Macro-economic assessment of climate change impacts: methods and findings

The paper introduces the challenges posed by the macro-economic assessment of climate change impacts and describes the main investigation methodologies used by the economic literature to address these challenges. Strengths and weaknesses of the different approaches are presented. The paper then presents the major findings from this literature providing a critical guidance in their interpretation. The paper concludes highlighting policy implications and discussing the evolution of the research developments in the future.

El artículo presenta los retos planteados en la evaluación macroeconómica de los impactos del cambio climático y describe las principales metodologías de investigación utilizadas en la literatura económica para abordar estos desafíos. Una vez que se presentan las fortalezas y debilidades de los diferentes enfoques, el artículo muestra los principales hallazgos de esta literatura proporcionando una guía crítica para su comprensión. El documento concluye destacando las implicaciones políticas y debatiendo la evolución de la investigación en el futuro.

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Keywords: Climate change impacts, macro-economic assessment, climate change cost, social cost of carbon.

Palabras clave: Impactos del cambio climático, evaluación macroeconómica, coste del cambio climático, coste social del carbono.

JEL codes: Q54, F64, Q51

Entry date: 2020/02/28 Acceptance date: 2020/04/23

1. INTRODUCTION

Assessing the economic costs of climate change impacts faces several challenges that emerged evidently since the first estimates were published in the early 90s'. Economic estimates are particularly uncertain and, therefore, debatable, for many reasons. Firstly, they cannot help incorporating the uncertainty transmitted across the evaluation chain by the other non-economic disciplines that necessarily concur in the assessment. Secondly, they have to incorporate social or human reactions, which are inherently unpredictable. Thirdly, they cannot avoid elements of subjectivity coming from the evaluator herself/himself. On the one hand, as a reaction, the economic assessment of climate change translated into the development and application of a wide range of different methodologies trying to respond to the different challenges. Probably, the most distinctive example of this process is the birth of integrated assessment models. However, many other quantitative and qualitative investigation approaches have been used. On the other hand, the consequence of this multi-disciplinarity and methodological diversity is a wide range of cost estimates and even of cost concepts that may confuse the non-expert. In fact, as will be highlighted in the paper, there are results which are extremely robust across the different assessments. More importantly, the differences, when present, can be explained and motivated. They all concur in defining the economic implications of climate change and need to be interpreted organically.

The aim of this paper is to help orientating in this wide, constantly developing and almost 30 years old literature by clarifying concepts, methodologies, estimates and the interpretation of the economic impacts of climate change. A precious help in this endeavour is offered by recent meta-analyses that did for us the work of combining the available climate change cost estimates into a summarizing and structured framework. We revise further studies shedding light on the important equity consequences of climate change considering either spatial or income distribution issues. Finally, this paper adopts a macro-economic or aggregated perspective. That is, it refers only marginally to all the literature, albeit important and perhaps wider, that assesses local impacts and costs of climate change.

The paper is structured as follows. Section 2 introduces the challenges posed by the macro-economic assessment of climate change impacts. Section 3 describes the different cost concepts applied and introduces the main investigation methodologies used by the economic discipline. Section 4 critically summarizes the major findings from the literature. Section 5 discusses the strengths and weaknesses of the different assessment approaches providing critical guidance in their interpretation. Section 6 concludes and discusses future research developments.

2. CHALLENGES IN THE MACRO-ECONOMIC ASSESSMENT OF CLIMATE CHANGE IMPACTS

In the spirit of the many surveys on the macro-economic assessments of climate change impacts (see e.g. Sanstad and Greening, 1998; Bosello, 2014; Auffhammer, 2018) we cannot avoid to briefly mention the enormous challenges that these assessments have to face.

The keyword is uncertainty. In rigorous terms, uncertainty is a situation in which the probability distribution function associated to a given event is not defined exactly (Knight, 1922). This situation is pervasive in all the investigation phases that eventually lead to an economic, or more correctly, a socio-economic evaluation of climate change impacts. Typically, the reaction of the climate system (usually interpreted as a variation of global temperature) to increasing concentrations of GHG, as well as the reaction of the environmental system to climate change stressors, are not perfectly known. These uncertainties clearly affect the economic evaluation. In addition, economic assessments of climate change suffer from their own peculiar uncertainty sources. These are: the intertemporal dimension, the global dimension and the non-market dimension of the problem.

The intertemporal dimension of climate change implies that climate change impact and policy assessments need to evaluate costs and benefits not only for the present, but also for the future (often far future) generations. This originates two different, albeit connected, issues. The first is the need to characterize the future society. Indeed, the type of society impacted – i.e. its wealth, its technology, its demographic structure etc. – do play a role in the determination of impacts. It influences what the IPCC defines as the exposure and vulnerability components of climate change risk (IPCC, 2014). Due to the near impossibility to forecast societal development fifty or more years ahead, this issue is typically accommodated through the use of scenarios based on storylines. These storylines are internally consistent descriptions (i.e. not predictions) of how the future may unfold. The Shared Socioeconomic Pathways, SSPs (Riahi *et al.*, 2017), are just the last out of many examples in this field. The second problem pertains to the evaluation of streams of costs and benefits occurring at different times. This implicitly asks for weighting the present against the future to reach comparable and/or aggregated measures of costs and benefits over time. This process originates the well-known problem of discounting (Pearce *et al.*, 1996): each weighting system unavoidably introduces an element of subjectivity in the assessment.

The global dimension of climate change poses somewhat similar challenges. There is firstly the complexity linked to an evaluation of impacts that are highly diversified by type and region. Furthermore, the problem arises of either comparing or aggregating losses and gains for different societies or societal groups. This process of horizontal aggregation can eventually be performed, but, once again, using some equity-weighting systems. These systems, however, cannot avoid an element of subjectivity (Anthoff *et al.*, 2009).

The last source of uncertainty reported here, refers to the existence of climate-change gains and losses induced on non-market goods and services. Often, climate change impacts affect items which are highly relevant for human welfare but are not traded in official markets. Typical examples are the supporting and regulating services of ecosystems and biodiversity. Therefore, in many circumstances, the economic evaluation cannot benefit from the support of prices that, as imperfect indicators they may be, are anyway a starting point for an economic assessment. In particular cases (i.e. that of cultural services), the benefits originated and potentially at risk are not even related to the use of the service itself, but to its mere existence. No observable transaction or behavior can thus reveal the value lost or gained. Contingent valuation techniques or their evolution, choice experiments, have been developed to elicit these values. Nonetheless, notwithstanding continuous improvements, these methodologies, based on direct interviews/surveys, cannot totally eliminate the biases of responses determined by the hypothetical nature of the experiment. Furthermore, the results of these exercises are context specific and are difficult to generalize.

All this said, notwithstanding the uncertainties, current macroeconomic assessments provide enough information on costs of climate change and of climate change policies to offer some useful support to policymaking.

3. COST DEFINITION AND METHODOLOGICAL APPROACHES

The literature proposes different perspectives to consider climate change costs. The first refers to the concept of the social cost of carbon. This is defined as the money evaluation of the long-term damages produced by one unit (ton) of CO_2 (or carbon) emitted into the atmosphere. Economically speaking, it is a marginal cost concept (Anthoff *et al.*, 2009, Arent *et al.*, 2014). The second is a more aggregated measure where costs are expressed in terms of lost gross domestic product (GDP) (or of other indicators of economic performance) for a country, region, or community. Usually, these last exercises specify costs in given combinations of climate change and socio-economic scenarios (Riahi *et al.*, 2017).

Another differentiation distinguishes direct from indirect costs. The former accounts for an immediate economic evaluation of damages where a physical loss (e.g. of land, capital, but also life) is multiplied by a price. The latter takes into account the adjustments in the economic system triggered by the initial negative shocks. Changes in GDP are typical indicators of indirect costs as this variable should capture how the ability to produce goods and services of an economic system, considered with all its interactions and feedback, is affected by a climatic stressor.

There are also different methodologies used to perform the economic assessment that we group in three broad categories. The first makes use of simulation models, the second uses statistical/econometric approaches, and the third is the elicitation of expert opinions.[1]

Models used for the macroeconomic assessment of climate change impacts and policies are of many types and nature (for a comprehensive treatment of these see e.g. Sathaye and Shukla, 2013; Bosello, 2014). Their common feature is, however, to use explicit relations (structural or behavioral equations), to describe, even though in a simplified way, the process leading to the final economic outcome. Integrated Assessment Models (IAMs) offer a topical example in this vein: they summarize in a

[1] For the sake of the discussion we present the three methodologies as separated, however they are strictly intertwined. For instance, either the econometric instrument or expert elicitation are amply used to parameterize the structural relations, including the damage functions informing integrated assessment and economic models.

unifying mathematical structure (i.e. a single equation system) the causal chain going from climate pressures to socioeconomic reactions, costs and the related feedback. Enabling the joint description of the climate, the environment and the social-economic system within one model, a process called hard-linking, requires huge simplifications. In IAMs (that, can be extremely complex), this translates into the use of reduced-form relations. These are equations that compact with relatively few parameters complex behaviors, for instance, of the climate system in response to GHG emissions, or of the economic system (in the form of GDP, income, welfare losses) in response to temperature increase. The latter case originates reduced-form climate change damage functions. Examples in this vein are offered by models like: RICE (Nordhaus and Yang, 1996), FUND (Tol, 2006), and WITCH (Bosetti *et al.*, 2006). This simplification is at the same time the major pro and con of IAMs. On the one hand, it enables the study of complex dynamic and interacting decision processes; on the other hand, it can do this just «on aggregate», losing many specificities of the causal links and becoming more able to describe a result than to explain it.

However, also more traditional macroeconomic models like macro-econometric models or, especially, computable general equilibrium models are supporting climate change impact assessment. They do this downstream, i.e. processing climate change impact information from other models (e.g. crop, sea-level rise, energy, etc.), to get the final economic cost estimate. This is the so-called soft-link approach, where different models exchange information through an output-input-output process. This methodology allows to couple different models from different disciplines without the need to excessively simplify the different processes. However, it requires more computational time and power needed to operate many different models in sequence. Examples of this literature include: Kainuma *et al.* (2003), Bosello *et al.* (2012), Stehfest *et al.* (2014), Ciscar *et al.* (2018), Dellink *et al.* (2019).

Another stream of impact assessment studies uses econometric approaches. Notwithstanding the technical differences pertaining to the many different methodologies applicable (spanning from the analysis of cross section to panel data, country-level to spatially explicit data), their common feature is to estimate relations from past evidence to then project these relations into the future. Econometrics has been thus amply applied to estimate the impact of climate change on many dimensions relevant for human welfare (see e.g. Carleton and Hsiang, 2016 for a survey). Part of this literature analyses historical data to identify and estimate the relationship between observed changes in climate or weather and impact endpoint indicators such as GDP or income (see e.g. Dell, *et al.*, 2012; Burke *et al.*, 2015; Kahn *et al.*, 2019).

The last methodology applies expert elicitation. It consists of asking recognized experts to express their informed quantification (of different types) of climate change damages, under different climate scenarios usually coupled with confidence intervals and self-assessment on the degree of expertise. These methods are typically used when the evaluation refers to circumstances whose quantitative knowledge is extremely uncertain/low. They are meant either to replace or support quantitative approaches still insufficiently precise or to test the degree of confidence of experts in their modelling tools. Examples of these are Kriegler *et al.* (2009), Pindyck (2019), and also part of the parameterization of the damage function of the RICE model (Nordhaus and Boyer, 2000).

The next sections will present the findings of this literature in more detail.

4. SUMMARY OF COST ESTIMATES

4.1. Aggregate estimates

Many are the studies conducted to assess the economic costs of climate change. All of them rely on one or more of the methodologies cited in section 3 to provide estimates for different regions of the world and considering also a variegated set of climate impacts. Along time, a series of meta-analyses has been developed to synthesise the corpus of damage estimates and to systemize it according to the different characteristics of the studies. Examples of these meta-analyses are Tol (2018), Howard and Sterner (2017), Newbold and Marten (2014), Nordhaus (2013), and Tol (2009). This section draws from the most recent two meta-analyses, being also the most complete.

Tol (2018) reviews 22 studies containing 27 estimates of the total economic impact of climate change measured in terms of welfare equivalent-income loss and considering temperature increases with respect to preindustrial levels. According to those studies, there could be a benefit from global warming below 1.7°C, while for temperature increases above that level, net damages will be experienced. On average, the impacts of a 2.5°C increase of global mean temperature, translates into a 1.3 per cent of income loss for the average person. However, there is quite some disagreement about the size and sign of the impact across studies for the same level of warming (Tol, 2018). The studies examined, provide comparative static impacts, but there is the possibility that climate change could affect also the growth rate of the economy when analysed in a dynamic framework (Bretschger and Valente, 2011; Bosello and Parrado, 2014; Dellink *et al.*, 2019; Eboli *et al.*, 2010; Fankhauser and Tol, 2005; Hallegatte, 2005; Lemoine and Kapnick, 2016). This highlights the importance of looking not only at the effects on final output but also at the indirect effects that may affect productive processes which could be harmed and therefore reduce the expected economic growth in the future.

In another meta-analysis, Howard and Sterner (2017) review 41 studies including studies from grey literature. The final selection of 20 studies reporting 26 non-duplicate estimates is used to estimate the global willingness to pay to avoid total impacts of climate change measured as percentage of global GDP. Results from the study suggest that climate damages are likely between 7%-8% of GDP for a 3°C temperature increase when catastrophic risks are not factored in, while damages would rise to 9%-10% when these risks are included in the estimation.

The study also classifies damage estimates into six categories depending on the estimation methodology (Table 1).[2] The first category represents what the authors define the enumerative strategy. It is based upon bottom-up or sectoral economic impact assessments that are then aggregated to get insights into the total cost of climate change. Fankhauser (1995) and Tol (2002a,b) represent prominent examples in this field. Enumerative approaches have often provided the basis for the calibration of the reduced-form climate change damage function of IAMs.[3] These estimates report what in section 2 has been defined as the direct costs of climate change. Enumerative approaches indicate estimates ranging between a net benefit of 2.3% of GDP and a damage of 11.5% for a temperature increase between 1°C and 3°C. The second category regards expert elicitation. These assessments express losses in the range of 0% - 10.2% of GDP for a range of temperature increase between 1°C and 6°C.

Econometric evidence is divided into cross-section and panel regression results. The former highlights values ranging from a benefit of 0.1% to a damage of 16.3% of GDP for temperature increase between 0.7°C and 3.2°C. Panel regression estimates group more recent studies relating weather-climate and GDP data over time. Damages are estimated between 0.3% and 23% of GDP for temperature increases between 3.4°C and 4.3°C. The fifth category is represented by CGE models. These are able, starting from enumerative bottom-up estimates, to provide economic damage assessment accounting for market adaptation and economic feedbacks. They offer an evaluation of the indirect costs of climate change. CGE damage estimates are between 0.2% and 4.6% for temperature increases in the range of 1.5°C and 4.8°C. The last category represents science-based damage estimates. These consider physical thresholds to derive the damage estimates and are definitely in the higher range featuring losses of 4.9% to 99% of GDP for temperature increases between 3°C and 12°C.

Table 1. **RANGE OF DAMAGE ESTIMATES BY CATEGORY OF STUDY**

Estimate category	Temperature increase range	GDP variation
Enumerative	1°C - 3°C	2.3% to -11.5%
Expert elicitation	1°C - 6°C	0% to -10.2%
Cross sectional	0.7°C - 3.2°C	0.1% to -16.3%
Panel	3.4°C - 4.3°C	-0.3% to -23%
Computable General Equilibrium (CGE)	1.5°C - 4.8°C	-0.2% to -4.6%
Science-based	3°C - 12°C	-4.9% to -99%

Source: Howard and Sterner (2017).

[2] For a discussion of the pros and cons of each damage estimate category see section 2 of Howard and Sterner (2017).

[3] More recently, the enumerative approach has been applied also to quantify adaptation cost and effectiveness and to calibrate adaptation modules in IAMS (de Bruin *et al.*, 2009; Agrawala *et al.*, 2011; Bosello *et al.*, 2013).

4.2. **Distributional Issues**

Global estimates provide an idea of the average cost of climate change impacts, but it is also important to consider their distributional effects accounting for large asymmetries both in impacts and in the country and regional social-economic characteristics. The consolidated result from the literature is that poorer areas are more adversely affected than the richer ones (Table 2). In this vein, just to quote a recent contribution, Dellink *et al.* (2019), use a dynamic recursive CGE to analyse six types of impacts in a general equilibrium framework (agriculture, coastal zones, energy demand, extreme precipitation events, health and tourism demand). They find that for a temperature increase of 2.5°C the global average loss of GDP is 2%, with health and agriculture contributing to 0.9%, and 0.8% of total GDP loss respectively. However, for the same global temperature increase, the Middle East and Northern Africa lose 3.3%, South and South-East Asia 3.7%, Sub-Saharan Africa 3.8%, India more than 4% of GDP. These figures are in stark contrast with GDP losses in developed regions: OECD Europe loses 0.2%, OECD Pacific 0.3%, OECD America 0.6%, and USA around 0.5% of GDP.

Similar conclusions are drawn by Diffenbaugh and Burke (2019) using not simulation models, but fixed-effect panel econometrics to measure the effects on economic inequality of global warming. The study finds a very high likelihood of increased economic inequality between countries due to anthropogenic climate forcing; and larger decreases in GDP per capita for most poor countries due to global warming.

There are several factors leading to this outcome: developing countries are, for their majority, located at middle and low latitudes where global warming is more severe; these economies are also more dependent upon agriculture, which is a sector more sensitive to climatic variations; finally, these countries are endowed with a lower adaptive capacity deriving from limitation related to institutional and economic aspects. Indeed, these considerations led the IPCC's Fifth Assessment Report (AR5) to explicitly include equity issues among the five major «reasons for concern» related to climate change (IPCC, 2014).

Nonetheless, climate change can exert unequal macroeconomic impacts also across developed regions. An example in this direction is the recently concluded PESETA III project (Ciscar *et al.*, 2018) that analyses the economic impacts of climate change in the EU, considering temperature increases of 2°C and 3°C by 2071-2100. It shows that the European Union as a whole could lose between 0.55% and 2% of GDP for those temperature increases. However, while northern European regions are projected to lose less than 1% of GDP, South Central Europe is expected to lose between 0.81%-2.57% of GDP and Southern Europe between 1.65% and 4.2% (Ciscar *et al.*, 2018).

Table 2. **DISTRIBUTION OF GDP IMPACTS OF CLIMATE CHANGE ACCORDING TO DIFFERENT STUDIES**

Study	Warming	Impact at the global level	Worst-off region		Best-off region	
	°C	% GDP	% GDP	Name	% GDP	Name
Nordhaus (1994)	3.0	-1.3	--	--	--	--
Nordhaus (1994)	3.0	-4.8 (-30 to 0.0)	--	--	--	--
Fankhauser (1995)	2.5	-1.4	-4.7	China	-0.7	Eastern EU and FSU
Tol (1995)	2.5	-1.9	-8.7	Africa	-0.3	
Nordhaus and Yang (1996)	2.5	-1.7	-2.1	Developing Countries	0.9	FSU
Plambeck and Hope (1996)	2.5	-2.5 (-0.05 to -11.4)	-8.6 (-0.6 to -39.5)	Asia w/o China	0 (-0.2 to 1.5)	Eastern EU and FSU
Nordhaus and Boyer (2000)	2.5	-1.5	-4.9	India	0.7	Russia
Tol (2002b)	1.0	2.3	-4.1	Africa	3.7	Western Europe
Asian Development Bank (2009)	4.2	-0.6 (average annual basis in 2100)	-2.2 market impacts -5.7 +non-market -6.7 + cat. events (average annual basis in 2100)	Indonesia, Philippines, Thailand, Vietnam	--	--
Roson and Van der Mensbruegghe (2012)	4.8	-4.6	-12.5	East Asia (w/o China and Japan)	2.1	FSU
Bosello *et al.* (2012)	2.0	-0.5	-3.2	South Asia	0.7	FSU
Bosello *et al.* (2014)	2.5	-0.6	-4.2	India	0.7	FSU
Dellink *et al.* (2019)	2.5	-2.0	-4.3	India	1.1	Russia

Source: Our adaptation from the quoted studies.

4.3. **Marginal cost estimates**

The information provided by the previous assessments constitutes also the basis to estimate the social cost of carbon (SCC). During the last decades, several values have been proposed and have been constantly revised. Probably, the most comprehensive overview of this evolution is offered by Tol (2018). The author surveys around 114 studies published from 1982 to 2015 reporting a total of 1231 estimates.

Considering a 3% pure rate of time preference, the mode of these studies reports a damage of $28 per ton of carbon and a mean of $44 per ton of carbon (Tol, 2018).

The estimates of SCC magnify the role of subjective elements in the evaluation. The main drivers of differences across estimates are the assumptions on the discount factor or on the equity weights applied to account for distributional concerns. This issue was well exemplified in the recent past by the debate accompanying the release of the Stern Review (Stern, 2006; Tol and Yohe 2006, 2007; Weitzmann, 2007). In particular, critiques on the high-damage estimates reported by Stern i.e. the «5% of global GDP each year, now and forever [...] to 20% of GDP or more» and the corresponding high marginal cost of emissions, 314 $ per tons of carbon – were indeed largely determined by the very low pure rate of time preference and the long time period (200 years) considered in the study.

All this said, the literature, and the practice, show some tendency to use values higher than that mean of studies and to progressively update upward the estimates of the SCC (Wang *et al.*, 2019). Some examples of this trend follow. On its more recent study, Nordhaus (2017) increases its DICE model calibration of the SCC for the year 2015 to a value of $79 per ton of CO_2 (in 2010 US$), for a discount rate of 3%. Howard and Sterner (2017) use a damage function in their DICE-2013R model that computes a SCC that is up to four-fold the SCC estimate produced by the original DICE model. Pindyck, one of the authors more critical against the modelling approach to climate change impact assessment (Pindyck 2013, 2017), considering experts opinions as a more reliable source of information, eventually finds that among those experts expressing the higher degree of confidence, the estimated SCC ranges in the interval $80-100. Moore *et al.* (2017) show that incorporating the most recent estimates of damage functions for the agricultural sector into the FUND integrated assessment model would double the SCC.[4] Ricke *et al.* (2018), combining more recent climate model projections, social economic projections and economic estimates of damages identify a median of $417 t$CO_2$ for the SCC that results also unequally distributed across countries. Larger losses are incurred by India, China, Saudi Arabia, and also the United States.

5. DISCUSSION

By looking at the range of results presented by the different study categories it is possible to identify some robust findings.

[4] To this prudential attitude surely contributes the structural risk and uncertainty of climate change impacts that can originate low probability catastrophic events. In a series of papers, Weitzman (2007, 2009a,b, 2010), showed that some forms of interaction between declining probability and increasing damages can increase the willingness to pay to avoid the damages (i.e., to mitigate) nominally to infinite. In this uncertain and catastrophic environment, the standard cost-benefit analyses performed by integrated assessment models, and their prescriptions are considered inadequate.

Firstly, it emerges that model-based studies, econometric approaches, enumerative methods and expert elicitation find qualitatively similar results on the cost of climate change. In particular, they agree on the non-linearity in temperature pattern of economic impacts and their uneven distribution across countries, with developing regions more exposed and vulnerable to negative climate change effects than developed areas. However, quantitative estimates differ greatly within and between approaches. Econometric studies tend to find higher damages, especially for a temperature increase in the range of 1°C to 2°C than model estimates, especially CGE based. More specifically and according to cross-sectional evidence, per capita income could fall up to 8.5% with 1°C additional increase in temperature. Model-based approaches, on the contrary, report losses often lower than 1% of world GDP for similar temperatures, with some studies reporting slight gains.

What originates such differences?

The first remark regards the inclusion of adaptation in the damage estimates. All approaches could do this to some extent but in different ways. CGE models do this by construction. More specifically, they have been explicitly built to capture market adjustments triggered by shocks that perturb price signals. They thus account for market-driven adaptation mechanisms, i.e. changes in firms and households demand and supply decisions in response to changing prices. These adjustments are, however, typically instantaneous and friction/cost less. The optimism of CGE models in factoring adaptation has indeed been indicated as a shortcoming and one of the reasons for the low estimates of climate change costs (Patt *et al.*, 2010). Econometric approaches could be better equipped than CGE models to account for the many frictions in autonomous and planned adaptation processes, because these are implicitly part of the data scrutinized. This is thus a potential explanation of the higher damage estimates by econometric studies. There is then an extended literature that discusses how different econometric approaches can account for adaptation (for an extensive discussion see Auffhammer, 2018). Namely, cross sectional approaches appear to be ill suited to capture long-term adaptation, but only short-term one.[5] Differently panel approaches, can account for long-term adaptation applying appropriate techniques (e.g. including polynomial specification of the explanatory climate variables or resorting to a «long differencing» approach[6]). This thus can explain why, for instance, cross sectional data tend to provide larger estimates of climate change economic damages than panel estimates.

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5 For completeness of the treatment, it is worth mentioning that if the omission of long-run adaptation may bias upward estimates of macroeconomic cost of climate change in cross sectional analyses, the short-term adaptation they consider is anyway assumed to be costless, which, on its turn can bias downward the cost estimates. This has been shown for instance in the context of Ricardian analyses (Quiggin and Horovitz, 1999).

6 For instance, Burke and Emerick (2016) suggest to regress the difference between five year moving averages of the dependent variable (e.g. crop yields) over a sufficient time (e.g. two decades apart), on five year moving averages of the weather/climate explanatory variable (e.g. temperature) also two decades apart, all measured in areas showing sufficient climate variation, to account for long-run adaptation.

The second remark to explain differences in evaluation is related to which impacts are considered. CGE models, even though able to examine many impact areas (see e.g. Eboli *et al.*, 2010, Ciscar *et al.*, 2018, Dellink *et al.*, 2019), cannot include all impacts. In particular, CGE models, whose economic assessments are based upon observable market transactions, encounter the largest difficulties in measuring non-market losses due for instance to ecosystem and biodiversity, but also health deterioration. Therefore, these impacts are not usually part of the economic estimation, even though, in the practice, they could be added on top of the losses computed by the CGE models, once they have been quantified with other methodologies (see e.g., Ciscar *et al.*, 2018).

The economic evaluation of extreme events/disaster losses is also challenging. Typically, CGE models account for extreme events or disasters increasing expected annual losses (in assets, land etc.). Therefore, on the one hand, they span overtime losses that in reality happen in one year. On the other hand, the evaluation remains deterministic missing to include elements like uncertainty and risk aversion that can have non-negligible effects on damage evaluation. Both issues thus contribute to underestimating losses estimates.

On the contrary, these aspects can be better captured by econometric approaches (in principle) as long as they influence the dependent variable (e.g. GDP loss) one wants to explain. Naturally, also econometrics finds it difficult to include catastrophic (not extreme) impacts linked to the existence of climate tipping points. These are low probability events that can provoke sudden or abrupt changes triggering economic losses of a totally different order of magnitude (see e.g. Lenton *et al.*, 2008 for examples and quantification). The economic consequences of these events are hardly captured by econometric studies because they have not been observed in the historical period that provides the data for the estimations.

These events can be more easily included by enumerative approaches and be duly incorporated in the educated opinions elicited from experts. The inclusion of these elements obviously contributes to increasing the estimate of economic losses from climate change.

6. CONCLUSIONS

In roughly 30 years of research, the literature on the economic assessment of climate change impacts expanded greatly. And so did methodologies: integrated assessment models became progressively more elaborated; soft linked approaches produced increasingly complex coupled modelling frameworks; econometric techniques were innovatively applied to investigate the relationship between temperature change and economic performance.

All this literature produced a wide spectrum of estimates. In this huge variety, some results are robust across studies and methodologies. There is a consolidated agreement that while there could be some economic benefits for global temperature increases below 1°C, higher temperatures will produce net GDP losses. However, at this point, estimates diverge. Losses can be considerably high, larger than 10% of world GDP, already for a relatively low level of warming between 1 and 1.5°C according to econometric assessments. In the same range of temperature, GDP or welfare costs stay relatively low, below 1%, according to model-based assessments. Semi-quantitative assessments based upon expert elicitation are somehow in between.

The difference in results can be imputed to the very different nature of the investigation approaches. In particular, econometrics should be able to capture, by construction, all the frictions and imperfections that are part of the historical experience, while modelling approaches need to do that explicitly. Accordingly, limits in autonomous adaptation, non-market losses, and irreversibility, for instance, are difficult to capture with models. At the same time, models are able to depict, track and explain complex decision processes and economic dynamics that econometric fails to capture.

This suggests the first path for future research: econometric approaches can increasingly support the parameterization if not the choice of the functional form of behavioural equations in models to improve their empirical foundations. This can be easier in integrated assessment models, where the use of reduced-form equations is extended. It will be more challenging in other types of economic models like, for instance, CGE.

The choice of the discount rate and of the equity weighting process remains a field of unsettled debate. These factors play a paramount role in determining the results, especially of integrated assessment models. However, being these choices subjective, the only recommendation can be that of transparency of the assumptions.

All this said, there seems to be a recent tendency in the modelling literature to revise upward the estimates of the cost of climate change and of the social cost of carbon and thus to reduce the gap with econometric estimates.

The other widespread agreement across methodologies is on the huge adverse distributional implications of climate change impacts. This has either a spatial dimension – climate change increases inequality between regions –or a social dimension – climate change increases inequality between rich and poor within a country, a region, a city, a community. This highlights the second line of research: macroeconomic assessments, irrespective of the methodology, should improve their ability to go finer spatially and to explicitly account for income stratification. Some promising advancements in these directions are already available. Some econometric research is already exploiting the increasing availability of social-economic data with a high spatial resolution to produce gridded global maps of climate change impacts on economic performance. IAMs are starting to apply downscaling techniques to derive «high granularity spatially explicit» damage functions and emphasize sub-national differences.

To highlight some further areas for future investigation of macroeconomic climate change impact assessment, it is finally worth stressing that there are still impacts, as well as important factors influencing them, that are largely unexplored. Among the first are: water resources, transport, migration, ecosystem and biodiversity, conflicts (Tol, 2018); few attempts have been also undertaken to study the economics of climatic and social-economic tipping points; among the second, for instance, the role of institutions, behaviour, gender. It must be recognized that many of these are difficult to be implemented into a comprehensive macroeconomic assessment and in cost-benefit analysis (see Dietz *et al.*, 2018, for an extensive discussion of possible benefits and costs of some of those impacts). However, this should not prevent from trying to account for them and to provide a wider and more complete macroeconomic assessment of climate change.

All this said, despite the challenges still pending and unresolved uncertainties, the macroeconomic assessments of climate change have provided and are still providing useful insights. Policy-making can be informed of non-trivial economic reactions triggered by climate impacts and policies. The general public can be supported in framing correctly the social dimension of the climate change problem, gaining awareness of its implications and of the necessary measures to take in order to deal with it.

REFERENCES

Arent, D.; Tol, R.S.J.; Faust, E.; Hella, J.P.; Kumar, S.; Strzepek, K.M.; Toth, F.L.; Yan, D. (2014): «Key economic sectors and services», in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, 659–708. Cambridge: Cambridge University Press.

Agrawala, S.; Bosello, F.; Carraro, C.; de Bruin, K.; de Cian, E.; Dellink, R.; Lanzi, E. (2011): «Plan or react? Analysis of adaptation costs and benefits using Integrated Assessment Models», *Climate Change Economics*, 2(3): 175-208.

Anthoff, D.; Tol, R. S. J.; Yohe, G.W. (2009): «Risk aversion, time preference, and the social cost of carbon», *Environmental Research Letters*, *4*(2).

Auffhammer, M. (2018): «Quantifying Economic Damages from Climate Change», *The Journal of Economic Perspectives*, 32(4): 33-52.

Asian Development Bank (ADB) (2009): «The Economics of Climate Change in Southeast Asia: A Regional Review». Manila: ADB.

Bosello, F. (2014): «The role of economic modelling for climate change mitigation and adaptation strategies», in A. Markandya, I. Galarraga, E. Sainz de Murieta (eds.) *Routledge Handbook of the Economics of Climate Change Adaptation*, Routledge, Oxon and New York-Bosello F.

Bosello, F.; Carraro C.; de Cian, E. (2013): «Adaptation can help mitigation: an integrated approach to post 2012 climate policy», *Environment and Development Economics*, 18: 270–290.

Bosello, F.; Nicholls, R.J.; Richards, J.; Roson, R.; Tol, R.S.J. (2012): «Economic impacts of climate change in Europe: sea-level rise», *Climatic Change*, 112(1): 63-81.

Bosello, F.; Parrado, R. (2014): «Climate change impacts and market driven adaptation: the costs of inaction including market rigidities», *FEEM Working Paper*, No. 64.2014

Bosetti, V.; Carraro, C.; Galeotti, M.; Massetti, E.; Tavoni, M. (2006): «A World Induced Technical Change Hybrid Model», *The Energy Journal* SI2006 (01).

Bretschger, L.; Valente, S. (2011): «Climate change and uneven development». *Scandinavian Journal of Economics*, 113(4):825-45.

Burke, M.; Emerick, K. (2016): «Adaptation to Climate Change: Evidence from US Agriculture», *American Economic Journal: Economic Policy*, 8(3): 106-40.

Burke, M.; Hsiang, S.M.; Miguel, E. (2015): «Global Non-Linear Effect of Temperature on Economic Production», *Nature*, 527(7577): 235-39.

Carleton, T.A.; Hsiang, S.M. (2016): «Social and economic impacts of climate», *Science*, 353(6304).

Ciscar, J.C.; Ibarreta, D.; Soria, A.; Dosio, A.; Toreti, A.; Ceglar, A.; Fumagalli, D.; Dentener, F.; Lecerf, R.; Zucchini, A.; Panarello, L.; Niemeyer, S.; Pérez-Domínguez, I.; Fellmann, T.; Kitous, A.; Després, J.; Christodoulou, A.; Demirel, H.; Alfieri, L.; Dottori, F.; Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Cammalleri, C.; Barbosa, P.; Micale, F.; Vogt, J.V.; Barredo, J.I.; Caudullo, G.; Mauri, A.; de Rigo, D.; Libertà, G.; Houston Durrant, T.; Artés Vivancos, T.; San-Miguel-Ayanz, J.; Gosling, S.n.; Zaherpour, J.; de Roo, A.; Bisselink, B.; Bernhard, J.; Bianchi, L.; Rozsai, M.; Szewczyk, W.; Mongelli, I.; Feyen, L. (2018): «Climate impacts in Europe: Final report of the JRC PESETA III project», *EUR 29427 EN, Publications Office of the European Union*, Luxembourg, ISBN 978-92-79-97218-8, doi:10.2760/93257, JRC112769.

Darwin, R. (2004): «Effects of Greenhouse Gas Emissions on World Agriculture, Food Consumption, and Economic Welfare», *Climatic Change*, 66(1): 191-238.

De Bruin, K.C.; Dellink, R.B.; Tol, R.S.J. (2009): «AD-DICE: an implementation of adaptation in the DICE model», *Climatic Change*, 95: 63-81.

Dell, M.; Jones, B.F.; Olken, B.A. (2012): «Temperature Shocks and Economic Growth: Evidence from the Last Half Century», *American Economic Journal: Macroeconomics*, 4(3): 66-95.

Dellink, R.; Lanzi, E.; Chateau, J. (2019): «The Sectoral and Regional Economic Consequences of Climate Change to 2060», *Environmental and Resource Economics*, 72(2), 309-363.

Dietz, S.; Bowen, A.; Dixon, C.; Gradwell, P. (2016): «Climate value at risk' of global financial assets», *Nature Climate Change*, 6(7), 676-679.

Dietz, S.; Bowen, A.; Doda, B.; Gambhir, A.; Warren, R. (2018): «The Economics of 1.5°C Climate Change», *Annual Review of Environment and Resources 2018*, 43:1, 455-480.

Diffenbaugh, N.S.; Burke, M. (2019): «Global warming has increased global economic inequality», *Proceedings of the National Academy of Sciences of the United States of America*, 116(20), 9808-9813.

Eboli, F.; Parrado, R.; Roson, R. (2010): «Climate- change feedback on economic growth: explorations with a dynamic general equilibrium model», *Environment and Development Economics*, 15(5):515-33.

Fankhauser, S. (1995): «Valuing climate change. The economics of the greenhouse», *Earthscan*, London.

Fankhauser, S.; Tol, R.S.J. (2005): «On climate change and economic growth», *Resource and Energy Economics*, 27(1):1-17.

Hallegatte, S. (2005): «The long-time scales of the climate-economy feedback and the climatic cost of growth», *Environmental Modeling and Assessment*, 10(4):227-89.

Howard, P.H.; Sterner, T. (2017): «Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates», *Environmental and Resource Economics*, 68(1), 197-225. https://doi.org/10.1007/s10640-017-0166-z

Kahn, M.E.; Mohaddes, K.; Ryan N.C. NG; Pesaran, M.H.; Raissi, M.; Yang, J.C. (2019): «Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis», *Federal Reserve Bank of Dallas, Globalization Institute Working Papers*, 2019(365). https://doi.org/10.24149/gwp365

Kainuma, M.; Matsuoka, Y.; Morita, T. (2003): (Eds.) «Climate Policy Assessment Asia-Pacific Integrated Modeling», Springer-Verlag.

Knight, F.H. (1921): «Risk, uncertainty, and profit». Hart, Schaffner & Marx; Houghton Mifflin Company, Boston.

Kriegler, E.; Hall, J.W.; Held, H.; Dawson, R.; Schellnhuber, H.J. (2009): «Imprecise probability assessment of tipping points in the climate system», *PNAS*, 106 (13), 5041-5046

IPCC, (2014), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Lemoine, D.; Kapnick, S. (2016): «A top-down approach to projecting market impacts of climate change», *Nature Climate Change*, 6(1):51-55.

Lenton, T.M.; Held, H.; Kriegler, E.; Hall, J.W.; Lucht, W.; Rahmstorf, S.; Schellnhuber, H.J. (2008): «Tipping elements in the Earth's climate system», *PNAS*, 105 (6), 1786-1793.

Moore, F.C.; Baldos, U.; Hertel, T., *et al.* (2017): «New science of climate change impacts on agriculture implies higher social cost of carbon», *Nature Communications*, 8:1607.

Newbold S.C.; Marten A.L. (2014): «The value of information for integrated assessment models of climate change». *Journal of Environmental Economics and Management* 68(1):111-123.

nordhaus, w.d. (1994): «Managing the Global Commons: The Economics of Climate Change». Cambridge: The MIT Press.

— (2007): «A Review of the Stern Review in Climate Change», *Journal of Economic Literature*, *XLV*(September), 686-702.

— (2013): «The Climate Casino: Risk, Uncertainty and Economics for a Warming World». New Haven - London, Yale University Press, 2013, 378 pp.

— (2017): «Revisiting the social cost of carbon». *Proceedings of the National Academy of Sciences of the United States of America*, 114(7), 1518-1523. https://doi.org/10.1073/pnas.1609244114

Nordhaus, W.D.; Yang, Z. (1996): «A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies», *American Economic Review*, 86 (4), pp. 741-765.

Nordhaus, W.D.; Boyer, J.G. (2000): «Warming the World: Economic Models of Global Warming». Cambridge, Massachusetts - London, England: The MIT Press.

Patt, A.G.; Van Vuuren D.; Berkhout, F.; Aaheim, A.; Hof, A.F.; Isaac, M.; Mechler, M. (2010): «Adaptation in integrated assessment modelling, where do we stand?», *Climatic Change*, 99: 383-402.

Pearce, D.W.; Cline, W.R.; Achanta, A.; Fankhauser, S.; Pachauri, R.K.; Tol, R.S.J.; Vellinga, P. (1996): «The social cost of climate change: greenhouse damage and the benefits of control», in J. Bruce, H. Lee, and E. Haites (eds), Climate Change 1995: Economic and Social Dimensions of Climate Change, Cambridge: Cambridge University Press, pp. 179-224.

Pindyck, R.S. (2013): «Climate Change Policy: What Do the Models Tell Us?». Journal of Economic Literature, 51(3), 860-872.

— (2017): «The Use and Misuse of Models for Climate Policy», *Review of Environmental Economics and Policy*, vol 11(1), 100-114.

— (2019): «The social cost of carbon revisited», *Journal of Environmental Economics and Management*, 94, 140-160.

Plambeck, E.L.; Hope, C.W. (1996): «PAGE95 - An Updated Valuation of the Impacts of Global Warming», *Energy Policy*, 24(9):783-93.

Quiggin, J.; Horowitz, J.K. (1999): «The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment», *American Economic Review*, 89(4), 1044-45.

riahi, k.; van vuuren, d.p.; kriegler, e.; edmonds, j.; o'neill, b.c.; fujimori, s.; tavoni, m., *et al.* (2017): «The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview», *Global Environmental Change*, 42, 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Ricke, K.; Drouet, L.; Caldeira, K.; Tavoni, M. (2018): «Country-level social cost of carbon», *Nature Climate Change* 8, 895-900.

ROSON, R.; VAN DER MENSBRUEGGHE, D. (2012): «Climate change and economic growth: impacts and interactions», *International Journal of Sustainable Economy*, Inderscience Enterprises Ltd, vol. 4(3), pages 270-285.

SANSTAD, A.H.; GREENING, L.A. (1998): «Economic models for climate policy analysis: A critical discussion», *Environmental Modeling & Assessment* 3: 3-18.

SATHAYE, J.; SHUKLA, P.R. (2013): «Methods and Models for Costing Carbon Mitigation». (October 2013). *Annual Review of Environment and Resources*, Vol. 38, pp. 137-168, 2013.

STEHFEST, E.; VAN VUUREN, D.; KRAM, T.; BOUWMAN, L.; ALKEMADE, R.; BAKKENES, M.; BIEMANS, H.; BOUWMAN, A.; DEN ELZEN, M.; JANSE, J.; LUCAS, P.; VAN MINNEN, J.; MÜLLER, C.; PRINS, A. (2014): «Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications», The Hague: PBL Netherlands Environmental Assessment Agency.

STERN, N.H.; PETERS, S.; BAKHSKI, V.; BOWEN, A.; CAMERON, C.; CATOVSKY, S.; CRANE, D.; CRUICKSHANK, S.; DIETZ, S.; EDMONDSON, N.; GARBETT, S.-L.; HAMID, L.; HOFFMAN, G.; INGRAM, D.; JONES, B.; PATMORE, N.; RADCLIFFE, H.; SATHIYARAJAH, R.; STOCK, M.; TAYLOR, C.; VERNON, T.; WANJIE, H.; ZENGHELIS, D. (2006*): Stern Review: The Economics of Climate Change.* London: Her Majesty's Treasury. Sterner.

TOL, R.S.J. (1995): «The Damage Costs of Climate Change Toward More Comprehensive Calculations». *Environmental and Resource Economics* 5(4):353–74.

— (2002a): «Estimates of the damage costs of climate change, Part I: benchmark estimates», *Environmental and Resource Economics,* 21 (1), 47-73.

— (2002b): «Estimates of the damage costs of climate change: Part II. dynamic estimates», *Environmental and Resource Economics,* 21 (1), 135-160.

— (2006): «Multi-Gas Emission Reduction for Climate Change Policy: An Application of FUND», *Energy Jour*nal, 27, 235-250.

— (2009): «The economic effects of climate change», *Journal of Economic Perspectives,* 23(2):29-51.

— (2018): «The Economic Impacts of Climate Change», 12(1), 4-25. https://doi.org/10.1093/reep/rex027

WANG P.; DENG, X.; ZHOU, H.; YU, S. (2019): «Estimates of the social cost of carbon: A review based on meta-analysis», *Journal of Cleaner Production*, 209: 1494-1507.

WEITZMAN, M.L. (2007): «A review of the Stern review on the economics of climate change», *Journal of Economic Literature,* 45 (3):703-724.

— (2009a): «On modeling and interpreting the economics of catastrophic climate change», *Review of Economics and Statistics*, 2009, vol. 91 (pg. 1-19).

— (2009b): «Additive damages, fat-tailed climate dynamics, and uncertain discounting», *Economics: The Open-Access, Open-Assessment E-Journal*, 2009, vol. 3 (pg. 1-29).

— (2010): «Risk-Adjusted Gamma Discounting», *Journal of Environmental Economics and Management,* 2010, vol. 60 (pg. 1-13).