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

Supplementary Information

1. Overview of the two integrated modelling tools FAIR and WITCH

Integrated Assessment Models (IAMs) are economic tools that have become widely used to study climate change policies. They generally represent the most relevant interactions among energy, land use and the economic system, and often include modules to describe the physical processes associated with climate change, such as the carbon cycle. To remain numerically tractable, most IAMs represent these processes and interactions in a simplified and stylized manner. IAMs can use different decision rules to provide a normative outcome of the most cost-effective distribution of mitigation effort across countries, sectors, and technologies that minimize the aggregate economic costs. The WITCH model (Bosetti et al. 2006, De Cian et al. 2012) maximizes the regional welfare of the regions represented in the model (Table S11), subject to the physical constraint on the carbon budget to limit global warming to a certain target. The FAIR model (Hof et al. 2010) minimizes the costs of achieving a given carbon budget by allocating the effort across regions based on their marginal abatement costs.

The large-scale modeling efforts that have tried to incorporate impacts and adaptation rely on aggregate data and reduced-form damage functions. WITCH and FAIR assume that the economic damages from climate change are small for moderate temperature increases and larger in a non-linear pattern with subsequent rises in temperature. Both WITCH and FAIR use regional damage functions that aggregate sectoral impacts from the literature into aggregate Gross Domestic Product (GDP) changes for different temperature levels, as described in Section 2. The numerous adaptation strategies that are possible in the real world are grouped into one combined category (FAIR) or into three stylized groups of reactive, proactive, and building adaptive capacity (WITCH).

Gross damages are defined as damages caused by climate change if no adaptation or mitigation actions are implemented. Mitigation and adaptation can reduce gross damages, but at a cost (mitigation costs and adaptation costs). When mitigation and adaptation actions are implemented, climate change cost components include protection costs (adaptation), mitigation costs, and residual damages, the latter defined as the damages that remain after implementing adaptation and mitigation. The literature also defines the sum of residual damages and protection costs as net damages.

This study considers two mitigation targets, 3°C and 2°C. These targets are implemented by assuming that all countries will face a uniform carbon price starting in 2020. Before 2020 regions implement present and planned climate-related policies and regulations, which include a collection of national emission targets, GHG intensity reduction targets, and nuclear power and renewable energy targets (Kriegler et al. 2014). Table S12 describes in detail the scenarios examined. Adaptation is implemented at the regional level, without any kind of global coordination on climate damages. In the remainder of this Section we describe the adaptation module of each model.
The two models, FAIR and WITCH, differ in the structure of the adaptation module. In FAIR gross damages ($GD$) are a function of the temperature change relative to pre-industrial levels ($\Delta T$), while adaptation costs ($PC$) are a function of the level of adaptation ($P$). Both are described as a fraction of GDP ($Y$):

$$\frac{GD_{r,t}}{Y_{r,t}} = \alpha_{1,r} \Delta T_t + \alpha_{2,r} \Delta T_t^{\alpha_{3,r}}$$  \hspace{1cm} (1)

$$\frac{PC_{r,t}}{Y_{r,t}} = \gamma_{1,r} P_{r,t}^{\gamma_{2,r}}$$  \hspace{1cm} (2)

In WITCH, gross damages are also defined as a fraction of GDP and depend on the temperature change relative to pre-industrial levels:

$$\frac{GD_{r,t}}{Y_{r,t}} = \omega_{1,\text{neg},r} \Delta T_t + \omega_{2,\text{neg},r} \Delta T_t^{\omega_{3,\text{neg},r}} + \omega_{4,\text{neg},r} + \omega_{1,\text{pos},r} \Delta T_t + \omega_{2,\text{pos},r} \Delta T_t^{\omega_{3,\text{pos},r}} + \omega_{4,\text{pos},r}$$  \hspace{1cm} (3)

Adaptation only reduces the negative climate change impacts, implying that actions to exploit the positive opportunities that might arise due to climate change are not taken into account. The left-over damage is the residual damage, $RD$.

$$\frac{RD_{r,t}}{Y_{r,t}} = \left[ \frac{\omega_{1,\text{neg},r} \Delta T_t + \omega_{2,\text{neg},r} \Delta T_t^{\omega_{3,\text{neg},r}} + \omega_{4,\text{neg},r}}{1 + \theta_{\text{ADA},r,t}^{\theta_{\text{ADA}}}} \right] + \omega_{1,\text{pos},r} \Delta T_t + \omega_{2,\text{pos},r} \Delta T_t^{\omega_{3,\text{pos},r}} + \omega_{4,\text{pos},r}$$  \hspace{1cm} (4)

In WITCH the structure describing adaptation is more articulated. Total protection costs include three variables describing three broad categories of adaptation: reactive adaptation, proactive adaptation, and specific adaptive capacity building:

$$PC_{r,t} = I_{\text{RADA},r,t} + I_{\text{PRADA},r,t} + I_{\text{SCAP},r,t}$$  \hspace{1cm} (5)

These three forms of adaptation are combined in nested Constant Elasticity of Substitution (CES) functions that describe different substitution possibilities between different adaptation strategies and yield the total amount of adaptation $Q_{\text{ADA},r,t}$. A first nest combines adaptation activities ($Q_{\text{ACT}}$) and adaptive capacity ($Q_{\text{CAP}}$):

$$Q_{\text{ADA},r,t} = \omega_{eff,r}^{Q_{\text{ACT},r,t}} Q_{\text{ACT},r,t}^{\rho_{\text{ADA}}} + (1 - \omega_{\text{ACT},r}) Q_{\text{CAP},r,t}^{\rho_{\text{ADA}}} \frac{1}{\rho_{\text{ADA}}}$$  \hspace{1cm} (6)

The adaptation activity nest combines reactive adaptation ($I_{\text{RADA}}$) and proactive adaptation ($K_{\text{PRADA}}$):

$$Q_{\text{ACT},r,t} = \omega_{eff,r}^{Q_{\text{ACT},r,t}} (\omega_{\text{RADA},r} I_{\text{RADA},r,t}^{\rho_{\text{ACT}}} + (1 - \omega_{\text{RADA},r}) K_{\text{PRADA},r,t}^{\rho_{\text{ACT}}} \frac{1}{\rho_{\text{ACT}}})$$  \hspace{1cm} (7)

The adaptation capacity nest combines generic capacity ($Q_{\text{GCAP}}$) and specific capacity ($Q_{\text{SCAP}}$):

$$Q_{\text{CAP},r,t} = \omega_{gcap(r)}^{Q_{\text{CAP},r,t}} Q_{\text{CA}} + (1 - \omega_{gcap}) Q_{\text{CAP},r,t}^{Q_{\text{GCAP}}} \frac{1}{\rho_{\text{GCAP}}}$$  \hspace{1cm} (8)

Generic capacity is exogenous and grows at the growth rate of total factor productivity $tfp$. The initial stock is proportional to the 2005 average stock of knowledge $K_{\text{R&D}}$ and human capital $K_{\text{EDU}}$. 
The two adaptation modeling structures imply a different temporal distribution of adaptation and its effectiveness. In FAIR adaptation expenditure is undertaken every year and it does not affect damages in the next period. Costs and benefits of adaptation always fall in the same period. While many adaptation measures have this characteristic, other adaptation measures might have a time-lag between the period of investments and building a stock of defensive capital and the period during which the resulting defensive capital will reduce damage without entailing major investment costs. The modeling approach used by WITCH explicitly distinguishes the characteristics of different adaptation measures.

Tables S8 to S10 give the parameters used to calibrate Eq.(1) - (9). Section 2 and 3 describe the data used in the calibration of the damages and adaptation costs functions. For the sectors described in Section 2 and 3 WITCH aggregates sectoral adaptation cost and effectiveness data into the three categories of proactive, reactive, and specific capacity. FAIR groups sectoral data into one combined adaptation category.

2. Climate change damages

A broad literature has examined fair allocation rules to share mitigation costs, but the paucity of damage and adaptation cost estimates at the macroeconomic scale has limited the analysis of equitable schemes that share the full burden of climate change, including mitigation costs, adaptation costs, and residual damages. Damage and adaptation cost estimates compound the uncertainty of all the steps required to arrive at those estimates, and evaluating to what extent policy conclusions depend on those estimates has not been assessed by the literature. Addressing this question requires different damage and adaptation estimates, to which current IAMs modeling adaptation can be compared to. Although Agrawala et al. (2010, 2011) use two IAMs with a different adaptation modeling structure and different data sources to calibrate adaptation costs and impacts, the two models differ with respect to the adaptation costs and effectiveness assumptions, whereas for most sectors, damage functions still build on Nordhaus and Boyer (2000), see Table S1-S3.

This paper considers an updated set of adaptation and damage cost function estimates that build on new sources to demonstrate how an equitable, climate cost-based allocation of emissions will depend on adaptation costs and damage estimates. By differentiating the sources of impact estimates and, to some extent the sources of adaptation cost estimates, this study adds new model-based evidence on equitable schemes that share the full burden of climate change, including mitigation costs, adaptation costs, and residual damages. Tables S1-S3 summarize the main assumptions on climate impacts, adaptation costs, and adaptation effectiveness, and compare those of the models used in this study with Agrawala et al. (2010, 2011), which is the most comprehensive published study on this topic.
| Source                                      | This study and de Bruin et al. (2009) | This study | Agrawala et al. (2010, 2011) | Agrawala et al. (2010, 2011) |
|---------------------------------------------|--------------------------------------|------------|-----------------------------|-----------------------------|
| **Model**                                   | FAIR and AD-RICE                     | WITCH      | AD-DICE, AD-RICE            | WITCH                       |
| **Agriculture**                             | Nordhaus and Boyer (2000). Studies done on crop yield variation under different temperatures and precipitation using the FARM model. | ClimateCost Project: Iglesias et al. (2011). | De Bruin et al. (2009). | Nordhaus and Boyer (2000). Studies done on crop yield variation under different temperatures and precipitation using the FARM model. |
| **Other vulnerable markets**                | Nordhaus and Boyer (2000). Energy and water. Extrapolation from US data. | ClimateCost Project: Mima et al. (2011), Criqui (2001), Criqui et al. (2009). | De Bruin et al. (2009). | Nordhaus and Boyer (2000). Energy and water. Extrapolation from US data. |
| **Coastal impacts**                         | Nordhaus and Boyer (2000). Extrapolation from US data. | ClimateCost Project: Brown et al. (2011), Vafeidis et al. (2008). | De Bruin et al. (2009). | Authors’ estimates based on the DIVA model. Source: Agrawala et al. (2010, 2011). |
| **Health**                                  | Nordhaus and Boyer (2000). Malaria, dengue, tropical diseases and pollution | Nordhaus (2007), ClimateCost Project: Kovats and Lloyd (2011). | De Bruin et al. (2009). | Nordhaus and Boyer (2000). Malaria, dengue, tropical diseases and pollution. |
| **Settlements and ecosystems**              | Nordhaus and Boyer (2000). Willingness To Pay (WTP) to climate proof certain highly climate sensitive settlements. | Willingness-To-Pay (WTP) approach based on authors’ estimates. | De Bruin et al. (2009). | Nordhaus and Boyer (2000). Willingness To Pay (WTP) to climate proof certain highly climate sensitive settlements. |
| **Catastrophic events**                    | Nordhaus and Boyer (2000). Willingness To Pay (WTP) to avoid catastrophic events. | Nordhaus (2007). | De Bruin et al. (2009). | Nordhaus and Boyer (2000). Willingness To Pay (WTP) to avoid catastrophic events. |
| **Non-market time effect**                  | Nordhaus and Boyer (2000). Extra enjoyment of leisure activities | Not included. | De Bruin et al. (2009). | Nordhaus and Boyer (2000). Extra enjoyment of leisure activities. |

Table S1: Climate change impact assumptions in different IAMs across studies.
| Source | This study and de Bruin et al. (2009) | This study | Agrawala et al. (2010, 2011) | Agrawala et al. (2010, 2011) |
|--------|------------------------------------|------------|-----------------------------|-----------------------------|
| **Model** | FAIR and AD-RICE | WITCH | AD-RICE | WITCH |
| **Agriculture** | Change in crop planting date, increased fertilizer application, installation of irrigation systems and the development of new varieties. Source: Tan and Shibasaki (2003), Rosenzweig and Parry (1994) | Agrawala et al. (2010, 2011) | De Bruin et al. (2009) | Adaptation costs on water infrastructure extrapolated from UNFCCC (2007). Source: UNFCCC (2007) |
| **Other vulnerable markets** | Ad-hoc assumptions. | Agrawala et al. (2010, 2011). Differences in energy demand and their costs. | De Bruin et al. (2009) | Differences in energy demand and their costs. Source: De Cian et al. (2013). Changes in water infrastructures necessary to meet water demand. Source: UNFCCC (2007). |
| **Coastal impacts** | Costs estimation based on the FUND model. Source: Tol (2007). | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | Authors' estimates based on the DIVA model. Source: Agrawala et al. (2010, 2011). |
| **Health** | WHO (2008), Murray and Lopez (1996). | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | Treatment costs associated to climate-related illnesses. Source: Tol and Dowlatabadi (2001). |
| **Settlements and ecosystems** | Nordhaus and Boyer (2000) and ad-hoc assumptions. | Expenditure on the conservation of protected areas (UNFCCC 2007); costs to adapt vulnerable infrastructure equal to 5% of investments (World Bank 2006). | De Bruin et al. (2009). | Starting from Nordhaus and Boyer (2000) estimates of net damages, adaptation costs and residual damages have been separated using the proportion for coastal protection from DIVA. Source: Agrawala et al. (2010, 2011). |
| **Catastrophic events** | Ad-hoc assumptions. | Not included. Early warning system costs are included as adaptive capacity. Source: Agrawala et al. (2010, 2011) | De Bruin et al. (2009). | Not included. Early warning system costs are included as adaptive capacity. Source: Agrawala et al. (2010, 2011). |
| **Non-market time effect** | Ad hoc assumptions, most damages are adaptation costs as people will adapt their leisure activities to fit the new climate. | Not included. | De Bruin et al. (2009). | Adaptation is cost free. Source: Agrawala et al. (2010, 2011). |

Table S2: Adaptation cost assumptions in different IAMs across studies.
| Source                        | This study and de Bruin et al. (2009) | This study | Agrawala et al. (2010, 2011) | Agrawala et al. (2010, 2011) |
|------------------------------|---------------------------------------|------------|-----------------------------|-----------------------------|
| **Model**                    | FAIR and AD-RICE                       | WITCH      | AD-RICE                     | WITCH                      |
| **Agriculture**              | Implementation of adaptation measures can be very effective in this sector. Source: Tan and Shibasaki (2003), Rosenzweig and Parry (1994), Nordhaus and Boyer (2000). | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | Medium levels of effectiveness for agricultural measures. High level of effectiveness for water infrastructures. Source: Tan and Shibasaki (2003), EEA (2007), Kirshen et al. (2006). |
| **Other vulnerable markets** | High effectiveness of air conditioning in offsetting the negative impacts of increasing temperatures. Source: Martens (1998), Gawith et al. (1999). | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | High effectiveness of air conditioning in offsetting the negative impacts of increasing temperatures in developed countries, medium in developing countries. Source: ad hoc assumptions. |
| **Coastal impacts**          | FUND model. Source: Tol (2007).        | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | DIVA model. Source: Agrawala et al. (2010). |
| **Health**                   | Medium-high level of effectiveness of adaptation: it is high for certain measures like disease treatment but low for others such as air pollution. Source: WHO (2008), Murray and Lopez (1996). | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | Medium-high level of effectiveness of adaptation: it is high for certain measures like disease treatment but low for others such as air pollution. Source: WHO (2008). |
| **Settlements and ecosystems** | Low effectiveness for ecosystems, high for human settlements. Source: Nordhaus and Boyer (2000), ad hoc assumptions. | Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | Low effectiveness for ecosystems, medium-high for human settlements as migration is considered as an option. The ecosystem damage component is evaluated slightly more. Source: Nordhaus and Boyer (2000), Agrawala et al. (2010, 2011). |
| **Catastrophic events**      | Low level of effectiveness due to the actual catastrophic consequences of extreme events. Source: Nordhaus and Boyer (2000), ad hoc assumptions. | Very small adaptation possibility for catastrophic events is considered in the next adaptive capacity. Source: Agrawala et al. (2010, 2011). | De Bruin et al. (2009). | Very small adaptation possibility for catastrophic events is considered. Source: Nordhaus and Boyer (2000), ad hoc assumptions. |
| **Non-market time effect**   | High level of effectiveness, due to the fact that adaptation will depend simply on adjusting individual’s activities. Source: Nordhaus and Boyer (2000), ad hoc assumptions. | Not included. | De Bruin et al. (2009). | High level of effectiveness, due to the fact that adaptation will depend simply on adjusting individual’s activities. Source: Nordhaus and Boyer (2000), ad hoc assumptions. |

Table S3: Adaptation effectiveness assumptions in different IAMs across studies.
FAIR uses the regional residual damage and adaptation cost functions estimated by de Bruin et al. (2009) for the RICE model. In de Bruin et al (2009) the main source of net damage is Nordhaus and Boyer (2000). This data is supplemented with relevant literature on adaptation costs and ad hoc assumptions to separate adaptation costs from residual damages. The impact categories considered are: Agriculture, Other Vulnerable Markets, Coastal, Health, Non-Market Time Use, Catastrophic, and Settlements.

In the WITCH model, damage functions are based on sectorial climate impact estimates developed in the ClimateCost project1 (Watkins 2011, Bosello et al 2012, Bosello and De Cian 2014), integrated with Nordhaus (2007) estimates for the impact categories health and catastrophic events. For the impact category settlements and ecosystems, which is also considered in Nordhaus and Boyer (2000) as well as in de Bruin et al (2009), new estimates are developed, see below. WITCH considers the same impact categories as de Bruin et al. (2009) with the exception of the category non-market time use, which is not included. Both models calibrate damages at the point where global atmosphere temperature increases by 2.5 °C as compared to the 1900 level.

Of the sectors examined by the ClimateCost project, only those overlapping with Nordhaus and Boyer (2000) have been included, namely coastal impacts, energy demand (which is included in the other vulnerable markets category), agriculture, and health for Europe (reduced work capacity due to thermal discomfort). The direct impacts on specific sectors have been evaluated by sectoral models (Brown et al 2011, Vafeidis et al 2008; Mima et al 2011, Criqui 2001, Criqui et al 2009; Iglesias et al 2011; and Kovats and Lloyd 2011, respectively). All estimates, with the exception of health, which are only available for Europe, have been assessed for a number of macro-regions covering the world. The macroeconomic impacts on regional GDP have been calculated for each impact category separately using the computable general equilibrium (CGE) model ICES (Eboli et al 2010, Bosello et al 2012). Therefore, differently from the damage estimates provided by de Bruin et al. (2009), the damage estimates for these three categories include autonomous, or market-driven adaptation. Indirect impact estimates resulting from CGE models are generally smaller than the direct impact estimates from sectorial studies, especially when production factors, such as land or crop yields, are affected. Input substitution makes it possible to buffer the direct impacts. Input substitution interacts with terms of trade effect on the international market and change in the sectorial composition of the economy.

The impacts have been estimated for a temperature increase above pre-industrial levels of 1.9°C and they have been extended to other temperature increases, including the calibration point 2.5°C, using sector specific assumptions. For the categories coastal impacts and agriculture we use a power relationship as in Nordhaus and Boyer (2000). We assume that for warming above 3°C all regions begin to lose, following the evidence that crop productivities decline in all regions for such a threshold. Energy and health impacts have been extended using a linear trend. Catastrophic impacts are interpolated using a linear function up to the temperature increase of 3 degree Celsius above pre-industrial levels, and using a quadratic equation above that threshold. The remainder of this section describes in detail models’ assumptions and data sources for each impact category.

**Agriculture**
De Bruin et al. (2009) consider the changes in average crop productivity due to variation in precipitation and temperature, assuming that crop production will be adjusted to the new climate, as in Nordhaus and Boyer (2000). The WITCH model uses the changes in the average productivity of crops from the ClimateCrop model (Iglesias et al. 2011). Crop response depends on temperature. CO2 fertilisation and extreme events, and water management practices are also taken into account. Spatially integrating all these elements, the ClimateCrop model estimates climate change impacts and the effect of the implementation of different adaptation strategies.

**Coastal**
De Bruin et al. (2009) consider that residual damages from land loss. Dike building is modelled as adaptation and it is accounted for as protection cost. As in Nordhaus and Boyer (2000), estimates for the USA are

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1 [http://www.climatecost.cc/](http://www.climatecost.cc/)
extrapolated to other regions, based on a coastal vulnerability index (the coastal area to total land area ratio). The WITCH model uses the estimates of coastal land loss due to sea-level rise (Brown et al 2011), based on the Dynamic Integrated Vulnerability Assessment (DIVA) model (Vafeidis et al. 2008). DIVA is an engineering model designed to study the vulnerability of coastal areas to the rise in sea-level. The model is based on a world database of natural system and socio-economic factors for world coastal areas. Changes in natural as well as socio-economic conditions of possible future scenarios are implemented through a set of impact-adaptation algorithms. Impacts are then assessed both in physical (i.e. sq. km of land lost) and economic (i.e. value of land lost and adaptation costs) terms.

Health
In both de Bruin et al. (2009) and WITCH, this category refers to damages due to malaria, dengue, tropical diseases and pollution. De Bruin et al. (2009) use the estimates from Nordhaus and Boyer (2000). The WITCH model uses Nordhaus (2007). For Europe, the WITCH model also includes the impacts on labour productivity estimated by Kovats and Lloyd (2011). They assess the change in working conditions due to heat stress produced by the increase in temperature, and they estimate the expected decrease in labour productivity for four European macro-regions (Western, Eastern, Northern and Southern).

Settlements and ecosystems
Both de Bruin et al (2009) and WITCH estimates rely on a Willingness-To-Pay (WTP) approach. De Bruin et al (2009) use the estimates of impacts on settlements and ecosystems from Nordhaus and Boyer (2000). In WITCH we replace Nordhaus and Boyer’s estimates with updated calculations of the WTP, following the approach used in the MERGE model (Manne and Richels, 2005). In MERGE, the WTP to avoid the non-market damages of a 2.5°C temperature increase above pre-industrial levels is 2% of GDP when per capita income is above 40,000 USD 1990. The 2% figure was the US EPA expenditure on environmental protection in 1995. A s-shaped relationship between per capita income and WTP is then used to infer the WTP for other regions. WITCH follows a similar approach, but using an updated proxy for the WTP, considering the EU expenditure on environmental protection. The most recent Eurostat data referring to public sector expenditure reports a total value in 2001 of 54 billion EUR, 0.6% of EU25 GDP, or of 120 EUR per capita. This value encompasses activities such as protection of soil and groundwater, biodiversity and landscape, noise protection, radiation, along with more general research and development, administration and multifunctional activities. We then use the expression reported in Warren et al. (2006), which links average per capita environmental expenditure and per capita income to extrapolate a relationship between WTP and per-capita income:

\[
WTP_{n,t=2.5°C} = \frac{1}{\gamma \Delta T_{n,t=2.5°C}^{2.5}} \left(1 + 100e^{-(0.23\times GDP_{t=2.5°C}^{\#GDP_{t=2.5°C}^{\#}}})\right)
\]

In Eq.(10) the parameters \(\gamma\) and \(\varepsilon\) have been calibrated to give exactly 0.6% of GDP when per capita income is $28,780 and \(\Delta T=2.5^\circ C\). The s-shaped relationship between per-capita income and WTP has been used to compute the WTP in the different model regions, which is reported in Table S4. The resulting estimates fall between Nordhaus and Boyer (2000) and MERGE estimates as described in Warren et al.(2006). The WTP reference value used for rich countries crucially determines the final results. Using the EU values as the benchmark for calculations yields lower damages than in the MERGE model, but higher than Nordhaus and Boyer (2000). A WTP approach tends to produce higher evaluations for non-market ecosystem losses in high-income countries, although ecosystem/biodiversity richness is highly concentrated in developing countries. Note

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2 “Environmental Protection Expenditure in Europe by public sector and specialized producers 1995-2002” http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-NQ-05-010/EN/KS-NQ-05-010-EN.PDF viewed on November 24th 2011.

3 Nordhaus and Boyer (2000) estimate an annual willingness to pay to avoid the disruption of settlements and ecosystems associated with a 2.5°C increase in global average temperature of about $67 per household (2006 values). Both relate to irreversible effects on immobile ecosystems or infrastructures. Hanemann (2008) revised Nordhaus and Boyer’ estimates for the United States, almost doubling them to $120 (in 2006 values).
that our estimates, which are assumed to be for ecosystems only, exceed Nordhaus and Boyer’s estimates, which also include the willingness to pay to protect infrastructure.

| Region      | This study | Nordhaus and Boyer (2000) | MERGE as in Warren et al 2006 |
|-------------|------------|--------------------------|-------------------------------|
| USA         | 0.61       | 0.1                      | 2                             |
| Western EU  | 0.61       | 0.25                     | 2                             |
| Eastern EU  | 0.54       | 0.1                      | 2                             |
| KOSAU       | 0.61       | 0.1                      | 2                             |
| CAJANZ      | 0.50       | 0.25                     | 2                             |
| TE          | 0.61       | 0.05                     | 1.5                           |
| MENA        | 0.25       | 0.05                     | 0.9                           |
| SSA         | 0.02       | 0.1                      | 0.04                          |
| SASIA       | 0.03       | 0.1                      | 0.2                           |
| CHINA       | 0.52       | 0.05                     | 1.8                           |
| EASIA       | 0.23       | 0.1                      | 0.3                           |
| LACA        | 0.54       | 0.1                      | 1.9                           |
| INDIA       | 0.03       | 0.1                      | 2                             |

Table S4. WTP for ecosystems protection related to a temperature increase of 2.5°C (% of regional GDP)

Other vulnerable markets
This category refers to the effect of climate change on other markets, energy and water in the case of FAIR, and energy in the case of WITCH. De Bruin et al. (2009) use US data extrapolated to other regions by using the average temperature effects from Nordhaus and Boyer (2000). The WITCH model uses the change in residential energy demand due to increasing temperatures derived from the POLES model (Mima et al. 2011, Criqui 2001, Criqui et al. 2009). POLES is a bottom-up partial-equilibrium model of the world energy system extended to include information on water resource availability and adaptation measures. It determines future energy demand and supply according to energy price trends, technological innovation, climate impacts and alternative mitigation policy schemes. The model considers both heating and cooling degree-days in order to determine the evolution of demand for different energy sources (coal, oil, natural gas, electricity) over the time-horizon considered.

Non-market time use
Because of climate change, people’s leisure hours will be affected. In colder regions, a warmer climate will lead to extra enjoyment of outdoor leisure activities. In warmer climates, however, leisure activities will be more restricted if the amount of extremely hot days increases. This category is included only in the damage functions estimated by de Bruin et al. (2009), on the basis of Nordhaus and Boyer (2000).

Catastrophic
In both FAIR and WITCH this category refers to the willingness to pay to avoid catastrophic events. Whereas de Bruin et al. (2009) use Nordhaus and Boyer (2000), the WITCH model relies on Nordhaus (2007).

Compared to Agrawala et al. (2010, 2011) updated total impacts are larger, driven by larger estimates for the impact categories coastal, health, catastrophic impacts, settlements and ecosystems. Impacts on the agriculture sectors are larger in developing countries, but smaller in developed countries and Latin America. Impacts in the sector other vulnerable markets, which now only includes the impacts on energy demand, are also smaller across all regions, as Agrawala et al. (2010, 2011) include also the water system.
Table S5. Updated damage estimates as used by the WITCH model in this study and comparison to Agrawala et al. (2010, 2011)

3. Adaptation costs and effectiveness

FAIR and the WITCH model use relevant literature supplemented with ad hoc assumptions to estimate the optimal levels of adaptation and its effectiveness. For each impact category, regional data on costs and benefits
of adaptation possibilities are collected and used to calibrate the parameters of the adaptation functions used in the model.

Very few empirical studies have focused on estimating aggregate costs and benefits of adaptation (Heal et al. 2014). Furthermore, the few studies that do exist often focus on specific local adaptation options because the costs and benefits of adaptation are location specific. Agrawala and Fankhauser (2008) give an excellent overview of the current literature available on adaptation costs and benefits, which is the main data source for de Bruin et al. (2009) behind the FAIR model. The calibration of adaptation costs and effectiveness of the WITCH has been developed by adjusting Agrawala et al. (2010, 2011) estimates to the impact categories considered in this study. For example, the category other vulnerable markets only includes the costs associated with changes in energy demand. Adaptation costs in the impact category settlements and ecosystems have been updated with expenditure on the conservation of protected areas and with revised calculation of costs to adapt vulnerable infrastructure, see below. Moreover, the category non-market time use is not considered in the WITCH model. The remainder of this section describes the data sources of adaptation costs and effectiveness by impact category. More details are provided by Agrawala and Fankhauser (2008) and Agrawala et al. (2010, 2011).

Agriculture
De Bruin et al. (2009) use the regional estimates from Tan and Shibasaki (2003) and Rosenzweig and Parry (1994), which mostly refer to low-cost adaptation measures, such as changing plant timing. Following Agrawala et al. (2010, 2011), the WITCH model assumes that the most significant cost component of climate change adaptation in agriculture is related to irrigation and water conservation practices, and therefore model adaptation in agriculture as a proactive strategy. The main data source is UNFCCC (2007), which reports estimates of the future total cost on water infrastructure in a climate change scenario (B1 SRES scenario), assuming that 25% of those investments will be climate-change driven. As Agrawala et al. (2010, 2011), we assume that the agricultural sector absorbs 70% of the water infrastructure costs reported by the UNFCCC study, and that 15% (as discussed in Agrawala et al. 2010 this is a more reasonable assumption) of these will be necessary in the future for adapting to climate change. De Bruin et al. (2009) base the evaluation of adaptation effectiveness on Tan and Shibasaky (2003), who report changes in yields with and without adaptation under climate change for different crops and world regions, whereas for the WITCH model we use the same assumptions as in Agrawala et al. (2010, 2011).

Coastal
De Bruin et al. (2009) use regional estimates of adaptation costs and effectiveness to sea-level rise from the FUND model (Tol 2007), which calculates both the optimal protection level of adaptation for more than 200 countries by using the cost-benefit module developed by Fankhauser (1994). The WITCH model uses the estimates from the DIVA model as described in Agrawala et al. (2010, 2011). As shown in Table S6-S7, the coastal adaptation potential is higher in FAIR than in WITCH because the cost-benefit module used in the FUND model is more optimistic about protection levels.

Health
De Bruin et al. (2009) use regional estimates of adaptation from the study by Murray and Lopez (1996). This study assumes a level of adaptation based on general improvements in health care, and it also uses data from the WHO malaria report 2008, which estimates the use of mosquito nets in various vulnerable regions as an adaptation measure. The WITCH model assumes that adaptation in the health sector is reactive, and cost estimates are from Tol and Dowlatabadi (2001), as in Agrawala et al. (2010, 2011). Tol and Dowlatabadi (2001) assess the treatment cost associated with climate-driven malaria, dengue, schistosomiasis, diarrhoeal, cardiovascular and respiratory diseases, for different scenarios of temperature increases on a global scale. The effectiveness of adaptation is based on a survey of the literature, which shows that protection levels range between 20% in Africa and 40% in other non-OECD countries. In developed regions protection levels are much higher, ranging from 60% to 90%. The WITCH model relies on the assumptions of Agrawala et al. (2010, 2011).
Settlements and ecosystems
De Bruin et al. (2009) estimate adaptation in this sector by using ad-hoc assumptions, building on Nordhaus and Boyer (2000) estimates. In WITCH, the adaptation costs in the categories settlements and ecosystems have been updated. For the ecosystems category, we use the UNFCCC (2007) study revise adaptation costs. We use the observed expenditure on conservation of protected areas (PAs) as a proxy of the investments needed to protect natural ecosystems. The global value reported is $7 billion. UNFCCC (2007) estimates an annual increase in expenditure to increase protected areas by 10% up to $12-22 billion in 2030. That range refers to the estimated cost of improving protection, expanding the network of protected areas, and compensating local communities that currently depend on resources from fragile ecosystems. We scaled up the estimated range $12-22 billion to 2050 linearly using the ratio of temperature increase in 2060 relative to the temperature increase in 2030 in the WITCH model (to $21-38 billion), and compute a lower and higher bound for adaptation costs. In this study we use the lower estimate. The global estimated adaptation costs are allocated to the different regions proportionally to the damage in the ecosystems category.

To estimate adaptation costs in the settlements category the WITCH model applies the methodology described in UNFCCC (2007) to the model investments in physical capital in 2060. According to that study, the average annual share of infrastructure vulnerable to the impacts of climate change is 2.7% of average annual investments in infrastructure globally. The World Bank (2006) estimates the additional costs of adapting vulnerable infrastructure to climate change between 5% and 20% of investments. For this study we consider the rate of 5%. The expenditure needed to eliminate the infrastructure gap identified in Parry et al. (2009) is assumed to be zero for developed countries, and it is included in the specific capacity category. We use aggregate figures for low and middle income countries provided by Parry (2009, Table 6.1) to compute the average annual regional investments needed to address the infrastructure adaptation deficit. The aggregate figure is distributed to regions proportionally to the GDP share. The adaptation effectiveness assumptions used by the WITCH model in this study are based on Agrawala et al. (2010, 2011).

Other vulnerable markets
De Bruin et al. (2009) assume that dryer, hotter regions will have more trouble adapting and that developing regions may lack the infrastructure to adapt. The WITCH model follows Agrawala et al. (2010, 2011) and use adaptation costs due to changes in heating and cooling expenditure from De Cian et al. (2013), an econometric study that estimates the elasticity of electricity, natural gas, coal and oil products to temperature changes by using panel data. With respect to effectiveness, it is assumed that in developed countries the protection level is quite high, 80%, while it is 40% in developing countries, as Agrawala et al. (2010, 2011). De Bruin et al. (2009) also assume higher effectiveness of adaptation in developed countries.

Non-market time use
This category is modelled only in FAIR, following de Bruin et al. (2009), whereas it is not included in the WITCH model. Most of the climate change costs in this category will consist of adaptation costs, as people adapt their leisure activities in accordance with the new climate, leaving low residual damages. The net costs in this category are mostly changes in adaptation costs, and adaptation is more effective in developed countries, where it reduces up to 90% of gross damages.

Catastrophic
As the events considered in this category are large-impact events and catastrophes, the potential to reduce their impacts through adaptation is assumed to be small in both models. Therefore, both protection costs and protection levels are assumed to be small. In the WITCH model, the costs to address catastrophic events through early warning systems as in Agrawala et al. (2010, 2011) are considered part of specific capacity. Protection levels are also assumed to be very low (10% in developed countries as opposed to 20% assumed in de Bruin et al. 2009), especially in developing countries (0.10% in developed countries as opposed to 20% assumed in de Bruin et al. 2009).
### Table S6. De Bruin et al. (2009) impacts by sector (net damage in % of GDP), estimates of optimal adaptation (PL: fraction of gross damages reduced), and ratio of residual damages to adaptation costs (RD/PC) from empirical data at the calibration point (+2.5°C increase above pre-industrial levels). EU, Western Europe; HIO, Middle East; MI, Brazil, Korea region; LMI: Mexico, Rest of Central, South America, Northern Africa, Turkey, the Kazakhstan region; LI, Mekong region, Indonesia, Southern Asia.

| Sector                  | USA  | China | Japan | EU   | India | HIO | MI    | LMI  | Africa | LI |
|-------------------------|------|-------|-------|------|-------|-----|-------|------|--------|----|
| **Agriculture**         |      |       |       |      |       |     |       |      |        |    |
| Net damages             | 0.06 | -0.37 | -0.46 | 0.49 | 1.08  | 0   | 1.13  | 0.04 | 0.05   | 0.04|
| PL                      | 0.58 | 0.63  | 0.43  | 0.48 | 0.63  | 0.48| 0.58  | 0.655| 0.53   | 0.58|
| PC/RD                   | 0.89 | 1.14  | 1.14  | 0.89 | 0.89  | na | 0.89  | 0.89 | 0.89   | 0.89|
| **Health**              |      |       |       |      |       |     |       |      |        |    |
| Net damages             | 0.02 | 0.09  | 0.02  | 0.02 | 0.69  | 0.23| 0.32  | 0.32 | 3      | 0.66|
| PL                      | 0.6  | 0.41  | 0.42  | 0.6  | 0.36  | 0.82| 0.78  | 0.5  | 0.35   | 0.4 |
| PC/RD                   | 0.7  | 0.72  | 0.73  | 0.7  | 0.77  | 0.85| 0.89  | 0.77 | 0.79   | 0.76|
| **Settlements**         |      |       |       |      |       |     |       |      |        |    |
| Net damages             | 0.1  | 0.05  | 0.25  | 0.25 | 0.1   | 0.05| 0.1   | 0.1  | 0.1    | 0.1 |
| PL                      | 0.75 | 0.75  | 0.75  | 0.75 | 0.75  | 0.75| 0.75  | 0.75 | 0.75   | 0.75|
| PC/RD                   | 0.43 | 0.43  | 0.43  | 0.43 | 0.43  | 0.43| 0.43  | 0.43 | 0.43   | 0.43|
| **Non market time use** |      |       |       |      |       |     |       |      |        |    |
| Net damages             | -0.28| -0.26 | -0.31 | -0.43| 0.3   | 0.24| -0.04 | -0.04| 0.25   | 0.2 |
| PL                      | 0.9  | 0.7   | 0.9   | 0.9  | 0.3   | 0.7 | 0.7   | 0.3  | 0.3    | 0.3 |
| PC/RD                   | 9    | 9     | 9     | 9    | 9     | 9   | 9     | 9    | 9      | 9   |
| **Other vulnerable markets** | |       |       |      |       |     |       |      |        |    |
| Net damages             | 0    | 0.13  | 0     | 0    | 0.4   | 0.91| 0.41  | 0.29 | 0.09   | 0.46|
| PL                      | 0.8  | 0.6   | 0.8   | 0.8  | 0.6   | 0.6 | 0.7   | 0.6  | 0.5    | 0.5 |
| PC/RD                   | 0.24 | 0.25  | 0.24  | 0.24 | 0.25  | 0.24| 0.24  | 0.25 | 0.25   | 0.25|
| **Catastrophic**        |      |       |       |      |       |     |       |      |        |    |
| Net damages             | 0.44 | 0.52  | 0.45  | 1.91 | 2.27  | 0.46| 0.47  | 1.01 | 0.39   | 1.09|
| PL                      | 0.2  | 0.2   | 0.2   | 0.2  | 0.2   | 0.2 | 0.2   | 0.2  | 0.2    | 0.2 |
| PC/RD                   | 0.95 | 0.95  | 0.95  | 0.95 | 0.95  | 0.95| 0.95  | 0.95 | 0.95   | 0.95|
Table S7. WITCH impacts by sector (net damage in % of GDP at 2.5°C climate change), estimates of optimal adaptation (PL: fraction of gross damages reduced), and adaptation costs at the calibration point (+2.5°C increase above pre-industrial levels).

| FAIR region         | RICE region | α 1  | α 2  | α 3  | γ 1  | γ 2  |
|---------------------|-------------|------|------|------|------|------|
| Western Africa      | AFRICA      | 0.00  | 0.01 | 0.00 | 0.95 | 1.22 |
| Western Europe      | AFIRCA      | 0.00  | 0.01 | 0.00 | 0.95 | 1.22 |
| Rest of Southern Africa | AFIRCA    | 0.00  | 0.01 | 0.00 | 0.95 | 1.22 |
| China region        | CHINA      | -0.02 | 0.00 | 0.10 | 1.22 | 1.58 |
| Western Europe      | EUROPE     | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Middle East         | HIO        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| India               | INDIA      | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Japan               | JAPAN      | -0.01 | 0.00 | 0.00 | 0.95 | 1.22 |
| Mekong region       | LI         | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Indonesia region    | LI         | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Southern Asia       | LI         | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Mexico              | LMI        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Rest Central America | LMI       | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Rest South America  | LMI        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Northern Africa     | LMI        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| South Africa        | LMI        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Turkey              | LMI        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Kazakhstan region   | LMI        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Brazil              | MI         | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| Korea region        | MI         | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |
| USA                 | USA        | 0.00  | 0.00 | 0.00 | 0.95 | 1.22 |

Table S8. Calibration of the de Bruin et al. (2009) adaptation cost function and gross damage function applied to the FAIR regions.  

4 Three RICE regions (Eastern Europe, Russia and Other High Income) have been excluded because they have very low, near zero, net benefits from climate change, making them hard to calibrate. For these regions, we assume zero adaptation costs for calculating global adaptation costs.
### Table S9. Gross damage function parameters in the WITCH model

| Region | \( \omega_1,\text{neg}(n) \) | \( \omega_2,\text{neg}(n) \) | \( \omega_3,\text{neg}(n) \) | \( \omega_4,\text{neg}(n) \) | \( \omega_1,\text{pos}(n) \) | \( \omega_2,\text{pos}(n) \) | \( \omega_3,\text{pos}(n) \) | \( \omega_4,\text{pos}(n) \) |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| USA    | 0.003           | 0.001           | 2.000           | 0.007           | -0.001         | 0.000           | 2.000           | 0.001           |
| Western EU | 0.003           | 0.001           | 2.000           | 0.007           | -0.004         | 0.001           | 2.000           | 0.002           |
| Eastern EU | 0.005           | 0.001           | 2.000           | 0.000           | 0.000           | 0.000           | 2.000           | 0.000           |
| KOSAU  | 0.007           | 0.000           | 2.000           | 0.000           | -0.008         | 0.001           | 2.000           | 0.005           |
| CAJAZ  | 0.002           | 0.001           | 2.000           | 0.008           | 0.000           | 0.000           | 2.000           | 0.000           |
| TE     | 0.005           | 0.001           | 2.000           | 0.000           | -0.004         | 0.001           | 2.000           | 0.003           |
| MENA   | 0.004           | 0.003           | 2.000           | 0.000           | 0.000           | 0.000           | 2.000           | 0.000           |
| SSA    | 0.010           | 0.003           | 2.000           | 0.000           | 0.000           | 0.000           | 2.000           | 0.000           |
| SASIA  | 0.004           | 0.010           | 2.000           | 0.000           | -0.001         | 0.000           | 2.000           | 0.000           |
| CHINA  | 0.004           | 0.001           | 2.000           | 0.000           | -0.007         | 0.001           | 2.000           | 0.004           |
| EASIA  | 0.003           | 0.008           | 2.000           | 0.000           | 0.000           | 0.000           | 2.000           | 0.000           |
| LACA   | 0.007           | 0.001           | 2.000           | 0.000           | 0.000           | 0.000           | 2.000           | 0.000           |
| INDIA  | 0.005           | 0.010           | 2.000           | 0.000           | -0.001         | 0.000           | 2.000           | 0.000           |

### Table S10. Adaptation cost function parameters in the WITCH model

| Region                    | \( \rho(\text{ADA}) \) | \( \rho(\text{ACT}) \) | \( \rho(\text{GCAP}) \) | \( \epsilon \) | \( \omega_{\text{eff}}^{\text{ADA}} \) | \( \omega_{\text{eff}}^{\text{ACT}} \) | \( \omega_{\text{gcap}} \) | \( \omega_{\text{act}} \) | \( \omega_{\text{rada}} \) |
|---------------------------|----------------|----------------|----------------|-------------|----------------|----------------|----------------|----------------|----------------|
| USA                       | -0.111         | 0.170          | -4.000         | 0.630       | 1.400         | 1.000         | 0.500         | 0.900         | 0.400         |
| Western EU                | -0.111         | 0.170          | -4.000         | 0.630       | 2.500         | 1.000         | 0.500         | 0.900         | 0.400         |
| Eastern EU                | -0.111         | 0.170          | -4.000         | 0.700       | 0.800         | 1.000         | 0.500         | 0.900         | 0.500         |
| KOSAU                     | -0.111         | 0.170          | -4.000         | 0.900       | 2.500         | 1.000         | 0.500         | 0.900         | 0.500         |
| CAJAZ                     | -0.111         | 0.170          | -4.000         | 0.700       | 0.500         | 1.000         | 0.500         | 0.900         | 0.100         |
| TE                        | -0.111         | 0.170          | -4.000         | 0.600       | 0.500         | 1.000         | 0.500         | 0.900         | 0.300         |
| MENA                      | -0.111         | 0.170          | -4.000         | 0.750       | 1.000         | 1.000         | 0.500         | 0.900         | 0.300         |
| SSA                       | -0.111         | 0.170          | -4.000         | 0.600       | 1.400         | 1.000         | 0.300         | 0.750         | 0.600         |
| SASIA                     | -0.111         | 0.170          | -4.000         | 0.700       | 3.900         | 1.000         | 0.100         | 0.470         | 0.550         |
| CHINA                     | -0.111         | 0.170          | -4.000         | 0.900       | 1.400         | 1.000         | 0.500         | 0.500         | 0.750         |
| EASIA                     | -0.111         | 0.170          | -4.000         | 0.250       | 0.060         | 1.000         | 0.900         | 0.700         | 0.850         |
| LACA                      | -0.111         | 0.170          | -4.000         | 0.550       | 0.700         | 1.000         | 0.500         | 0.600         | 0.550         |
| INDIA                     | -0.111         | 0.170          | -4.000         | 0.300       | 0.380         | 1.000         | 0.900         | 0.800         | 0.700         |
| Scenario Name | Near-term Target | Impacts | Long-term GHG Target | Policy implementation |
|---------------|-----------------|---------|----------------------|-----------------------|
| BAU           | None            | None    | None                 | -                     |
| BAU w/Adap    | None            | Included| None                 | -                     |
| 2°C-Tax       | Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)). | None | 450 ppm-eq           | Global tax regime with a harmonized carbon price. No trading of emission allowances |
| 2°C-Tax w/Adap| Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)). | Included | 450 ppm-eq           | Global tax regime with a harmonized carbon price. No trading of emission allowances |
| 3°C-Tax w/Adap| Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)). | Included | 650 ppm-eq           | Global tax regime with a harmonized carbon price. No trading of emission allowances |
| 2°C-EqMitCosts| Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)). | None | 450 ppm-eq           | Carbon price harmonization with trading of emission allowances. Emission allowances allocated on equal regional cost. Relative mitigation costs in % GDP losses wrt to No Policies are equalized across regions in each time period. |
| 3°C-EqMitCosts| Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)). | None | 650 ppm-eq           | Carbon price harmonization with trading of emission allowances. Emission allowances allocated on equal regional cost. Relative mitigation costs in % GDP losses wrt to No Policies are equalized across regions in each time period. |

Table S11. Definition of regional aggregates used in the paper.
| Scenario                | Description                                                                 | Included | Concentration Level |
|-------------------------|-----------------------------------------------------------------------------|----------|---------------------|
| 2°C-EqFullCosts w/Adap  | Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)).          | Included | 450 ppm-eq          |
|                         | Carbon price harmonization with trading of emission allowances. Emission allowances allocated on equal regional cost. Relative full climate change costs (mitigation costs+adaptation costs+residual damages) % GDP losses wrt to No Policies are equalized across regions in each time period. |
| 3°C-EqFullCosts w/Adap  | Lenient Copenhagen Pledges until 2020 (see Kriegler et al. (2014)).          | Included | 650 ppm-eq          |
|                         | Carbon price harmonization with trading of emission allowances. Emission allowances allocated on equal regional cost. Relative full climate change costs (mitigation costs+adaptation costs+residual damages) % GDP losses wrt to No Policies are equalized across regions in each time period. |

Table S12. Definition of scenarios analysed in the paper.
4. Further results

The Tables below report the net exports of emission allowances under the equal mitigation costs scheme (Table S13), the change in net export financial flows and in emission allocation due to the inclusion of impact and adaptation costs (Table S14 and S15). Table S16 displays the regional mitigation costs in the 2°C Tax scenario without impacts and adaptation using different discount rates.

The two models used here differ not only with respect to the modeling of climate change impacts and adaptation, but also in terms of global and regional mitigation costs (see Table S16), which lead to different trading positions when a global market is established (Table S13). FAIR mitigation cost estimates are lower than those of WITCH. Differences are due to the different cost metrics used by the models. FAIR measures mitigation costs as the total area under the regional marginal abatement cost (MAC) curves of the different GHGs and of the different emissions sources among which abatement is allocated. WITCH computes the change in consumption pathway relative to an alternate consumption pathway that does not include emission reduction. As shown by the literature, 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). Under the 2°C global tax regime, regional discounted mitigation costs using a 3% discount factor vary between 1.7% and 20% of GDP in WITCH, while the range is between 0.3% and 1.6% in FAIR (see Table S16). 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 much stronger impact of including residual damages and adaptation costs into the burden-sharing rule in the FAIR model as compared to WITCH. Yet, large differences in quantities are compensated by a higher carbon price estimate in the WITCH model, leading to similar changes in financial values, see Figures S2 and S4.

| Region       | 3°C WITCH | 3°C FAIR | 2°C WITCH | 2°C FAIR |
|--------------|-----------|----------|-----------|----------|
| AFRICA       | -66.86    | -292.39  | -10.49    | -245.40  |
| CHINA+       | -206.86   | -247.23  | 126.97    | 149.23   |
| EUROPE       | 190.10    | 95.94    | -506.33   | -1030.93 |
| INDIA+       | -203.98   | -370.53  | -189.67   | -763.53  |
| LATIN_AM     | 171.10    | 475.53   | 173.74    | 517.18   |
| MIDDLE_EAST  | 352.87    | 808.18   | 882.06    | 2366.96  |
| NORTH_AM     | -91.00    | -114.31  | -547.36   | -820.14  |
| PAC_OECD     | -135.04   | -212.67  | -319.36   | -410.25  |
| REF_ECON     | 262.09    | 610.10   | 496.27    | 1050.30  |
| REST_ASIA    | -263.54   | -652.80  | -121.60   | -583.29  |
| REST_WORLD   | -11.05    | -99.14   | 17.24     | -227.85  |

Table S13: Net exports of emission allowances (billion US$ 2005/yr), TaxEqMitCosts (policy scenario a in Table 1). Positive net exports represent the value of the emission allocations sold in the trading scheme. Negative net exports represent how many emission allocations are purchased under the trade program.
|        | 3° WITCH | 3° FAIR | 2° WITCH | 2° FAIR |
|--------|----------|---------|----------|---------|
|        | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 |
| AFRICA | 21.47 | 141.81 | 31.00 | 138.00 | 20.71 | 107.07 | 41.00 | 131.00 |
| CHINA+ | -120.64 | -300.56 | -107.00 | -335.00 | -119.79 | -278.80 | -104.00 | -299.00 |
| EUROPE | 8.72 | -111.48 | 57.00 | 109.00 | 27.84 | -40.34 | 48.00 | 76.00 |
| INDIA+ | 96.84 | 452.23 | 89.00 | 359.00 | 92.63 | 333.01 | 98.00 | 316.00 |
| LATIN_AM | 4.76 | -14.13 | 25.00 | 38.00 | 4.47 | -11.86 | 21.00 | 37.00 |
| MIDDLE_EAST | -5.08 | -9.30 | 15.00 | 29.00 | -17.61 | -36.20 | 13.00 | 28.00 |
| NORTH_AM | -2.82 | -153.45 | -101.00 | -295.00 | 3.43 | -85.07 | -98.00 | -255.00 |
| PAC_OECD | 5.75 | -55.86 | -47.00 | -107.00 | 5.25 | -22.32 | -45.00 | -94.00 |
| REF_ECON | -19.88 | -64.16 | -4.00 | -24.00 | -26.89 | -55.78 | -5.00 | -19.00 |
| REST_ASIA | 32.35 | 177.28 | 27.00 | 83.00 | 28.70 | 125.52 | 26.00 | 76.00 |
| REST_WORLD | -17.28 | -58.35 | 2.00 | -16.00 | -18.20 | -34.86 | 1.00 | -11.00 |

Table S14: Change in Net exports of emission allowances (billion US$ 2005/yr) TaxEqMitCosts w Adap (policy scenario b in Table 1) vs. TaxEqMitCosts (policy scenario a in Table 1)

|        | 3° WITCH | 3° FAIR | 2° WITCH | 2° FAIR |
|--------|----------|---------|----------|---------|
|        | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 |
| AFRICA | 1743.04 | 1743.58 | 1865.00 | 2143.00 | 59.65 | 118.01 | 784.00 | 1404.00 |
| CHINA+ | -7500.88 | -4454.46 | -6236.00 | -5189.00 | -349.62 | -297.80 | -2024.00 | -3245.00 |
| EUROPE | -429.45 | -1515.05 | 3507.00 | 1701.00 | 49.00 | -76.85 | 932.00 | 790.00 |
| INDIA+ | 7376.52 | 5953.81 | 5419.00 | 5587.00 | 243.89 | 354.71 | 1913.00 | 3421.00 |
| LATIN_AM | -694.04 | 265.10 | 1537.00 | 621.00 | 25.17 | 1.69 | 430.00 | 405.00 |
| MIDDLE_EAST | -2105.15 | 650.88 | 923.00 | 456.00 | 4.54 | 18.90 | 253.00 | 318.00 |
| NORTH_AM | 39.28 | -2308.04 | -5829.00 | -4420.00 | -19.68 | -120.38 | -1847.00 | -2630.00 |
| PAC_OECD | 1010.44 | -972.63 | -2750.00 | -1596.00 | 0.47 | -37.66 | -850.00 | -968.00 |
| REF_ECON | -2676.55 | -352.01 | -224.00 | -374.00 | -43.11 | -38.49 | -106.00 | -203.00 |
| REST_ASIA | 3386.17 | 1901.72 | 1672.00 | 1297.00 | 73.79 | 126.40 | 494.00 | 815.00 |
| REST_WORLD | -1166.72 | -910.07 | 118.00 | -226.00 | -44.10 | -48.52 | 23.00 | -107.00 |

Table S15: Change in Emission allocation (MtCO2eq) TaxEqMitCosts w Adap (policy scenario b in Table 1) vs. TaxEqMitCosts (policy scenario a in Table 1)
|                | WITCH          | FAIR           |
|----------------|----------------|----------------|
|                | 3%  5%  0%     | 3%  5%  0%     |
| AFRICA         | 12.0 9.37 14.85| 1.19 1.05 1.24 |
| CHINA+         | 10.65 6.97 17.07| 0.95 0.74 1.11 |
| EUROPE         | 1.71 1.09 2.8  | 0.3 0.19 0.49  |
| INDIA+         | 6.36 4.79 8.33 | 1.57 1.38 1.63 |
| LATIN_AM       | 6.95 4.71 10.11| 0.74 0.54 0.92 |
| MIDDLE_EAST    | 20.36 16.05 23.91| 1.36 1.03 1.65 |
| NORTH_AM       | 3.73 2.21 6.53 | 0.49 0.3 0.79  |
| PAC_OECD       | 2.66 1.63 4.67 | 0.29 0.18 0.5  |
| REF_ECON       | 13.12 9.42 18.57| 0.92 0.69 1.13 |
| REST_ASIA      | 8.45 6.76 10.08| 1.39 1.09 1.6  |
| REST_WORLD     | 3.31 2.6 4.19  | 0.74 0.5 1.05  |
| WORLD          | 6.53 4.27 10.01| 0.79 0.54 1.07 |

|                | WITCH          | FAIR           |
|----------------|----------------|----------------|
|                | 3%  5%  0%     | 3%  5%  0%     |
| AFRICA         | 0.37 0.36 0.35 | 0.51 0.45 0.55 |
| CHINA+         | 0.99 0.48 2.08 | 0.39 0.3 0.48  |
| EUROPE         | 0.27 0.16 0.55 | 0.12 0.08 0.2  |
| INDIA+         | 0.23 0.03 0.56 | 0.66 0.56 0.71 |
| LATIN_AM       | 1.61 0.96 2.76 | 0.3 0.22 0.39  |
| MIDDLE_EAST    | 5.01 3.76 6.36 | 0.52 0.37 0.67 |
| NORTH_AM       | 0.71 0.33 1.63 | 0.16 0.1 0.25  |
| PAC_OECD       | 0.7 0.32 1.74  | 0.12 0.07 0.22 |
| REF_ECON       | 4.16 2.58 7    | 0.34 0.25 0.43 |
| REST_ASIA      | 0.43 0.26 0.68 | 0.58 0.44 0.69 |
| REST_WORLD     | 1.01 0.58 1.97 | 0.3 0.21 0.44  |
| WORLD          | 1.03 0.59 1.83 | 0.32 0.21 0.44 |

Table S16: Discounted policy costs in the 2°C and 3°C tax scenarios without damages and adaptation costs (policy scenarios a in Table 1). Net present value, 2005-2100, 0%, 3%, 5% discount rates.
Figures S1 shows how the regional allocation of emission rights changes when moving from a global tax regime without transfers to a cap-and-trade system aiming either for equal mitigation costs (top panel, policy scenario c in Table 1) or equal overall climate change costs (middle panel, policy scenario d in Table 1). Figure S2 shows the associated changes in financial flows. Figures S3-S4 show the same information in percentage changes relative to the total allocation or GDP. Bottom panels show the net effect of adding impact and adaptation to mitigation in equalized costs, as discussed in the paper.

When climate policy equates regional mitigation effort, low-mitigation-cost regions abate more and bear higher mitigation costs compared to the equal-marginal-abatement-cost allocation implied by the global tax regime. Since these regions are also low-climate-impact regions, accounting for damage and adaptation costs in the burden-sharing rule further reduces the amount of emissions allocated to them. The equal mitigation cost scheme allocates more emission rights to energy exporting countries to compensate for their relatively high mitigation costs. Since impact costs for the energy exporting regions are only slightly above the global average, adding damages and adaptation costs to the climate-change burden would only marginally increase the allocation to the Middle East and transition economies.

Results depend on the interaction between different factors: mitigation cost estimates, relative size of impact and adaptation costs with respect to mitigation costs, carbon prices, and trading position when the global carbon market is established (Figure S1 top panel, or Table S13). Red and blue rectangular areas highlight regions where emission allocations (or financial flows) decrease or increase, respectively, compared to the global tax regime.

Regions marked in yellow show ambiguous results across models. In Europe or Latin America, for example, climate impact estimates can be equal (FAIR) or lower (WITCH) than the global average. In the case of Middle East, climate impact estimates can be equal (WITCH) or higher (FAIR) than the global average. Discrepancies between the sign of change in allocation and financial values (bottom panels of Figure S1 and S2) are due to concurrent changes in allocation and carbon price when impacts and adaptation costs are included. Consider Middle East and Latin America in 2050. Small increases in the emissions allocation can translate into ambiguous results in terms of financial flows because including climate impact cost components into the analysis leads to a moderate reduction in the carbon price in 2050 in WITCH. Consider Europe and Latin America in the 3°C policy scenario, in 2030. Europe and Latina America are net exporters (see Table S13). Even though including impacts and adaptation slightly reduces their allocation (see Table S15), the value accruing to Europe and Latin America slightly increases (Table S14) because the carbon price goes up (only in 2030 and in the 3°C policy scenario).
Figure S1: Top panel shows the change in emission allocation equating mitigation costs (policy scenario c in Table 1) relative to emissions in the global tax regime without adaptation (scenario a in Table 1). Middle panel: change in emission allocation equating total climate change costs (policy scenario d in Table 1) relative to emissions in the global tax regime without adaptation (scenario a in Table 1). Bottom panel: change in emission allocation between the equal total cost regime (policy scenario d) and the equal mitigation cost regime (policy scenario c). The colored rectangular areas identify the regions in which the change in emission allocation increases (blue), decreases (red), is ambiguous (yellow).
Figure S2: Top panel shows the financial transfers associated with emission allocation trading under policy scenario c (equal mitigation costs). Middle panel: financial transfers associated with emission allocation trading under policy scenario d (equal total costs). Bottom panel: change in the financial transfers between the equal total cost regime (policy scenario d) and the equal mitigation cost regime (policy scenario c). The colored rectangular areas identify the regions in which net exports or the change in net exports increases (blue), decreases (red), is ambiguous (yellow).
Figure S3: Top panel shows the change in emission allocation equating mitigation costs (policy scenario c in Table 1) relative to emissions in the global tax regime without adaptation (scenario a in Table 1) as a share of the total allocation. Middle panel: change in emission allocation equating total climate change costs (policy scenario d in Table 1) relative to emissions in the global tax regime without adaptation (scenario a in Table 1) as a share of the total allocation. Bottom panel: change in emission allocation between the equal total cost regime (policy scenario d) and the equal mitigation cost regime (policy scenario c). The colored rectangular areas identify the regions in which the change in emission allocations increases (blue), decreases (red), is ambiguous (yellow).
Figure S4: Top panel shows the financial transfers associated with emission allocation trading under policy scenario c (equal mitigation costs) as a percentage of GDP. Middle panel: financial transfers associated with emission allocation trading under policy scenario d (equal total costs) as a share of GDP. Bottom panel: change in the financial transfers between the equal total cost regime (policy scenario d) and the equal mitigation cost regime (policy scenario c). The colored rectangular areas identify the regions in which net exports or the change in net exports increases (blue), decreases (red), is ambiguous (yellow).
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