Research Papers
Issue RP0228
October 2014

CIP - Climate Impacts and Policy Division

Documentation on the development of damage functions and adaptation in the WITCH model

By **Francesco Bosello**
University of Milan,
Fondazione Eni Enrico Mattei (FEEM),
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
Isola di San Giorgio Maggiore,
30124 Venezia, Italy

Enrica De Cian
Fondazione Eni Enrico Mattei (FEEM),
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
Isola di San Giorgio Maggiore,
30124 Venezia, Italy

SUMMARY This document describes two recent updates that have been made to the WITCH damage and adaptation modules. First, a new set of damage functions and of adaption cost curves embedding the more recent available knowledge have been calibrated. Second, the damage function has been modified to separate positive damages (benefits from climate change) from negative impacts. Adaptation only reduces the negative impacts while it does not contribute to enhancing positive impacts.

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under the REA grant agreement n^o 298436 (DYNAMIC), and from the European Community's Seventh Framework Programme under Grant Agreement n^o 308337 (Project BASE).

1. INTRODUCTION

This document describes an updated set of damage functions and adaption cost curves that have been developed for the WITCH model (Bosetti et al. 2006, De Cian et al. 2012). Concerning impacts and damages, the main data sources are the FP7 ClimateCost project (Bosello et al. 2012) and Nordhaus (2007). To estimate the climate change impacts on ecosystems we use a willingness-to-pay approach. Adaptation costs and protection levels are mostly based on Agrawala et al. (2010), and revised estimates are described in Section 4. The document is organized as follows. Section 2 describes the data sources used for computing market damages. Section 3 describes the assumptions made to obtain non-market impacts. Section 4 briefly reviews the assumptions on adaptation costs and describes the updates. Section 5 lists and explains the equations of the model.

2. THE MARKET DAMAGE COMPONENT

ClimateCost has quantified the physical and economic impacts of climate change on the rise in sea-level, energy demand, agricultural productivity, tourism flows, net primary productivity of forests, floods, and reduced work capacity because of thermal discomfort. All impacts, except those on floods and health, which focus on the EU, have been assessed for a number of macro-regions covering the world. The joint macro-economic effects of all climate change impacts (GDP change) have been evaluated using a recursive-dynamic computable general equilibrium (CGE) model (Bosello et al. 2012). Therefore, the market damage component is net of the autonomous adaptation and the ω_s coefficients in Eq. (3) account for autonomous adaptation to market impacts. The updated damage function only uses the economic impacts on the rise in sea-level, changes in crop productivity and in energy demand to replace the respective damage categories previously calibrated using Nordhaus and Boyer (2000). We decided not to include those impact categories for which adaptation cost estimates are not available at the aggregate level on a global scale, namely tourism, net primary productivity of forests, and floods.

Estimates of coastal land loss due to the rise in sea-level are based on the DIVA model (Vafeidis et al. 2008). DIVA (Dynamic Integrated Vulnerability Assessment) 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 reported with a spatial resolution of 5°. The temporal resolution is 5-year time steps until 2100 and 100-year time steps from 2100 to 2500. 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.

Changes in the average productivity of crops are from the ClimateCrop model (Iglesias et al. 2009; Iglesias et al. 2010). Crop response depends on temperature, CO_2 fertilisation and extremes. Water management practices are also taken into account. Spatially integrating all these elements, the model estimates climate change impacts and the effect of the implementation of different adaptation strategies.

Responses of residential energy demand to increasing temperatures are derived from the POLES model (Criqui 2001, Criqui et al. 2009). It 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 prices trend, technological innovation, climate impacts and alternative mitigation policy schemes. The present version of 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.

The impacts that have been quantified for the 1.9°C temperature increase have been extended to other temperature increases using sector specific assumptions and reasonable judgments based on available knowledge. For the rise in sea levels and agriculture we use a power relationship (Nordhaus and Boyer, 2000). Energy impacts have been extended using a linear trend.

According to the estimates of the ClimateCost project, agriculture appears to be the most vulnerable sector, accounting for 56% of total market impacts already at a 1.92°C warming. 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 (IPCC 2007). Table 1 summarizes the estimated impacts for the calibration point and compares them to Nordhaus (2007).

Table 1. Market impacts of 1.92°C global average temperature increase (reference year 2050) on real GDP by region and impact: % change compared to the case with no temperature increase

	All impacts		**Energy**		**SLR**		**Agriculture**	
	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)
USA	0.17	0.12	-0.01	0	-0.05	-0.08	0.05	-0.02
MEUR	-0.15	-0.25	-0.05	0	-0.03	-0.35	0.07	-0.02
NEUR	0.18	-0.25	-0.07	0	-0.11	-0.35	0.23	-0.02
EEUR	-0.21	0.15	-0.02	0	-0.04	-0.01	-0.15	-0.02
FSU	0.81	1.78	0.01	0.61	-0.03	-0.04	0.49	0.63
KOSAU	0.09	0.48	-0.04	0.25	-0.04	-0.07	0.01	0.04
CAJANZ	-0.09	0.02	-0.02	0	-0.16	-0.21	0.19	-0.02
NAF	-2.67	-0.97	-0.03	-0.25	-0.02	-0.02	-2.10	-0.51
MDE	-0.83	-0.64	-0.19	-0.15	-0.10	-0.03	-0.10	-0.27
SSA	-1.50	-0.97	0.00	-0.25	-0.02	-0.02	-1.09	-0.51
SASIA	-3.10	-0.77	0.22	-0.22	-0.32	-0.07	-3.02	-0.25
CHINA	0.20	-0.12	0.04	-0.25	-0.03	-0.06	0.43	-0.02
EASIA	-2.82	-0.60	0.01	-0.16	-0.10	-0.07	-2.36	-0.40
LACA	-0.71	-0.58	-0.04	-0.22	-0.05	-0.08	-0.11	-0.32

The extended names of the regions are: USA – United States, MEURO – Mediterranean Europe, NEURO – Northern Europe , EEURO - Eastern Europe, CAJANZ - Canada, Japan, New Zealand, CHINA - China and Taiwan, SASIA - South Asia, SSA - Sub-Saharan Africa, LACA - Latin America, Mexico, and the Caribbean, KOSAU - Korea, South Africa, Australia, FSU – Former Soviet Union, EASIA - South East Asia, MED- Middle-East, NAF - North Africa. The results presented in the table have been obtained using a model with a slightly finer regional disaggregation (14 instead of 12 regions) than that of the WITCH model. This is also why the regional matching is not perfect.

3. THE NON-MARKET DAMAGE COMPONENT

The non-market damage component includes ecosystem losses, non-market health impacts, and catastrophic damages.

Damage estimates for health and catastrophic damage are from Nordhaus (2007). Only for Europe do health impacts also include the impacts on labour productivity estimated in ClimateCost by Kovats and Lloyd (2011). They assess the change in working conditions due to heat stress produced by the increase in temperature, and their effects on labour productivity. By linking climate data, a combined measurement of heat and humidity, and effects on the human body (Kjellstrom *et al.* 2009), they are able to estimate the expected decrease in labour productivity for four European macro-regions (Western, Eastern, Northern and Southern). The authors also consider sectoral impacts, taking into account future changes in the distribution of labour force across sectors.

Nordhaus and Boyer (2000) estimate impacts on settlements and ecosystems, which include natural (ecosystems) and human (cities, states) settlements. The authors cite unpublished estimates of the capital value of climate-sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system, for a 2.5°C temperature increase (0.1% of GDP in the US). They adjust the willingness to pay for income levels. We replace Nordhaus and Boyer's estimates, using updated calculations of the WTP and following the approach used in the MERGE model (Manne et al. 2005). In principle, an elicited WTP to avoid a given loss in ecosystems should encompass all their non-market values and therefore reasonably approximate the lost value in case they are not protected[1]. 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. An S-shaped relationship between per capita income and WTP is then used to infer the WTP for other regions. We follow a similar approach, but using an updated proxy for the WTP, for which we consider 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[2]. 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:

---

[1] In practice the limitations of this approach are well known and many criticisms have been raised against WTP and other stated preference approaches. However, the usual response is that in the end, they represent the only viable way to capture existence values.

[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.

$$WTP_{n,t|t=2.5°C} = \gamma \Delta T_{n,t|t=2.5°C}^{\varepsilon} \frac{1}{1+100e^{(-0.23*GDPn,t|t=2.5°C/POPn,t|t=2.5°C)}} \qquad (1)$$

In Eq.(1) the parameters γ and ε have been calibrated to give exactly 0.6% of GDP when per capita income is 28,780 USD and ΔT=2.5°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 2. Table 2 also compares the values with Hanemann (2008), who applies the same procedure but starting from a WTP estimate for the US equal to 0.1% of GDP, Nordhaus and Boyer (2000), and the MERGE model as described in Warren (2006).

Table 2. WTP for ecosystems protection related to a temperature increase of 2.5°C (% of regional GDP)

	Current study	Hanemann (2008)	Nordhaus and Boyer (2000)	(Merge as in Warren, 2006)
USA	0.69	0.1	0.1	2
Western EU	0.69	0.1	0.25	2
Eastern EU	0.69	0.1	0.1	2
KOSAU	0.69	0.1	0.1	1.99
CAJAZ	0.69	0.1	0.25	2
TE	0.5	0.08	0.05	1.47
MENA	0.31	0.05	0.05	0.89
SSA	0.01	0.002	0.1	0.04
SASIA	0.06	0.009	0.1	0.18
CHINA	0.61	0.09	0.05	1.76
EASIA	0.1	0.02	0.1	0.3
LACA	0.66	0.099	0.1	1.92
WORLD	0.49	0.07	0.1	2
USD billion (2005)	1120	169		4569

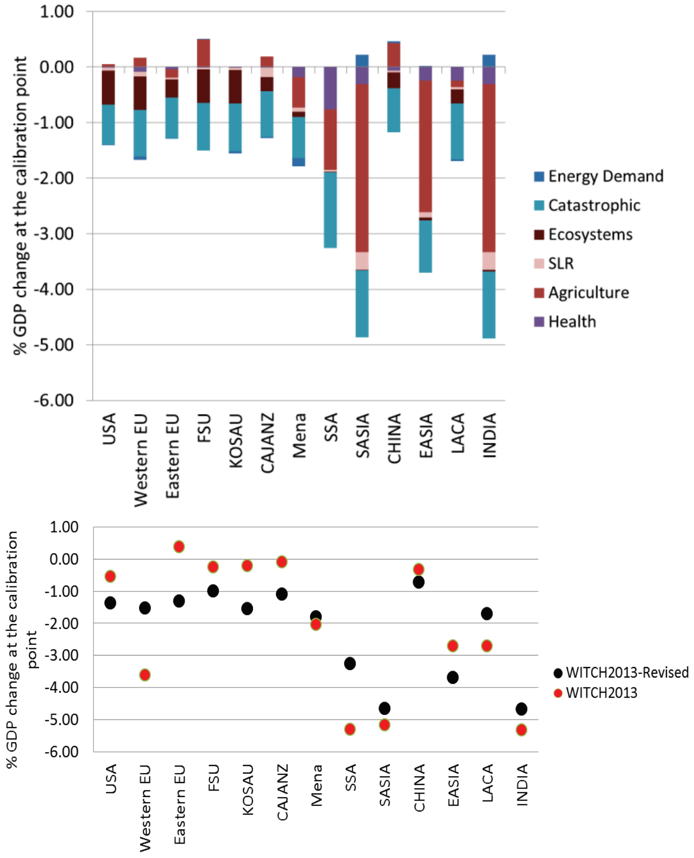
As shown in Table 2, the WTP reference value used for rich countries crucially determines the final results[3]. Using the EU values as the benchmark for calculations yields lower damages than in the MERGE model, but anyway higher than in Hanemann (2008), and Nordhaus and Boyer (2000). This also emphasises the large uncertainty when assigning an economic value to non-market impacts. Table 2 shows that 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 that our estimates, which are assumed to be for ecosystems only,

---

[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 to about 67 USD 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 USD (in 2006 values).

exceed Nordhaus and Boyer's estimates, which also include the willingness to pay to protect infrastructure. We replace Nordhaus and Boyer's estimates with ours. Figure 1 summarizes the impact categories considered, showing the damage magnitude at the calibration point (2.5°C above preindustrial levels)[4].

Figure 1. Climate change impacts at calibration point (2.55°C above pre-industrial levels) and comparison with previous version of the model



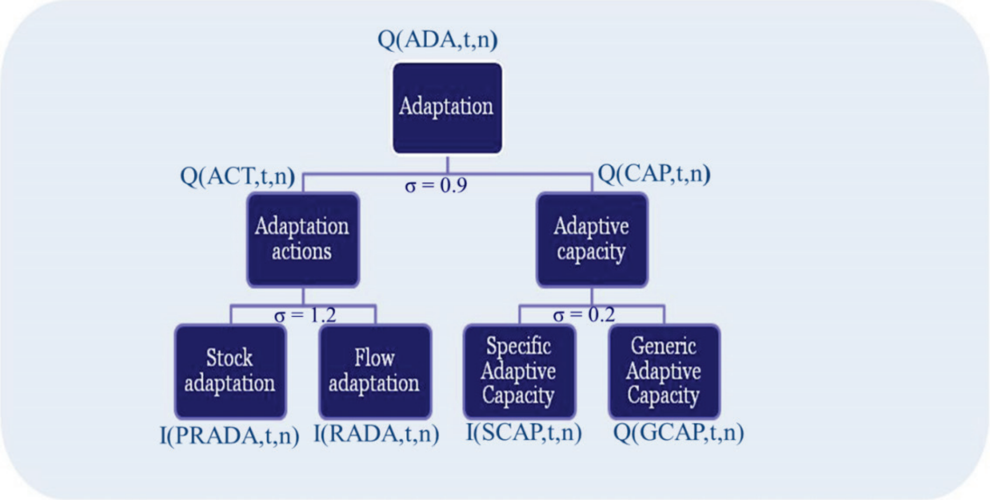
4. ADAPTATION COSTS AND EFFECTIVENESS

The adaptation module closely follows the specification and calibration described in Agrawala et al. (2010. 2011). This section only highlights the updates. For the sectors described in the previous section we have collected data on the adaptation cost and effectiveness of various strategies that are subsequently aggregated into the three categories shown in Figure 2: proactive, reactive, and specific capacity.

---

[4] The damage function is a quadratic function and therefore has two parameters to calibrate. We also consider a higher temperature level, 4°C, as second point for calibration.

Figure 2. Adaptation tree



Proactive adaptation (IPRADA)

Agriculture

We assume that the most significant cost component of climate change adaptation in agriculture is related

to irrigation and water conservation practices. We classify these forms of adaptation as proactive. The UNFCCC (2007) reports some estimates of the total future cost related to water infrastructure in a climate change scenario (B1 SRES scenario), assuming that 25% of that investment will be climate change-driven. We assume that the agricultural sector absorbs 70% of the water infrastructure costs reported by the UNFCCC study, and that between 15% and 25% of these will be necessary in the future for adapting to climate change. The effectiveness of adaptation in agriculture is instead based on Tan and Shibasaky (2003) reporting changes in yields with and without adaptation under climate change for different crops and world regions. Effectiveness assumptions are based on Tan and Shibasaky (2003) and are summarized in Table 6.

Coastal areas

Costs and effectiveness of coastal protection are obtained from the DIVA model. The model can simulate different scenarios of coastal protection. We use adaptation costs and effectiveness data associated with optimal adaptation to a global average rise in sea-level of 0.44 meters and to a global average temperature increase of 2.5°C above pre-industrial levels. Coastal protection costs, such as dike building, beach nourishment, wetland nourishment and average protection level are measured in terms of years of protection, where maximum protection (100%) corresponds to 10,000 years.

Ecosystems

Estimates of adaptation costs for addressing impacts on ecosystems are derived from UNFCCC (2007). This study uses the observed global expenditure on conservation of protected areas (PAs) to identify the investment needed for protecting natural ecosystems. Their reported values, $ 7 billion globally, are based on an earlier study by James et al. (2001). UNFCCC (2007) also reports an annual increase in expenditure of $ 12-22 billion to increase protected areas by 10%. 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[5]. We use the range 12-22 billion USD to compute a lower and higher boundary for adaptation.

Infrastructure

To estimate the investment needs to adapt infrastructure to climate change, we apply the methodology described in UNFCCC (2007) to WITCH investments in physical capital in 2060. According to UNFCCC (2007), 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 conservative rate of 5%. These estimates however do not consider the infrastructure deficit, that is the fact that current infrastructure investments are already inadequate, a situation which is likely to imply higher climate-proofing investments. 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 as a component of the specific capacity (Table 3). No precise estimates are available to determine the effectiveness of this kind of adaptation, even though it can be reasonably inferred that these protection activities are relatively effective. Accordingly, we set it to 40% (Table 6).

Reactive adaptation (IRADA)

Energy

Adaptation costs in the energy sector are determined in WITCH by changes in heating and cooling expenditure. These are derived from De Cian et al. (2013), a panel-data econometric study estimating world-wide demand elasticity of different energy vectors, electricity, natural gas, coal and oil products, in response to temperature changes. The effectiveness of this adaptation is difficult to assess. It is assumed, quite arbitrarily, that in developed countries it will be quite high,

---

[5] Upper figures provided by Parry et al. (2009) are in the range of 291-341.5 billion USD.

80%, while it will be 40% in developing countries. This would mean that in 2060 80% and 40% of the population in developed and developing countries, respectively, would be able to protect themselves from thermal discomfort .

Health

Costs of adaptation in the health sector are derived from Tol and Dowlatabadi (2001), who assess the additional climate change-driven treatment cost associated with malaria, dengue, schistosomiasis, diarrhoeal, cardiovascular and respiratory diseases, for different scenarios of temperature increases, for all countries of the world. The effectiveness of adaptation is based on survey literature, which shows that protection levels range from 20% in Africa to 40% in other non OECD countries. In developed regions it is assumed that protection levels, if financial resources are also considered, are much higher, ranging from 60% to 90%.

Specific capacity

Determining the cost of adaptive capacity building (specific capacity) is another challenging task. In the present exercise four specific components for that expenditure are identified:

1. Expenditure needed to eliminate the infrastructure gap identified in Parry et al. (2009). Assumed zero for developed countries.
2. Expenditure needed to empower women through education (Blankenspoor et al. 2010)
3. Early warning systems (Adam et al. 2000)
4. R&D expenditure in the agriculture sector (UNFCCC 2007)

When positive, the first item accounts for 95% of the investments in specific capacity. We assume the same effectiveness as for adaptation in the infrastructure domain. For early warning systems, we assume an effectiveness of 0.1.

Tables 3 to 6 summarize all the data used for the calibration of the protection costs and levels.

Table 3. Specific capacity costs at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Expenditure in adaptation R&D (Billion $)	Early Warning Systems (Million $)	Empower women (bn $)	Address infrastructure deficit (bn $)	Total (bn $)	Expenditure in adaptation R&D (% of GDP)	Early Warning Systems (% of GDP)	Empower women (% of GDP)	Address infrastructure deficit (% of GDP)	Total (% GDP)
USA	3.2192	5.0000	0.0000	0.0000	3.2242	0.0093	0.000014	0.000000	0.000000	0.0093
Western EU	2.4189	5.0000	0.0000	0.0000	2.4239	0.0079	0.000016	0.000000	0.000000	0.0079
Eastern EU	0.0671	5.0000	0.0000	0.0000	0.0721	0.0027	0.000203	0.000000	0.000000	0.0029
KOSAU	0.3317	5.0000	0.0000	0.0000	0.3367	0.0043	0.000064	0.000000	0.000000	0.0043
CAJAZ	1.1092	5.0000	0.0000	0.0000	1.1142	0.0091	0.000041	0.000000	0.000000	0.0092
TE	0.0932	5.0000	0.0000	0.0000	0.0982	0.0009	0.000051	0.000000	0.000000	0.0010
MENA	0.1888	5.0000	0.0000	21.0980	21.2919	0.0017	0.000045	0.000000	0.189172	0.1909
SSA	0.0109	5.0000	2.2493	22.5427	24.8078	0.0001	0.000042	0.018876	0.189172	0.2082
SASIA	0.0099	5.0000	0.8216	7.6467	8.4833	0.0002	0.000124	0.020327	0.189172	0.2099
CHINA	0.2688	5.0000	0.0000	61.6905	61.9643	0.0008	0.000015	0.000000	0.189172	0.1900
EASIA	0.0383	5.0000	1.7163	26.4720	28.2315	0.0003	0.000036	0.012265	0.189172	0.2017
LACA	0.0734	5.0000	1.1794	37.7641	39.0219	0.0004	0.000025	0.005908	0.189172	0.1955
INDIA	0.0402	5.0000	4.3288	40.2860	44.6599	0.0002	0.000023	0.020327	0.189172	0.2097

Table 4. Reactive protection costs at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Cooling Expenditure (Billion $)	Disease Treatment Costs (Billion $)	TOTAL (Billion $)	Cooling Expenditure (% of GDP)	Disease Treatment Costs (% of GDP)	TOTAL (% of GDP)
USA	3.3	1.1	4.4	0.009	0.003	0.013
Western EU	-7.8	-0.7	-8.5	-0.025	-0.002	-0.028
Eastern EU	-0.5	-0.1	-0.6	-0.022	-0.003	-0.025
KOSAU	11.3	1.9	13.2	0.145	0.024	0.169
CAJAZ	-7.3	3.0	-4.3	-0.060	0.025	-0.035
TE	0.8	0.1	0.9	0.008	0.001	0.009
MENA	22.3	2.1	24.4	0.200	0.019	0.219
SSA	23.8	0.5	24.3	0.200	0.004	0.204
SASIA	10.3	0.2	10.5	0.255	0.004	0.259
CHINA	42.8	0.3	43.1	0.131	0.001	0.132
EASIA	35.7	4.7	40.4	0.255	0.034	0.289
LACA	1.9	5.7	7.6	0.009	0.029	0.038
INDIA	54.2	19.7	73.9	0.255	0.092	0.347

Table 5. Anticipatory protection costs at the calibration point (+2.5°C increase above pre-industrial levels, 2055. Lower and upper bound)

	Agriculture (irrigation) (Billion $)	Coastal Protection (Billion $)	Infrastructure (Billion $)	Ecosystems (Billion $)	TOTAL (Billion $)	Agriculture (irrigation) (% of GDP)	Coastal Protection (% of GDP)	Infrastructure (% of GDP)	Ecosystems (% GDP)	TOTAL (% of GDP)
USA	3.0	3.6	10.4	6.0	23.0	0.009	0.010	0.030	0.017	0.07
Western EU	4.7	5.0	9.6	5.8	25.1	0.015	0.016	0.031	0.019	0.08
Eastern EU	7.4	0.3	0.6	0.4	8.6	0.301	0.010	0.024	0.015	0.35
KOSAU	11.0	1.8	2.0	2.1	16.8	0.141	0.023	0.026	0.027	0.22
CAJAZ	1.6	2.9	3.2	5.8	13.5	0.013	0.024	0.026	0.048	0.11
TE	10.1	1.7	1.7	0.2	13.6	0.103	0.017	0.017	0.002	0.14
MENA	28.8	1.2	2.1	0.2	32.3	0.258	0.011	0.019	0.001	0.29
SSA	30.2	2.7	2.8	0.1	35.8	0.254	0.022	0.024	0.001	0.30
SASIA	11.7	1.3	0.9	0.1	13.9	0.288	0.032	0.021	0.002	0.34
CHINA	6.5	1.3	7.1	0.1	14.9	0.020	0.004	0.022	0.000	0.05
EASIA	2.3	4.3	2.9	0.1	9.6	0.016	0.030	0.021	0.001	0.07
LACA	4.3	7.7	5.1	0.2	17.3	0.022	0.039	0.025	0.001	0.09
INDIA	34.4	1.3	5.1	0.1	40.9	0.161	0.006	0.024	0.000	0.19

Table 6. Protection level at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Agriculture (irrigation) (%)	Coastal Protection (%)	Infrastructure (%)	Ecosystems (%)	Cooling Expenditure (%)	Disease Treatment Costs (%)	Expenditure in adaptation R&D (%)	Early Warning Systems (%)	Address infrastructure deficit (%)	Simple average	Weighted average (with damage share)	Weighted average (with protection costs)
USA	0.48	0.75	0.40	0.40	0.80	0.90	0.48	0.10	0.40	0.62	0.27	0.46
Western EU	0.43	0.54	0.40	0.40	0.80	0.90	0.43	0.10	0.40	0.57	0.30	0.49
Eastern EU	0.43	0.63	0.40	0.40	0.80	0.60	0.43	0.10	0.40	0.54	0.26	0.32
KOSAU	0.27	0.62	0.40	0.40	0.80	0.81	0.27	0.10	0.40	0.54	0.24	0.48
CAJAZ	0.38	0.37	0.40	0.40	0.80	0.69	0.38	0.10	0.40	0.52	0.25	0.54
TE	0.38	0.37	0.40	0.40	0.80	0.70	0.38	0.10	0.40	0.51	0.22	0.33
MENA	0.33	0.55	0.40	0.40	0.40	0.60	0.33	0.10	0.40	0.43	0.28	0.36
SSA	0.23	0.30	0.40	0.40	0.40	0.20	0.23	0.00	0.40	0.26	0.13	0.31
SASIA	0.33	0.47	0.40	0.40	0.40	0.35	0.33	0.00	0.40	0.35	0.26	0.33
CHINA	0.33	0.76	0.40	0.40	0.40	0.40	0.33	0.10	0.40	0.44	0.21	0.39
EASIA	0.33	0.25	0.40	0.40	0.40	0.36	0.33	0.01	0.40	0.31	0.25	0.36
LACA	0.38	0.46	0.40	0.40	0.40	0.80	0.38	0.00	0.40	0.45	0.22	0.41
INDIA	0.33	0.47	0.40	0.40	0.40	0.80	0.33	0.00	0.40	0.44	0.29	0.42

5. MODEL EQUATIONS

This section describes the equations of the adaptation and damage module in the WITCH model. The main modification that has been made to the model is splitting the damage function into a positive and negative component, see Eq.(2). Adaptation only reduces negative impacts. We assume no adaptation measures that could take advantage of positive impacts.

Production function

$$Y(t,n) = \frac{tfp0\left[\alpha(n)\left(\left(tfp_y(t,n)K_C(t,n)^{\beta}\,L(t,n)^{1-\beta}\right)^{\rho}+(1-\alpha(n))ES(t,n)^{\rho}\right)^{\frac{1}{\rho}}\right]}{\Omega(t,n)} - \textstyle\sum_f C_f(t,n) - \sum_j C_j(t,n) - \sum_e C_e(t,n) - \sum_{ghg} C_{ghg}(t,n) \tag{2}$$

Damage coefficient

$$\Omega(t,n) = 1 + \frac{\left[\omega_{1,neg(n)}T(t)+\omega_{2,neg(n)}T(t)^{\omega_{3,neg(n)}}\right]}{1+Q(ADA,t,n)^{\varepsilon(n)}} + \omega_{1,pos(n)}T(t) + \omega_{2,pos(n)}T(t)^{\omega_{3,pos(n)}} \tag{3}$$

Adaptation nest between activities (ACT) and capacity (CAP

$$Q(ADA,t,n) = \omega_{eff(n)}^{ADA(n)}\left(\omega_{act(n)}Q(ACT,t,n)^{\rho_{ADA}} + (1-\omega_{act(n)})Q(CAP,t,n)^{\rho_{ADA}}\right)^{\frac{1}{\rho_{ADA}}} \tag{4}$$

Adaptation activity nest between reactive adaptation (RADA) and proactive adaptation (PRADA

$$Q(ACT,t,n) = \omega_{eff(n)}^{ACT(n)}\left(\omega_{rada(n)}I(RADA,t,n)^{\rho_{ACT}} + (1-\omega_{rada(n)})K(PRADA,t,n)^{\rho_{ACT}}\right)^{\frac{1}{\rho_{ACT}}} \tag{5}$$

Adaptation capacity nest between generic capacity (GCAP) and specific capacity (SCAP

$$Q(CAP,t,n) = \left(\omega_{gcap(n)}Q(GCAP,t,n)^{\rho_{GCAP}} + (1-\omega_{gcap(n)})K(SCAP,t,n)^{\rho_{GCAP}}\right)^{\frac{1}{\rho_{GCAP}}} \tag{6}$$

Generic capacity is exogenous and grows at the growth rate of total factor productivity, tfp_y(t,n). The initial level is given by the 2005 average stock of knowledge K(R&D) and human capital K(EDU)

$$Q(GCAP,t,n) = \frac{K(R\&D,t,n)+K(EDU,t,n)}{2}tfp_y(t,n) \tag{7}$$

Specific capacity and proactive adaptation are stocks that accumulate following the standard perpetual rule

$$\mathrm{K(SCAP,t,n) = K(SCAP,t,n)(1-\delta_{SCAP}) + \Delta_t I(SCAP,t,n)} \quad (8)$$

$$\mathrm{K(PRADA,t,n) = K(PRADA,t,n)(1-\delta_{PRADA}) + \Delta_t I(PRADA,t,n)} \quad (9)$$

Adaptation investments and expenditure are subtracted from the budget constraint

$$\mathrm{C(t,n) = Y(t,n) - I_C(t,n) - I(PRADA,t,n) - I(SCAP,t,n) - I(RADA,t,n) - I_{GRID}(t,n) - \sum_j (I_{R\&D_j}(t,n) + I_j(t,n) + OM_j(t,n)) - \sum_j (I_{OUT,f}(t,n) + OM_{OUT,f}(t,n))} \quad (10)$$

	Definition	Unit
$\mathrm{C(t,n)}$	Consumption	Trillon $
$\mathrm{I_C(t,n)}$	Investment in final good	Trillon $
$\mathrm{I_j(t,n)}$	Investment in energy tech.	Trillon $
$\mathrm{I_{GRID}(t,n)}$	Investment in electric grid	Trillon $
$\mathrm{I_{OUT,f}(t,n)}$	Investment in extraction	Trillon $
$\mathrm{I_{R\&D_j}(t,n)}$	Investment in R&D	Trillon $
$\mathrm{OM_j(t,n)}$	O&M costs in energy tech.	Trillon $
$\mathrm{OM_{OUT,f}(t,n)}$	O&M costs in extraction	Trillon $
$\mathrm{Y(t,n) - I_C}$	Net Output	Trillon $
$\mathrm{tfp0}$	Initial level of TFP	unitless
$\mathrm{C_e(t,n)}$	GHG emissions costs	Trillon $
$\mathrm{C_f(t,n)}$	Net cost of Primary Energy Supplies	Trillon $
$\mathrm{C_j(t,n)}$	Energy technology penalty costs	Trillon $
$\mathrm{C_{oghg}(t,n)}$	Carbon tax	Trillon $
$\mathrm{ES(t,n)}$	Energy services	Trillon $
$\mathrm{K_C(t,n)}$	Capital in final good	Trillon $
$\mathrm{Q_E(ghg,t,n)}$	Emissions	Gt-eqC
$\mathrm{tfp_y(t,n)}$	Total factor productivity	unitless
$\mathrm{L(t,n)}$	Population	Million people
$\mathrm{I(PRADA,t,n)}$	Investment proactive adaptation	Trillon $
$\mathrm{I(RADA,t,n)}$	Investment reactive adaptation	Trillon $
$\mathrm{I(SCAP,t,n)}$	Investment specific capacity	Trillon $
$\mathrm{K(PRADA,t,n)}$	Capital in proactive adaptation	Trillon $
$\mathrm{K(SCAP,t,n)}$	Capital in specific capacity	Trillon $
δ_{SCAP}	Proactive adaptation capital depreciation rate	0.03
δ_{PRADA}	Proactive adaptation capital depreciation rate	0.1

REFERENCES

Adams RM, Houston LL, McCarl BA (2000). The benefits to Mexican agriculture of an El Niñosouthernoscillation (ENSO) early warning system. Agricultural and Forest Meteorology 115: 183–

194.

Agrawala S, Fankhauser S (eds) (2008). Economic aspects of adaptation to climate change: costs, benefits and policy instruments. OECD, Paris.

Agrawala S, Bosello F, Carraro C, De Cian E, Lanzi E, de Bruin K, Dellink R (2010). PLAN or REACT? Analysis of adaptation costs and benefits Using Integrated Assessment Models. OECD Environment Working Papers, No. 23, OECD Publishing. doi: 10.1787/5km975m3d5hb-en

Agrawala S, Bosello F, Carraro C, De Cian E, Lanzi E, de Bruin K, Dellink R Dellink (2011). PLAN or REACT? Analysis of adaptation costs and benefits Using Integrated Assessment Models. Climate Change Economics, Vol.2 (3), 1-36.

Blankenspoor B, Dasgupta S, Laplante L, Wheeler D (2010). Economics of Adaptation to Extreme Weather Events in Developing Countries. Discussion Paper Number 1. Washington, DC: World Bank.

Bondeau A, Smith PC, Zaehle SON, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Muller C, Reichstein M (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology, 13, 679-706.

Bosello F, Eboli F, Pierfederici R (2012). Assessing the Economic Impacts of Climate Change. An Updated CGE Point of View. FEEM Note di Lavoro, No. 2.2012.

Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M (2006). WITCH: A World Induced Technical Change Hybrid Model. Energy J Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

Criqui P, (2001). POLES: Prospective Outlook on Long-term Energy Systems, Institut d'Economie et de Politique de l'Energie, 2001, available on line at: http://webu2.upmf-grenoble.fr/iepe/textes/POLES8p_01.pdf

Criqui P, Mima S, Menanteau P (2009). Trajectories of new energy technologies in carbon constraint cases with the POLES Model, IARU International Scientific Congress on Climate Change, p. 16.

De Cian E, Bosetti V, Tavoni M (2012). Technology innovation and diffusion in "less than ideal" climate policies: An assessment with the WITCH model. Climatic Change 114, 121-143.

De Cian E, Lanzi E, Roson R, (2013). Seasonal temperature variations and energy demand A panel cointegration analysis for climate change impact assessment. Climatic Change, Vol. 116, pp. 805-825.

Hanemann, WM (2008). What is the Cost of Climate Change?, CUDARE Working Paper No. 1027, University of California, Berkeley

Iglesias A, Garrote L, Quiroga S, Moneo M (2009). Impacts of climate change in agriculture in Europe. PESETA FP6 project, available on line at: http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=2900

Iglesias A, Quiroga S, Garrote L (2010). Report Analysis for Europe. Deliverable D2B.2, ClimateCost project.

James A, Gaston K, Balmford A (2001). Can we afford to conserve biodiversity? BioScience 51, pp43–52.

Kjellstrom T, Kovats RS, Lloyd SJ, Holt T, Tol RSJ (2009). The Direct Impact of Climate Change on Regional Labor Productivity. Archives of Environmental & Occupational Health, Vol. 64(4), 217-227.

Manne A, Richels R (2005). Merge: An Integrated Assessment Model for Global Climate Change. Energy and Environment, 175-189.

Nordhaus, WD (1994). Managing the Global Commons: The economics of the greenhouse effect. The MIT Press

Nordhaus WD, Boyer JG (2000). Warming the World: the Economics of the Greenhouse Effect. The MIT Press

Nordhaus WD (2007). Accompanying Notes and Documentation on Development of DICE-2007 Model: Notes on DICE-2007.delta.v8 as of September 21, 2007 http://aida.wss.yale.edu/~nordhaus/homepage/Accom_Notes_100507.pdf.

Parry M, N Arnell, P Berry, D Dodman, S Fankhauser, C Hope, S Kovats and R Nicholls (2009). Assessing the costs of adaptation to climate change, Imperial College, London.

UNFCCC (2007). Investments and Financial Flows to Address Climate Change, background paper on analysis of existing and planned investments and financial flows relevant to the development of effective and appropriate international response to climate change, p. 273

Tan G, Shibasaki R (2003). Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration. Ecological Modelling 168: 357–370.

Tol RSJ, Dowlatabadi H (2001). Vector-borne diseases, development and climate change. Integrated Assessment, 2: 173-181.

Vafeidis A, Nichols RJ, McFadden L, Tol RSJ, Hinkel J, Spencer T, Grashoff PS, Boot G and Klein RJT, (2008). A new global coastal database for impact and vulnerability analysis to sea-level rise. Journal of Coastal Research, 24, 917-924.

Warren et al. (2006). Spotlighting impacts functions in integrated assessment. WP 91, Tyndall Centre for Climate Change Research.

World Bank (2006). Investment Framework for Clean Energy and Development. World Bank, Washington DC.

CMCC Research Papers

20

Centro Euro-Mediterraneo sui Cambiamenti Climatici

© **Centro Euro-Mediterraneo sui Cambiamenti Climatici 2014**

Visit **www.cmcc.it** for information on our activities and publications.

The Euro-Mediteranean Centre on Climate Change is a Ltd Company with its registered office and administration in Lecce and local units in Bologna, Venice, Capua, Sassari, Viterbo, Benevento and Milan. The society doesn't pursue profitable ends and aims to realize and manage the Centre, its promotion, and research coordination and different scientific and applied activities in the field of climate change study.

cmcc
Centro Euro-Mediterraneo
sui Cambiamenti Climatici