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Assessing future climate change impacts in the EU and the USA: insights and lessons from two continental-scale projects

Assessing future climate change impacts in the EU and the USA: insights and lessons from two continental-scale projects

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Abstract

Climate change will impact many economic sectors and aspects of natural and human wellbeing. Quantifying these impacts as they vary across regions, sectors, time, and social and climatological scenarios supports detailed planning, policy, and risk management. This article summarises and compares recent climate impact assessments in Europe (the JRC PESETA III project) and the USA (the American Climate Prospectus project). Both implement a multi-sector perspective combining high resolution climate data with sectoral impact and economic models. The assessments differ in their coverage of sectors and scenarios, mix of empirical and process-based methods, handling of uncertainty, and representation of damages. Despite the dissimilarities, projected relative economic impacts are comparable, with human mortality as the dominant impact category. Both studies further show a large spatial heterogeneity of impacts that may amplify pre-existing economic inequality in the EU and US, and that mitigation can considerably reduce economic impacts. The comparison highlights the various decision-points involved in interdisciplinary climate impact modelling and lessons learnt in both projects, on the basis of which we provide recommendations for further research.

1. Introduction

There is a growing consensus that societies need to be prepared for ongoing and future climate change. Limiting future damages requires societal and policy action to protect human populations, as well as natural and economic assets. The 2015 Paris Agreement could represent a milestone for climate policy in the long term, as it sets up an iterative framework to move toward ambitious and coordinated international greenhouse gas emission reduction efforts. The Paris Agreement also reinforces the importance of adaptation policy to reduce expected climate impacts.

Quantifying the possible effects of climate change at the national and subnational levels provides key inputs for both mitigation and adaptation policy design. The current scientific understanding of overall climate impacts and adaptation remains quite limited (Stern 2013, Carleton & Hsiang 2016). There are some recent large multi-model comparison projects; the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) project (e.g. Warszawski *et al* 2014) covers multiple climate impacts or sectors, while e.g. the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al 2013, 2015) focuses on a single sector, agriculture. In recent years a growing number of studies has also evaluated impacts for specific sectors, such as on energy (e.g., Van Vliet *et al*, 2016), transport (e.g., Bubeck *et al* 2019), agriculture (e.g., Baker *et al* 2018) and health (e.g., Mitchell *et al* 2018), or for specific climate hazards, such as river floods (e.g., Dottori *et al* 2018), coastal storms and sea level rise (Vousdoukas *et al* 2018), and multi-hazard (Forzieri *et al* 2018). Studies that have assessed the integrated economic effects of climate change, on the other hand, are rare. Some studies relate historical response of per capita GDP growth rates to temperature which are projected into the future (e.g., Burke *et al* 2018), whereas other studies integrate in a coherent framework sectoral impacts from detailed bottom-up empirical or biophysical modelling assessments (e.g., Martinich and Crimmins, 2019; Ciscar *et al* 2011).

Two related key challenges in integrated climate impact and adaptation research are to improve the sectoral and spatial resolution of impact projections and to combine them in a coherent framework. Different economic activities and social groups will experience very different consequences from changes in the climate, and the interdependencies between sectors make the final outcomes difficult to disentangle. The heterogeneity between regions, in terms of exposure, vulnerability, coping capacity of affected communities, makes the spatial resolution of impact estimates a growing concern.

This article reviews and critically compares two recent continental-scale integrated assessments of climate impacts: the Joint Research Centre (JRC) Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis (PESETA) projects for the European Union (EU) (Ciscar *et al* 2018) and the American Climate Prospectus (ACP) project for the United States (US) (Hsiang *et al* 2017). Analysing their distinctive approaches and methodologies, as well as their results, highlights the strengths of the different approaches and the benefits of learning from international efforts. This work complements Jacobs *et al* (2016), which summarises the main lessons of the third US National Climate Assessment (NCA), highlighting features of the scientific, management and communication processes that led to its success in two main ways. First, the PESETA and ACP projects were aimed at comprehensive economic evaluation, demanding additional interdisciplinary coordination and innovation. Second, by assessing these two comparable projects, we highlight shared and divergent solutions to common problems, identifying a range of concrete decision points.

The main purpose of the JRC PESETA projects (Ciscar *et al* 2011, 2014, 2018) has been to analyse in a consistent way the potential impacts of climate change in Europe. The project responded to a need to provide quantitative modelling support to the European Commission services, particularly in the context of the 2013 EU Strategy on Adaptation to Climate Change (European Commission, 2013).

The PESETA projects involved the coordination of different teams within the Joint Research Centre (JRC) of the European Commission, with scientists in a wide range of disciplines, from river flood modelling to economics. High-resolution biophysical impact assessment models used high spatiotemporal resolution climate data to derive a broad set of climate impacts covering, in the JRC PESETA III project: coastal floods, river floods, droughts, agriculture, energy demand, transport, water resources, habitat loss, forest fires, labour productivity, and mortality due to heat. The six biophysical impacts with an assessed economic valuation were integrated into a general equilibrium economic model in order to assess the economic implications for economic activity (GDP) and households' welfare.

The ACP aimed to develop an economy-wide perspective on the impacts of climate change on the US using a consistent, data-driven, empirical approach that quantified the uncertainties around the damages from climate change (Houser *et al* 2015; Hsiang *et al* 2017). The work was commissioned by the Risky Business Project, which was led by New York City Mayor Michael Bloomberg, former U.S. Secretary of the Treasury Hank Paulson, and business leader Tom Steyer, along with seven other "Risk Committee" members, including leaders in government, business, and academia. The research team consisted of climate scientists, economists, policy scholars, and data scientists. The results drew upon econometric estimates and process-based climate impact models to study impacts on agriculture, labour productivity, health, crime, energy demand, and coastal communities, integrating results from multiple previous studies where possible. These damages were then combined in a general equilibrium framework to develop an economy-wide damage function relating GDP losses with average temperature.

The next section briefly reviews the main elements of the methodologies of the two studies. Section 3 summarises and compares their main results. Section 4 discusses a series of lessons which can be a guide for further research.

2. Methodologies

The PESETA III and ACP projects share similar overarching structures (Table 1): changes in climate force biophysical impact models, which result in economic consequences. The two projects chose regional climate scenarios with high space-time resolution in order to capture spatial variation in climate impacts. The regional climate scenarios provide climate data (such as temperature and precipitation), which feed the specific climate data needs of the biophysical impact models (e.g., providing extreme precipitation, among other climate variables, to the river flood assessment). The two projects then computed biophysical impacts by running process-based and statistical models, computing impacts for distinct sectors. The biophysical impact models are not linked in any of the studies, so the impact models are independently run. To translate physical impacts into economic terms, each project applied a series of valuation assumptions, and then used a computational general equilibrium model (CGE) to represent the economy-wide reallocation driven by these impacts, in the end integrating the various biophysical impacts under common economic metrics.

Table 1. Projects' main steps

Steps	PESETA III	ACP
Climate modelling	1 emission concentration scenario (RCP8.5), 5 to 11 climate realizations	3 emission concentration scenarios (RCP2.6, RCP4.5 and RCP8.5), 29 - 43 climate realizations of each
Biophysical impact modelling	9 process-based models and 2 statistical models	2 process-based models and 5 econometric models
Process-based biophysical impact models	Agriculture, Energy demand, Transport infrastructure, River floods, Coastal floods, Droughts, Water, Habitat Suitability, Forest Fires	Energy demand, coastal flood
Statistical/econometric biophysical impact models	Mortality, Labour productivity	Mortality, Labour productivity, Crop yields, Crime, Energy demand
Economic modelling	Direct and indirect damages (static CGE)	Direct and indirect damages (dynamic CGE)
GDP and population assumptions	Constant	Dynamic

However, in implementation the two projects made distinct decisions reflecting their underlying motivations and strengths. While the main objective of the ACP was assessing climate risk with high resolution data, PESETA's main purpose was to make a multi-sector, consistent impact assessment. We will consider each step in the computation process in sequence. Table 2 details the differences in scope in the two projects.

Table 2. Projects' scope

Scope	PESETA III	ACP
Countries	EU total, five EU multi-country regions and gridded results	USA total, its states and counties
Projection Period(s)	2°C warming, 2071-2100	Annual, reported for 3 time periods: 2020-2039, 2040-2059, 2080-2099
Reference period	1981-2010	2011
Uncertainty	Across climate models	Across climate, weather, and statistical model uncertainty
Adaptation	Limited, only private adaptation	Analysed for maize, mortality, and crime

Both projects used bias-corrected and downscaled climate data. The PESETA project selected two policy-relevant categories of climate scenarios: a high-emissions scenario and a climate stabilisation scenario meeting the 2°C global temperature target. For PESETA III, the former was identified with the international climate modeling community's Representative Concentration Pathway (RCP) 8.5 (van Vuuren *et al* 2011); the latter was assessed using a time-slice approach, employing the years in RCP 8.5 centered around 2°C of warming. The PESETA III climate realizations came from the Coordinated Regional-climate Downscaling Experiment over Europe (EURO-CORDEX, http://www.cordex.org/) (e.g., Jacob *et al* 2014), which used regional climate models to downscale global climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor *et al* 2012) to a relatively high spatial resolution (0.11 degree, ~12.5km). The overall number of climate realizations was limited (between five and eleven in PESETA III) due to the high computational cost of running the process impact models. The climate realizations were selected to approximately cover the range of the climate uncertainty. In the PESETA coastal assessment, coastal extreme sea levels were the result of the contributions from the mean sea level, tide, surge, and waves. Projections of sea-level rise (SLR) were taken from Hinkel *et al* (2014), which combined thermosteric and ocean dynamic sea-level contributions from CMIP5 CGMs with contributions from ice-sheets and glaciers derived from temperature and precipitation anomalies from the GCMs. Dynamic simulations of tidally forced ocean circulation were performed for each relative SLR scenario using a flexible mesh setup of the DFLOWFM, and projections of waves and storm surges were based on hydrodynamic simulations with

Delft3D-FLOW and WW3, respectively, driven by atmospheric forcing from CMIP5 GCMs for RCP4.5 and RCP8.5 (for more details see Vousdoukas *et al* 2017).

The ACP project also used RCP 8.5, as well as RCP 4.5 and 2.6 scenarios (van Vuuren *et al* 2011). These three RCPs respectively represent high emissions, moderate emissions reductions (consistent with stabilization of emissions at the current level through mid-century and then a subsequent decline), and stringent emissions reductions (consistent with the Paris Agreement goal of net-zero greenhouse gas emissions in the second half of the century). Specifically, the ACP started with 1/8°-resolution statistically bias-corrected and downscaled CMIP5 projections (Brekke *et al* 2014). To capture higher-resolution features (e.g., urban heat islands and land-sea interactions) and preserve the sub-monthly variability of the observed weather, the gridded projections were mapped to weather stations using the delta method (the projected monthly-mean shifts were applied to the historical climatology) and temporally downscaled using historical patterns of submonthly variability (Rasmussen *et al* 2016). One weather station was assigned to each US county.

Because equal-weighted GCM ensembles provide an unbalanced and incomplete sample of the distribution of climate responses to forcing (e.g., Tebaldi and Knutti, 2007), the ACP developed a novel approach for weighting model runs and for representing distributional tails, the Surrogate Model/Mixed Ensemble method (SMME; Rasmussen *et al* 2016). In SMME, a probabilistic simple climate model (for the ACP, the Model for the Assessment of Greenhouse Gas-Induced Climate Change, or MAGICC; Meinshausen et al 2011) is used to estimate the distribution of global mean surface temperature (GMST) responses to forcing; then, weights are applied to the available GCMs to recover the shape of the GMST distribution. To represent tails of the GMST projections that are not represented in the GCM ensembles, surrogate models are developed by scaling the spatial pattern of warming from the available GCMs to higher or lower global mean temperatures.

For the ACP, SLR was modeled at the local level using a novel probabilistic sea-level rise projection framework (Kopp et al, 2014), which has since been extensively used in other research and stakeholder contexts. Tropical and extratropical cyclone incidence and associated flooding were modeled using synthetic storms and process models for the Atlantic and Gulf of Mexico coasts of the United States (Knutsen *et al* 2013; Emanuel, 2013).

There are two main approaches to modelling climate impacts, process-based and empirical modelling, each with its strengths and limitations. Process-based models are explicit and detailed in their representation the specific mechanisms linking climate change to the impact considered by the model, while empirical models focus on the statistical association between weather variables and the impact of interest, e.g. between temperature and crop yield changes. The empirical approach is more reliable within the sample of observations; yet, it assumes that the derived relationships are valid beyond the conditions of the historical observations, which is not necessarily the case. Process-models, on the other hand, include mechanisms and rules that provide a degree of relevance when applied to non-stationary systems. Yet, because of their relatively high degree of process representation they are more demanding in terms of the required calibration of the parameters underlying the model equations, which can be challenging.

Most of the PESETA impact models were process-based, translating climate change by casual mechanisms from climate variables to impacts. For instance, the river floods analysis was based on a spatially distributed hydrological model specifically developed for the simulation of hydrological processes in European river basins, followed by spatially detailed (100-m resolution) 2-D hydraulic modelling of inundation areas when flooding occurred. Process-based models rely not only on daily temperature and precipitation but also other climate variables, such as evapotranspiration, humidity and wind speed. The process-based models were applied at high-spatial resolution, ranging between 100 m to 25-50 km, thus allowing a detailed analysis of the geographical patterns of impacts, from the grid-level to the EU. Results from the sectoral climate impact models were further aggregated over five large EU regions.

The ACP sectoral impact models were mostly empirical, using statistical models that relate climate variables (mainly daily temperature exposure and seasonal precipitation) to the impact of interest for each sector. This approach allowed the use of many climate realizations to extensively sample climate risk (over 30,000 Monte Carlo draws were used across the statistical uncertainty of the impact models and across an ensemble of climate models), while relying on a solid empirical basis, as the climate impact projections are based ultimately upon statistically estimated functions. Another key feature of the ACP was its county-level spatial resolution, allowing a detailed analysis of the geographical patterns of impacts. The ACP architecture was also designed to allow for the continuous updating of its sectoral impact models under the DMAS system (Rising and Hsiang, 2014). For certain sectors where empirical approaches were not available or inappropriate, the ACP also used process models; specifically, changes in energy demand and expenditures were modeled using the National Energy Modeling System (Gabriel *et al* 2001), while sea-level inundation and coastal storm impacts used models developed by Risk Management Solutions, Inc. (Hsiang *et al* 2017).

Finally, the two projects implemented the same economic modelling setting, that of multi-sectoral general equilibrium. The climate impacts derived from the sectoral impact models are valued in economic terms (details for the specific sectors can be found in Table 3) and, then, applied to the CGE model as either changes in productivity levels (e.g., crop yield changes) or changes in values (e.g., capital losses due to river floods).

The main advantage of this setting is that it allows computing of indirect cross-sectoral and cross-regional effects. Direct damages in one sector and region affect the rest of the sectors in the same region and in other regions. Those indirect effects are captured through the trade linkages of the economic model. There was one key difference between the two projects, though: while the PESETA project represented the effects of future climate on the today's economy, the ACP applied a dynamic approach for impacts to capital (keeping the structure of the economy fixed), which accumulates over time and is exposed to climate shocks. The GDP and population dynamics affect the scale of the climate impacts, but as a share of GDP and population the impacts are driven mainly by climate change. The advantage of the static analysis is the absence of controversial assumptions regarding the evolution of population and economic activity over the next few generations; the disadvantage is that it does not capture long-term and endogenous cumulative impacts.

In both projects, the incorporation of economic sectors into the general equilibrium model was incomplete because of the difficulty of allocating an economic valuation to some sectoral impact categories. Thus, the ACP analysis integrated six of seven sectors (crime was not integrated), while the PESETA project integrated six of eleven sectors (droughts and habitat losses, for example, could not be considered).

Table 3. Comparison across common sectors

	JRC PESETA III	ACP
	Agriculture	

Direct Impacts	Yield change modelled as productivity shock [t/Ha]	Changes in crop-specific yields [% change]
Adaptation	Autonomous adaptation: not considered Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered	Autonomous adaptation: historically observed adaptations; consumption smoothed with storage; irrigation expansion studied for maize Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered
Model(s)	AgMIP crop models (average of the five ISIMIP fast track climate models and the seven AgMIP global gridded crop models)	Econometric (Schlenker and Roberts 2009, Hsiang *et al* 2013, McGrath and Lobell 2013)
CGE Implementation	Productivity change for crops	Productivity change for crops
	Energy Demand	
Direct Impacts	Effect of climate change on residential demand (heating and cooling) [toe]	Effect of climate change on energy demand [Btu]
Adaptation	Autonomous adaptation: temperature change induces demand change Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered	Autonomous adaptation: substitution across end-use technologies Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered
Model(s)	POLES (Kitous and Despres, 2018)	NEMS (EIA 2013)
CGE Implementation	Change in obliged consumption	Energy demand changes in residential and service sectors
	Temperature-related Mortality	
Direct Impacts	Heat-related Mortality [deaths]	Changes in death rate due to heat and cold [deaths / 100,000]
Adaptation	Autonomous adaptation: not considered Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered	Autonomous adaptation: as historically observed; effects of convergence in vulnerability analyzed Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered

Model(s)	Exposure-response functions (Forzieri *et al* 2017)	Econometric (Deschenes and Greenstone 2011, Barreca *et al* 2013)
CGE Implementation	Welfare loss (ex-post)	Change in labour supply
	Coastal Property	
Direct Impacts	Capital destruction [€]	Capital destruction ($)
Adaptation	Autonomous adaptation: not considered Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered	Autonomous adaptation: Costs account for insurance policy claims Price-driven adaptation: considered in the CGE economic model Public adaptation: not considered
Model(s)	Vousdoukas *et al* (2018)	Kopp *et al* (2014), North Atlantic Hurricane Model (RMS)
CGE Implementation	Additional obliged consumption, capital loss	Additional obliged consumption, capital loss

Four sectors (compared in Table 3) are shared by the two projects: agricultural, energy demand, health, and coastal property. While the models used differ across the projects for each sector, there are more commonalities than differences. In both projects, agricultural impacts are derived from changes in yields caused by altered climate variables relevant for crop production; the energy analysis focuses on changing heating and cooling demands days; health is represented by temperature-related mortality impacts; and coastal property losses are quantified through capital destruction. The process for applying these impacts to the CGE model is identical between the two projects, except for mortality. In the case of mortality, both projects estimated welfare loss with the Value of Statistical Life (VSL), which was not included in their CGE analyses, but the ACP additionally included in the CGE the economic damages of lost labour. Two of the four sectors, agriculture and health, are represented by statistical, econometric models in the ACP, and have an implicit level of autonomous adaptation that is observed in historical data. The agriculture model in PESETA is process-based and evaluated at a lower resolution. The other two sectors, energy and coastal property, use process-based models in both projects, but differ in ways that reflect the strengths of each team. The two projects consider energy demand changes due to climate change, considering the technologies for end-use services. The coastal property system in the ACP includes high resolution property data to estimate damages, whereas PESETA coastal flood damages are based on damage functions linked to land use classes. The PESETA coastal hazard model considers specific models for assessing the effects of storm surge, tides and waves, on top of sea level rise, whereas ACP includes a storm surge hazard model with the effects of waves and tides implicit in the damage function.

Three adaptation categories can be considered. Firstly, autonomous adaptation is defined as adaptation that private agents choose (under current implied preferences) when exposed to higher temperatures; e.g. for agriculture it would be changing the planting date to raise the crop yields. Secondly, price-driven adaptation is the re-allocation of activity in the economy when sectors are impacted (and modelled here by CGEs); e.g. in agriculture it would cover the readjustments in the agro-food industry due to the change in the crops' relative prices. Thirdly, planned adaptation reflects policy-driven (public) investments; e.g. in agriculture it would involve the subsidies to build irrigation systems.

The modelling of adaptation is relatively limited in the two projects. Within the general equilibrium (CGE) models, market-driven adaptation is considered as any direct impact would trigger a sequence of adjustments in all the markets via price changes (e.g. in production factor prices, trade flows), which can be considered as a form of private adaptation. Empirical analyses used in the ACP were chosen to capture "ecological validity", to reflect existing endogenous adaptation to weather events. To study longer-term adaptation, the ACP also undertook adaptation side cases, considering the effects of the spread of irrigation on crop yield and the spread of air conditioning on mortality. Public adaptation policies were not however taken into account in either project.

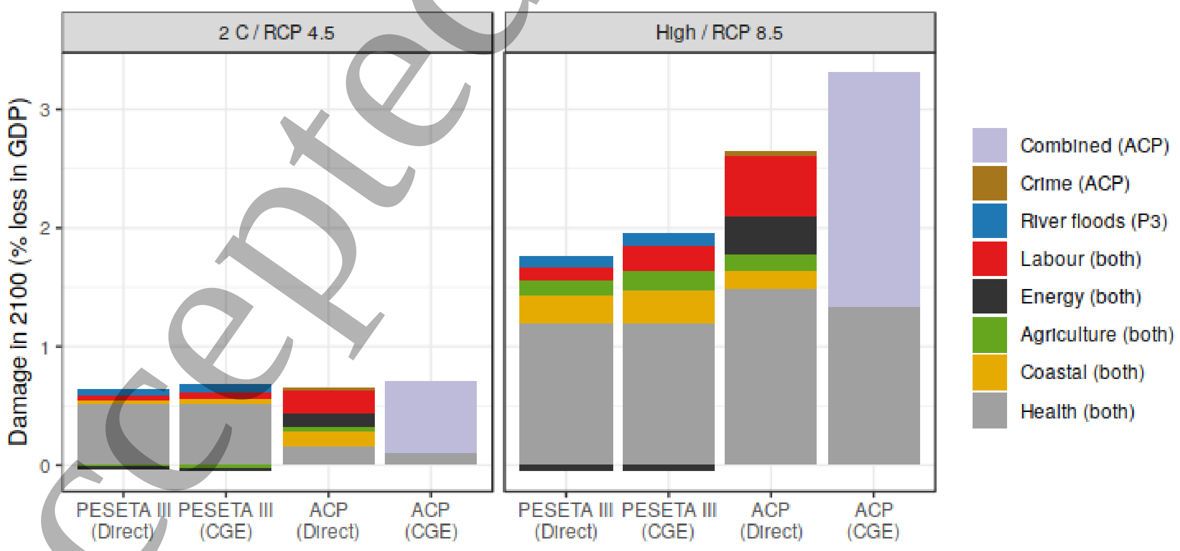
3. Results

Key questions regarding the understanding of climate change impacts are addressed by the projects. There are four broad categories of results, which provide insights on a number of issues.

Firstly, the order of magnitude of the total estimated climate damage is fairly similar on both sides of the Atlantic, according to the two projects. Even if there are some distinctive differences in the methodologies, the overall estimate of climate impact lies in a relatively close range. In particular, the last stage of the PESETA study (Ciscar *et al* 2018) concludes that the six economic impacts considered would lead to an overall welfare loss (as a % of GDP) of around 2% if high-level warming (3°C or more) by the end of the century were to affect today's economy. The ACP concludes that, at the end of the century (2080-2099) under RCP 8.5, the welfare loss from the six impact categories evaluated is likely 0.7% to 2.4% if mortality is valued through lost income and hurricanes are assumed not to change, and 1.4% to 5.7% if mortality is valued using a VSL and hurricanes intensify. The former is elevated to 2.3 to 4.3% through general equilibrium effects (Houser et al,. 2015). Figure 1 represents the sectoral direct welfare damages and general equilibrium welfare damages, all as % of GDP, for a low-moderate emission scenario (2°C and RCP4.5) and the high emissions scenario (RCP8.5) in the two projects.

Secondly, the human mortality impact category is dominant in the two assessments, representing more than half of the overall estimated climate impact in economic terms for the high emissions scenarios. This result heavily depends on the assumption regarding the value of a statistical life (VSL). In the EU, the VSL is assumed to be 1.14 million Euro/person (2007 Euro and based on 2003 incomes, Holland 2014; same value for all member states); in the US, it was estimated at $7.9 million/person (2008$ and based on 1990 incomes, US EPA 2010, p. 7-8). In the ACP, likely late-century mortality impacts under RCP 8.5 are valued at $13-$41 billion (0.1% of baseline GDP) if lives lost are valued in terms of lost wages and at $90-$506 billion (1.5% of baseline GDP) if valued using the VSL (Houser et al, 2015).

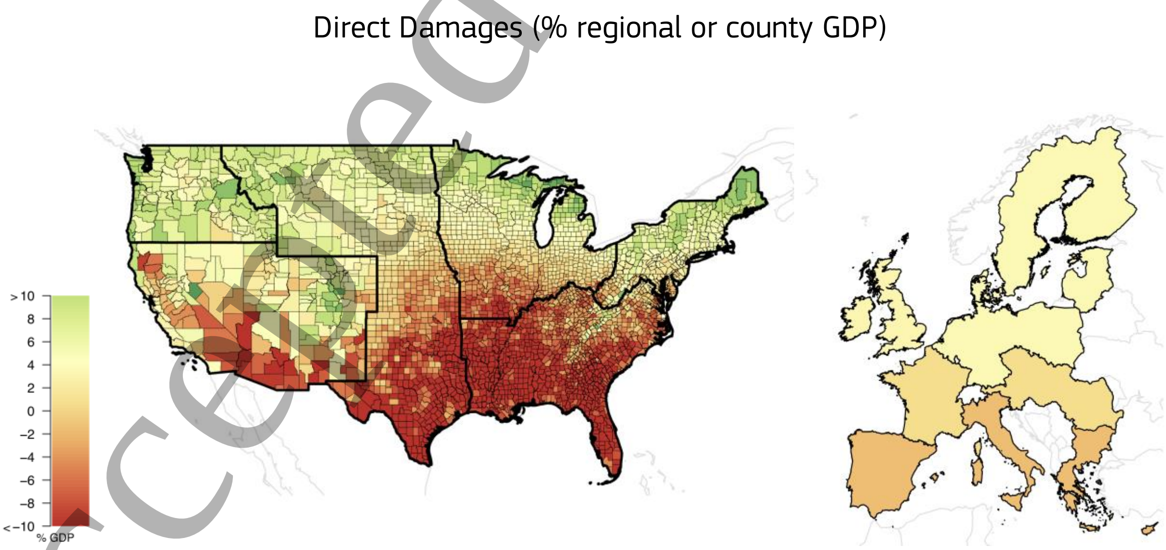
Figure 1. Distribution of damages by sector



Damages, as a percent of EU (for PESETA III) or US (for ACP) GDP, under a low/moderate emissions scenario (left) or a high scenario (right). The ACP values represent the median across damage uncertainty for each sector, evaluated in welfare terms. For the ACP, a sectoral breakdown of the CGE results is not available; these are shown combined. To provide a consistent comparison to PESETA III, the ACP CGE results are supplemented by an additional health impact that represents the difference between the ACP market value of the mortality impact (which is incorporated in the CGE) and the ACP mortality impact valued using the VSL.

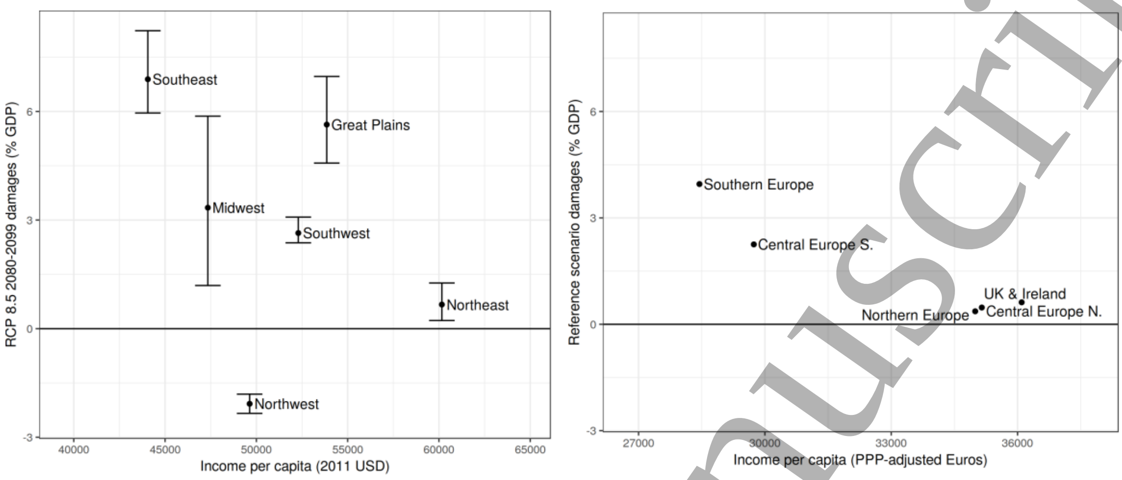
Thirdly, there are large geographic asymmetries at the continental scale in both the EU and US (Figure 2), and in both cases these asymmetries serve to amplify pre-existing economic inequality. In the EU there is a clear gradient of growing losses towards the southern regions (a north-south divide). Figure 3 left shows the negative association between damage and regional income in the US, the error bounds are the 17th - 83rd quantile and the dot is at the median, and Figure 3 right shows the results for the EU (median of the considered climate realizations).

Figure 2. Total welfare damages under the high-emissions scenario



The direct damages, prior to CGE modelling. At this level of analysis, the ACP results (Hsiang *et al* 2017) can be displayed at a county level, showing a strong north-south divide. The PESETA III direct damages are calculated at the same scale as the CGE, also show a gradient but with less sharp extremes.

Figure 3. Damage and regional income in the USA and EU under the high-emissions scenario



Regional equilibrium impacts, versus regional income. Equilibrium losses for the ACP include the additional non-market losses from mortality impacts, to be consistent with PESETA III results.

In the US there is a similar spatial pattern: in general, poorer regions in the South undergo the largest losses. Furthermore, from the ACP's county-level analysis of direct damages, it is possible to identify specific hot spots where damages are very large, with some southern counties registering median estimated losses exceeding 20% of gross county product. There are also counties at the other end of the spectrum, with some northern counties registering median gains of around 10% of gross county product.

Finally, moving from a reference scenario to a low temperature case results in large avoided climate damages. PESETA III concludes that more than half of the welfare losses would be avoided under the 2°C scenario. A similar conclusion is obtained by the ACP project, which also derives a damage function relating direct damages in the US to global mean temperature. Hsiang *et al* (2017) find that direct damages to the US are very likely (central 90% probability) to be between -0.2 and 1.6% of GDP at 2°C warming above the late nineteenth century, 1.0-4.5% of GDP at 4°C warming, and 5.5-13.9% of GDP at 8°C warming. The possibility for negative numbers at lower levels of warming occurs because in some regions modest of levels warming can be beneficial.

4. Lessons for further research

Climate impact analysis at high sectoral and space/time resolution is a common feature of both the PESETA and ACP projects. The PESETA project has put the emphasis on detailed process-based modelling with multi-sectoral impact coverage. By contrast, the ACP focused on leveraging an emerging understanding of the empirical relationships between climate and weather variability and economic impacts to explore climate risks and uncertainties. Both projects have contributed to the understanding of the extent of potential climate damages at considerably higher spatial and thematic resolution than employed in the integrated assessment models commonly used for climate change benefit-cost analysis (e.g. the DICE model, Nordhaus, 1994). Spatial and sectoral detail helps communication of climate damages, but engenders a corresponding level of scrutiny. This section discusses the main lessons learnt and suggests possible directions for further research in order to address some of the related key challenges.

In a nutshell, the main common lessons are the following:

1. The potential for climate change to exacerbate inequality is a central concern.

2. Current treatments of adaptation are limited and need considerably more research.

3. Even state-of-the-art comprehensive impact assessments are quite incomplete and omit some potentially major impact categories.

4. Climate impact analyses require tight interdisciplinary integration between climate scientists, impact modelers and economists.

5. An integrated strategy for stakeholder engagement and communications can enhance the impact of climate change impact analyses.

These lessons are further developed and analysed in what follows.

1. The potential for climate change to exacerbate inequality is a central concern.

The first common lesson from the two projects is that there is a high degree of inequality in the geographical distribution of climate impacts. In both the EU and US, climate consequences are largely heterogeneous across space and, furthermore, have a clear north/south spatial gradient. Since both the EU and US also have a north/south spatial gradient of wealth, this pairing of spatial gradients leads climate impacts to fall disproportionately on lower income populations. This is the case even though both PESETA III and ACP had fairly limited treatments of climate adaptation, for which the potential is expected to be greater in wealthier regions. However, when interpreting the geography of results one should note that the spatial pattern in the results only reflect the specific sectoral impacts considered, which are only a subset of potential impact categories.

When the ACP was originally conceived, a great deal of the team's attention was focused on the characterization of tail risks. This focus led, for example, to the development of the SMME method for probabilistic projections of local, daily climate realizations. Yet the final analysis indicated that varying the level of inequality aversion has a greater effect on calculated social welfare metrics than varying the level of risk aversion. For example, Hsiang *et al* (2017) found expected damages of 3.6% of GDP at 4°C of warming above the 1980-2010 baseline. With moderate levels of inequality aversion and risk aversion, the welfare impact increased by about 1.4x, while at high levels of inequality aversion and moderate levels of risk aversion, it increased by about 3.3x. Conversely, with high levels of risk aversion and moderate levels of inequality aversion, it increased by about 1.5x. Despite the deliberate focus on characterizing tail outcomes, the unequal distribution of impacts turned out to be a more important story from a social welfare perspective.

2. Current treatments of adaptation are limited and need considerably more research.

A second common lesson is that much more work is needed to incorporate climate adaptation into impact analyses. The extent to which climate impacts can be alleviated via specific adaptation policies and measures is currently poorly understood. Much better modelling of adaptation, at the appropriate spatial (local/regional) and temporal (next few decades) scales is required, including the quantification of the costs and benefits of endogenous adaptation and of adaptation policies and measures. The new research being pursued by the project teams studied here reflects these priorities. The JRC PESETA IV project plans to further assess adaptation in several areas, such as coastal areas, river floods and agriculture. The Climate Impact Lab, which is extending the work of the ACP to develop global empirical estimates, has placed adaptation at its centre. For instance, it has recently conducted an assessment of how the costs and benefits of adaptation could affect global temperature-related mortality from climate change (Carleton *et al* 2018). The Climate Impact Lab's empirical approach leverages cross-sectional variations in the observed relationships between weather exposure and impacts to estimate how changes in income and the experienced climate affect populations' sensitivity, as well as to estimate the costs of adapting to changed climates.

3. Even state-of-the-art comprehensive impact assessments are quite incomplete and omit some potentially major impact categories.

A third common lesson from both studies is that the current state-of-the-art in climate impact assessment is highly incomplete. Presenting aggregated climate impacts when there are likely large unknowns has the potential to undervalue the impacts of global warming. In particular, it is important in projects such as PESETA and the ACP to present clearly individual sectoral estimates and unequivocally communicate the incompleteness of aggregated estimates. Focusing too heavily on aggregated economic damage estimates can create the false impression of comprehensiveness in the assessment. The ACP addressed this issue with a 35-page qualitative discussion of unquantified impacts (Houser *et al* 2015).

Non-market climate impact categories that are not represented include losses of ecosystem services because of the inability of nature to adapt to the speed of climate change, as well as human health impacts (e.g. vector and water-borne diseases) that are not directly related to temperature exposure. Both studies used VSL valuations of death rates, which do not account for a range of economic losses associated with mortality and morbidity, such as the cost of health services. Furthermore, neither study considered the possible consequences of passing critical thresholds in the climate system (e.g. slowdown of the Atlantic Meridional Overturning Circulation) or of non-linear tipping points in human and natural systems arising from the cumulative effects of gradual climate changes. There is a limited understanding of many critical thresholds in the climate system (e.g. Lenton, 2008 and 2013), extremely limited understanding of their economic consequences (Kopp *et al* 2016), and poor understanding of the economic consequences of human-system tipping points (Kopp *et al* 2016).

Another impact that is not covered relates to the possible transboundary effects due to climate impacts in the rest of the world. The JRC PESETA III has addressed trade-related effects, finding that climate impacts in the rest of the world can add around 7% of damage to the EU, but there are other transmission mechanisms, such as migration or conflict, that should be considered in comprehensive regional climate assessments. A limiting factor is the need to rely on global sectoral impact studies that are consistent in all the dimensions, like common climate realizations, non-overlapping sectoral impacts, and coherent economic valuation issues.

Uncertainty remains a major issue in interdisciplinary climate assessment, and one around which the design of the ACP in particular focused. The ACP gave careful attention to representing climate uncertainty and, where possible, parametric uncertainty in its impact models. The latter was possible, however, only in sectors using empirical impact models, where the parametric uncertainty could be estimated from the data. Neither project was able to treat uncertainty in impacts relating to process models; in these sectors, assessments were typically based on a single model. Recent model inter-comparison projects such as Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) have shown that estimated impacts can vary substantially between models (e.g. Warszawski *et al* 2014) and can show considerable bias, especially the impact of climate extremes (Schewe *et al* 2018). There is further large uncertainty in the economic valuation of impacts for specific impact categories (e.g., Jongman *et al* 2012) as well as of their combined effects assessed with integrated economic models. The incorporation of multiple models for each sector in the analysis as well as for the economic integration, provided they exist, would allow for a better quantification of structural biophysical and economic uncertainty related to impact modelling.

A global climate impact assessment, which ideally should be based on global estimates at the sectoral level, even if this is more challenging and complex from a methodological perspective, is required for the reliable assessment of the social cost of carbon dioxide (SCC), a key figure affecting many regulatory initiatives in North America (National Academies, 2017). Ricke *et al* (2018) have updated the SCC based on the top-down empirical analysis of global climate damages by Burke *et al* (2015), finding a median SCC of US$417/t$CO_2$, and standard estimates of the SCC are likely also too low in view of the recent estimates of some sectoral damages. For instance, Moore *et al* (2017a) find that the component of the social cost of carbon due to agriculture impacts of the FUND model changes from producing net benefits of $2.7/t$CO_2$ to net costs of $8.5 (and as a result the FUND SCC estimate more than doubles), when they replace the FUND agricultural damage function with one based on a meta-analysis of the AR5 IPCC studies (Moore *et al* 2017b).

4. Climate impact analyses require tight interdisciplinary integration between climate scientists, impact modelers and economists.

A fourth common lesson is that climate impact analysis requires tightly coupled interdisciplinary collaboration. The two projects found very productive interactions between researchers in different disciplines to be a demanding and slow process, at times requiring the re-evaluation of core disciplinary assumptions. Much of the research effort in the climate science community is focused on GCMs with detailed physical representations of atmospheric and ocean processes, but these GCMs on the one hand lack the spatial resolution desired for many biophysical and economic analyses, while at the same time are too computationally costly to employ directly for uncertainty quantification. Much of the physical science work in the ACP was focused on leveraging GCM projections in a manner that worked around these limitations. In PESETA III, higher resolution regional climate model (RCM) projections were used, yet the nested RCMs cannot correct for errors in large-scale dynamical structures transmitted from GCMs and have inherent climate biases that can be quite large when underpinning processes are poorly constrained by observations (Vautard, 2018). Similarly, a major interest of the economic and policy analysis community are the climate consequences of specific temperature thresholds (e.g., 2°C), but the standard Representative Concentration Pathways are intended to model the (uncertain) climatic response to specified greenhouse forcing, not specific temperature outcomes

Impact modellers further require consistent assumptions from both climate scientists and economists. For example, integrated assessment modellers rely on damage functions, but these functions need to be applied to future climate projections that are processed in a manner consistent with the climate data used in their construction. The demand for modellers to represent feedback between the economy, the climate, and social tipping points is growing, but the interdisciplinary research basis for performing this work is lacking (Kopp et al, 2016).

Ensuring that the fidelity of the science is maintained requires communication and repeated interactions. It is a challenging but rewarding process, and one that also has implications for graduate and postdoctoral training. One significant factor contributing to the relatively rapid pace of the ACP – roughly two years from initial conception (first publicly described in Kopp *et al* 2013) to initial publication as a working report (Houser *et al* 2014) – was that the lead economist had an undergraduate degree in Earth sciences and that the lead climate scientist had extensive experience working with economists and policy analysts. This experience suggests that cross-training at a graduate or postdoctoral level between natural scientists and economists could greatly facilitate the assessment process. Similarly, the PESETA team has a diversity of academic backgrounds, from physics to engineering and economics.

Despite the progressively greater availability of high-quality models, large-scale projects like the ones presented here remain a significant challenge. Applying any individual model requires specialized expertise, system and data setup, calibration, and validation. Intersectoral linkages are costly to implement because of the diversity of frameworks, scales, assumptions, and interfaces involved. Yet, there is a clear added value because feedbacks between different sectors can be included in the analysis, which can be relevant for some sectors, such as agriculture and water (irrigation, availability of water) or health and energy (air conditioning is a crucial adaptation to reduce mortality). Important progress is being made in the integrated assessment modelling (IAM) community (e.g. IAM Consortium, Stehfest *et al* 2014).

5. An integrated strategy for stakeholder engagement and communications can enhance the impact of climate change impact analyses.

A fifth common lesson is that the impactful analyses require an integrated strategy for communications and stakeholder engagement. The ACP was commissioned by a philanthropic partnership, the Risky Business Project. This project was run by a 10-member risk committee of government, business, and academic luminaries (including five former U.S. Cabinet members), who helped communicate the outcomes of the ACP's analyses through the media and through directed outreach. The Risky Business Project also produced an accessible summary of the analysis results, including data and graphics for use by the media (Risky Business Project, 2014). As a consequence, it received extensive media coverage, and some of the Risk Committee members who had not previously been engaged in climate policy became vocal on the topic. Among other uses, the results of the analysis were employed in a Congressional Budget Office assessment of future hurricane damages (Dinan, 2016) and in White House budget analyses for Fiscal Years 2016 and 2017.

The JRC PESETA III project was requested by the Directorate General of Climate Action of the European Commission in order to support the evaluation of the European adaptation strategy (European Commission, 2018). All along the project, the Commission services were involved in the review of the various project outcomes, in particular, the policy cards. The cards are intended to summarise the main findings and policy conclusions of each sectoral study for policymakers, without using technical terms so that the main messages can be understood by non-experts.

The user perspective is becoming essential for climate impact researchers. In the case of the two projects reviewed here, the intended audiences influenced key decisions of the structure of the analysis. Because the ACP was designed with investors in mind, it prioritized the modelling of risk and uncertainty. The PESETA project focus has been supporting climate policy and other related European policies. Communication has several dimensions and can be very challenging given the many uncertainties in climate impact modelling. Some policymakers and private entities continue to rely on central quantitative results, like the median total impact. Yet the median impact hides the wide distribution of possible futures and the changing variance over time. For instance, worst case analysis showing how bad impacts can get could be valuable information but is rarely showcased. More relevant resources can be allocated to communication and visualisation of results, allowing a better use and diffusion of the impact studies. But it remains essential to take the perspective of the stakeholders, the ultimate user and beneficiary of the climate impact assessment.

Both the ACP and PESETA projects were aimed at bridging the gap between science and policy. Throughout the ACP, decisions on the structure of the analysis were intended to make the results salient to a decision-making community focused on risks and returns, with a particular emphasis on the local perspective (results at the county level). The PESETA project was developed through close communication with the European Commission, to address their concerns and construct policy-relevant scenarios, in particular of relevance for the two main branches of climate policy (mitigation and adaptation) and for other areas such as regional and development policies. Integrated impact analysis plays a special role at the boundary between the sector- and discipline-specific research upon which it is grounded and the needs of a wider community. Integrated projects like the ACP and PESETA projects are driven to evolve in response to both new scientific understandings and new discussions and questions amongst policy-makers. As a result, more work will continue to be needed, and research on how to bridge the gap between science and policy is required even while projects like these continue to endeavour to bridge it.

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