THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, VERSION 2.8

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Resolution

FUND2.9 is defined for 16 regions, specified in Table R. The model runs from 1950 to 2300 in time-steps of a year.

Population and income

Population and per capita income follow exogenous scenarios. There are five standard scenarios, specified in Tables P and Y.

Emission, abatement and costs

Carbon dioxide (CO_2)

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

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

where M denotes emissions, E denote energy use, Y denotes GPD 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) $$\psi_{r,t} = g^{\psi}_{r,t-1} \psi_{r,t-1} - \alpha \tau^{\psi}_{r,t-1}$$

and

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

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. Policy also affects emissions via

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

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

and

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

Thus, the parameter $0<\alpha<1$ 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, $\alpha=0.5$, $\kappa_\psi=\kappa_\varphi=0.9$. Alternatively, 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 costs of emission reduction C are given by

(CO2.6) $$\frac{C_{r,t}}{Y_{r,t}}=\frac{\beta_{r,t}\tau_{r,t}^2}{H_{r,t}H_t^g}$$

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

(CO2.7) $$\beta_{r,t}=1.57-0.17\sqrt{\frac{M_{r,t}}{Y_{r,t}}-\min_s\frac{M_{s,t}}{Y_{s,t}}}$$

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, and a 80% (85%) emission reduction would completely ruin its economy; later emission reductions are cheaper by Equations (CO2.6) and (CO2.7). 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

(CO2.8) $$H_{r,t}=H_{r,t-1}\sqrt{1+\gamma_R\tau_{r,t-1}}$$

and

(CO2.9) $$H_t^G=H_{t-1}^G\sqrt{1+\gamma_G\tau_{r,t}}$$

Knowledge accumulates with emission abatement. More knowledge implies lower emission reduction costs. Equations (CO2.6) and (CO2.8) together constitute learning by doing. The parameters γ determines which part of the knowledge is kept within the region, and which part spills over to other regions as well. In the base case, $\gamma_R=0.9$ and $\gamma_G=0.1$. Note that, although there is learning by doing – Equations (CO2.8) and (CO2.9) – technology diffusion – Equation (CO2.7) – as well as permanent effects of emission reduction on the growth path of the economy – Equations (CO2.2) and (CO2.3) – the model does assume that policy interventions are always costly, and that larger interventions are more costly.

Emissions from land use change and deforestation are exogenous, and cannot be mitigated. Numbers are found in Tables CO2F.

Methane (CH_4)

Methane emissions are exogenous, specified in Table CH4. Note that there is no distinction between scenarios.

Nitrous oxide (N_2O)

Nitrous oxide emissions are exogenous, specified in Table N2O. Note that there is no distinction between scenarios.

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.

Atmosphere and climate

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.

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)[1], its parameters are due to Hammitt *et al.* (1992).[2] 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.

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[1] Maier-Reimer, E. and Hasselmann, K. (1987) Transport and Storage of Carbon Dioxide in the Ocean: An Inorganic Ocean Circulation Carbon Cycle Model. *Climate Dynamics* **2** 63-90.
[2] Hammitt, J.K., Lempert, R.J. and Schlesinger, M.E. (1992) A Sequential-Decision Strategy for Abating Climate Change. *Nature* **357** 315-318.

Radiative forcing

Radiative forcing is specified as follows:

$$RF_t = 6.3\ln\left(\frac{CO_2}{275}\right) + 0.036\sqrt{CH_4 - 790} + 0.14\sqrt{N_2O - 285} -$$

$$2\cdot 0.47\ln\left(1 + 2.01\cdot 10^{-5} CH_4^{0.75} N_2O^{0.75} + 5.31\cdot 10^{-15} CH_4^{2.52} N_2O^{1.52}\right) + \quad \text{(C.3)}$$

$$0.00052(SF_6 - 0.04) - 0.03\frac{SO_2}{14.6} - 0.08\frac{\ln\left(1 + S/34.4\right)}{\ln\left(1 + 14.6/34.4\right)}$$

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*), with a half-time of 50 years. In the base case, global mean temperature *T* rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50}\frac{2.5}{6.3\ln(2)} RF_t \quad \text{(C.4)}$$

Global mean sea level is also geometric, with its equilibrium level determined by the temperature and a life-time of 50 years. Temperature and sea level are calibrated to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

Impacts

Agriculture

For the impact of the rate of climate change on agriculture, the assumed model is:

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

a^r denotes the change in agricultural production due the rate of climate change (see Table A); *t* denotes time; *r* denotes region; ΔT denotes the change in the global mean temperature; α is a parameter, denoting the benchmark change in agricultural production (cf. Table 1); $\beta = 2.0$ (1.5-2.5) is a parameter, denoting the non-linearity of the reaction to temperature; ρ=10 (5-15) is a parameter, denoting the speed of adaptation.

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

$$A^l_{t,r} = \frac{-2A^B_r T^{opt}_r}{1 - 2T^{opt}_r} T_t + \frac{A^B_r}{1 - 2T^{opt}_r} T_t^2 \quad \text{(A.2)}$$

A^l denotes the change in agricultural production due to the level of climate change; *t* denotes time; *r* denotes region; *T* denotes the change in global mean temperature relative to 1990; A^B is a parameter, denoting the benchmark change in agricultural production (cf. Table A); T^{opt} is a parameter, denoting the optimal temperature (cf. Table A).

CO2 fertilisation has a positive, but saturating effect on agriculture, specified by

(A.3) $$A^f_{t,r} = \gamma_r \ln\left(\frac{CO_{2,t}}{275}\right)$$

A^f denotes the change in agricultural production due to the CO2 fertilisation; t denotes time; r denotes region; T denotes the atmospheric concentration of carbon dioxide; 275 ppm is the pre-industrial concentration; γ is a parameter, see Table A.

The share of agricultural production in total income falls with per capita income. The elasticity across the nine regions is -0.31. So,

(A.4) $$\frac{GAP_{t,r}}{Y_{t,r}} = \frac{GAP_{1990,r}}{Y_{1990,r}}\left(\frac{y_{1990,r}}{y_{t,r}}\right)^{\varepsilon}$$

GAP denotes gross agricultural product; Y denotes gross domestic product; y denotes gross domestic product per capita; t denotes times; r denotes regions; $\varepsilon = 0.31$ (0.15-0.45) is a parameter.

Forestry

The model is:

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

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; T denotes the global mean temperature; α is a parameter; see Table EFW; $\varepsilon = 0.31$ (0.11-0.51) is a parameter; $\beta = 1$ (0.5-1.5) is a parameter; $\gamma = 0.44$ (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%.

Water resources

The impact of climate change on water resources follows:

(W.1) $$W_{r,t} = \alpha_r(1-\tau)^{t-1990}\left(\frac{Y_{r,t}}{Y_{r,1990}}\right)^{\beta} T_t^{\gamma}$$

where W denotes the change in water resources, expressed in billion dollars; t denotes time; r denotes region; Y denotes income; T denotes the global mean temperature; α is a parameter, the benchmark estimate; see Table EFW; $\beta = 0.85$ (0.70 - 1.00) is a parameter; $\gamma = 1$ (0.5-1.5) is a parameter; $\tau = 0.005$ (0.000-0.010) is a parameter.

Energy consumption

For space heating, the model is:

(E.1) $$SH_{t,r} = a_r T_t^{\beta}\left(\frac{y_{t,r}}{y_{t,1990}}\right)^{\varepsilon}\left(\frac{P_{t,r}}{P_{t,1990}}\right)\prod_{s=1990}^{t} AEEI_{s,r}$$

SH denotes the amount of money spent less on space heating; t denotes time; r denotes region; T denotes the change in the global mean temperature relative to 1990; y denotes per capita income; *P* denotes population size; α is a parameter; cf. Table EFW; *β* is a parameter; *β* = 1 (0.5-1.5); *ε* is a parameter; *ε* = 0.8 (0.6-1.0); *AEEI* is a parameter (Tables AEEI); it is about 1% per year in 1990, converging to 0.2% in 2200; its standard deviation is set at a quarter of the mean.

For space cooling, the model is:

$$\text{(E.2)}\quad SC_{t,r} = a_r T_t^{\beta}\left(\frac{y_{t,r}}{y_{t,1990}}\right)^{\varepsilon}\left(\frac{P_{t,r}}{P_{t,1990}}\right)\prod_{s=1990}^{t} AEEI_{s,r}$$

SC denotes the amount of money spent additionally on space cooling; *t* denotes time; *r* denotes region; *T* denotes the change in the global mean temperature relative to 1990; *y* denotes per capita income; *P* denotes population size; *α* is a parameter; cf. Table EFW; *β* is a parameter; *β* = 1 (0.5-1.5); *ε* is a parameter; *ε* = 0.8 (0.6-1.0); *AEEI* is a parameter (Tables AEEI).

Sea level rise

Table SLR shows the accumulated loss of drylands and wetlands for a one metre rise in sea level. Land loss is assumed to be a linear function of sea level rise. The value of dryland is assumed to be linear in income density ($/km^2), with an average value of $4 million per square kilometre for the OECD. Wetland value follows: is assumed to be logistic in per capita income, with an:

$$\text{(SLR.1)}\quad V_{t,r} = \alpha \frac{y_{t,r}/30{,}000}{1+y_{t,r}/30{,}000}\max\left(2, 1-\sigma+\sigma\frac{L_{\max,r}}{L_{\max,r}-L_{t,r}}\right)$$

where *V* is wetland value; *y* is per capita income; *L* is the wetland lost to date; $L_{\max}$ is a parameter, given the maximum amount of wetland that can be lost to sea level rise; *α* is a parameter such that the average value for the OECD is $5 million per square kilometre; and *σ*=0.05 is a parameter.

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 three times the regional per capita income per migrant. In the receiving country, costs equal 40% of per capita income per migrant.

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. The level of protection, that is, the share of the coastline protected, is based on a cost-benefit analysis:

$$\text{(SLR.2)}\quad L = \min\left\{0, 1-\frac{1}{2}\left(\frac{PC+WL}{DL}\right)\right\}$$

L is the fraction of the coastline to be protected. *PC* is the net present value of the protection if the whole coast is protected.

Table SLR reports average costs per year over the next century. *PC* 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* thus equal

$$\text{(SLR.3)}\quad PC = \sum_{t=1}^{\infty}\left(\frac{1}{1+\rho+g}\right)^{t} PC_a = \frac{1+\rho+g}{\rho+g} PC_a$$

where PC_a is the average annual costs of protection.

WL is the net present value of the wetlands lost due to full coastal protection. Land values are assumed constant, reflecting how much current decision makers care about the non-marketed services and goods that get lost. The amount of wetland lost is assumed to increase linearly over time. The net present costs of wetland loss *WL* follow from

$$\text{(SLR.4)}\quad WL = \sum_{t=0}^{\infty} t\left(\frac{1}{1+\rho+g}\right)^{t} WL_0 = \frac{1+\rho+g}{(\rho+g)^2} WL_0$$

where WL_0 denotes the value of wetland loss in the first year.

DL denotes the net present value of the dryland lost if no protection takes place. Land values are assumed to rise at the same pace as the economy grows. The amount of dryland lost is assumed to increase linearly over time. The net present costs of dryland loss *DL* are

$$\text{(SLR.5)}\quad DL = \sum_{t=0}^{\infty} t\left(\frac{1}{1+\rho+g}\right)^{t} DL_0 = \frac{(1+g)(1+\rho+g)}{\rho^2} DL_0$$

where DL_0 is the value of dryland loss in the first year.

Ecosystems

Tol (1999) assesses the impact of climate change on ecosystems, biodiversity, species, landscape *etcetera* based on the "warm-glow" effect. Essentially, the value people are assumed to place on such impacts are independent of any real change in ecosystems *etcetera*. This values is specified as

$$\text{(E.1)}\quad \frac{E_{t,r}}{Y_{t,r}} = \alpha P_{t,r} \frac{y_{t,r}/y_b}{1+y_{t,r}/y_b} \frac{\Delta T_{t,r}/\tau}{1+\Delta T_{t,r}/\tau} \left(1-\sigma+\sigma\frac{B_0}{B_t}\right)$$

where *E* denotes the value of the loss of ecosystems; *t* denotes time; *r* denotes region; Y denotes GDP; *y* denotes per capita income; *P* denotes population size; Δ*T* denotes the change in regional temperature; *B* is the number of species; α is a parameter such that *E* equals $50 per person if per capita income equals the OECD average in 1990; y_b = $30,000 is a parameter; τ=0.025 is a parameter; σ=0.05 is a parameter; and B_0=14,000,000 is a parameter.

The number of species follows

$$\text{(E.2)}\quad B_t = B_{t-1}\left(1-\rho-\gamma\Delta T_{t-1}^2\right)$$

where ρ = 0.003 is a parameter; and γ = 0.625 is a parameter.

Human health: Diarrhoea

The number of additional diarrhoea deaths D^d is given by

(HD) $$D_{r,t}^{d}=\mu_{r}^{d}P_{r,t}\left(\frac{y_{r,t}}{y_{r,0}}\right)^{\varepsilon}\left(T_{r,t}^{\eta}-T_{r,0}^{\eta}\right)$$

where P denotes population, y per capita income, and T regional temperature; μ is the mortality in 1995, ε=-1.58 (0.23) and η=1.14 (with a standard deviation of 0.51) are parameters; r indexes region, and t time. Equation (HD) was estimated based on the WHO Global Burden of Diseases data.[3] Diarrhoea morbidity has the same equation as mortality, but with ε=-0.42 (0.12) and η=0.70 (0.26). Table HD gives impact estimates, ignoring economic and population growth.

Human health: Vector-borne diseases

The model for vector-borne diseases is:

(HV) $$m_{r,t,d}=m_{r,1990,d}\alpha_{r,d}\left(T_{t}-T_{1990}\right)^{\beta}\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\gamma}$$

m denotes mortality (see Table HV); t denotes time; r denotes regions; d denotes disease; α is a parameter, the benchmark impact of climate change on vector-borne diseases; see Table HV; y denotes per capita income; T denotes the change in the global mean temperature relative to 1990; β=1 (0.5) and γ=-2.65 (0.69) are parameters.

Mortality is valued at 200 times the per capita income, with a standard deviation of 100.

Morbidity is proportional to mortality, using the factor specified in Table HM. Morbidity is valued at 80% of per capita income per year of illness, with a standard deviation of 1.

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 (1999) extrapolates these findings to all other countries, based on formulae of the shape:

(HC.1) $$\Delta M_{d}=\alpha_{d}+\beta_{d}T_{B}$$

where ΔM denotes the change in mortality due to a one degree global warming; T_B is the current temperature in the country; and α and β are parameters, given in Table HC1. 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. If warming exceeds one degree, 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) $$\Delta M_{r,d}=\alpha_{r,d}T+\beta_{r,d}T^{2}$$

where T denotes the change in global mean temperature; α and β are parameters, specified in Tables HC.2-4.

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[3] http://www.who.int/health_topics/global_burden_of_disease/en/

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. (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.

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).

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

(HC.3) $$U_t = \frac{\alpha\sqrt{y_t} + \beta\sqrt{PD_t}}{1 + \alpha\sqrt{y_t} + \beta\sqrt{PD_t}}$$

where U is the fraction of people living in cities, y is per capita income, PD is population density and t is time; α and β are parameters, estimated from national data for the year 1995; α=0.031 (0.002) and β=-0.011 (0.005); R^2=0.66.

Mortality is valued at 200 times the per capita income, with a standard deviation of 100.

Morbidity is proportional to mortality, using the factor specified in Table HM. Morbidity is valued at 80% of per capita income per year of illness, with a standard deviation of 1.