

Alleviating inequality in climate policy costs: an integrated perspective on mitigation, damage and adaptation

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LETTER

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Equity considerations play an important role in international climate negotiations. While policy analysis has often focused on equity as it relates to mitigation costs, there are large regional differences in adaptation costs and the level of residual damage. This paper illustrates the relevance of including adaptation and residual damage in equity considerations by determining how the allocation of emission allowances would change to counteract regional differences in total climate costs, defined as the costs of mitigation, adaptation, and residual damage. We compare emission levels resulting from a global carbon tax with two allocations of emission allowances under a global cap-and-trade system: one equating mitigation costs and one equating total climate costs as share of GDP. To account for uncertainties in both mitigation and adaptation, we use a model-comparison approach employing two alternative modeling frameworks with different damage, adaptation cost, and mitigation cost estimates, and look at two different climate goals. Despite the identified model uncertainties, we derive unambiguous results on the change in emission allowance allocation that could lessen the unequal distribution of adaptation costs and residual damages through the financial transfers associated with emission trading.

1. Introduction

The recent Paris Agreement forms an important step forward in international climate policy. In evaluating climate policy in general and the Paris Agreement in particular, most analyses focus on mitigation, such as the national determined climate pledges and the long-term temperature target. The Paris Agreement, however, also includes an adaptation goal. The two goals are connected by the focus on limiting global average temperature change well below 2 °C. Climate policy is complex not only because of difficulties of reaching stringent mitigation targets but also because of the

difficulty of reconciling regional efforts with the inequality of climate change impacts. This is even more important since the current pledges are not in line with the 2 °C target, implying a serious risk of higher global warming and thus of higher climate impacts. It is therefore interesting to consider the fairness of international climate policy by looking not only at mitigation costs as usually done, but also at the costs of adaptation and residual damages. Given the unequal distribution of the costs of mitigation policies, climate impacts, as well as of adaptation costs, when defining equitable policies it is imperative to discuss them mutually, recognizing the influence of

uncertainty. A global cap-and-trade regime could compensate countries with high adaptation costs and damages by allocating emission allowances in such a way that trading of emission allowances would lead to financial transfers that counteract the unequal distribution of adaptation costs and residual damage (Hof *et al* 2010, De Cian and Tavoni 2012, Tavoni *et al* 2013, 2015). While such a scheme is somewhat theoretical, it provides a useful analytical framework for evaluating real-world climate policies.

There are only few existing studies that have analyzed emission allowance allocation schemes in which mitigation costs, adaptation costs, and residual damages are all considered. These studies all relied on a single model (Hof *et al* 2010, Pattanayak and Kavi Kumar 2014). Yet, the elements involved when examining the balance of different regional costs, i.e. mitigation costs, adaptation costs, and damage estimates, are all very uncertain and thus model-dependent. It is important for policy-makers and analysts to consider these uncertainties when designing policy strategies that hold under a range of models' specifications and mitigation goals. Multi-model Intercomparison Projects (MIPs) are used to take into account key model uncertainties (Clarke *et al* 2009, Luderer *et al* 2012, Blanford *et al* 2014, Krieglner *et al* 2015, Tavoni *et al* 2015), but so-far MIP assessments of equitable climate policies have focused only on the distribution of mitigation costs (den Elzen and Höhne 2008, den Elzen and Höhne 2010, Ekholm *et al* 2010, Luderer *et al* 2012, Tavoni *et al* 2015). It seems that the paucity of regional damage and adaptation cost estimates, and of Integrated Assessment Models (IAMs) taking into account these estimates, has prevented MIP exercises to explore how uncertainties in climate impact and adaptation cost estimates could affect policy conclusions regarding effort-sharing schemes.

This paper aims at filling this gap. We illustrate the relevance of including adaptation and residual damage in equity considerations by determining how emission allowances in a global cap-and-trade regime would be allocated to counteract the regional differences in adaptation costs and residual damage as compared to an allocation of allowances which only counteracts differences in mitigation costs. In order to identify key factors determining the outcome of such a broader equity view, we employ two different IAMs (a simulation and an optimization model), two sets of damage and adaptation cost curves, as well as two different long-term climate goals.

First, we evaluate the residual damages and adaptation costs for two long-term global average temperature change levels (2 °C and 3 °C by the end of the century). We then map the distribution of mitigation effort on the one hand and damages and adaptation costs on the other hand to give an overview of how these aspects will qualitatively affect the change in allocation of allowances. We then use our modeling frameworks to quantify the change in emission allowance allocation if total

climate costs (costs of mitigation, adaptation, and residual damage) were to be equalized, assuming allowances can be traded freely in a global cap-and-trade scheme.

2. Methods

For our analysis we use FAIR (Hof *et al* 2010, den Elzen *et al* 2014) and WITCH (Bosetti *et al* 2006, De Cian *et al* 2012), two widely used global IAMs. Both models describe the interactions between energy, land use, climate change, and the economy. They both use aggregate adaptation cost curves and simple damage functions that relate global mean temperature increase above pre-industrial levels to change in regional economic production (GDP).

Despite the lively debate about climate change damage functions and how they relate to integrated assessment (Dell *et al* 2012, Dell *et al* 2014, Burke *et al* 2015), only a few studies have gathered regional, sectorial data on climate impacts and adaptation costs at global scale, and used them to integrate the costs and benefits of adaptation in IAMs (de Bruin *et al* 2009, Agrawala *et al* 2010, 2011). In order to explore how considerations on equitable emission allowance allocations depend on damage and adaptation cost estimates, here we update the set of damage and adaptation cost functions used in the WITCH model, and compare it to the FAIR model, which utilizes the damage and adaptation estimates provided by de Bruin *et al* (2009). The damage curves of de Bruin *et al* (2009) are based on Nordhaus and Boyer (2000). Estimates of adaptation costs have been used to separate adaptation costs and residual damages, as described in detail in the supplementary information (SI), available at stacks.iop.org/ERL/11/074015⁷.

The damage functions implemented in the WITCH model are based on sectorial climate impact estimates developed in the ClimateCost project⁸ (Watkiss 2011, Bosello and De Cian 2014) and integrated with Nordhaus (2007) estimates for the impact categories health and catastrophic events. For the category settlements and ecosystems, new estimates are computed using a Willingness-To-Pay approach. Details are provided in the SI. The updated impact estimates for the categories coastal, health, catastrophic, settlements and ecosystems are for most regions larger than those reported in Agrawala *et al* (2010, 2011; table S5). Adaptation cost estimates have been developed by adjusting Agrawala *et al* (2010, 2011) data to the impact categories considered in this study.

Both FAIR and WITCH calculate the optimal level of adaptation, i.e. the level at which the marginal costs of adaptation equalizes the marginal benefits of reducing damage. WITCH and FAIR make different

⁷ The supplementary information provides more details about the two models used in the analysis and the scenarios considered.

⁸ <http://www.climatecost.cc/>

Table 1. Summary of baseline and policy scenarios.

Scenarios	Climate target	
Baseline scenarios		
Without adaptation	Business As Usual (BAU)	
With adaptation	Business As Usual (BAU w Adap)	
Policy scenarios	3 °C (4.5 W m⁻²)	2 °C (2.8 W m⁻²)
<i>Global tax regime</i>		
Without adaptation (a)	3 °C-Tax	2 °C-Tax
With adaptation (b)	3 °C-Tax w/Adap	2 °C-Tax w/Adap
<i>Effort sharing regime</i>		
Allocation equalizing mitigation costs without adaptation (c)	3 °C-EqMitCosts	2 °C-EqMitCosts
Allocation equalizing total costs with adaptation (d)	3 °C-EqFullCosts w/Adap	2 °C-EqFullCosts w/Adap

assumptions with respect to adaptation costs and effectiveness. FAIR (see de Bruin *et al* 2009, Hof *et al* 2010) groups together the cost estimates of various forms of adaptation into one aggregate adaptation variable, assuming that costs and benefits fall into the same time period (see section S11, equations (1)–(2)). WITCH (Agrawala *et al* 2011, Bosello *et al* 2013) distinguishes between three types of adaptation strategies, proactive, reactive, and adaptive capacity, which are combined together to reduce climate impacts (see section S11, equations (3)–(9)). Increasing adaptive capacity, for example by fostering education, does not reduce the damage directly, but facilitates adaptation activities and improves their effectiveness. Reactive adaptation describes actions that are implemented when or right after climatic impacts effectively occur, such as adjusting energy demand for cooling. Anticipatory adaptation, such as building dikes, describes the effect of a stock of defensive capital being operational before the damage materializes, and remaining effective against damages over time.

WITCH and FAIR represent mitigation options with a different level of detail, and differences with respect to the economic, technological and sectorial representation are discussed in Kriegler *et al* (2013). FAIR calculates the allocation of abatement across regions by means of dynamic and path-dependent marginal abatement cost curves, which differ across regions and are based on the global energy model IMAGE/TIMER (van Vuuren *et al* 2014) to which IMAGE is connected. WITCH is an inter-temporal general equilibrium model that embeds the energy sector in a growth model. As a consequence, the two models differ considerably in the estimates of mitigation potential and costs.

The climate policy scenarios considered in this paper explore two emission reduction pathways posing different challenges for adaptation (tables 1 and S12). The more stringent policy case leads to a radiative forcing of 2.8 W m⁻² in 2100, which yields a likely chance of reaching the 2 °C target as projected by the MAGICC climate model (similar to the LIMITS scenarios described by Tavoni *et al* 2013, 2015). In the less ambitious policy, radiative forcing reaches 4.5 W m⁻² in 2100,

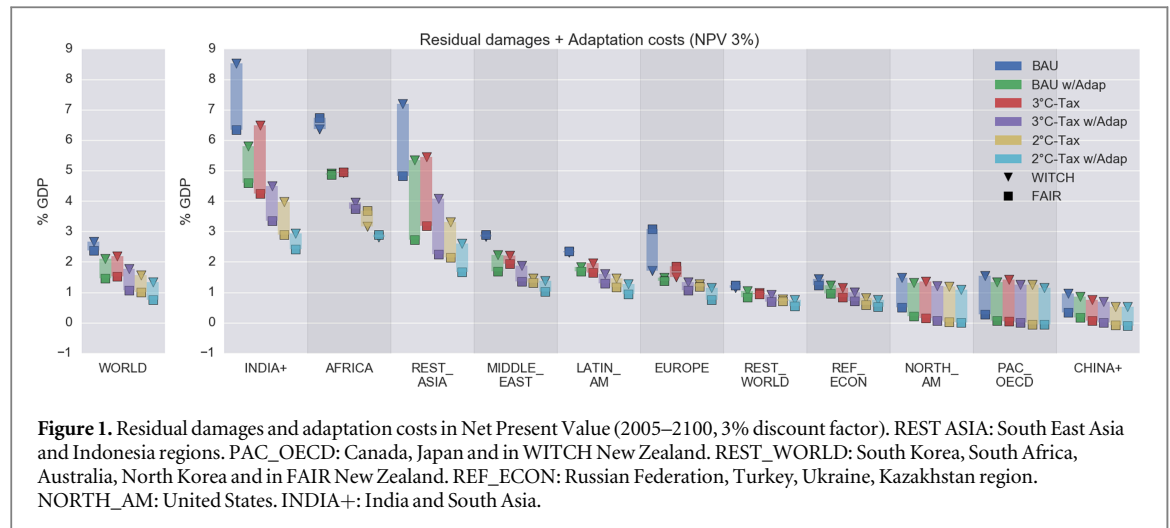
yielding a likely chance of reaching the 3 °C target. We refer to these scenarios as 2 °C and 3 °C, respectively. Prior to 2020, we assume that regions implement present and planned climate-related policies and regulations, which include a collection of national emission targets, greenhouse gas emission (GHG) intensity reduction targets, nuclear power and renewable energy targets (Kriegler *et al* 2013). Globally coordinated mitigation starts immediately after 2020, when a global carbon market is also assumed to be fully operational. Two baseline scenarios without mitigation policies analyze the extent of climate damages and adaptation costs in the absence of climate policy targets, and are used as reference to compute mitigation costs.

In the first two mitigation scenarios (a and b), the long-term temperature target is reached in a global cost-optimal way by means of a global tax (global tax regime in table 1). In each region mitigation is financed domestically and there is no international compensation scheme or carbon emission trading. These scenarios are compared to a set of effort sharing schemes (scenarios c and d), in which emission allowances are distributed in such a way that emission trading under a global cap-and-trade system equalizes mitigation costs (scenario c) or total climate change costs (scenario d) as share of GDP across regions and over time. Both scenarios (c) and (d) are based on the horizontal equity rule (Rose *et al* 1998). Scenario (c) equalizes regional mitigation costs ($TMC_{i,t}$) as a share of GDP ($Y_{i,t}$):

$$a_{i,t} \left| \frac{TMC_{i,t}}{Y_{i,t}} = \frac{TMC_{j,t}}{Y_{j,t}} \quad \forall i \neq j \in N, \forall t \in \{2020, \dots, 2100\} \right.$$

Scenario (d) equalizes the sum of mitigation costs, residual damages ($RD_{i,t}$), and associated adaptation costs ($PC_{i,t}$):

$$a_{i,t} \left| \frac{TMC_{i,t} + PC_{i,t} + RD_{i,t}}{Y_{i,t}} = \frac{TMC_{j,t} + PC_{j,t} + RD_{j,t}}{Y_{j,t}} \quad \forall i \neq j \in N, \right. \\ \left. \times \forall t \in \{2020, \dots, 2100\} \right.$$



where a_i is the emission allocation to country i at time t , and N is the number of regions in the model (on regional aggregates see table S11).

3. Results

We begin by exploring the distributional consequences in baseline and policy scenarios under global tax regimes, and subsequently explore ways to compensate regions and achieve higher equity.

3.1. Projecting the distribution of residual damage and adaptation costs

According to both FAIR and WITCH results, limiting global warming to 2 °C approximately halves the global economic damages associated with climate change throughout this century compared to baseline, both with and without adaptation (figure 1). Yet, it should also be noted that the estimated global impacts remain above 1% of the projected Global World Product (GWP) in most cases. Without adaptation, the projected global economic damage varies from 2.4%–2.7% in the baseline, to 1.5%–2.2% in the 3 °C scenario, and 1%–1.6% in the 2 °C scenario. Adaptation reduces global residual damage significantly and especially at higher temperatures. Adding adaptation costs provides the following total projected costs of damage and adaptation: 1.5%–2.1% in the baseline, between 1.1%–1.8% for 3 °C, and 0.8%–1.4% for 2 °C.

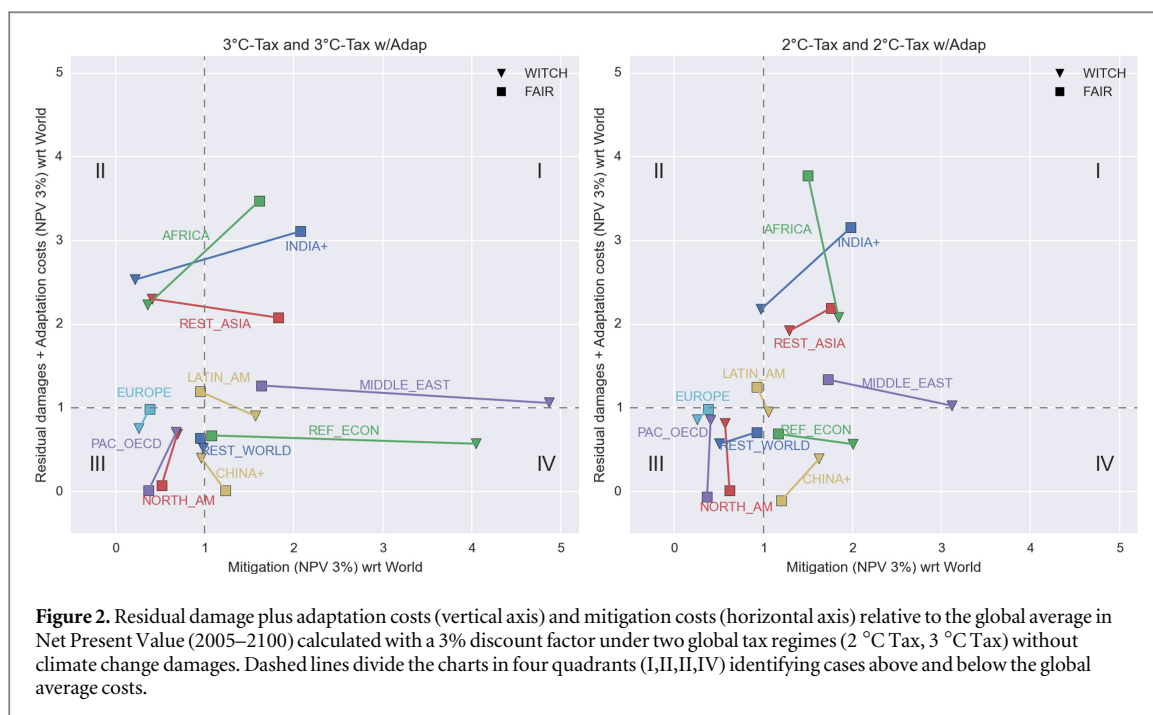
Figure 1 shows the global as well as the regional costs for the BAU, 3 °C, and 2 °C scenarios. The chart highlights strong regional disparities, which remain even in the low mitigation scenarios. This is particularly the case in India, Africa, and Rest of Asia (South East Asia and Indonesia region, table S11), where the climate change impacts associated with a 2 °C warmer climate can be as high as 3%–4% without adaptation, and 2%–3% if adaptation is implemented. Based on the two sets of models and their cost estimates, China

appears to suffer the least (in net) from climate change, as agriculture in China is assumed to benefit from climate change. Furthermore, de Bruin *et al* (2009) damage functions assume that climate change could lead to benefits in leisure activities (see SI). In the South East Asia and Indonesia regions adaptation reduces damages significantly according to the FAIR model, which assumes adaptation measures dealing with health, coastal, and agricultural impacts are more effective than WITCH (tables S6, S7). In Europe, adaptation measures to cope with climate change impacts on coastal areas, settlements, and infrastructure are assumed to lower residual damages considerably, especially in the FAIR model. FAIR and WITCH rely on different impact models for the assessment of coastal impacts and adaptation, and assume different protection levels in the areas of settlements and ecosystems adaptation, with FAIR being more optimistic than WITCH (see tables S3, S6, S7). Figure 1 provides clear evidence that the distribution of damages and adaptation costs will remain profoundly unequal irrespective of the stringency of the mitigation effort and the possibility of adapting to climate change.

3.2. Mapping the distribution of effort

The unequal distribution of residual damages and adaptation costs outlined in figure 1 has repercussions for the analysis of equitable climate policies, as the distribution of damages and adaptation costs does not necessarily match that of mitigation costs. Figure 2 provides a regional mapping of mitigation costs on the horizontal axis and of adaptation costs plus residual impacts on the vertical axis when the climate target is achieved via the global tax regime without inter-regional transfers. The four quadrants (I,II,III,IV) identified by the horizontal and vertical dashed lines show cases in which regions pay more or less than the global average for either mitigating climate change and/or adaptation/residual impacts.

Despite model differences, some clear results emerge. The industrialized countries (OECD



countries, Europe, North America, Pacific OECD, and Rest of the World) are clustered in quadrant III. Both their mitigation costs as well as climate change impacts are lower than the world average. Some of the world’s poorest regions (Africa, Rest of Asia, India) are clustered in quadrant I, with both relatively high climate change impacts as well as mitigation costs under the 2 °C target. Regions in or close to quadrant IV (the energy exporting regions Middle East and Transition Economies) are projected to have relatively high mitigation costs, with a large range across the two models, and impacts close to the world average. Latin America is close to the global average both with respect to mitigation costs and impacts. China appears to have somewhat higher than average mitigation costs under both mitigation scenarios, but lower than average impacts.

Figure 2 corroborates the regional disparity of mitigation costs highlighted in Stern *et al* (2012) and Tavoni *et al* (2013, 2015). The additional key insight is that including residual damages and adaptation costs further exacerbates the distributional consequences of a policy based on a global tax regime. For most regions, the collocation of regions with respect to either dimensions holds for both 2 °C and 3 °C across models, although the grouping into four clusters is somewhat clearer under the more stringent policy.

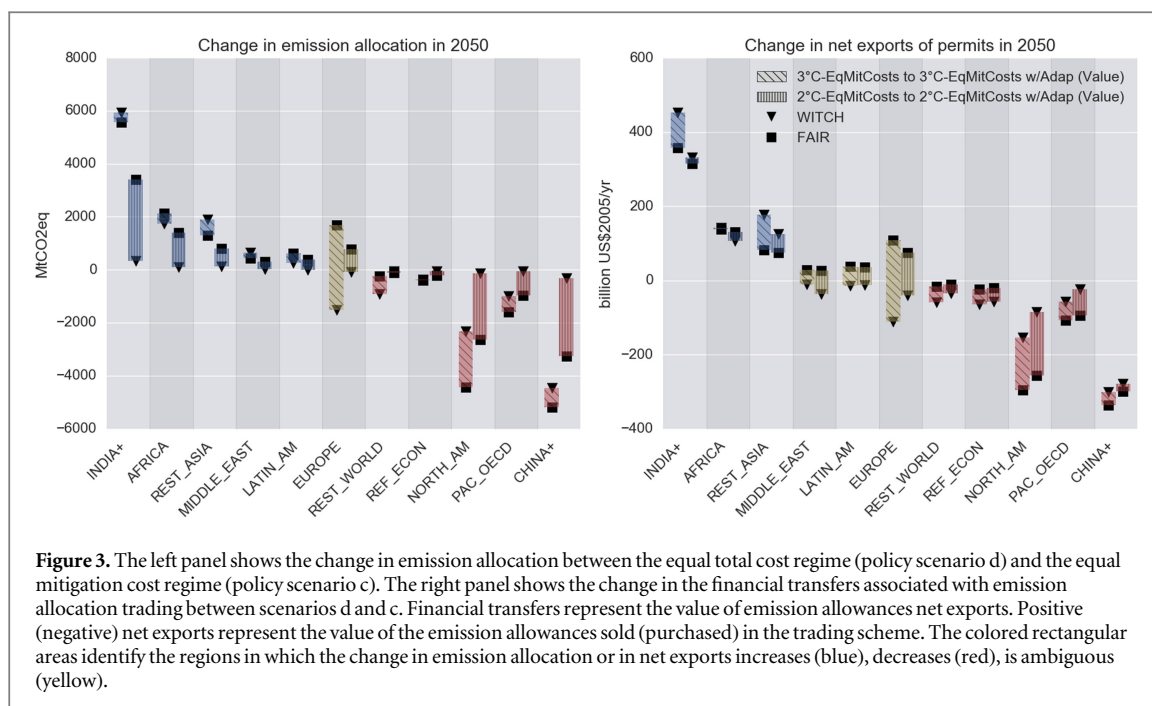
3.3. Emission allowance allocation and financial transfers to equalize effort

Given the climate change cost disparities presented in figure 2, we analyze the emission allowance allocation scheme that could equalize the total climate costs per unit of GDP across regions. First, we determine the level of greenhouse gas emissions resulting from a global tax regime without adaptation (policy scenario

a in table 1). These levels are compared with the emission allowances resulting from two different emission allocation schemes: one in which mitigation costs as share of GDP are equalized (policy scenario c in table 1, figure S1 top panel), and one in which total climate change costs as share of GDP are equalized (policy scenario d in table 1, figure S1 middle panel). Both allocation schemes assume a well-functioning global cap-and-trade system.

Figure 3, left panel, shows the difference between the two emission allocation schemes, illustrating the net effect of including adaptation and impact costs in the burden accounting. The right panel illustrates the impacts on the financial transfers associated with emission allocation trading in a well-functioning global carbon market. Positive net exports represent the value of the emission allowance sold (exported) in the trading scheme, whereas negative net exports represent the value of the emission allowance purchased (imported). Red and blue rectangular areas can be directly mapped into the regions located in quadrant III + IV and II + I in figure 2, respectively. Regions marked in yellow show ambiguous results across models. These are the regions that generally collocate across quadrants in figure 2 (Europe, Latin America, Middle East) because the two models make different assumptions on climate impacts and adaptation costs.

The magnitude of changes in emission allocation is generally larger for FAIR because FAIR projects lower mitigation costs than WITCH (see section S4 and tables S16). FAIR estimates the direct cost of mitigation as the area under Marginal Abatement Cost curves (MACs) of the abatement options used. WITCH measures the indirect costs of climate policy as change in GDP or consumption after investments



have been allocated in a cost-effective way to low-carbon options. MIPs have shown that differences in model structures and assumptions significantly affect models' cost estimates of climate policy targets (van Vuuren *et al* 2009, Paltsev and Capros 2013, Blanford *et al* 2014)⁹. MAC-based cost indicators give lower estimates of policy costs than macroeconomic indicators because consumption and GDP include the macroeconomic feedback of changes in the energy system (Paltsev and Capros 2013, Tavoni *et al* 2013). FAIR and WITCH are almost on opposite ends of the spectrum, with FAIR estimating lower costs, though the variation in both absolute costs and regional differences is within the range of uncertainty as identified by the IPCC 5th assessment report (Clarke *et al* 2014). As a consequence, the share of residual damages and adaptation costs in the total costs of climate change is larger in FAIR than in WITCH, leading to a stronger net effect of adding residual damages and adaptation costs to the burden accounting. Differences in mitigation costs are smaller in the 3 °C policy scenario, and this is reflected in the reduced range displayed in figure 3. Large differences in quantities are compensated by higher carbon price estimates in the WITCH model, leading to similar changes in financial values.

Results on how the emission allowance allocation would need to change depend on the level of

⁹ Other factors explaining differences in regional cost estimates include baseline assumptions about socio-economic dynamics and baseline emissions, which determine the regional relative abatement effort, regional characteristics such as fuel mix, fossil energy trade exposure, energy intensity, and the availability and extent of low carbon energy resources, and technology costs, all of which differ between the models (Tavoni *et al* 2013). Of particular importance when considering low stabilization targets are assumptions related to negative emission technologies, land use and non-CO₂ emissions (Blanford *et al* 2014).

mitigation cost compared to residual damages and adaptation costs (figure 2), carbon price estimates, and the trading position on the global carbon market (SI section 4, for a discussion). Discrepancies between change in allocation and financial values are due to concurrent changes in allocation and allowance price when residual damages and adaptation costs are included. Consider Middle East and Latin America in 2050. Small increases in the allocation of allowances can translate into ambiguous results in terms of financial flows because including climate impact cost components into the analysis can lead to a moderate reduction in the carbon price in 2050, which occurs in the WITCH model.

Unambiguous results can be identified for the remaining regions. Relatively high-damage countries would be entitled to additional emission allowances as compensation, compared to an emission allocation equating only mitigation costs. Under the 2 °C policy, the monetary value of these additional allowances could reach about \$523-566 billion in 2050 (which is 33%–36% more than the equal mitigation cost regime), with the following regional distribution, India (\$316-333 billion in 2050), Africa (\$107-131 billion in 2050), and Rest of Asia (\$76-126 billion in 2050). The additional financial flows related to the net exports of emission allowances are relatively insensitive to the temperature targets, although the 3 °C target would entail somewhat higher financial transfers to compensate for the larger residual climate damages and adaptation costs in developing countries. The relative insensitivity is due to the small difference in temperature change between the climate target scenarios by 2050.

A core group of low-impact regions, China, the United States, and Pacific OECD, would be buying the

additional emission allowances from high-impact regions under the scheme equating total climate costs. In terms of total financial transfers compensating for all costs of climate change, mitigation, residual damages, and adaptation, North America, Pacific OECD, and Europe would still remain the major buyers of emission allocations (figure S2, top panel).

4. Discussion

Most quantitative studies on effort-sharing focus only on the equity regarding mitigation costs. In the negotiations on international climate policy, however, also the unequal distribution of climate impacts and adaptation measures plays a role. The scarcity of consistent estimates of climate impacts and adaptation costs at the national and regional scale with world coverage has limited the ability of IAMs to provide integrated assessment of equity issues. While earlier studies provided some insights into this question, here we also address the role of uncertainty by using two IAMs equipped with different damage and adaptation cost functions to investigate the regional distribution of mitigation, adaptation, and damage costs resulting from climate change policies and determine how unequal total climate change costs can be compensated by trading emission allowances in a global cap-and-trade scheme. Our multi-model analysis highlights the key factors influencing the results as well as the outcomes with respect to the regional distribution holding across a set of key uncertainties.

The results show that in both models a 3 °C climate goal leaves considerable residual impacts and adaptation costs. The adaptation challenge is smaller with a 2 °C goal, but residual damages and adaptation costs remain high enough to induce a considerable reallocation of emission allowances. The allowance allocation equalizing the total burden of climate change as share of GDP would differ substantially from the allocation equating only mitigation costs. Despite model differences, unambiguous results can be identified for the regions showing a clear ranking in terms of relative mitigation, adaptation, and climate impact costs. Should adaptation costs and residual damages be included in the burden to be shared, high-impact regions would receive more emission allowances. Compared to the emission allocation equating only mitigation costs, additional financial resources totaling to \$523–566 billion in 2050 would flow to the high-impact countries in Africa, the rest of Asia, and in India through the sales of emission allowances in the carbon market in both climate scenarios. Less clear results emerge for the regions whose ranking in terms of relative impacts or mitigation costs varies across models.

The results of the present study should not be considered as the definitive costs and equitable financial transfers or emissions allowance allocations, but

rather as an initial estimate that serves to highlight the key factors influencing equity, how shifts in expected costs will influence equitable distributions, and to advance thinking on the topic of equity in global responses to climate change. Moreover, results assume a global cap-and-trade system being in place from 2020 onwards, which is not easy to implement in the real world and does not seem in line with the current bottom-up process. Given the significant equity repercussions and the remaining uncertainty in damage and adaptation cost estimates, our analysis points to the need to further joint assessments of mitigation and adaptation policies. Several projects and initiatives are developing new aggregate regional estimates of adaptation costs and impacts at the scale that is relevant for IAMs¹⁰ that could be used in future integrated assessments and MIP exercises.

Acknowledgments

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References

- Agrawala S, Bosello F, Carraro C, De Cian E, Lanzi E, de Bruin K and Dellink R 2010 Plan or React? Analysis of adaptation costs and benefits *Using Integrated Assessment Models OECD Environment Working Papers 23* (Paris: OECD) (doi:10.1787/5km975m3d5hb-en)
- Agrawala S, Bosello B, Carraro C, de Bruin K, De Cian E, Dellink R B and Lanzi E 2011 Plan or React? Analysis of adaptation costs and benefits using integrated assessment models *Climate Change Economics* **2** 175–208
- Blanford G J, Kriegler E and Tavoni M 2014 Harmonization versus fragmentation: overview of climate policy scenarios in EMF27 *Clim. Change* **123** 383–96
- Bosello F, Carraro C and De Cian E 2013 Adaptation can help mitigation: an integrated approach to post-2012 climate policy *Environmental and Development Economics* **18** 270–90
- Bosello F and De Cian E 2014 Documentation on the development of damage functions and adaptation module in the WITCH model *CMCC Research Papers Issue RP0228* (www.cmcc.it/publications/rp0228-documentation-on-the-development-of-damage-functions-and-adaptation-in-the-witch-model)
- Bosetti V, Carraro C, Galeotti M, Massetti E and Tavoni M 2006 WITCH: a world induced technical change hybrid model *Energy J.* **27** 13–38
- Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9
- Clarke L *et al* 2014 Assessing transformation pathways *Climate Change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press) ch 6 (www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter6.pdf)
- Clarke L, Edmonds J, Krey V, Richels R, Rose S and Tavoni M 2009 International climate policy architectures: overview of the

¹⁰ See for example, <http://base-adaptation.eu/>, <http://econadapt.eu/>.

- EMF 22 international scenarios *Energy Economics* **31** (Supplement 2) S64–81
- de Bruin K C, Dellink R B and Agrawala S 2009 Economic aspects of adaptation to climate change: integrated assessment modelling of adaptation costs and benefits *OECD Environment Working Papers* (Paris: OECD) p 6
- De Cian E and Tavoni M 2012 Do technology externalities justify restrictions on emission permit trading? *Resour. Energy Econ.* **34** 624–46
- De Cian E, Bosetti V and Tavoni M 2012 Technology innovation and diffusion in less than ideal climate policies. An assessment with the WITCH model *Clim. Change* **114** 121–43
- Dell M, Jones B F and Olken B A 2014 What do we learn from the weather? The new climate-economy literature *Journal of Economic Literature* **52** 740–98
- Dell M, Jones B F and Olken B A 2012 Climate change and economic growth: evidence from the last half century *Am. Economic J. Macroeconomics* **4** 66–95
- den Elzen M and Höhne N 2008 Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets *Clim. Change* **91** 249–74
- den Elzen M and Höhne N 2010 Sharing the reduction effort to limit global warming to 2C *Climate Policy* **10** 247–60
- den Elzen M, Hof A, van den Berg M and Roelfsema M 2014 Climate policy *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model Description and Policy Applications* ed E Stehfest *et al* (The Hague: PBL Netherlands Environmental Assessment Agency) pp 303–11 (www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)
- Eklholm T, Soimakallio S, Moltmann S, Höhne N, Syri S and Savolainen I 2010 Effort sharing in ambitious, global climate change mitigation scenarios *Energy Policy* **38** 1797–810
- Hof A F, den Elzen M G J and van Vuuren D P 2010 Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes *Mitigation and Adaptation Strategies for Global Change* **15** 19–40
- Kriegler E *et al* 2013 What does the 2 °C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios *Clim. Change Economics* **4** 1340009
- Kriegler E *et al* 2015 Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy *Technol. Forecast. Soc. Change* **90** 24–44
- Luderer G, De Cian E, Hourcade J C, Leimbach M, Waisman H and Edenhofer O 2012 On the regional distribution of mitigation costs in a global cap-and-trade regime *Clim. Change* **114** 59–78
- Nordhaus W D and Boyer J G 2000 *Warming the World: the Economics of the Greenhouse Effect* (Cambridge, MA: MIT Press)
- Nordhaus W D 2007 *The Challenge of Global Warming* (New Haven, CT: Yale University) (aida.econ.yale.edu/~nordhaus/homepage/dice_mss_091107_public.pdf)
- Paltsev S and Capros P 2013 Cost concepts for climate change mitigation *Clim. Change Econ.* **4** 1340003
- Pattanayak A and Kavi Kumar K S 2014 Accounting for impacts due to climate change in GHG mitigation burden sharing *Clim. Policy* **5** 724–42
- Rose A, Stevens B, Edmonds J and Wise M 1998 International equity and differentiation in global warming policy: an application to tradeable emission permits *Environmental Resource Economics* **12** 25–51
- Stern D I, Pezzey J C V and Lambie N R 2012 Where in the world is it cheapest to cut carbon emissions? *Australian J. Agric. Res. Econ.* **56** 315–31
- Tavoni M *et al* 2013 The distribution of the major economies' effort in the Durban platform scenarios *Climate Change Economics* **4** 1340009
- Tavoni M *et al* 2015 Post-2020 climate agreements in the major economies assessed in the light of global models *Nat. Clim. Change* **5** 119–26
- van Vuuren D P *et al* 2009 Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials *Energy Policy* **37** 5125–39
- van Vuuren D P *et al* 2014 Energy supply and demand *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model Description and Policy Applications* ed E Stehfest *et al* (The Hague: PBL Netherlands Environmental Assessment Agency) (www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)
- Watkins P (ed) 2011 *The ClimateCost Project. Final Report. Volume 1: Europe* (Sweden: Stockholm Environment Institute)