THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, VERSION 3.6

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1. Resolution

FUND 3.6 is defined for 16 regions, specified in Table R. The model runs from 1950 to 3000 in time-steps of a year.

2. Population and income

Population and per capita income follow exogenous scenarios. There are five standard scenarios, specified in Tables P and Y. The FUND scenario is based on the EMF14 Standardised Scenario, and lies somewhere in between the IS92a and IS92f scenarios (Leggett *et al.*, 1992). The other scenarios follow the SRES A1B, A2, B1 and B2 scenarios (Nakicenovic and Swart, 2001), as implemented in the IMAGE model (IMAGE Team, 2001).

We assume that all regions are in a steady state after the year 2300. For the years 2301-3000per capita income growth rates are constant and equal to the values of the year 2300, while population does not change.

3. Emission, abatement and costs

3.1. Carbon dioxide (CO2)

Carbon dioxide emissions are calculated on the basis of the Kaya identity:

(CO2.1) $$M_{t,r} = \frac{M_{t,r}}{E_{t,r}} \frac{E_{t,r}}{Y_{t,r}} \frac{Y_{t,r}}{P_{t,r}} P_{t,r} =: \psi_{t,r} \varphi_{t,r} Y_{t,r}$$

where M denotes emissions, E denote energy use, Y denotes GDP and P denotes population; t is the index for time, r for region. The carbon intensity of energy use, and the energy intensity of production follow from:

(CO2.2) $$\Psi_{t,r} = g^{\Psi}_{t-1,r} \Psi_{t-1,r} - \alpha_{t-1,r} \tau_{t-1,r}$$

and

(CO2.3) $$\varphi_{t,r} = g^{\varphi}_{t-1,r} \varphi_{t-1,r} - \alpha_{t-1,r} \tau_{t-1,r}$$

where τ is policy intervention and α is a parameter. The exogenous growth rates g are referred to as the Autonomous Energy Efficiency Improvement (AEEI) and the Autonomous

Carbon Efficiency Improvement (ACEI). See Tables AEEI and ACEI for the five alternative scenarios (values for the years 2301-3000 again equal the values for the year 2300). Policy also affects emissions via

(CO2.1') $$M_{t,r} = \left(\psi_{t,r} - \chi^{\psi}_{t,r}\right)\left(\varphi_{t,r} - \chi^{\varphi}_{t,r}\right)Y_{t,r}$$

(CO2.4) $$\chi^{\psi}_{t,r} = \kappa_{\psi}\chi_{t-1,r} + (1-\alpha_{t-1,r})\tau^{\psi}_{t-1,r}$$

and

(CO2.5) $$\chi^{\varphi}_{t,r} = \kappa_{\varphi}\chi_{t-1,r} + (1-\alpha_{t-1,r})\tau^{\varphi}_{t-1,r}$$

Thus, the variable $0<\alpha<1$ governs which part of emission reduction is *permanent* (reducing carbon and energy intensities at all future times) and which part of emission reduction is *temporary* (reducing current energy consumptions and carbon emissions), fading at a rate of $0<\kappa<1$. In the base case, $\kappa_{\psi}=\kappa_{\varphi}=0.9$ and

(CO2.6) $$\alpha_{t,r} = 1 - \frac{\tau_{t,r}/100}{1+\tau_{t,r}/100}$$

So that $\alpha=0.5$ if $\tau=\$100/\text{tC}$. One may interpret the difference between permanent and temporary emission reduction as affecting commercial technologies and capital stocks, respectively. The emission reduction module is a reduced form way of modelling that part of the emission reduction fades away after the policy intervention is reversed, but that another part remains through technological lock-in. Learning effects are described below. The parameters of the model are chosen so that FUND roughly resembles the behaviour of other models, particularly those of the Energy Modeling Forum (Weyant, 2004; Weyant *et al.*, 2006).

The costs of emission reduction C are given by

(CO2.7) $$\frac{C_{t,r}}{Y_{t,r}} = \frac{\beta_{t,r}\tau^2_{t,r}}{H_{t,r}H^g_t}$$

H denotes the stock of knowledge. Equation (CO2.6) gives the costs of emission reduction in a particular year for emission reduction in that year. In combination with Equations (CO2.2)-(CO2.5), emission reduction is cheaper if smeared out over a longer time period. The parameter β follows from

(CO2.8) $$\beta_{t,r} = 0.784 - 0.084\sqrt{\frac{M_{t,r}}{Y_{t,r}} - \min_s \frac{M_{t,s}}{Y_{t,s}}}$$

That is, emission reduction is relatively expensive for the region that has the lowest emission intensity. The calibration is such that a 10% emission reduction cut in 2003 would cost 1.57% (1.38%) of GDP of the least (most) carbon-intensive region; this is calibrated to Hourcade *et al.* (1996, 2001). An 80% (85%) emission reduction would completely ruin the economy. Later emission reductions are cheaper by Equations (CO2.7) and (CO2.8). Emission reduction is relatively cheap for regions with high emission intensities. The thought is that emission reduction is cheap in countries that use a lot of energy and rely heavily on fossil fuels, while other countries use less energy and less fossil fuels and are therefore closer to the technological frontier of emission abatement. For relatively small emission reduction, the costs in *FUND* correspond closely to those reported by other top-down models, but for higher emission reduction, *FUND* finds higher costs, because *FUND* does not include backstop technologies, that is, a carbon-free energy supply that is available in unlimited quantities at fixed average costs.

The regional and global knowledge stocks follow from

(CO2.9) $H_{t,r} = H_{t-1,r} \sqrt{1 + \gamma_R \tau_{t-1,r}}$

and

(CO2.10) $H_t^G = H_{t-1}^G \sqrt{1 + \gamma_G \tau_{t,r}}$

Knowledge accumulates with emission abatement. More knowledge implies lower emission reduction costs. The parameters γ determine which part of the knowledge is kept within the region, and which part spills over to other regions as well. In the base case, γ_R=0.9 and γ_G=0.1. The model is similar in structure and numbers to that of Goulder and Schneider (1999) and Goulder and Mathai (2000).

Emissions from land use change and deforestation are exogenous, and cannot be mitigated. Numbers are found in Tables CO2F, again for five alternative scenarios.

3.2. Methane (CH_4)

Methane emissions are exogenous, specified in Table CH4 (emissions for the years 2301-3000 are equal to emissions in the year 2300). There is a single scenario only, based on IS92a (Leggett *et al.*, 1992). The costs of emission reduction are quadratic. Table OC specifies the parameters, which are calibrated to USEPA (2003).

3.3. Nitrous oxide (N_2O)

Nitrous oxide emissions are exogenous, specified in Table N2O (emissions for the years 2301-3000 are equal to emissions in the year 2300). There is a single scenario only, based on IS92a (Leggett *et al.*, 1992). The costs of emission reduction are quadratic. Table OC specifies the parameters, which are calibrated to USEPA (2003).

3.4. Sulfurhexafluoride (SF_6)

SF_6 emissions are linear in GDP and GDP per capita. Table SF6 gives the parameters. The numbers for 1990 and 1995 are estimated from IEA data (http://data.iea.org/ieastore/product.asp?dept_id=101&pf_id=305). There is no option to reduce SF_6 emissions.

3.5. Sulphur dioxide (SO_2)

Sulphur dioxide emissions follow grow with population (elasticity 0.33), fall with per capita income (elasticity 0.45), and fall with the sum of energy efficiency improvements and decarbonisation (elasticity 1.02). The parameters are estimated on the IMAGE scenarios (IMAGE Team, 2001). There is no option to reduce SO_2 emissions.

3.6. Dynamic Biosphere

Emissions from the terrestrial biosphere follow

(DB.1) $E_t^B = \beta\left(T_t - T_{2010}\right)\frac{B_t}{B_{\max}}$

with

(DB.2) $B_t = B_{t-1} - E_{t-1}^B$

where

- E^B are emissions (in million metric tonnes of carbon);
- t denotes time;
- T is the global mean temperature (in degree Celsius);
- B_t is the remaining stock of potential emissions (in million metric tonnes of carbon, GtC;
- $B_{\max}$ is the total stock of potential emissions; $B_{\max}$ = 1,900 GtC;
- β is a parameter; β = 2.6 GtC/ºC (with a gamma distribution with shape=4.9 and scale=662.8).

The model is calibrated to the review of (Denman et al. 2007). Emissions from the terrestrial biosphere before the year 2010 are zero.

4. Atmosphere and climate

4.1. Concentrations

Methane, nitrous oxide and sulphur hexafluoride are taken up in the atmosphere, and then geometrically depleted:

(C.1) $C_t = C_{t-1} + \alpha E_t - \beta\left(C_{t-1} - C_{pre}\right)$

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table C displays the parameters α and β for all gases. Parameters are taken from Schimel *et al*. (1996).

The atmospheric concentration of carbon dioxide follows from a five-box model:

(C.2a) $Box_{i,t} = \rho_i Box_{i,t} + 0.000471 \alpha_i E_t$

with

(C.2b) $C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to *Box i* (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes (ρ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). The model is due to Maier-Reimer and Hasselmann (1987), its parameters are due to Hammitt *et al.* (1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is—on average—removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

For sulphur, emissions are used rather than concentrations.

4.2. Radiative forcing

Radiative forcing is specified as follows:

(C.3)
$$RF_t = 5.35 \ln \frac{CO2_t}{275} + 0.036\left(\sqrt{CH4_t} - \sqrt{790}\right) + 0.12\left(\sqrt{N2O_t} - \sqrt{285}\right)$$
$$-0.47 \ln(1 + 2.01 \times 10^{-5} CH4_t^{0.75} 285^{0.75} + 5.31 \times 10^{-15} CH4_t^{2.52} 285^{1.52})$$
$$-0.47 \ln(1 + 2.01 + 10^{-5} 790^{0.75} N2O_t^{0.75} + 5.31 \times 10^{-15} 790^{2.52} N2O_t^{1.52})$$
$$+2 \times 0.47 \ln(1 + 2.01 \times 10^{-5} 790^{0.75} 285^{0.75} + 5.31 \times 10^{-15} 790^{2.52} 285^{1.52})$$
$$+0.00052(SF6_t - 0.04) - 0.03 \frac{SO2_t}{14.6} - 0.08 \frac{\ln\left(1 + \frac{SO2_t}{34.4}\right)}{\ln\left(1 + \frac{14.6}{34.4}\right)} + 0.9$$

Parameters are taken from Ramaswamy *et al.* (2001).

4.3. Temperature and sea level rise

The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing RF). In the base case, global mean temperature T rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents, so:

(C.4)
$$T_t = \left(1 - \frac{1}{\varphi}\right) T_{t-1} + \frac{1}{\varphi} \frac{CS}{5.35 \ln 2} RF_t$$

where CS is climate sensitivity, set to 3.0 (with a gamma distribution with shape=6.48 and scale=0.55). φ is the e-folding time and set to

(C.5)
$$\varphi = \max(\alpha + \beta^l CS + \beta^q CS^2, 1)$$

where α is set to -31.9 (0.12), β^l is set to 32.7 (0.03) and β^q is set to -0.00993 (0.001568), such that the best guess e-folding time for a climate sensitvitiy of 3.0 is 66 years.

Regional temperature is derived by multiplying the global mean temperature by a fixed factor (see Table RT) which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000).

Global mean sea level is also geometric, with its equilibrium level determined by the temperature and a life-time of 500 years:

(C.6)
$$S_t = \left(1 - \frac{1}{\rho}\right) S_{t-1} + \gamma T_t$$

where ρ = 500 (with a triangular distribution bounded by 250 and 1000) is the e-folding time. γ = 2 (with a gamma distribution with shape=6 and scale=0.4) is sea-level sensitivity to temperature.

Temperature and sea level are calibrated to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

5. Impacts

5.1. Agriculture

The impacts of climate change on agriculture at time t in region r are split into three parts: impacts due to the rate of climate change $A_{t,r}^r$; impacts due to the level of climate change $A_{t,r}^l$; and impacts from carbon dioxide fertilisation $A_{t,r}^f$:

(A.1)
$$A_{t,r} = A_{t,r}^r + A_{t,r}^l + A_{t,r}^f$$

The first part (rate) is always negative: As farmers have imperfect foresight and are locked into production practices, climate change implies that farmers are maladapted. Faster climate change means greater damages. The third part (fertilization) is always positive. CO_2 fertilization means that plants grow faster and use less water. The second part (level) can be positive or negative. There is an optimal climate for agriculture. If climate change moves a region closer to (away from) the optimum, impacts are positive (negative); and impacts are smaller nearer to the optimum.

For the impact of the rate of climate change (i.e., the annual change of climate) on agriculture, the assumed model is:

(A.2) $$A^r_{t,r} = \alpha_r \left(\frac{\Delta T_t}{0.04}\right)^\beta + \left(1 - \frac{1}{\rho}\right) A^r_{t-1,r}$$

where

- A^r denotes damage in agricultural production as a fraction due the rate of climate change by time and region;
- t denotes time;
- r denotes region;
- ΔT denotes the change in the regional mean temperature (in degrees Celsius) between time t and $t-1$;
- α is a parameter, denoting the regional change in agricultural production for an annual warming of 0.04°C (see Table A, column 2-3);
- β = 2.0 (1.5-2.5) is a parameter, equal for all regions, denoting the non-linearity of the reaction to temperature; β is an expert guess;
- ρ = 10 (5-15) is a parameter, equal for all regions, denoting the speed of adaptation; ρ is an expert guess.

The model for the impact due to the level of climate change since 1990 is:

(A.3) $$A^l_{t,r} = \delta^l_r T_t + \delta^q_r T^2_t$$

where

- A^l denotes the damage in agricultural production as a fraction due to the level of climate change by time and region;
- t denotes time;
- r denotes region;
- T denotes the change (in degree Celsius) in regional mean temperature relative to 1990;
- δ^l_r and δ^q_r are parameters (see Table A), that follow from the regional change (in per cent) in agricultural production for a warming of 2.5°C above today or 3.2°C above pre-industrial and the the optimal temperature (in degree Celsius) for agriculture in each region.

CO_2 fertilisation has a positive, but saturating effect on agriculture, specified by

(A.4) $$A^f_{t,r} = \gamma_r \ln \frac{CO2_t}{275}$$

where

- A^f denotes damage in agricultural production as a fraction due to the CO2 fertilisation by time and region;
- t denotes time;
- r denotes region;
- $CO2$ denotes the atmospheric concentration of carbon dioxide (in parts per million by volume);
- 275 ppm is the pre-industrial concentration;
- γ is a parameter (see Table A, column 8-9).

The parameters in Table A are calibrated, following the procedure described in Tol (2002a), to the results of Kane *et al*. (1992), Reilly *et al*. (1994), Morita *et al*. (1994), Fischer *et al*. (1996), and Tsigas *et al*. (1996). These studies all use a global computable general equilibrium model, and report results with and without adaptation, and with and without CO_2 fertilisation. The regional results from these studies are assumed to hold for each country in the respective regions. They are averaged over the studies and the climate scenarios for each country, and aggregated to the *FUND* regions. The standard deviations in Table A follow from the spread between studies and scenarios. Equation (A.4) follows from the difference in results with and without CO2 fertilization. Equation (A.3) follows from the results with full adaptation. Equation (A.2) follows from the difference in results with and without adaptation.

Equations (A.1-4) express the impact of climate change as a percentage of agricultural production. In order to express this as a percentage of income, we need to know the share of agricultural production in total income. This is assumed to fall with per capita income, that is,

(A.5) $$\frac{GAP_{t,r}}{Y_{t,r}} = \frac{GAP_{1990,r}}{Y_{1990,r}}\left(\frac{y_{1990,r}}{y_{t,r}}\right)^{\epsilon}$$

where

- GAP denotes gross agricultural product (in 1995 US dollar per year) by time and region;
- Y denotes gross domestic product (in 1995 US dollar per year) by time and region;
- y denotes gross domestic product per capita (in 1995 US dollar per person per year) by time and region;
- t denotes time;
- r denotes region;
- ϵ = 0.31 (0.15-0.45) is a parameter; it is the income elasticity of the share of agriculture in the economy; it is taken from Tol (2002b), who regressed the regional share in agriculture on per capita income, using 1995 data from the World Resources Institute (http://earthtrends.wri.org).

5.2. Forestry

The model is:

$$F_{t,r} = \alpha_r \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\varepsilon} \left(0.5 \left(\frac{T_t}{1.0} \right)^{\beta} + 0.5 \gamma \ln \left(\frac{CO_{2,t}}{275} \right) \right) \tag{F.1}$$

where

- F denotes the change in forestry consumer and producer surplus (as a share of total income);
- t denotes time;
- r denotes region;
- y denotes per capita income (in 1995 US dollar per person per year);
- T denotes the global mean temperature (in degree centigrade);
- α is a parameter, that measures the impact of climate change of a 1ºC global warming on economic welfare; see Table EFW;
- ε = 0.31 (0.11-0.51) is a parameter, and equals the income elasticity for agriculture;
- β = 1 (0.5-1.5) is a parameter; this is an expert guess;
- γ = 0.44 (0.29-0.87) is a parameter; γ is such that a doubling of the atmospheric concentration of carbon dioxide would lead to a change of forest value of 15% (10-30%); this parameter is taken from Gitay *et al*., (2001).

The parameter α is estimated as the average of the estimates by Perez-Garcia *et al*. (1995) and Sohngen *et al*. (2001). Perez-Garcia *et al*. (1995) present results for four different climate scenarios and two management scenarios, while Sohngen *et al*. (2001) use two different climate scenario and two alternative ecological scenarios. The results are mapped to the FUND regions assuming that the impact is uniform elative to GDP. The impact is averaged within the study results, and then the weighted average between the two studies is computed and shown in Table EFW. The standard deviation follows.

5.3. Water resources

The impact of climate change on water resources follows:

$$W_{t,r} = \min \left\{ \alpha_r Y_{1990,r} (1-\tau)^{t-2000} \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\beta} \left(\frac{P_{t,r}}{P_{1990,r}} \right)^{\eta} \left(\frac{T_t}{1.0} \right)^{\gamma}, \frac{Y_{t,r}}{10} \right\} \tag{W.1}$$

where

- W denotes the change in water resources (in 1995 US dollar) at time t in region r;
- t denotes time;
- r denotes region;
- y denotes per capita income (in 1995 US dollar) at time t in region r;
- P denotes population at time t in region r;
- T denotes the global mean temperature above pre-industrial (in degree Celsius) at time t;

- α is a parameter (in percent of 1990 GDP per degree Celsius) that specifies the benchmark impact; see Table EFW;
- β = 0.85 (0.15, >0) is a parameter, that specifies how impacts respond to economic growth;
- η = 0.85 (0.15,>0) is a parameter that specifies how impacts respond to population growth;
- γ = 1 (0.5,>0) is a parameter, that determines the response of impact to warming;
- τ = 0.005 (0.005, >0) is a parameter, that measures technological progress in water supply and demand.

These parameters are from calibrating *FUND* to the results of Downing *et al*. (1995, 1996).

5.4. Energy consumption

For space heating, the model is:

(E.1)
$$SH_{t,r} = \alpha_r Y_{1990,r} \frac{\operatorname{atan} T_t}{\operatorname{atan} 1.0} \left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon} \left(\frac{P_{t,r}}{P_{1990,r}}\right) \Bigg/ \prod_{s=1990}^{t} AEEI_{s,r}$$

where

- SH denotes the decrease in expenditure on space heating (in 1995 US dollar) at time t in region r;
- t denotes time;
- r denotes region;
- Y denotes income (in 1995 US dollar) at time t in region r;
- T denotes the change in the global mean temperature relative to 1990 (in degree Celsius) at time t;
- y denotes per capita income (in 1995 US dollar per person per year) at time t in region r;
- P denotes population size at time t in region r;
- α is a parameter (in dollar per degree Celsius), that specifies the benchmark impact; see Table EFW, column 6-7
- ϵ is a parameter; it is the income elasticity of space heating demand; ϵ = 0.8 (0.1,>0,<1);
- $AEEI$ is a parameter (cf. Tables AEEI and Equation CO2.3); it is the Autonomous Energy Efficiency Improvement, measuring technological progress in energy provision; the global average value is about 1% per year in 1990, converging to 0.2% in 2200; its standard deviation is set at a quarter of the mean.

These parameters are from calibrating *FUND* to the results of Downing *et al*. (1995, 1996). Savings on space heating are assumed to saturate. The income elasticity of heating demand is taken from Hodgson and Miller (1995, cited in Downing *et al*., 1996), and estimated for the UK. Space heating demand is linear in the number of people for want of scenarios of number of households and house sizes. Energy efficiency improvements in space heating are assumed to be equal to the average energy efficiency improvements in the economy.

For space cooling, the model is:

(E.2)
$$SC_{t,r} = \alpha_r Y_{1990,r} \left(\frac{T_t}{1.0}\right)^{\beta} \left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon} \left(\frac{P_{t,r}}{P_{1990,r}}\right) \Bigg/ \prod_{s=1990}^{t} AEEI_{s,r}$$

where

- SC denotes the increase in expenditure on space cooling (1995 US dollar) at time t in region r;
- t denotes time;
- r denotes region;
- Y denotes income (in 1995 US dollar) at time t in region r;
- T denotes the change in the global mean temperature relative to 1990 (in degree Celsius) at time t;
- y denotes per capita income (in 1995 US dollar per person per year) at time t in region r;
- P denotes population size at time t in region r;
- α is a parameter (see Table EFW, column 8-9);
- β is a parameter; β = 1.5 (1.0-2.0);
- ϵ is a parameter; it is the income elasticity of space heating demand; ϵ = 0.8 (0.6-1.0);
- $AEEI$ is a parameter (cf. Tables AEEI and Equation CO2.3) ; it is the Autonomous Energy Efficiency Improvement, measuring technological progress in energy provision; the global average value is about 1% per year in 1990, converging to 0.2% in 2200; its standard deviation is set at a quarter of the mean.

These parameters are from calibrating *FUND* to the results of Downing *et al*. (1995, 1996). Space cooling is assumed to be more than linear in temperature because cooling demand accelerates as it gets warmer. The income elasticity of cooling demand is taken from Hodgson and Miller (1995, cited in Downing *et al*., 1996), and estimated for the UK. Space cooling demand is linear in the number of people for want of scenarios of number of households and house sizes. Energy efficiency improvements in space cooling are assumed to be equal to the average energy efficiency improvements in the economy.

5.5. Sea level rise

Table SLR shows the accumulated loss of drylands and wetlands for a one metre rise in sea level. The data are taken from Hoozemans et al. (1993), supplemented by data from Bijlsma et al. (1995), Leatherman and Nicholls (1995) and Nicholls and Leatherman (1995), following the procedures of Tol (2002a).

Land loss without protection is assumed to be a function of sea level rise:

(SLR.1)
$$D_{t,r} = \min\left[\delta_r\left(S_t^{\gamma_r} - S_{t-1}^{\gamma_r}\right), \zeta_r\right]$$

where

- $D_{t,r}$ is the dryland lost at time t in region r;
- t denotes time;

- r denotes region;
- δ_r is the annual unit dryland loss due to sea level rise (in square kilometre per metre) in region r; note that is assumed to be constant over time;
- S_t is sea level rise above pre-industrial levels at time t; note that is assumed to equal for all regions;
- γ_r is a parameter, calibrated to a digital elevation model;
- ζ_r is the maximum dryland loss in region r, which is equal to the area in the year 2000.

The value of dryland is assumed to be linear in income density ($/km^2):

(SLR.2) $$VD_{t,r} = \varphi \left(\frac{Y_{t,r} / A_{t,r}}{YA_0} \right)^{\varepsilon}$$

where

- *VD* is the unit value of dryland (in million dollar per square kilometre) at time *t* in region *r*;
- *t* denotes time;
- *r* denotes region;
- *Y* is the total income (in billion dollar) at time *t* in region *r*;
- *A* is the area (in square kilometre) at time *t* of region *r*;
- φ is a parameter; φ = 4 (2,>0) million dollar per square kilometre (Darwin *et al.*, 1995);
- YA_0=0.635 (million dollar per square kilometre) is a normalisation constant, the average incomde density of the OECD in 1990;
- ε is a parameter, the income density elasticity of land value; ε = 1 (0.25).

Wetland loss is assumed to be a linear function of sea level rise:

(SLR.3) $$W_{t,r} = \omega_r^S \Delta S_t + \omega_r^M P_{t,r} \Delta S_t$$

where

- $W_{t,r}$ is the wetland lost at time *t* in region *r*;
- *t* denotes time;
- *r* denotes region;
- $P_{t,r}$ is fraction of coast protected against sea level rise at time *t* in region *r*;
- ΔS_t is sea level rise at time *t*; note that is assumed to equal for all regions;
- ω^S is a parameter, the annual unit wetland loss due to sea level rise (in square kilometre per metre) in region *r*; note that is assumed to be constant over time;
- ω^M is a parameter, the annual unit wetland loss due to coastal squeeze (in square kilometre per metre) in region *r*; note that is assumed to be constant over time.

Cumulative wetland loss is given by

(SLR.4) $W_{t,r}^{C} = \min\left(W_{t-1,r}^{C} + W_{t-1,r}, W_{r}^{M}\right)$

where

- W^C is cumulative wetland loss (in square kilometre) at time t in region r
- W^M is a parameter, the total amount of wetland that is exposed to sea level rise; this is assumed to be smaller than the total amount of wetlands in 1990.

Wetland loss (SLR.3) goes to zero if all wetland threatened by sea-level rise in a region is lost.

Wetland value is assumed to increase with income and population density, and fall with wetland size:

(SLR.5) $$VW_{t,r} = \alpha \left(\frac{y_{t,r}}{y_0}\right)^{\beta} \left(\frac{d_{t,r}}{d_0}\right)^{\gamma} \left(\frac{W_{1990,r} - W_{t,r}^{C}}{W_{1990,r}}\right)^{\delta}$$

where

- VW is the wetland value (in dollar per square kilometre) at time t in region r;
- t denotes time;
- r denotes region;
- y is per capita income (in dollar per person per year) at time t in region r;
- d is population density (in person per square kilometre) at time t in region r;
- W^C is cumulative wetland loss (in square kilometre) at time t in region r;
- W_{1990} is the total amount of wetlands in 1990 in region r;
- α is a parameter, the net present value of the future stream of wetland services; note that we thus account present and future wetland values in the year that the wetland is lost; $\alpha = \alpha' \frac{1+\rho+\eta g_{t,r}}{\rho+\eta g_{t,r}} = \alpha' \frac{1+0.03+1\times0.02}{0.03+1\times0.02} = 21\alpha'$
- α' = 280,000 \$/km^2, with a standard deviation of 187,000 \$/km^2; α is the average of the meta-analysis of Brander et al. (2006); the standard deviation is based on the coefficient of variation of the intercept in their analysis;
- β is a parameter, the income elasticity of wetland value; β = 1.16 (0.46,>0); this value is taken from Brander et al. (2006);
- y_0 is a normalisation constant; y_0 = 25,000 \$/p/yr (Brander, personal communication);
- d_0 is a normalisation constant; d_0 = 27.59;
- γ is a parameter, the population density elasticity of wetland value; γ = 0.47 (0.12,>0,<1); this value is taken from Brander et al. (2006);
- δ is a parameter, the size elasticity of wetland value; δ = -0.11 (0.05,>-1,<0); this value is taken from Brander et al. (2006);

If dryland gets lost, the people living there are forced to move. The number of forced migrants follows from the amount of land lost and the average population density in the region. The value of this is set at 3 (1.5,>0) times the regional per capita income per migrant (Tol, 1995). In the receiving country, costs equal 40% (20%,>0) of per capita income per migrant (Cline, 1992).

Table SLR displays the annual costs of fully protecting all coasts against a one metre sea level rise in a hundred years time. If sea level would rise slower, annual costs are assumed to be proportionally lower; that is, costs of coastal protection are linear in sea level rise. The level of protection, that is, the share of the coastline protected, is based on a cost-benefit analysis:

$$\text{(SLR.6)}\quad P_{t,r} = \max\left\{0, 1 - \frac{1}{2}\left(\frac{\mathrm{NPV}VP_{t,r} + \mathrm{NPV}VW_{t,r}}{\mathrm{NPV}VD_{t,r}}\right)\right\}$$

where

- P is the fraction of the coastline to be protected;
- NPV*VP* is the net present value of the protection if the whole coast is protected (defined below);
- NPV*VW* is the net present value of the wetland lost due to coastal squeeze if the whole coast is protected (defined below);
- NPV*VD* is the net present value of the land lost without any coastal protection (defined below).

Equation (SLR.6) is due to Fankhauser (1994). See below.

Table SLR reports average costs per year over the next century. NPV*VP* is calculated assuming annual costs to be constant. This is based on the following. Firstly, the coastal protection decision makers anticipate a linear sea level rise. Secondly, coastal protection entails large infrastructural works which last for decades. Thirdly, the considered costs are direct investments only, and technologies for coastal protection are mature. Throughout the analysis, a pure rate of time preference, ρ, of 1% per year is used. The actual discount rate lies thus 1% above the growth rate of the economy, g. The net present costs of protection *PC* equal

$$\text{(SLR.7)}\quad \mathrm{NPV}VP_{t,r} = \sum_{s=t}^{\infty}\left(\frac{1}{1+\rho+\eta g_{t,r}}\right)^{s-t}\pi_r \Delta S_t = \frac{1+\rho+\eta g_{t,r}}{\rho+\eta g_{t,r}}\pi_r \Delta S_t$$

where

- NPV*VP* is the net present costs of coastal protection at time t in region r;
- t denotes time;
- r denotes region;
- π_r is the annual unit cost of coastal protection (in million dollar per vertical metre) in region r; note that is assumed to be constant over time;
- ΔS_t is sea level rise at time t; note that is assumed to equal for all regions;
- g is the growth rate of per capita income at time t in region r;
- ρ is a parameter, the rate of pure time preference; ρ = 0.03;
- η is a parameter, the consumption elasticity of marginal utility; η = 1;

NPV*VW* is the net present value of the wetlands lost due to full coastal protection. Wetland values are assumed to rise in line with Equation (SLR.4). All growth rates and the rate of wetland loss are as in the current year. The net present costs of wetland loss *WL* follow from

(SLR.8)
$$NPV\,VW_{t,r} = \sum_{s=t}^{\infty} W_{t,r} VW_{s,r} \left(\frac{1}{1+\rho+\eta g_{t,r}} \right)^{s-t} =$$
$$W_{t,r} VW_{t,r} \frac{1+\rho+\eta g_{t,r}}{\rho+\eta g_{t,r} - \beta g_{t,r} - \gamma p_{t,r} - \delta w_{t,r}}$$

where

- NPV*VW* denotes the net present value of wetland loss. at time *t* in region *r*;
- *t* denotes time;
- *r* denotes region;
- ω_r is the annual unit wetland loss due to full coastal protection (in square kilometre per metre sea level rise) in region *r*; note that is assumed to be constant over time;
- ΔS_t is sea level rise at time *t*; note that is assumed to equal for all regions;
- *g* is the growth rate of per capita income at time *t* in region *r*;
- *p* is the population growth rate at time *t* in region *r*;
- *w* is the growth rate of wetland at time *t* in region *r*; note that wetlands shrink, so that $w < 0$;
- ρ is a parameter, the rate of pure time preference; $\rho = 0.03$;
- η is a parameter, the consumption elasticity of marginal utility; $\eta = 1$;
- β is a parameter, the income elasticity of wetland value; $\beta = 1.16$ (0.46,>0); this value is taken from Brander et al. (2006);
- γ is a parameter, the population density elasticity of wetland value; $\gamma = 0.47$ (0.12,>0,<1); this value is taken from Brander et al. (2006);
- δ is a parameter, the size elasticity of wetland value; $\beta = -0.11$ (0.05,>-1,<0); this value is taken from Brander et al. (2006);

NPV*VD* denotes the net present value of the dryland lost if no protection takes place. Land values are assumed to rise at the rate of income growth. All growth rates and the rate of wetland loss are as in the current year. The net present costs of dryland loss are

(SLR.9) $$NPV\,VD_{t,r} = \sum_{s=t}^{\infty} D_{t,r} VD_{t,r} \left(\frac{1+\varepsilon y d_{t,r}}{1+\rho+\eta g_{t,r}} \right)^{s-t} = D_{t,r} VD_{t,r} \frac{1+\rho+\eta g_{t,r}}{\rho+\eta g_{t,r} - \varepsilon y d_{t,r}}$$

where

- NPV*VD* is the net present value of dryland loss at time *t* in region *r*;
- *t* denotes time;
- *r* denotes region;
- *D* is the current dryland loss without protection at time t in region r;
- *VD* is the current dryland value;
- *g* is the growth rate of per capita income at time *t* in region *r*;
- ρ is a parameter, the rate of pure time preference; $\rho = 0.03$;

- η is a parameter, the consumption elasticity of marginal utility; η = 1;
- ε is a parameter, the income elasticity of dryland value; ε = 1.0, with a standard deviation of 0.2;
- d is the current income density growth rate at time in region r

Protection levels are bounded between 0 and 1.

5.6. Ecosystems

Tol (2002a) assesses the impact of climate change on ecosystems, biodiversity, species, landscape *etcetera* based on the "warm-glow" effect. Essentially, the value, which people are assumed to place on such impacts, are independent of any real change in ecosystems, of the location and time of the presumed change, *etcetera* – although the probability of detection of impacts by the “general public” is increasing in the rate of warming. This value is specified as

(E.1) $$E_{t,r} = \alpha P_{t,r} \frac{y_{t,r}/y_r^b}{1+y_{t,r}/y_r^b} \frac{\Delta T_t/\tau}{1+\Delta T_t/\tau}\left(1-\sigma+\sigma\frac{B_0}{B_t}\right)$$

where

- E denotes the value of the loss of ecosystems (in 1995 US dollar) at time t in region r;
- t denotes time;
- r denotes region;
- y denotes per capita income (in 1995 dollar per person per year) at time t in region r;
- P denotes population size (in millions) at time t in region r;
- ΔT denotes the change in temperature (in degree Celsius);
- B is the number of species, which makes that the value increases as the number of species falls – using Weitzman’s (1998) ranking criterion and Weitzman’s (1992, 1993) biodiversity index, the scarcity value of biodiversity is inversely proportional to the number of species;
- α=50 (0-100, >0) is a parameter such that the value equals \$50 per person if per capita income equals the OECD average in 1990 (Pearce and Moran, 1994);
- y^b = is a parameter; y^b = \$30,000, with a standard deviation of \$10,000; it is normally distributed, but knotted at zero.
- τ=0.025ºC is a parameter;
- σ=0.05 (triangular distribution,>0,<1) is a parameter, based on an expert guess; and
- B_0=14,000,000 is a parameter.

The number of species follows

(E.2) $$B_t = \max\left\{\frac{B_0}{100}, B_{t-1}\left(1-\rho-\gamma\frac{\Delta T^2}{\tau^2}\right)\right\}$$

where

- ρ = 0.003 (0.001-0.005, >0.0) is a parameter;

- γ = 0.001 (0.0-0.002, >0.0) is a parameter; and

These parameters are expert guesses. The number of species is assumed to be constant until the year 2000 at 14,000,000 species.

5.7. Human health: Diarrhoea

The number of additional diarrhoea deaths $D^d_{r,t}$ in region *r* and time *t* is given by

$$\text{(HD.1)}\quad D^d_{t,r} = \mu^d_r P_{t,r} \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\varepsilon} \left(\frac{T_{t,r}}{T_{pre-industrial,r}} \right)^{\eta}$$

where

- $P_{r,t}$ denotes population,
- *r* indexes region
- *t* indexes time,
- $y_{r,t}$ is the per capita income in region *r* and year *t* in 1995 US dollars,
- $T_{r,t}$ is regional temperature in year *t*, in degrees Celcius (C);
- μ_r^d is the rate of mortality from diarrhoea in 2000 in region r, taken from the WHO Global Burden of Disease (see Table HD, column 3);
- ε = -1.58 (0.23)is the income elasticity of diarrhoea mortality
- η = 1.14 (0.51) is a parameter, the degree of non-linearity of the response of diarrhoea mortality to regional warming.

Equation (HD.1), specifically parameters ε and η, was estimated based on the WHO Global Burden of Diseases data (http://www.who.int/health_topics/global_burden_of_disease/en/). Diarrhoea morbidity has the same equation as mortality, but with ε=-0.42 (0.12) and η=0.70 (0.26); base morbidity is given in Table HD, column 4. Table HD gives impact estimates, ignoring economic and population growth.

See section 5.12. for a description of the valuation of mortality and morbidity.

5.8. Human health: Vector-borne diseases

The number of additional deaths from vector-borne diseases, $D^v_{r,t}$ is given by:

$$\text{(HV)}\quad D^v_{t,r} = D^v_{1990,r} \alpha^v_r \left(T_t - T_{1990} \right)^{\beta} \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\gamma}$$

where

- $D^v_{t,r}$ denotes climate-change-induced mortality due to disease *v* in region *r* at time *t*;
- $D^v_{1990,r}$ denotes mortality from vector-borne diseases in region *r* in 1990 (see Table HV, column "base");
- *t* denotes time;

- r denotes region;
- v denotes vector-borne disease (malaria, schistosomiasis, dengue fever);
- α is a parameter, indicating the benchmark impact of climate change on vector-borne diseases (see Table HV, column "impact"); the best guess is the average of Martin and Lefebvre (1995), Martens *et al.* (1995, 1997) and Morita *et al.* (1995), while the standard deviation is the spread between models and the scenarios.
- $y_{r,t}$ denotes per capita income;
- T_t denotes the regional mean temperature in year t, in degrees Celcius (C);
- β = 1.0 (0.5) is a parameter, the degree of non-linearity of mortality in warming; the parameter is calibrated to the results of Martens *et al*. (1997);
- γ = -2.65 (0.69) is the income elasticity of vector-borne mortality, taken from Link and Tol (2004), who regress malaria mortality on income for the 14 WHO regions..

See section 5.12. for a description of the valuation of mortality and morbidity. Morbidity is proportional to mortality, using the factor specified in Table HM.

5.9. Human health: Cardiovascular and respiratory mortality

Cardiovascular and respiratory disorders are worsened by both extreme cold and extreme hot weather. Martens (1998) assesses the increase in mortality for 17 countries. Tol (2002a) extrapolates these findings to all other countries, based on formulae of the shape:

(HC.1) $$D^c = \alpha^c + \beta^c T_B$$

where

- D^c denotes the change in mortality (in deaths per 100,000 people) due to a one degree global warming;
- c indexes the disease (heat-related cardiovascular under 65, heat-related cardiovascular over 65, cold-related cardiovascular under 65, cold-related cardiovascular over 65, respiratory);
- T_B is the current temperature of the hottest or coldest month in the country (in degree Celsius);
- α and β are parameters, specified in Table HC.1.

Equation (HC.1) is specified for populations above and below 65 years of age for cardiovascular disorders. Cardiovascular mortality is affected by both heat and cold. In the case of heat, T_B denotes the average temperature of the warmest month. In the case of cold, T_B denotes the average temperature of the coldest month. Respiratory mortality is not age-specific.

Equation (HC.1) is readily extrapolated. With warming, the baseline temperature T_B changes. If this change is proportional to the change in the global mean temperature, the equation becomes quadratic. Summing country-specific quadratic functions results in quadratic functions for the regions:

(HC.2) $$D_{t,r}^c = \alpha_r^c T_t + \beta_r^c T_t^2$$

where

- $D_{t,r}^{c}$ denotes climate-change-induced mortality (in deaths per 100,000 people) due to disease *c* in region *r* at time *t*;
- *c* indexes the disease (heat-related cardiovascular under 65, heat-related cardiovascular over 65, cold-related cardiovascular under 65, cold-related cardiovascular over 65, respiratory);
- *r* indexes region;
- *t* indexes time;
- *T* denotes the change in regional mean temperature (in degree Celsius);
- α and β are parameters, specified in Tables HC.2-4 (in probabilistic mode all probablitiy distributions are constrained so that only values with the same sign as the mean can be sampled).

One problem with (HC.2) is that it is a non-linear extrapolation based on a data-set that is limited to 17 countries and, more importantly, a single climate change scenario. A global warming of 1°C leads to changes in cardiovascular and respiratory mortality in the order of magnitude of 1% of baseline mortality due to such disorders. Per cause, the total change in mortality is restricted to a maximum of 5% of baseline mortality, an expert guess. This restriction is binding. Baseline cardiovascular and respiratory mortality derives from the share of the population above 65 in the total population.

If the fraction of people over 65 increases by 1%, cardiovascular mortality increases by 0.0259% (0.0096%). For respiratory mortality, the change is 0.0016% (0.0005%). These parameters are estimated from the variation in population above 65 and cardiovascular and respiratory mortality over the nine regions in 1990, using data from http://www.who.int/health_topics/global_burden_of_disease/en/.

Mortality as in equations (HC.1) and (HC.2) is expressed as a fraction of population size. Cardiovascular mortality, however, is separately specified for younger and older people. In 1990, the per capita income elasticity of the share of the population over 65 is 0.25 (0.08). This is estimated using data from http://earthtrends.wri.org

Heat-related mortality is assumed to be limited to urban populations. Urbanisation is a function of per capita income and population density:

(HC.3) $$U_{t,r} = \frac{\alpha\sqrt{y_{t,r}} + \beta\sqrt{PD_{t,r}}}{1 + \alpha\sqrt{y_{t,r}} + \beta\sqrt{PD_{t,r}}}$$

where

- *U* is the fraction of people living in cities;
- *y* is per capita income (in 1995 US$ per person per year);
- *PD* is population density (in people per square kilometre);
- *t* is time;
- *r* is region;
- α and β are parameters, estimated from a cross-section of countries for the year 1995, using data from http://earthtrends.wri.org; α=0.031 (0.002) and β=-0.011 (0.005); R^2=0.66.

See section 5.12. for a description of the valuation of mortality and morbidity. Morbidity is proportional to mortality, using the factor specified in Table HM.

5.10. Extreme weather: Tropical storms

The economic damage *TD* due to an increase in the intensity of tropical storms (hurricanes, typhoons) follows

$$\text{(TS.1)}\quad TD_{t,r} = \alpha_r Y_{t,r} \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\varepsilon} \left[\left(1 + \delta T_{t,r}\right)^{\gamma} - 1 \right]$$

where

- t denotes time;
- r denotes region
- TD is the damage due to tropical storms (1995 US$ per year) in region r at time t;
- Y is the gross domestic product (in 1995 US$ per year) in region r at time t;
- α is the current damage as fraction of GDP, specified in Table TS; the data are from the CRED EM-DAT database; http://www.emdat.be/;
- y is per capita income (in 1995 US$ per person per year) in region r at time t;
- ε is the income elasticity of storm damage; ε = -0.514 (0.027;>-1,<0) after Toya and Skidmore (2007);
- δ is a parameter, indicating how much wind speed increases per degree warming; δ=0.04/°C (0.005) after WMO (2006);
- T is the temperature increase since pre-industrial times (in degree Celsius) in region r at time t;
- γ is a parameter; γ=3 because the power of the wind in the cube of its speed.

The mortality *TM* due to an increase in the intensity of tropical storms (hurricanes, typhoons) follows

$$\text{(TS.2)}\quad TM_{t,r} = \beta_r P_{t,r} \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\eta} \left[\left(1 + \delta T_{t,r}\right)^{\gamma} - 1 \right]$$

where

- t denotes time;
- r denotes region
- TM is the mortality due to tropical storms (in people per year) in region r at time t;
- P is the population (in people) in region r at time t;
- β is the current mortality (as a fraction of population), specified in Table TS; the data are from the CRED EM-DAT database; http://www.emdat.be/;
- y is per capita income (in 1995 US$ per person per year) in region r at time t;
- η is the income elasticity of storm damage; η = -0.501 (0.051;<0) after Toya and Skidmore (2007);

- δ is parameter, indicating how much wind speed increases per degree warming; δ=0.04/ºC (0.005) after WMO (2006);
- T is the temperature increase since pre-industrial times (in degree Celsius) in region r at time t;
- γ is a parameter; γ=3 because the power of the wind in the cube of its speed.

See section 5.12. for a description of the valuation of mortality and morbidity.

5.11. Extreme weather: Extratropical storms

The economic damage due to an increase in the intensity of extratropical storms follows the equation below:

(ETS.1) $$ETD_{t,r} = \alpha_r Y_{t,r}\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\varepsilon}\delta_r\left[\left(\frac{C_{CO2,t}}{C_{CO2,pre}}\right)^{\gamma}-1\right]$$

where

- $ETD_{t,r}$ is the damage from extratropical cyclones at time t in region r;
- $Y_{t,r}$ is GDP in region r and time t;
- α_r is benchmark damage from extratropical cyclones for region r;
- y is per capita income at time t in region r;
- ε=-0.514(0.027,>-1,<0) is the income elasticity of extratropical storm damages (Toya and Skidmore 2007);
- δ_r is the storm sensitivity to atmospheric CO2 concentrations for region r;
- $C_{CO2,t}$ is atmospheric CO_2 concentrations;
- $C_{CO2,pre}$ is the CO_2 concentrations in the pre-industrial era;
- γ=1 is a parameter.

(EST.2) $$ETM_{t,r} = \beta_r P_{t,r}\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\varphi}\delta_r\left[\left(\frac{C_{CO2,t}}{C_{CO2,pre}}\right)^{\gamma}-1\right]$$

where

- $ETM_{t,r}$ is the mortality from extratropical cyclones at time t in region r;

- $P_{t,r}$ is population in region *r* and time *t*;
- β_r is benchmark mortality from extratropical cyclones for region r;
- y is per capita income at time t in region r;
- φ=-0.501(0.051,>-1,<0) is the income elasticity of extratropical storm mortality (Toya and Skidmore 2007);
- δ_r is the storm sensitivity to atmospheric CO2 concentrations for region r;
- $C_{CO2,t}$ is atmospheric CO_2 concentrations;
- $C_{CO2,\,pre}$ is the CO_2 concentrations in the pre-industrial era;
- γ=1 is a parameter.

See section 5.12. for a description of the valuation of mortality and morbidity.

5.12. Mortality and Morbidity

The value of a statistical life is given by

(MM.1) $$VSL_{t,r} = \alpha \left(\frac{y_{t,r}}{y_0} \right)^{\varepsilon}$$

where

- *VSL* is the value of a statistical life at time *t* in region *r*;
- α=4992523 (2496261,>0) is a parameter;
- *y* is per capita income at time *t* in region *r*;
- y_0=24963 is a normalisation constant;
- ε=1 (0.2,>0) is the income elasticity of the value of a statistical life;

This calibration results in a best guess value of a statistical life that is 200 times per capita income (Cline, 1992).

The value of a year of morbidity is given by

(MM.2) $$VM_{t,r} = \beta \left(\frac{y_{t,r}}{y_0} \right)^{\eta}$$

where

- *VM* is the value of a statistical life at time *t* in region *r*;
- β= 19970 (29955,>0) is a parameter;

- y is per capita income at time t in region r;
- y_0=24963 is a normalisation constant;
- η=1 (0.2,>0) is the income elasticity of the value of a year of morbidity;

This calibration results in a best guess value of a year of morbidity that is 0.8 times per capita income (Navrud, 2001).

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