, 2012a,b; Dellink et al., 2014; Nordhaus and Boyer, 2000; Stern, 2007). Estimates for the former are certainly more accurate as non-market impacts are less easily measurable. But their inclusion results in higher overall estimates of climate costs especially for developing countries. Indeed, non-market costs can explain most of the discrepancies among existing studies (Stern, 2007). Furthermore, in most cases "loss estimates are lower bound estimates because many impacts, e.g. loss of human lives, cultural heritage, ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses" (IPCC, 2012, p. 7). Accordingly, the inclusion of both market and non-market components is essential for a comprehensive climate cost measurement, notwithstanding the problems with non-market estimation.

To the best of our knowledge, the most comprehensive study providing information on economic losses occurred due to climatic damage for a large sample of countries is the Second Climate Vulnerability Monitor developed by DARA (2012a,b), an independent organization commissioned by the Climate Vulnerable Forum to assess the human and the economic costs of the climate crisis in view of the 18th Conference of Parties. It provides measures of the climate damages effectively sustained by 184 countries for a wide range of impacts summarized in 22 indicators, market and non-market based, covering four different areas: environmental disasters, habitat change, health impact and industry stress.[3]

A second issue is the definition of the damage function, linking damages in monetary terms to climate variables. Damages are mainly represented as a polynomial function (often quadratic) of either global mean temperature change (Bosetti et al., 2006a; Nordhaus and Sztorc, 2013) or the rate and magnitude of temperature increase (Hope, 2010, 2011; Waldhoff et al., 2014). Economic damages can be expressed as a fraction of world output (Bosetti et al., 2006a; Nordhaus and Sztorc, 2013) or, according to the willingness-to-accept (WTA) approach (Bosello and De Cian, 2014), in terms of the maximum price a consumer is willing to pay to avoid a temperature rise. This is usually the basis for monetizing non-market impacts and represents, at the regional level, the monetary national consumption and income reduction due to climate change. An evolution of the WTA approach is referred to as the Social Cost of Carbon (SCC) (van den Bergh and Botzen, 2015). Higher GHG concentrations give rise to temperature increase, precipitation variability and raised frequency of extreme events that in turn might result in damages (or disasters) to various sectors of the economy according to the relative vulnerability of a country to natural hazards. Given that emissions of GHG have the same effect on concentrations irrespective of wherever they are emitted, it is possible to consider the SCC as the global average damage due to an additional ton of GHG emitted at a given point in time, allowing for its natural decay rate.

A third aspect of climate damage assessment relates to the modelling approach adopted to include the damage function into an economic impact assessment model. Among the applied methods used to analyse the economic impact of climate damages on economic system, Integrated Assessment Models (IAM) combine economic and climatic module based on a damage function. In the DICE and RICE models by Nordhaus and Sztorc (2013) climate damages are a quadratic function of the global mean temperature change,[4] while the MERGE Model for Estimating the Regional and Global Effects of GHG reductions (Manne et al., 1995; Manne and Richels, 2005) follows the WTA approach. In the WITCH (World Induced Technical Change Hybrid) model (Bosetti et al., 2006b; De Cian et al., 2012) costs

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[3] The Climate Vulnerable Forum (CVF) is an international cooperation group founded in 2009 by the Maldives, that now includes 20 countries that face significant insecurity due to climate change.

[4] DICE (RICE) is the (regional) Dynamic Integrated model of Climate and the Economy model.

associated to market components are expressed as percentage change of the regional GDP, while for non-market impacts (health, ecosystem and catastrophes losses) the WTA approach is followed.[5]

Due to their high level of aggregation and long time horizon, these models have also been combined with a Computable General Equilibrium (CGE) framework (resulting in a hybrid approach) to better account for inter-sectoral linkages. Based on a production function approach, climate impacts can be linked to different drivers of economic growth in a CGE framework and expressed as percentage of GDP (OECD, 2015).[6] The evaluation of the effects of climate on GDP depends on the impact under scrutiny. For the agriculture sector for example, the cost is expressed in terms of land and crop productivity change (Bosello et al., 2012a; Ciscar et al., 2014). As an example of non-market aspects, health damages are often introduced into the production function as changes in labour productivity (Bosello et. al., 2009). Energy impacts are generally investigated by considering changes in energy demand for cooling and heating (Ciscar et el, 2014; OECD, 2015), while land loss due to sea level rise is the main measure of impacts in coastal zones (Bosello et al., 2012b; Darwin and Tol, 2001).[7]

A fourth aspect refers to how monetary damages affect GDP in such models. In particular, including the climate cost components with respect to only the direct impacts implies describing the costs of climate change as a percentage of GDP without taking into account other dynamic effects. When introducing the damage in a recursive way, the multiplicative effects due to economic interactions (indirect impacts) are also captured (Bosello et al., 2012a), with a wider effect on GDP due to sectoral and international adjustments (Eboli et al., 2010).

3. The GDynEP model with climatic damage

In order to evaluate the economic impacts of mitigation actions and climatic damage jointly, we use a

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[5] These impacts are derived from specific applied models. In particular, the impact on coastal land loss due to the sea level rise is driven by results from the DIVA (Dynamic Integrated Vulnerability Assessment) model (Vafeidis et al., 2008). The ClimateCrop model (Iglesias et al. 2009, 2010) is used for changes in the average productivity of crops in agriculture sector, while data on for the energy sector, as the changes in residential energy demand due to increasing temperatures, are derived from the POLES (Prospective Outlook on Long-term Energy Systems) model (Criqui, 2001; Criqui et al., 2009).

[6] An example is the CIRCLE project "Costs of Inaction and Resource Scarcity: Consequences for Long-term Economic Growth Project", where the dynamic general equilibrium ENV-linkages model is used to express climate impacts in monetary term and links them to GDP. In this case, the impacts covered are: loss of land and capital due to sea level rise, capital damages from hurricanes, changes in crop yields, fisheries catches, labour productivity, tourism flows, health care expenditures due to diseases and heat stress and energy demand for cooling and heating.

[7] For an extensive review on sectoral impacts see Markandya et al. (2017).

dynamic CGE model (GDynEP) based on the GTAP (Global Trade Analysis Project) structure enriched by a climatic exogenous module. GDynEP is a combination of different GTAP model versions and databases with a novel module that allows the cost of climatic damage to be included. The appeal of a CGE approach is the inclusion of detailed market interactions between sectors and countries that represent global economic mechanisms. There are different modelling approaches that could be adopted for such a policy evaluation exercise, as described in the previous Section. If the quantitative assessment is built for policy optimization, the modelling choice is likely to be an IAM such as the DICE/RICE. While IAMs have the advantage of directly including environmental science modules, the economic systems are less detailed. In GDynEP we take the GHG concentration and the emission path as exogenously provided by available physical models and interact it with economic mechanisms via a monetary damage function. This choice is driven by the fact that in this analysis we are not interested in finding an optimizing environmental policy, but rather in exploring the influence of alternative climatic damage estimations through the set of detailed inter-sectoral and international economic relationships on economic output and thereby on bargaining position of countries in the climate regime.

In the standard GTAP model versions there is only a stylized environmental mechanism that does not include the full range of factors that influence economic growth in the face of climatic shocks. These versions only look emissions produced by anthropogenic production and consumption activities. Consequently, our original contribution is to enrich the standard GTAP dynamic CGE model with a specific module that accounts for the economic impact of damage.

3.1 Model details

In order to obtain a GTAP-type model that includes both GHG emissions and a complete representation of the energy system the first step is to merge the GDynE (the energy version of the dynamic GDyn) developed by Golub (2013) and improved by Markandya et al. (2015) with the GTAP-Power database (Peters, 2016), which introduces for the first time in GTAP a detailed representation of the renewable electricity sector. The representation of the energy sector with distinguished fossil and non-fossil sources allows a better calibration of the scenarios for the sectors and countries responsible for GHG emissions, in terms of relative costs of reaching the mitigation target given the technical possibilities available for energy production.[8]

The second step is to introduce monetary damage due to climate change in the economic structure. We assume a damage function linked to GHG concentrations at the global level according to the SCC approach. By taking a global damage measure, it is possible to cover all cost types related to climatic damage, including non-market costs that are usually underestimated by those modelling approaches that compute climatic damage costs only directly related to impacts on productivity. We consider that the SCC reduces the global wealth according to a weak sustainability approach, following the methodological assumptions of the Genuine Savings (GS) calculation by the World Bank (Hamilton and Clemens, 1999) where the monetary value of climatic damage is a negative element of the savings function. The adoption of a weak sustainability criterion allows all forms of capital to be considered as perfectly substitutable (Hartwick, 1977, 1978; Solow, 1986). This in turn implies that the cost of damage is a negative component of the capital accumulation function, a component that could be compensated by additional savings from production activities or additional investments in human or technological capital formation (including investments in adaptation).

Translating these assumptions into model functions can be synthesized as follows.

We first consider the widest computation of global damage due to climate change as the most appropriate one to calculate the SCC. To the best of our knowledge the most comprehensive available measure of damage costs provoked by climate change is provided by DARA.

Since damage costs are available only till 2012, the evolution over time is shaped according to the SCC approach. From the global costs at 2011 (which is the starting point of the GTAP database) we

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[8] The included electricity generating technologies are Coal, Gas, Oil, Hydro, Wind, Solar, Nuclear and Other Base Load Power sources, while Gas, Oil, Hydro and Solar generating technologies are further divided between Base and Peak Load. All details on the aggregation choice for this GDynEP model version are reported in Appendix A. In order to merge GDynE and GTAP-Power, it is worth mentioning that in this model version we have adopted two simplifying assumptions. First, the transmission and distribution sector for electricity is included in the service sector and it is not taken as a distinguished one. This implies that there is no technical difference between renewables and the other energy sources in the transmission of electricity. This conservative assumption is adopted because we have no region-based data on distinguished institutional and technical features for the electricity transmission and distribution. Second, given that GDynEP is not a bottom up technical model, it deserves specific exogenous behavioral parameters for each stage of the production function. By introducing the renewable electricity sector, it is necessary to add a specific substitution elasticity parameter between fossil-based and renewable electricity. Given that there is not a specific value provided in the GTAP database, we have derived it from calibrating the BAU scenario in order to have a dynamic trend in renewable electricity production up to 2050 in line with BAU provided by IEA Outlook (IEA, 2015). We acknowledge that this is an extremely conservative hypothesis, especially when carbon mitigation scenarios are considered. Nonetheless, in this paper we test only the emission trading policy option without exploring the role of public support to clean technologies, and this allows taking this substitution parameter as constant. Future research lines would require specific efforts in empirically estimating substitution elasticities at least at the country level as well shaping the evolution of such parameter over time.

compute the initial SCC as an average cost for each ton of GHG concentrations in 2011. The projection of GHG concentrations allows the evolution over time of the SCC to be estimated, according to the specific emissions scenario under scrutiny.

Formally, the initial global average SCC (SCC_{t0}) is given by the ratio between the total monetary value of losses due to climatic damage (CCG_{t0}) calculated on DARA data at the world level and the stock of CO_2-eq in the atmosphere ($SCO2_{t0}$) as:

$$SCC_{t0} = \frac{CCG_{t0}}{SCO2_{t0}} \tag{1}$$

The atmospheric concentration enters the model as an exogenous variable with values provided by NOAA historical data.[9] Starting from DARA and NOAA data, the value of SCC_{t0} in 2011 is USD 195 per Gt of CO_2-eq.

Future projections on CO_2-eq concentration are taken from IPCC, as a simple mean between results obtained from different models applied to the IPCC RCP8.5 Reference Scenario (IPCC, 2014) and converted from PPM to CO_2 emissions according to the IPCC conversion factor.[10] The stock of CO_2-eq at time t ($SCO2_t$) is determined as:

$$SCO2_t = SCO2_{t-1} \cdot (1-d) + CO2_t \tag{2}$$

Where $CO2_t$ is the emission flow at time t and d the annual decay rate of CO_2-eq in the atmosphere. The projected concentration in the baseline in 2050 is about 630 PPM and the corresponding temperature increase is about 3°C (in a range from 2.6°C to 4.8°C relative to the period 1986–2005 as in RCP8.5 Reference Scenario in the IPCC Fifth Assessment Report).

The evolution of the SCC over time is calculated according to a simple function that considers average damages from climate change as a function of additional tons of GHG net of natural decay rate:[11]

$$SCC_t = SCC_{t-1} + (SCO2_t - SCO2_{t-1})^{\alpha} \tag{3}$$

Eq. (3) allows different evolution paths to be considered over time given a specific GHG concentration

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[9] NOAA estimates the concentration of CO_2 in the atmosphere at 404.06 PPM in 2011.

[10] The stock of GHG concentrated in the atmosphere used for the calculation of the average damage cost is taken from the PPM concentration measure available from IPCC (2014) and expressed in ton of CO_2-eq by applying the conversion criteria used by IPCC: 1 PPM CO_2 = 2.12 Gton Carbon; 1 ton Carbon = 3.66 ton CO_2; 1 PPM of CO_2 rise in the atmosphere is equal to 2.12*3.66 Gton CO_2 emission.

[11] For a comparison of alternative damage functions used in other IAM and CGE models, see Markandya et al. (2017).

according to the value assumed by parameter α. Given the purpose of this paper, we are not interested in providing an evaluation of climatic damage *per se*, but at considering how differently shaped profiles of SCC would influence the bargaining position of countries. Accordingly, a flexible way to include SCC in the economic system is required and this is possible by assigning different values to parameter α. According to eq. (1), the evolution over time of the total cost of climatic damage at the global level (that corresponds to the total economic losses) is given by:

$$CCG_t = SCC_t \cdot SCO2_t \tag{4}$$

Given the uncertainties about climate change impact and the exogenous nature of the climatic module in GDynEP, rather than pre-determining alternative damage functions, we test different trends for the costs by using alternative values for the parameter α. The total cost of climate change is calibrated with different levels of global GDP loss provided by models that include different types of cost. This procedure roughly corresponds to accounting for the influence of uncertainty on the level of damages for a given level of warming (Crost and Traeger, 2014). We investigate four different cost patterns by assigning four different values to α, associated with the same level of projected GHG concentration in 2050 (about 630 PPM corresponding to a temperature increase in a range from 2.6°C to 4.8°C relative to the period 1986–2005, in line with projections by the RCP8.5 scenario in IPCC Fifth Assessment Report). The first value (α=0.3) describes a cost path aligned with ENVLINK model by OECD (2015) with a 2% global GDP loss by 2050 for a temperature increase of 3°C where only market-based costs influencing the production function are included. Then we examine two intermediate levels: a 3% GDP loss (α=0.653) obtained as the average loss taken from recent studies that model recursively the global cost of climate change associated with the aforementioned temperature increase range (AD-RICE, DICE, ENVISAGE, ENVLINK, PAGE); and a second level that corresponds to a loss of global GDP equal to 4% in 2050 (α=0.761). The upper bound is represented by a 5% GDP loss that roughly reproduces the projection up to 2050 of the DARA estimates (available till 2030) representing the widest costs range (α=0.817).

The regionalization of the global cost over time is modelled by assigning the cost in accordance with the vulnerability of each region to climate change. While the initial regional costs is equivalent to those provided by DARA at 2011, the evolution over time is directly linked to the dynamics of a regional net vulnerability measure ($NV_{r,t}$) represented by the ratio between the Vulnerability Index (V_r) and the

Readiness Index (R_r) developed by Chen et al. (2015) for the calculation of the Notre Dame Global Adaptation Index (ND-GAIN). This is in line with the definition of environmental disaster as previously mentioned, since the climate disease turns into losses proportionally to the vulnerability of a community and to the population exposed.

The great advantage of the ND-GAIN with respect to other vulnerability assessment is that it synthesized a wide range of information in a single measure that is available for a comprehensive number of countries.[12] As the values available for the vulnerability and adaptation capacity at the country level refer to the current situation, the dynamics of the index are proxied by the population trends, that allow consideration of changes in population exposed to climate damages given a certain net vulnerability. Algebraically we have:

$$NV_{r,t} = \left(\frac{P_{r,t}}{P_{g,t}} \cdot \frac{V_{r,t0}}{R_{r,t0}}\right) \Big/ \sum_{r=1}^{N} \left(\frac{P_{r,t}}{P_{g,t}} \cdot \frac{V_{r,t0}}{R_{r,t0}}\right) \qquad (5)$$

Where the dynamics of the net vulnerability of a region depend on the relative population share of each region with respect to the world (i.e. $P_{r,t}$ and $P_{g,t}$ the regional and global population, respectively).[13]

The distribution of the global cost among regions ($CCR_{r,t}$) is given by:[14]

$$CCR_{r,t} = CCG_t \cdot NV_{r,t} \qquad (6)$$

The regional distribution of the global cost calculated starting from a damage function built on the SCC concept corresponds to an empirical computation of what Kotchen (2018) defines as the Domestic SCC (DSCC). DSCC measures the marginal damages to each country arising from an increase in emissions. The measure of $CCR_{r,t}$ corresponds to the total damage to each country given the increase in

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[12] The Vulnerability Index measures a country's exposure, sensitivity and adaptive capacity (components) to the negative effects of climate change. It considers six life-supporting sectors: food, water, health, ecosystem service, human habitat, and infrastructure. 36 indicators (two per component in each sector) contribute to the measure of vulnerability, obtained as a simple mean of the sector scores, which are the average scores of component indicators. Readiness measures the ability of a country's private and public sectors to absorb investment resources and successfully apply them to reduce climate change vulnerability. Readiness includes indicators for three components (social, economic and governance indicators) not weighted equally (Economic Readiness is 50% of the readiness score while governance and social readiness are 25%).

[13] The ratio between the vulnerability and readiness indices has been normalized (min = 0; max = 2) and then it is kept constant over time, as there is not information about future projections, especially because of uncertainties with regard to readiness issues. Thus, the variation in the regional distribution of damage cost is due to variations in population dynamics data. Population data do not take into account deaths caused by climate change since the vulnerability measure provided by ND-GAIN already includes number of deaths. In particular, the health component captures a country's vulnerability of public health to climate change, including projected change of deaths from climate change induced diseases.

[14] Although Farmer et al. (2015) emphasize the role of uncertainty in shaping the cost of climate change into IAMs, for the sake of simplicity in this work we ignore this factor that will be part of future work. By considering country vulnerability to climate change fixed over time in physical term, our modelling choice underestimates future damages that could be larger if vulnerability raises with increasing temperatures.

GHG concentration over a specific period. The increase in concentration means an emission flow that multiplied by the marginal DCC provides a total regional cost.

The regional cost enters the economic system following the approach of an adjusted Net National Product (NNP) developed in Weitzman (1976) that can serve as an indicator of welfare and measure what can be consumed today without reducing future consumption possibilities. Starting from the standard net savings function in System of National Accounts (SNAs), as represented by the sum of the difference between the production (Y) and consumption (C) measures of each *i-th* agent in each region r at time t:

$$S_{r,t} = \sum_{i=1}^{N} \left(Y_{i,r,t} - C_{i,r,t}\right) \tag{7}$$

by assuming that all savings are invested $\left(S_{r,t} = I_{r,t}\right)$, we can express the capital stock function as the sum of the capital stock available in the previous period net of the depreciation rate (β) and the total investments (I) net of the regional cost of climate change:[15]

$$K_{r,t} = I_{r,t} + (1-\beta)K_{r,t-1} - CCR_{r,t} \tag{8}$$

The output (Y) produced each period is a function of the endowments available over time (here represented by capital stock, K, human capital, L, and natural resources, R) as follows:

$$Y_{i,r,t} = f\left(K_{i,r,t}, L_{i,r,t}, R_{i,r,t}\right) \tag{9}$$

By assuming a weak sustainability criterion we also adopt a full substitutability between all forms of capital (economic, human, natural) in contributing at the formation of the output. Accordingly, the reduction in total capital stock due to environmental damage (or over depletion of natural capital) can be assigned indifferently to whatever form of capital (physical, human or natural), since the different components of the overall capital stock are fully replaceable by investments in whatever capital type.

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[15] Eq. (8) provides a stylized description of how damage cost is considered into the capital stock function of GDynEP. More precisely, GDynEP adopts the same capital accumulation function structure of GDyn (Ianchovichina and McDougall, 2000) in which international capital mobility is allowed. Accordingly, the cost of climate change can be considered as a negative component of the available net investments at the regional level (that derive from national and foreign savings). To this purpose, the adoption of a weak sustainability approach allows including all forms of capital (economic, natural and ecologic) into a unique total capital stock measures assuming full substitutability of different forms of capital (Hamilton, 1996; Neumayer, 2003). This allows treating the damage cost as a negative component of capital accumulation whatever form of capital is considered. Given that in GDynEP, economic capital ($K_{r,t}$) is the only form of capital that is dynamically modelled and changes over time according to market mechanisms, we have modelled the cost of climatic damage within the economic capital accumulation function.

Finally, by introducing the cost of climate change into the capital stock function as in eq. (8), and considering the relative use of capital as an input of the production function of each *i-th* agent as in eq. (9), the economic impact of climatic damage is distributed across agents according to their technical production coefficients and their capital intensity. Given that GDP is a monetary measure of the market value of all final goods and services produced in a period, according to eq. (9) the GDP is affected each period by the reduction in production capacity of each agent according to the negative impact on capital stock availability.

3.2 Country and sector coverage and scenarios

This GDynEP version is aggregated into 19 regions and 22 sectors. Regions are formed following the Kyoto Protocol scheme with Annex I and non-Annex I countries. The first group includes the European Union, United States, Russian Federation, Rest of Europe, Rest of OECD East and Rest of OECD West. Within the second group, we distinguish: i) single countries (emerging economies with strong bargaining positions in the negotiations and eligible to emission cut commitments, as Brazil, China, India), ii) three groups (one per geographic area) of energy exporting countries (African Energy Exporters, American Energy Exporters, Asian Energy Exporters) and iii) all the remaining developing countries without an energy-based economy further distinguished according to their geographical location (Western Africa, East and South Africa, American Energy Exporters, South America, Central America and Caribbean, Continental Asia, Rest of South Asia, South East Asia).[16]

We differentiate 22 industries, with the aim of maintaining a deep disaggregation for energy intensive industries and energy producers: agriculture; food, beverages and tobacco; textile; wood; pulp and paper; chemical and petrochemical; non-metallic minerals; iron and steel; other metals ; machinery equipment; transport equipment; other manufacturing industries; transport; water transport; air transport and services, while energy commodities have been disaggregated in coal, oil, gas, oil products, electricity from fossil and nuclear sources, electricity from renewable sources.[17]

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[16] Asian developing and emerging countries have also been distinguished in Rest of South Asia and South East Asian representing, respectively, developing and emerging countries according to their level of development.

[17] See Table A.2- A.5 in Appendix A for a detailed description of regional and sectoral aggregates.

The GTAP-Database (GTAP-Database 9.1, updated to 2011) is used for the starting period, and the temporal structure is a first 4-year period up to 2015, followed by seven 5-year periods up to 2050.

The Business as Usual (BAU) scenario corresponds to CO_2-eq emission projections provided by IPCC (2014) and distributed across regions according to the International Energy Agency (IEA, 2015) World Economic Outlook. It embodies the effects of only those government policies and measures that had been adopted by mid-2015 and considers the feasible technical change for each region.

BAU is based on projections for macro variables as GDP, population and labor force given by the combination of several sources. In particular, GDP projections are the simple average values of four sources: the OECD Long Run Economic Outlook, the GTAP Macro projections, the IIASA projections used for the OECD EnvLink model, and the CEPII macroeconomic projections used in the GINFORS model. Population projections are taken from the UN Statistics (UNDESA) while projections for the labour force (modelled as skilled and unskilled separately) are taken by comparing labour force projections provided by ILO (which result as aggregate) with those provided by the GTAP Macro projections (where skilled and unskilled labour force are disentangled). In order to calibrate emissions in BAU according to IEA projections, in GDynEP emissions are exogenously shocked while the endogenous variable adjusting over time is technical change at the regional level.

The burden sharing in the mitigation policy scenario is consistent with IEA (2015), given by a regional emission path that limits the global increase in temperature to around 2°C, limiting the GHG concentration in atmosphere at 450 PPM, based on the technological capabilities of regions.[18]

The policy instrument to achieve the target is required to meet the following criteria. First, it must be one that *ceteris paribus* allows overall mitigation costs to be minimized, since we are interested in assessing how such costs could be compensated by potential benefits from damage reduction. By adopting a benefit-cost analysis approach, the assessment of a climate policy linked to different evaluation criteria for climatic damage should be carried by comparing the benefits with a common benchmark. We adopt as a benchmark the lowest possible mitigation cost that corresponds to the choice

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[18] We acknowledge that the burden sharing adopted for the policy scenario is compatible with technological capabilities of regions but is not chosen on the basis of real policy feasibility (for instance strongly affected by the U.S. defection). The exclusion of the U.S. from mitigation actions would force to recalculate the burden sharing for all the other regions if the final goal is to reach anyway a 450 PPM concentration. This modelling choice will reduce comparability across scenarios selected for this specific paper. Further work could be done in the future to evaluate the effect of alternative burden sharing options.

of a social planner who would like to maximize the likelihood of an international climate agreement being signed and implemented.

Second, it is necessary to assume that all countries have an emission reduction path, in order to have a measure of the cost of participating at a collective action for each country (if one country has no target, by definition it also has no mitigation costs).

These features lead to a policy instrument based on a global emission trading (GET) system that meets the cost effectiveness criterion and involves all regions. In operational terms, each country has a specific mitigation target that is derived by the IEA (2015) on the basis of technical feasibility evaluation, and it imposes a carbon tax to reach the target. Given the possibility to trade permits across regions without any cap or limitation, each agent decides to buy or sell permits on the basis of the relative convenience of the carbon price with respect to its own marginal abatement cost. The market clearing condition allows all marginal costs to be equal to the unique carbon price on the global permits market.

To sum up, four scenario settings are shaped:

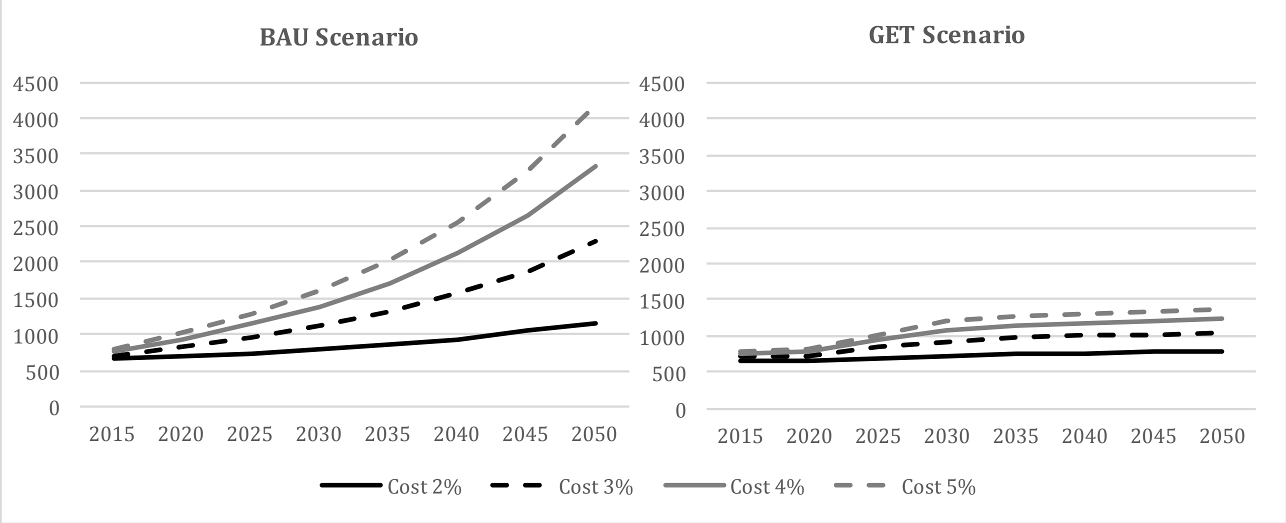
1. Business As Usual without considering the cost of climatic damage (BAU NO COST)
2. Global Emission Trading without considering the cost of climatic damage (GET NO COST)
3. Business As Usual including the cost of climatic damage (BAU COST)
4. Global Emission Trading including the cost of climatic damage (GET COST)

Settings #3-4 have been run according to the four cost patterns previously described, thus resulting in 8 scenarios.

4. Results

The damage patterns associated with emissions (and relative concentration paths) in BAU and GET scenarios are compared in Figure 1 to visualize the incidence of alternative values of the parameter α on climate cost path. The large difference between GHG concentrations over time in BAU vs. GET scenario explains the huge difference in damage profiles given the same damage function as given in eq. (3). Different values assigned to parameter α determine different damage paths given the same GHG concentration, while different emission paths influence GHG concentrations and consequently we see different damage profiles given the same value for the parameter α.

Figure 1 – Damage costs in BAU and GET scenarios (constant 2015 Bln USD)



By modelling damage costs in a dynamic framework shows the large discrepancy in GDP growth patterns when both direct and indirect impacts are considered. When comparing the two scenarios with the minimum and the maximum losses, it is worth mentioning that damage cost reduces GDP more than proportionally with respect to the monetary level of climatic damage, with an increasing negative impact associated with the wider range of losses included (Figure 2). The percentage reduction in GDP in the case of the direct impact is obtained by the ratio between the value of $CCR_{r,t}$ and the GDP level in BAU NO COST scenario, where GDP projections do not account for the reduction in capital formation due to damage cost. As a general remark, when comparing the damage costs in BAU vs. GET, the decline in damage associated to different GHG concentration patterns increases more than proportionally with the parameter α. This result could have implications for risk averse policy makers who are particularly concerned about pessimistic scenarios. According to Valentina and Vitale (2018), in the case of a policy maker with a high level of risk-aversion, the potential damage associated to a high value of the parameter α could justify the early adoption of aggressive mitigation policies.[19]

This result reveals that together with the necessity to converge to an international consensus on the

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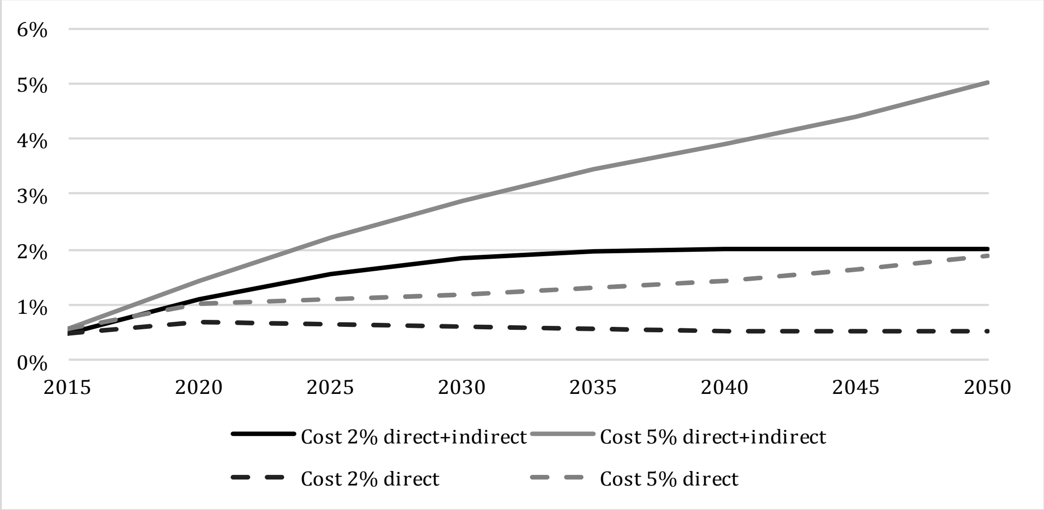
[19] In this paper we have not modeled the relation between the value adopted for parameter α and the level of risk-aversion of the social planner since we consider a common and univocal mitigation path that is driven by the IPCC and IEA bottom up climate-energy models. In the case of mitigation efforts endogenously decided according to the risk aversion of the policy maker, the value for parameter α would also influence timing profiles for mitigation actions. We will develop this relation in our future research agenda.

methodology to compute economic losses due to climate change, it is also necessary to reflect on the evaluation method for GDP impact assessment. This is strongly recommended in light of how the regional distribution of GDP change due to damage is affected by the specific cost pattern under scrutiny.

Figure 2 – Direct and indirect impact of damage cost as % of GDP in BAU



By considering the impact in 2050 (Table 1), China and developed countries are those that suffer the least from climate change whatever damage cost specification is considered. On the contrary, India registers low losses in the case when global costs are 2% and α=0.3, but when shifting toward the inclusion of all market and non-market components (α=0.8), it turns out to be among the most affected by climate costs. Developing countries (DCs) are those which suffer the most, with a GDP loss that can reach over 16% if the widest range of impacts and cost estimates is considered.

Among the DCs aggregate, Latin American countries register the lowest loss, while the costs to African countries are the highest. In fact, if we consider only market impacts (corresponding to the 2% GDP loss case), climate change causes a loss of GDP of about 7% for African countries, while they could face a 38% GDP loss in 2050 when the most inclusive damage function is adopted.

Although the quantitative assessment of climatic damage is still uncertain and incomplete, these results confirm that some of the least developed of the developing countries will suffer the highest costs. Accordingly, an accurate computation of the cost of climate change and its introduction in the definition of a global agreement is essential. In addition, given that the heterogeneous distribution of economic losses across DCs regions is strictly driven by differences in relative net vulnerability, a further issue to be included in the negotiation agenda (and in policy evaluation exercises) should be the actions to increase accuracy in comparing relative vulnerability and adaptation capacity at the country level.

Table 1 – GDP change in BAU COST w.r.t. BAU NO COST (in 2050)

GDP	Cost 2%	Cost 3%	Cost 4%	Cost 5%
World	-2.0%	-3.0%	-4.0%	-5.0%
Developed	-1.7%	-2.3%	-2.7%	-3.1%
DCs-Eex	-3.3%	-4.8%	-6.2%	-7.3%
DCs	-3.3%	-6.7%	-10.7%	-16.2%
DCs Africa	*-7.1%*	*-14.6%*	*-24.1%*	*-38.7%*
DCs Asia	*-1.9%*	*-4.0%*	*-6.0%*	*-7.7%*
DCs Latin America	*-1.0%*	*-1.4%*	*-1.8%*	*-2.0%*
China	-1.0%	-1.5%	-1.9%	-2.2%
India	-1.7%	-3.6%	-5.5%	-7.3%
Row	-2.3%	-3.2%	-4.0%	-4.6%

Note: acronyms for regions in GDynEP are DCs-developing countries, Eex-energy exporters, RoW-rest of the world.

The GDP change due to climate policy with respect to BAU in 2050 reveals that potential gains from mitigation actions would exceed abatement costs for some regions but not for others (Table 2). The implementation of a GET scheme without considering climate damage would cost the world around 5.2% of GDP by 2050. Emerging economies and energy exporters are those that lose the most, the former due to their stringent abatement commitment, the latter as a consequence of the decrease in the international demand for fossil fuels. Conversely, in DCs GDP losses are much lower thanks to their low abatement targets combined with an increase in competitive advantages on the international market with respect to those countries facing higher mitigation burdens.

The introduction of the costs of climate change into policy assessment changes this picture substantially. The loss in global GDP declines to 2.8% in the 5% cost scenario, since lower emission flows due to mitigation actions smooth the increase in GHG concentration in atmosphere and, consequently, the cost of climatic damage is lower with respect to BAU over time (as in Figure 1).

Not surprisingly, the highest benefits go to DCs, because they are relatively more vulnerable to climate change and do not base their economies on sectors affected by mitigation policies. In particular, African DCs see a shift in the trend of GDP in response to higher costs of climate change, thus creating also a benefit from the implementation of mitigation policies in terms of GDP change.

Table 2 – GDP change in GET w.r.t. BAU (in 2050)

GDP	No Cost	Cost 2%	Cost 3%	Cost 4%	Cost 5%
World	-5.2%	-5.1%	-4.5%	-3.9%	-2.8%
Developed	3.5%	3.6%	3.9%	4.2%	4.6%
DCs-Eex	-15.6%	-15.0%	-14.3%	-13.4%	-12.3%
DCs	-2.4%	-1.7%	0.6%	4.1%	11.3%
DCs Africa	*0.6%*	*1.7%*	*7.4%*	*18.0%*	*47.3%*
DCs Asia	*-11.5%*	*-11.1%*	*-9.9%*	*-8.4%*	*-6.5%*
DCs Latin America	*6.1%*	*6.7%*	*7.0%*	*7.4%*	*7.7%*
China	-16.2%	-16.3%	-16.2%	-15.9%	-15.6%
India	-17.3%	-17.6%	-16.5%	-15.2%	-13.5%
Row	-6.5%	-6.3%	-5.9%	-5.7%	-4.9%

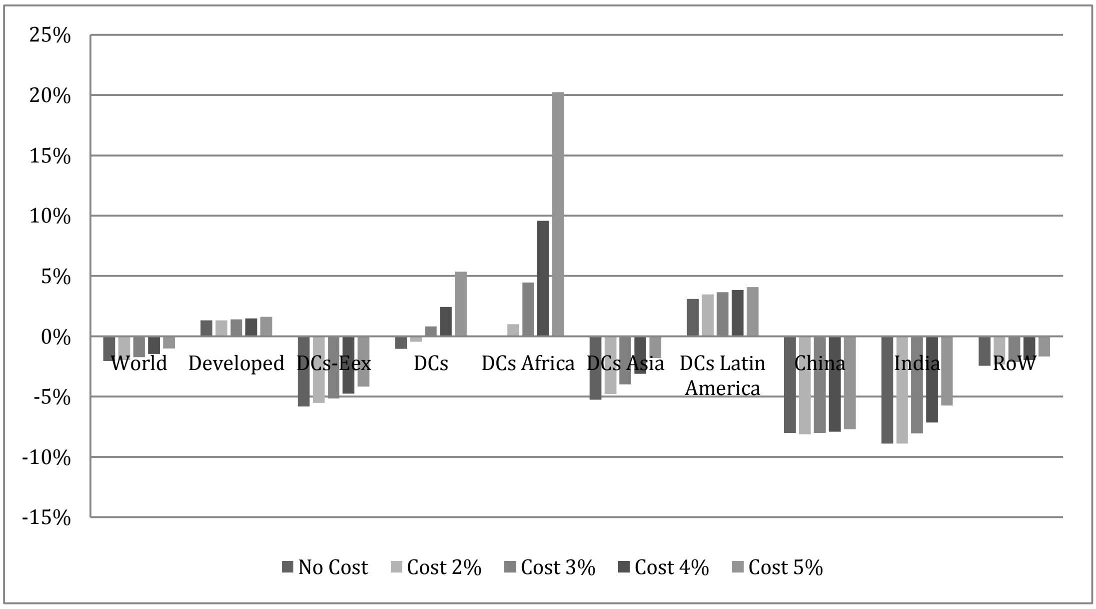
When considering the widest range of climatic impacts, it may occur that for poor countries the benefits associated with a reduction of climate costs exceed mitigation costs. If we look at the final cost in terms of GDP reduction in the BAU scenario when the climatic damage will impact at the highest level (5% for the whole world on average) African DCs will lose 38.7% of their GDP in 2050. In the case the Paris Agreement will be fully implemented and the emissions path will ensure an increase in temperature of a maximum of 2 degrees Celsius with a mitigation policy based on a global emission trading system, DC African countries will gain 47.3% in GDP terms with respect to the BAU scenario. By comparing this two results the net effect of a global mitigation action project are that African DCs turn out to about 8.6% better off in 2050 compared to a no action scenario.

In order to better investigate how countries would benefit from the participation in a global climate agreement, we show in Figure 3 the overall GDP change due to mitigation policies calculated as the net present value (NPV) computed at 2015 for the whole period 2015-2050 at a discount rate equal to 3%.

The computation of a NPV measure solves the accounting problem related to the temporal gap occurring between the implementation of mitigation actions with respect to the reduction in climatic damage. The fact that the benefits arising from a reduction in temperature increase will occur over a long-time horizon while high mitigation costs might be faced immediately could reduce the likelihood to cooperate, since the position of vulnerable countries would be divergent from that of polluting countries. By considering the discounted cumulative net cost-benefit result, it is possible to better inform countries on their relative position and effective convenience in cooperating.[20]

At the world level, whatever damage cost function is taken, the implementation of a GET scheme always entails a GDP loss at this discount rate. However, the negative GDP impact associated with the highest cost pattern is half the loss observed in the first scenario without damage cost (from a -2.1% GDP change to -1%). The role of damage costs is even more evident if we look at the differences in the regional distribution of GDP changes. Developed countries and Latin American DCs always benefit from mitigation actions in terms of GDP change. As for the African DCs, they face a small increase in their GDP in the first two scenarios, while they have a sharp increase associated with the participation in mitigation policies when the whole range of damage components are included (α=0.817), since the advantages coming from a reduction in climate change costs are much higher than the mitigation costs associated to their abatement actions. On the contrary, Asian DCs and energy exporters always lose when a global mitigation action is implemented whatever scenario is under scrutiny.

Figure 3 – GDP % change in GET w.r.t. BAU (NPV in 2015)



While for very vulnerable countries the introduction of the cost of climatic damage into the decision

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[20] In order to obtain accurate results, the discount rate should be both differentiated by region and declining over time (Philibert, 2003). However, in order to reduce uncertainty and facilitate the interpretability of results, we apply a single discount rate equal to 3%. This value is the most commonly used in SCC calculations and corresponds to the intermediate value applied by the US Government in its latest SCC computation (US Government, 2015).

making process might persuade them to actively participate in mitigation actions, this is not true for emerging economies. In fact, whatever the damage function considered, they do not benefit from the implementation of mitigation actions, due to their high abatement commitments. China, in particular, is one of the countries facing the highest mitigation costs. It is worth noting that despite this, after a long negotiation process, China ratified the Paris Agreement. This represents a step forward towards an active participation of the main emitter country. However, the contents of the NDC submitted by China reflect the high mitigation costs for this country; while most countries set abatement objectives to be reached by 2030, China declares its intention to reach the peak of emissions around 2030, without establishing a real mitigation target.[21] Furthermore, China also explicitly asks for international support and financing from the GCF, as a consequence of this high level of mitigation costs.

From a consideration of the economic impacts associated to costs and benefits from mitigation actions, it emerges that it will be difficult to support a global climate policy since even if developing regions are better off, mitigation reduces the GDP at world level whatever value of the parameter α is adopted. This implies that regions which are better off from the implementation of a global climate policy cannot compensate regions which are worse off. This result holds in the case where the maximum impact in terms of GDP by 2050 of climate change would be around 5%, which is an estimate deriving from a damage function based on historical values provided by the DARA Report. The increasing scientific knowledge on the evolution of physical characteristics of climate change could modify expectations on the costs related to climate damage and provide higher values for the parameter α, potentially driving to a radical shift from a net loss to a net gain at the global level in GDP terms by implementing a GET policy.[22]

Additionally, even though the current expectations on GDP impacts due to climate change are in the range of 2-5%, it is worth mentioning that if we adopt a welfare maximization perspective coherent with the SCC approach, the picture might radically change with alternative damage functions. Let us first graphically represent how the benefits and costs from mitigation actions interact in the GDynEP model

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[21] More specific targets are expressed in terms of use of renewable sources, afforestation and emission intensity.

[22] Further research work on this specific issue will be part of the next agenda on modelling climatic damage in GDynEP for assessing climate policy optimality under different uncertainty conditions.

in the case of the two cases of 2% and 5% damage. First, we consider the direct cost of climatic damage as provided by eq. (6) for scenarios with 630 PPM (BAU) and 450 PPM (GET), and in this second case the direct cost is represented by the residual damage after mitigation. Second, we compute the overall mitigation cost due to reaching the mitigation target (450 PPM scenario) via a GET policy, where the mitigation cost is given by the total value of domestic abatement costs at the regional level net of permits trading value (if the region is a net seller, revenue from permits are subtracted from abatement cost and vice versa). In this way it is possible to quantify only the direct impact on economic wealth related to climate mitigation and damage costs. We compare the overall costs faced in the GET Scenario (mitigation costs plus residual damage costs after mitigation) with damage costs faced in BAU. In Figure 4 we represent the case for a benefit-cost analysis where the cost of climate change will represent the 2% of GDP in 2050, while in Figure 5 we represent the 5% case. The area representing the net benefit from mitigation corresponds to the reduction in the cost provoked by climate change thanks to the mitigation action at the global level, here given by the area IJKM. The total cost of the mitigation policy is given by the sum of the abatement cost as represented by the area DLO (where the curve represents the marginal abatement cost and the total cost is given by the integral, the area under the curve) and the residual damage cost once the 450 PPM concentration is reached, given by the area DGJI. The net effect in benefit-cost term is therefore the difference between the benefit IJKM and the total cost DLO+ DGJI. Given that the targeted concentration pattern of 450 PPM is obtained by reducing the same amount of GHG emissions whatever damage function is adopted, graphically speaking the area DLO representing the mitigation cost is the same in the two cases. What drives the net benefit-cost result is the different monetary value associated to the climatic damage. In the lower case the welfare impact is clearly negative while the opposite occurs in the highest damage cost case.[23]

In order to complete the picture, we compare the overall costs faced in the GET Scenario (mitigation costs plus residual damage costs after mitigation) with damage costs faced in BAU in a NPV measure with a 3% discount rate at the regional level, according to the computation of the GDP effects.

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[23] We gratefully acknowledge Francesco Onufrio for inspiring us the combination of the different pictures of welfare aspects into a single graph as represented in Figures 4 and 5.

Figure 4 – Benefits and costs in GET w.r.t. BAU (Cost 2% of GDP damage case)

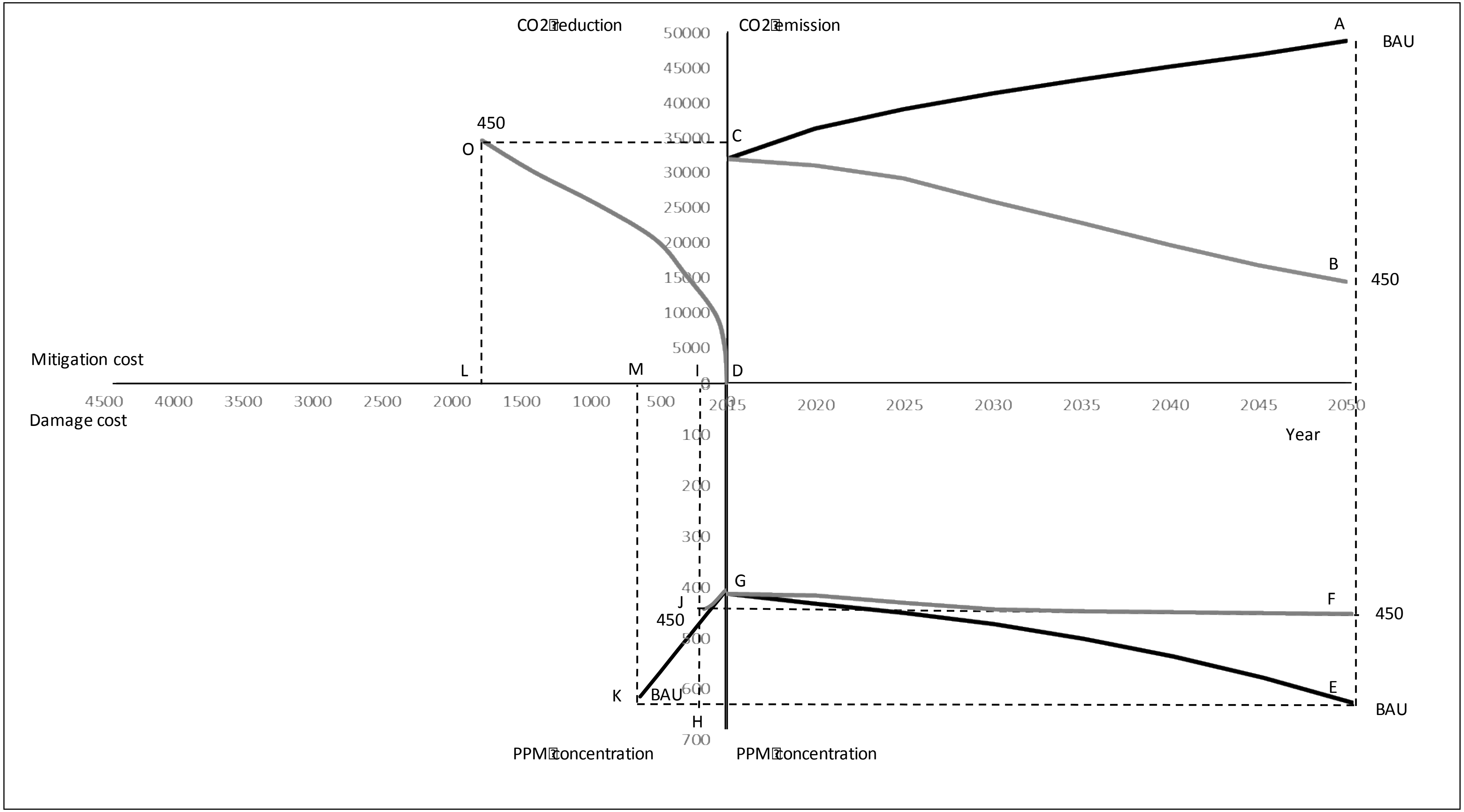


Figure 5 – Benefits and costs in GET w.r.t. BAU (Cost 5% of GDP damage case)

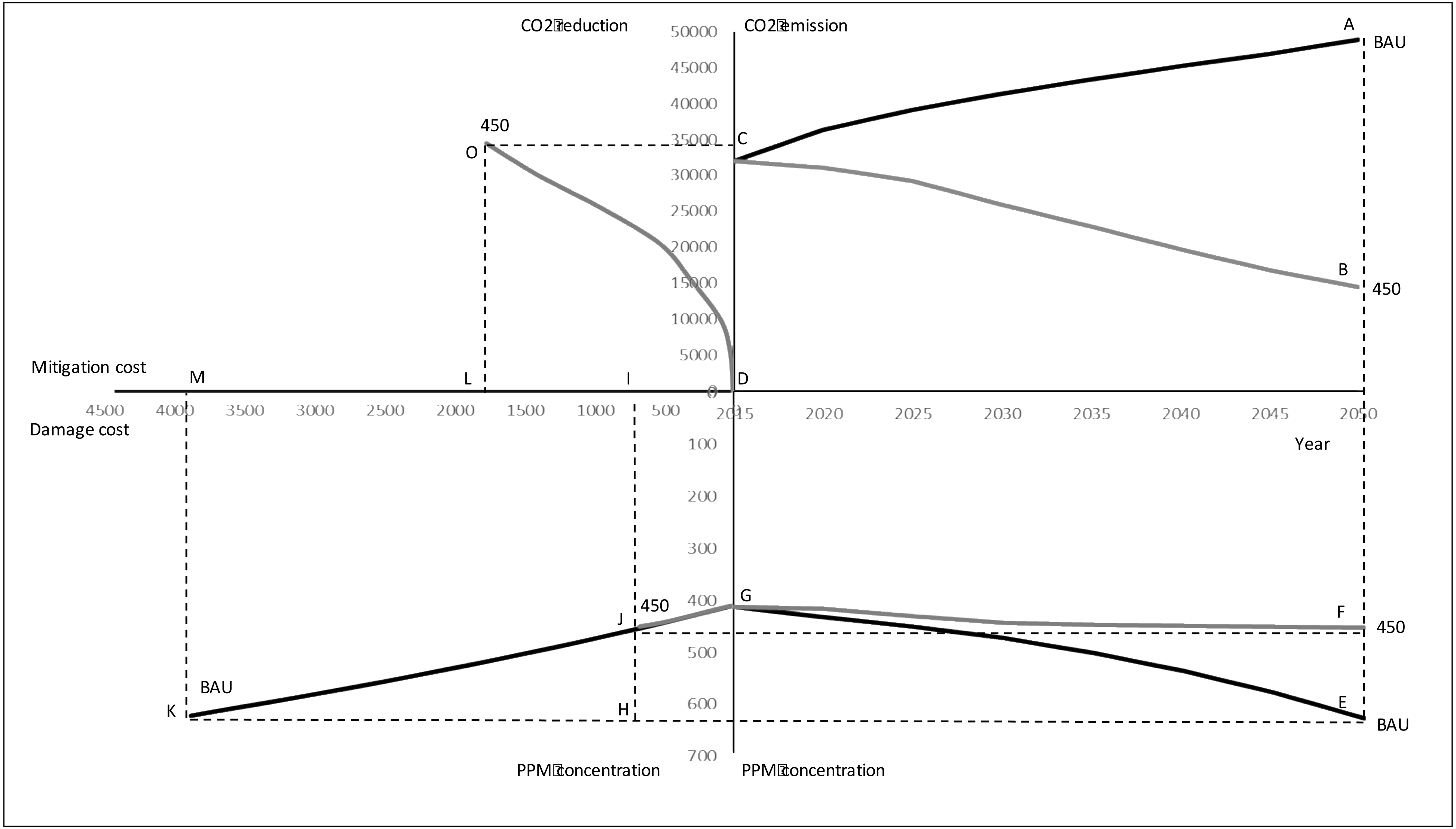
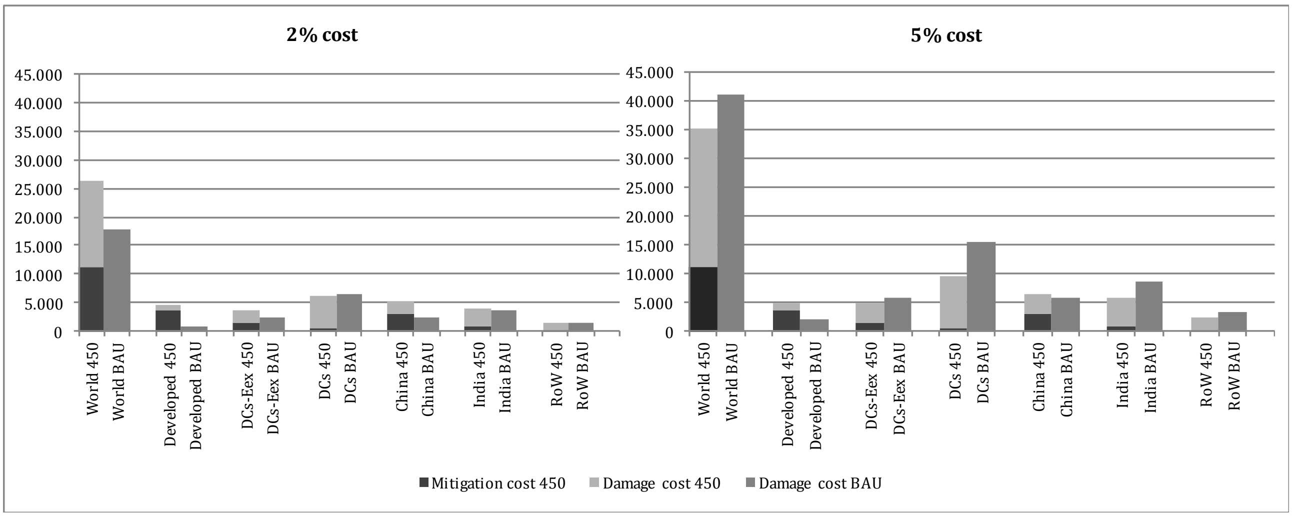


Figure 6 compares results for the lowest (Cost 2%) and the highest (Cost 5%) pattern, according to Figures 4 and 5. When the minimum damage cost function is taken into account, even though at the global level there is a net loss from the implementation of mitigation policies, DCs present a modest net gain. Moving to the highest cost pattern, a more comprehensive computation of climate costs may strengthen advantages in participating in mitigation also for countries facing a higher burden, as a consequence of their higher vulnerability to damage with respect to those regions facing a net loss.

Figure 6 –Costs in GET w.r.t. BAU with the 2% and 5% cost pattern (Bln USD, NPV at 2015)



Such differences in relative advantages from mitigation actions according to the economic measure under scrutiny (GDP change or welfare components) and the way damage is included in economy dynamics add evidence on the need to devote further research efforts in finalizing a common analytical framework on the internalization of damage costs into mitigation policy assessment. In the 2% case the global costs given by the sum of the mitigation and the residual damages are greater than the damage costs with BAU (the case of inaction). Henceforth, policy makers have a negligible risk that corresponds to the perception of low economic impacts related to climatic damage but it is a situation where it is impossible for all parties to gain from the action. In the 5% case the opposite is true, so it is possible to look for a solution where everyone gains. Since we do not know which is the right case, governments may be persuaded to work on a 5% (or higher) default value given their risk aversion at least provisionally and leave open the possibility of a change in policy as better information on climate damages and social wellbeing is generated from the international scientific community.

5. Conclusions

Internalizing the cost of climatic damage into policy design in a systematic way is an important factor in influencing country behavior and bargaining strategies in global climate negotiations. Mitigation policies entail significant GDP losses especially for emerging economies and energy exporters even when the policy instrument respects the cost-effectiveness criterion. However, when the cost of climatic damage is considered, GDP losses decrease or they might become even gains, at least in selected regions. The heterogeneity of countries is reflected in their vulnerability to climate impacts combined with differences in mitigation burdens. These factors explain why the negotiating attitude and the attractiveness of mitigation are both affected by the internalization of damage costs. Accordingly, the vulnerability of a country to climatic damage and the real impact of damages in terms of economic losses should be two additional components of any attempt to define the magnitude of the threat and its burden sharing.

The more exposed to climatic damage a country is, the higher its interest to act and to solicit actions from other parties in climate negotiations. This is also what emerges from the contents of NDCs submitted by developing countries, many of which set mitigation targets as a consequence of their high vulnerability to climate change. Given that future large emitters are the emerging economies, the main challenge for the forthcoming years is to persuade them to mitigate. In this respect, a precise evaluation of the cost of inaction might influence their bargaining behavior toward stronger efforts in mitigation activities.

These results also provide an equity implication that deserves further attention in negotiations discourse. In the case of high damage costs, a cost-effective climate action such as a global trading emissions system might bring to a win-win solution with a reduction in global GHG emissions and an increase in GDP of less developed countries. Nonetheless, results from modelling exercises remain distant from reality given the numerous theoretical assumptions with respect to crucial issues such as the barriers to the adoption and diffusion of clean technologies in underdeveloped economies or the absence of constrains in transforming the decrease in GHG concentration due to mitigation policies into a reduction in damage costs without any effective adaptation strategy.

To this purpose, international assistance should be provided to developing countries to take effective action, not only in terms of financial support but also in terms of technology transfer and capacity building. All developing countries highlight this point in their NDCs, together with the crucial role that international cooperation and instruments such as the GCF can play in this context. The Paris Agreement has already acknowledged the need for cooperation and financial support to assist developing countries (Art. 6 and Art. 9), hence it is of high relevance to properly evaluate vulnerability and adaptation needs, losses and damages from climate change together with the role of sustainable development in reducing the risks (Art. 7 and Art. 8). More generally, climate negotiations should take into account the whole range of characteristics of each country in order to choose a development path that would include climate change impacts, including mitigation actions and potential vulnerability to damages.

From our results three specific policy implications arise: i) there is an urgent need to develop a widely accepted methodology that provides a proper computation of the costs of climatic damage; ii) if inaction prevails in the coming years, the damage costs could enormously affect the GDP growth and would bring the world towards an unsustainable and unequitable development path; iii) together with measures to foster intra-generational equity, efficient compensating measures are required to facilitate the participation of those countries that, in spite of the reduction of climate economic damages, still face mitigation costs that are too high. In this respect, a key role can be played by the GCF, as highlighted in NDCs submitted by several developing and emerging countries, China included. Indeed, the perception of climatic damages together with national circumstances and priorities, influence bargaining positions expressed in NDCs, in terms of domestic efforts and international support. Accordingly, in addition to the establishment of better criteria and computation methods to evaluate climatic damages, there is also the need to define proper criteria for an equitable and effective resource allocation.

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Appendix

Table A.1 - DARA indicators

OVERALL INDEX	SUB-INDEX	INDICATORS
Aggregation of sub-indexes	Habitat Change	• Biodiversity • Desertification • Heating and Cooling • Labour Productivity • Permafrost • Sea-level Rise • Water
	Health Impact	• Diarrheal Infections • Heat & Cold Illnesses • Hunger • Malaria & Vector-borne • Meningitis
	Industry Stress	• Agriculture • Fisheries • Forestry • Hydro Energy • Tourism • Transport
	Environmental Disasters	• Floods and landslides • Storms • Wildfires • Drought

Source: DARA (2012), Methodological Documentation For The Climate Vulnerability Monitor 2nd Edition, p. 7

Table A.2 – ND-GAIN Vulnerability Indicators

Sector	Climate Risk		Adaptive Capacity
	Exposure	**Sensitivity**	
Water	Projected change in precipitation (High)	Internal and external fresh water extracted for all uses (High)	Population with access to improved water supply (Low)
	Projected change in temperature (High)	Mortality among under 5 yr.-olds due to water-borne diseases (High)	Population with access to improved sanitation (Low)
Food	Projected change in agricultural (cereal) yield (High)	Population living in rural areas (High)	Agricultural capacity fertilizer consumption, machinery and % land in irrigation) (Low)
	Coefficient of variation in cereal crop yields (High)	Food import dependency (High)	Children under 5 suffering from malnutrition (High)
Health	Estimated impact of future climate change on deaths from disease (High)	Health workers per capita (Low)	Longevity (Low)
	Mortality due to communicable (infectious) diseases (High)	Health expenditure derived from external resources (High)	Maternal mortality (High)
Human Habitat	Urban concentration in largest city (High)	Urban population living in Slums (High)	Value lost due to electrical outages (High)
	Urban Risk (High)	Excess urban growth (High)	Quality of trade and transport infrastructure (Low)
Ecosystem Service	Projected Biome Threat (High)	Ecological Footprint (Low)	Protected biomes (Low)
	Dependency on natural capital (High)	Threatened species (High)	International Environmental Conventions (Low)
Infrastructure (Coastal)	Land less than 10 m above sea-level (High)	Population living less than 10mabove sea-level (High)	Measured on the Readiness Axis
Infrastructure (Energy)	Population with access to reliable electricity (Low)	Energy at risk (High)	Measured on the Readiness Axis
Infrastructure (Transport)	Frequency of floods per unit area (High)	Roads paved (Low)	Measured on the Readiness Axis

Source: University of Notre Dame (2013). Global Adaptation Index. Detailed Methodology Report

Note: The marker “High” and “Low” refer to the direction of the relationship between each indicator and the overall vulnerability score. The indicator is marked “High” when the indicator contributes positively to vulnerability (i.e. high indicator value leads to high vulnerability score). The indicator is marked “Low” when it contributes negatively to vulnerability (i.e., high indicator value leads to low vulnerability score).

Table A.3 – ND-GAIN Readiness Indicators

Component	Indicator
Economic	IEF[24] Business freedom (High)
	IEF Trade freedom (High)
	IEF Fiscal Freedom (High)
	IEF Government Spending (Low)
	IEF Monetary Freedom (High)
	IEF Investment Freedom (High)
	IEF Financial Freedom (High)
Governance	WGI[25] Voice & Accountability (High)
	WGI Political Stability & Non-Violence (High)
	WGI Control of Corruption (High)
Social	Tertiary Education (High)
	IEF Labor Freedom (High)
	Mobiles per 100 persons (High)
	WGI Rule of Law (High)

Source: University of Notre Dame (2013). Global Adaptation Index. Detailed Methodology Report

Note: The marker "High" and "Low" refer to the direction of the relationship between each indicator and the overall vulnerability score. The indicator is marked "High" when the indicator contributes positively to vulnerability (i.e. high indicator value leads to high vulnerability score). The indicator is marked "Low" when it contributes negatively to vulnerability (i.e., high indicator value leads to low vulnerability score).

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[24] Index of Economic Freedom

[25] Worldwide Governance Indicators

Table A.4 – List of GDYnEP Region aggregates

	GDynEP code	Description
1	EU28	European Union
2	USA	United States
3	ROECD1	Rest of OECD East
4	ROECD2	Rest of OECD West
5	BRA	Brazil
6	CHN	China
7	IND	India
8	RUS	Russian Federation
9	REU	Rest of Europe
10	AS1	Asian Energy Exporters
11	AS2	Continental Asia
12	AS3	Rest of South Asia
13	AS4	South East Asia
14	AF1	African Energy Exporters
15	AF2	Western Africa
16	AF3	East and South Africa
17	LAM1	American Energy Exporters
18	LAM2	South America
19	LAM3	Central America and Caribbean Islands

Table A.5 - List of GDYnEP Sector aggregates

	GDynEP code	Description
1	coal	Coal
2	oil	Oil
3	gas	Gas
4	oil_pcts	Petroleum, coal products
5	ely_f	Electricity from fossil and nuclear energy sources
6	ely_rw	Electricity from renewable energy sources
7	agr	Agriculture
8	food	Food
9	textile	Textile
10	nometal	Non-metallic mineral products
11	wood	Wood
12	paper	Pulp and paper
13	chemical	Chemical and petrochemical
14	basicmet1	Basic metal 1
15	basicmet2	Basic metal 2
16	transeqp	Transport equipment
17	machinery	Machinery and equipment
18	oth_Manuf	Other manufacturing industries
19	transport	Transport
20	air_trans	Water Transport
21	water_trans	Air Transport
22	services	Services

Table A.6 - List of GDynEP countries and regions

GDynEP code	GTAP Code	Country	GDynEP code	GTAP Code	Country	GDynEP code	GTAP Code	Country
EU28	aut	Austria	REU	xee	Rest of Eastern Europe	AF2	bfa	Burkina Faso
EU28	bel	Belgium	REU	xer	Rest of Europe	AF2	cmr	Cameroon
EU28	cyp	Cyprus	REU	xsu	Rest of Former Soviet	AF2	civ	Cote d'Ivoire
EU28	cze	Czech Republic	REU	tur	Turkey	AF2	gha	Ghana
EU28	dnk	Denmark	REU	xtw	Rest of the World	AF2	gin	Guinea
EU28	est	Estonia	AS1	kaz	Kazakhstan	AF2	sen	Senegal
EU28	fin	Finland	AS1	bhr	Bahrain	AF2	tgo	Togo
EU28	fra	France	AS1	irn	Iran Islamic Republic	AF2	xwf	Rest of Western Africa
EU28	deu	Germany	AS1	kwt	Kuwait	AF3	eth	Ethiopia
EU28	grc	Greece	AS1	omn	Oman	AF3	ken	Kenya
EU28	hun	Hungary	AS1	qat	Qatar	AF3	mdg	Madagascar
EU28	irl	Ireland	AS1	sau	Saudi Arabia	AF3	mwi	Malawi
EU28	ita	Italy	AS1	are	United Arab Emirates	AF3	mus	Mauritius
EU28	lva	Latvia	AS2	mng	Mongolia	AF3	moz	Mozambique
EU28	ltu	Lithuania	AS2	npl	Nepal	AF3	rwa	Rwanda
EU28	lux	Luxembourg	AS2	pak	Pakistan	AF3	tza	Tanzania
EU28	mlt	Malta	AS2	kgz	Kyrgyztan	AF3	uga	Uganda
EU28	nld	Netherlands	AS2	arm	Armenia	AF3	zmb	Zambia
EU28	pol	Poland	AS2	aze	Azerbaijan	AF3	zwe	Zimbabwe
EU28	prt	Portugal	AS2	geo	Georgia	AF3	bwa	Botswana
EU28	svk	Slovakia	AS2	jor	Jordan	AF3	nam	Namibia
EU28	svn	Slovenia	AS2	xws	Rest of Western Asia	AF3	zaf	South Africa
EU28	esp	Spain	AS3	xoc	Rest of Oceania	AF3	xsc	Rest of South African
EU28	swe	Sweden	AS3	xea	Rest of East Asia	LAM1	mex	Mexico
EU28	gbr	United Kingdom	AS3	brn	Brunei Darussalam	LAM1	arg	Argentina
EU28	bgr	Bulgaria	AS3	khm	Cambodia	LAM1	ecu	Ecuador
EU28	hrv	Croatia	AS3	lao	Lao People's Democratic Republ	LAM1	ven	Venezuela
EU28	rou	Romania	AS3	phl	Philippines	LAM2	bol	Bolivia
USA	usa	United States of America	AS3	vnm	Viet Nam	LAM2	chl	Chile
ROECD1	aus	Australia	AS3	xse	Rest of Southeast Asia	LAM2	col	Colombia
ROECD1	nzl	New Zealand	AS3	bgd	Bangladesh	LAM2	pry	Paraguay
ROECD1	jpn	Japan	AS3	lka	Sri Lanka	LAM2	per	Peru
ROECD1	kor	Korea	AS3	xsa	Rest of South Asia	LAM2	ury	Uruguay
ROECD2	can	Canada	AS4	twn	Taiwan	LAM2	xsm	Rest of South America
ROECD2	xna	Rest of North America	AS4	idn	Indonesia	LAM3	cri	Costa Rica
ROECD2	che	Switzerland	AS4	mys	Malaysia	LAM3	gtm	Guatemala
ROECD2	nor	Norway	AS4	sgp	Singapore	LAM3	hnd	Honduras
ROECD2	xef	Rest of EFTA	AS4	tha	Thailand	LAM3	nic	Nicaragua
ROECD2	isr	Israel	AF1	egy	Egypt	LAM3	pan	Panama
BRA	bra	Brazil	AF1	mar	Morocco	LAM3	slv	El Salvador
CHN	chn	China	AF1	tun	Tunisia	LAM3	xca	Rest of Central America
CHN	hkg	Hong Kong	AF1	xnf	Rest of North Africa	LAM3	dom	Dominican Republic
IND	ind	India	AF1	nga	Nigeria	LAM3	jam	Jamaica
RUS	rus	Russian Federation	AF1	xcf	Central Africa	LAM3	pri	Puerto Rico
REU	alb	Albania	AF1	xac	South Central Africa	LAM3	tto	Trinidad and Tobago
REU	blr	Belarus	AF1	xec	Rest of Eastern Africa	LAM3	xcb	Caribbean
REU	ukr	Ukraine	AF2	ben	Benin			

Table A.7 - List of GDYnEP commodities and aggregates

GDynEP Sector	GTAP Code	Product description	GDynEP Sector	GTAP Code	Products description
agri	pdr	paddy rice	basicmet 1	i_s	ferrous metals
agri	wht	wheat	basicmet 1	nfm	metals nec
agri	gro	cereal grains nec	basicmet 2	fmp	metal products
agri	v_f	vegetables, fruit, nuts	transeqp	mvh	motor vehicles and parts
agri	osd	oil seeds	transeqp	otn	transport equipment nec
agri	c_b	sugar cane, sugar beet	macheqp	ele	electronic equipment
agri	pfb	plant-based fibers	macheqp	ome	machinery and equipment nec
agri	ocr	crops nec	oth_man_ind	omf	manufactures nec
agri	ctl	bovine cattle, sheep and goats, horses	services	TnD	transmission and distribution
agri	oap	animal products nec	ely_f	NuclearBL	Nuclear power
agri	rmk	raw milk	ely_f	CoalBL	Coal-fired power
agri	wol	wool, silk-worm cocoons	ely_f	GasBL	Gas-fired power (base load)
agri	frs	forestry	ely_rw	WindBL	Wind power
agri	fsh	fishing	ely_rw	HydroBL	Hydroelectric power (base load)
Coal	coa	coal	ely_f	OilBL	Oil-fired power (base load)
Oil	oil	oil	ely_rw	OtherBL	Other power
Gas	gas	gas	ely_f	GasP	Gas-fired power (peak load)
nometal	omn	minerals nec	ely_rw	HydroP	Hydroelectric power (peak load)
food	cmt	bovine cattle, sheep and goat meat products	ely_f	OilP	Oil-fired power (peak load)
food	omt	meat products	ely_rw	SolarP	Solar power
food	vol	vegetable oils and fats	gas	gdt	gas manufacture, distribution
food	mil	dairy products	services	wtr	water
food	pcr	processed rice	services	cns	construction
food	sgr	sugar	services	trd	trade
oth_man_ind	ofd	food products nec	transport	otp	transport nec
food	b_t	beverages and tobacco products	wat_transp	wtp	water transport
textile	tex	textiles	air_transp	atp	air transport
textile	wap	wearing apparel	services	cmn	communication
textile	lea	leather products	services	ofi	financial services nec
wood	lum	wood products	services	isr	insurance
paper	ppp	paper products, publishing	services	obs	business services nec
oil_pcts	p_c	petroleum, coal products	services	ros	recreational and other services
chem	crp	chemical, rubber, plastic products	services	osg	public admin. and def., education, health
nometal	nmm	mineral products nec	services	dwe	ownership of dwellings

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Reviewer#1 comments	**Detailed replies from authors**
Major issues	
1. It is stated in the abstract and the conclusions that the results of the model may change countries' bargaining strategies in climate negotiations. It is however not explained what negotiations are referred to and it is also not explained what bargaining positions are in this context and how they will be exactly changed by the results of the model. The paper should make these things explicit	We thank the Reviewer for addressing this point. We have added some explanations for this purpose, both in the Introduction and in the Results Sections. In the Conclusions we have amended the text by including comments on this point and also to additional issues arisen by the Reviewers.
2. The novelty in the modelling is the inclusion of climate damage in the CGE model. As I understand it, climate damage decreases the current capital stock (equation 8), which will (given unchanged investments?) also affect future capital stocks and hence the growth of the economy. This needs to be explained better. For one thing, the authors consider a capital stock that includes "all forms of capital (physical, human, natural)" but the GDyn model only includes physical capital as a factor of production. There may be something of a mis-match here. I would recommend that the authors explain in more detail how they understand the link between climate damage and capital loss and to provide some theoretical or empirical evidence that supports their modelling choice.	We thank the Reviewer for this suggestion. We have provided more details in model description and we hope the text is clearer now. The crucial point is the adoption of the weak sustainability criterion. In GTAP natural resources and human capital are present as endowments (we are sorry for not specifying it in the previous version of the paper). The depletion of whatever form of capital can be assigned to the overall capital stock wherever the specific depletion occurs, according to the weak sustainability criterion.
Minor issues	
3. A minor question is why the emission mitigation policy instrument "must be the policy choice that ceteris paribus allows overall mitigation costs to be minimized" (page 16). I simply do not understand this requirement	We have better explained this point in the modelling description by referring to the benefit-cost analysis approach where the optimal climate policy is one that ensures the minimum mitigation cost with the maximum benefit. We thank the Reviewer for addressing this point, and we have better explained it in the text.

Reviewer#2 comments	**Detailed replies from authors**
Major issues	
1. I would like to read something more on what the results suggest in terms of policy implication	We thank the Reviewer for arising this issue. We have added discussion on policy implications in the Conclusions.
2. Under this respect, the general message of this paper seems to be that climate costs matter as	We thank the Reviewer for addressing this point. We have commented on the specific

they heavily affect GDP both in aggregate and at regional level. However, the results do not support a global climate policy since we observe that, even if some countries and regions are better off, mitigation reduces the GDP at world level for any value of the cost parameter. This implies that regions which are better off from participating in the global climate policy cannot compensate regions which are worse off. The difficulty of enforcing international agreements when compensations between winners and losers are unfeasible (because, in aggregate, some gain less than the others lose) represents an underestimated issue in this paper. In fact, I think that this issue may represent a limitation with respect to the claim of contributing to the debate on climate negotiations and the authors should put greater effort in dealing with it. On the other hand, this paper provides an interesting equity implication that probably deserves more discussion. Namely, it arises that a cost-effective climate action, such as a global trading emissions system, might be used as a development policy that allows to increase GDP of less developed countries, pursuing also environmental objectives. I do not know if this result is completely new in the literature, but I think it should be emphasized in any case.	result related to GDP impact in the Results section and we have also tried to provide a better description of the link between this part of the analysis and the cost benefit analysis developed in the last part of the results description. With respect to the equity issue, we have expanded our comments in the Conclusions section, also according to suggestions from Reviewer #1.
Minor issues	
3. I would suggest to look at Kotchen (2018) which is a recent theoretical paper that could be somehow related to your paper.	We have considered the approach described in this contribution and linked with the interpretation of our results.
4. In the first paragraph of Section 3 (p. 8) you refer to some "literature review" that I have not found in the paper.	We have amended the text accordingly.
5. When damage costs are evaluated under the GET scenario vis-à-vis the BAU scenario, it appears that the decline in damages from BAU to GET increases more than proportionally in the parameter α. This result could have implications for risk averse policy makers who worry about the worst scenarios. This is an issue that could probably deserve further investigation and comments. On this issue you could have a look at Valentini and Vitale (ERE, forth.) and the related literature cited in their paper.	We really thank the Reviewer for addressing this point. We have better commented on this result also linking it with the suggested contribution.
6. Check the fonts in Table 1 and Table 2.	We have checked.

7. Your simulations show that China is one of the countries that would lose more in terms of GDP because of international climate policies. How do you explain this result in view of the current China's willingness to cooperate that emerged in the most recent COP agreement?	We have added comments on this result also linking it with the recent efforts in NDCs after the Paris Agreement.