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## Part 2: A dynamic model for the uncertainties of $CO_2$ impacts and costs

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# Assessment of Uncertainties: A dynamic model for the uncertainties of $CO_2$ impacts and costs

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## Abstract

The main focus of Deliverable D.12.1 [WP12 Report on uncertainties and their effects] was on the uncertainties of CO2 and the social cost penalties if an erroneous emission ceiling is chosen because of errors in the estimation of abatement and damage costs. The analysis of that report was based on a simple steady state model in order to obtain an assessment that is fully transparent, yet contains all the key variables. But since the reality of the problem involves time scales of many decades, it is desirable to confirm the validity of the steady state analysis by means of a more realistic dynamic model. That is the purpose of the present report. We have developed a dynamic model and used it to determine the socially optimal emission reduction, for comparison with the corresponding result that we had calculated with the steady state model of Deliverable D.12.1. The result is in good agreement, thus confirming the validity of the analysis of Deliverable D.12.1.

## 1. Emission and concentration data of the WRE scenarios

The choice of a suitable dynamic model for our purpose involves compromises between realism and transparency. Since we need to account for the time distribution of the damage and abatement costs, we take as starting point the data of Wigley at al [1996] for CO2 concentrations that result from the emissions scenarios WRE350, WRE450, WRE550, WRE650 and WRE750 (the numbers in these scenario names indicate their asymptotic $CO_2$ concentrations). The emissions are shown here in Fig.1 and the corresponding concentrations in Fig.2.

Fig.1. The emissions scenarios WRE350, WRE450, WRE550, WRE650 and WRE750 of Wigley at al [1996] (the numbers in these scenario names indicate their asymptotic $CO_2$ concentrations).

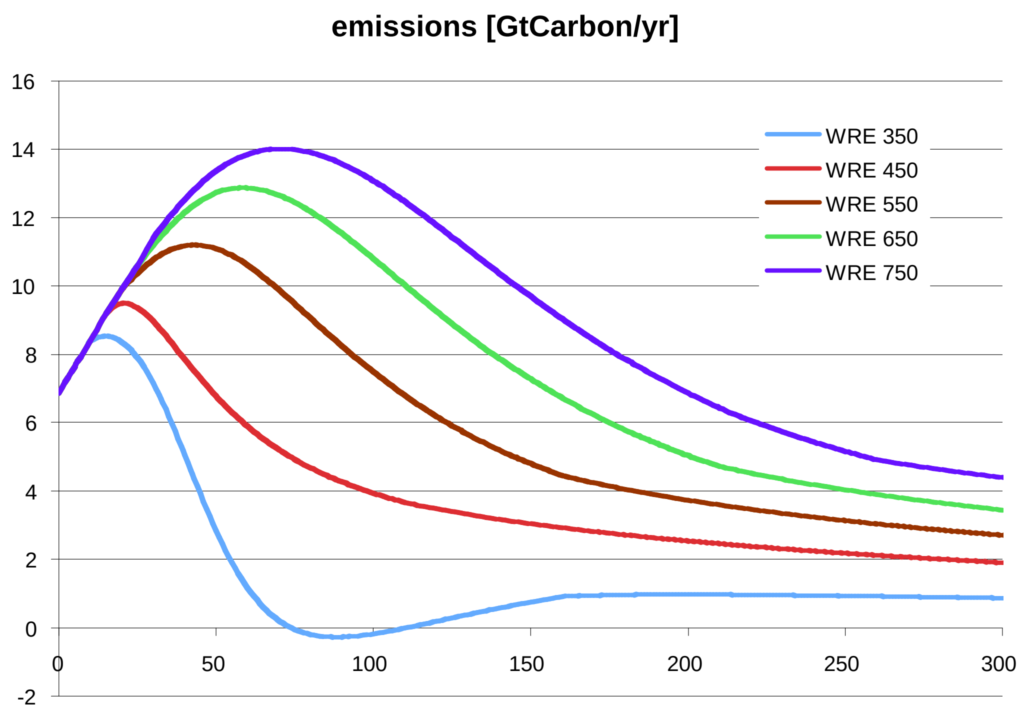
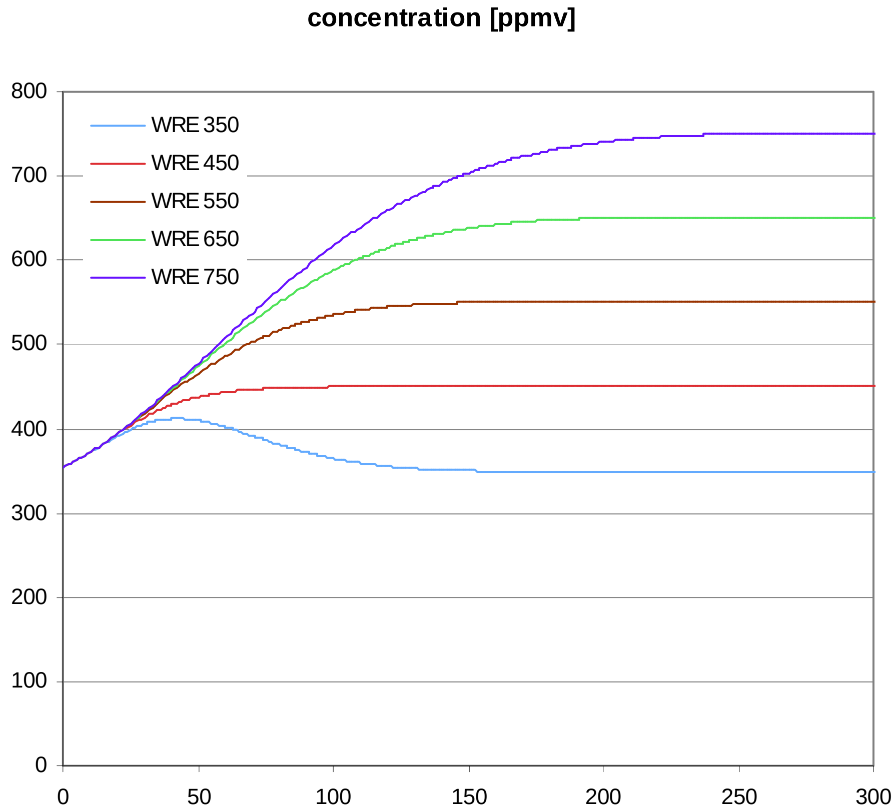


Fig.2. The concentrations resulting from the scenarios WRE350, WRE450, WRE550, WRE650 and WRE750.




## 2. Global average temperature increase

To calculate the corresponding evolution of the global average temperature rise we use the two-box model of Schneider and Thompson [1981] as described by Hammitt [1999]. The increase in annual mean surface temperature $\Delta T(t)$ is obtained by solving the following coupled differential equations numerically with time step 1 yr

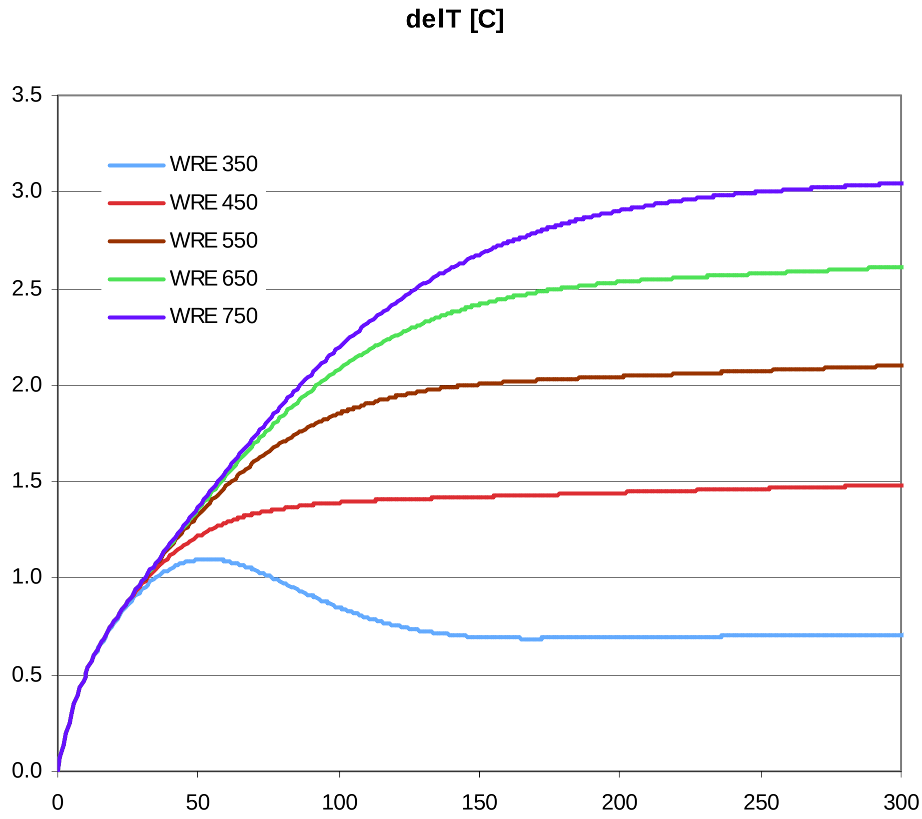
$$\frac{d}{dt}\Delta T(t) = \frac{1}{R}\left\{Q(t) - \lambda\Delta T(t) - \frac{R_d}{\tau_d}[\Delta T(t) - \Delta T_d(t)]\right\} \quad (1)$$

$$\frac{d}{dt}\Delta T_d(t) = \frac{1}{\tau_d}[\Delta T(t) - \Delta T_d(t)],$$

where $\Delta T(t)$ and $\Delta T_d(t)$ are the temperature of the atmosphere/land/ocean-mixed layer and the deep-ocean boxes (relative to their values in 1990), respectively. $Q(t) = 6.3 \ln(C(t)/C_0)$ W/m$^2$ is the radiative forcing from atmospheric $CO_2$; $\lambda = 6.3 \ln(2)/\Delta T_{2x}$ W/°C-m$^2$ is the climate-feedback factor, with climate sensitivity $\Delta T_{2x}$ the equilibrium increase in $\Delta T$ for a doubling of pre-industrial $CO_2$; $R = 20.83$ and $R_d = 223.7$ W-yr/°C-m$^2$ are the thermal inertia of the mixed-layer and deep-ocean boxes; and $\tau_d = 500$ yr is a parameter describing the rate of heat transfer between the mixed layer and deep ocean.

The temperature rise Δt(t) for the WRE scenarios is plotted in Fig.3.

Fig.3. The temperature rise Δt(t) for the WRE scenarios.




## 3. Reference Emission scenario

In the steady state model the reference emission is a single number, for which we took the present emissions $E_s$ = 25.7 $Gt_{CO2}$/yr. A dynamic model, by contrast, requires specifying an entire BAU scenario (business as usual). That involves, of course, assumptions about the future about which there is much uncertainty. A wide variety of possible scenarios has been presented in the literature, see e.g. Fig.3.1 of the Full Report of the Forth Assessment Report of IPCC, reproduced here in Fig.4. That figure extends only to 2100 whereas the dynamic model should have a larger time horizon, at least to 150 yr. Most of these scenarios assume a leveling off after 2100 which seems reasonable because that is necessary to keep the environment from becoming unbearable. Since the detailed time distribution of the emissions is not critical for our conclusions, we assume for simplicity a BAU scenario whose emissions increase linearly with time from 29.16 $Gt_{CO2}$/yr in 2000 to 69.16 $Gt_{CO2}$/yr in 2100, being constant thereafter; such a scenario lies in the middle of the gray zone in Fig.4. Of course, such sharp transition of the trend at 2100 is not realistic, but it does not matter because the optimization involves the entire time horizon of the analysis and fine details are washed out, especially so far into the future where the costs are reduced by discounting.

Fig.4. The reference emission scenarios of Fig.3.1 of the Full Report of the Forth Assessment Report of IPCC.

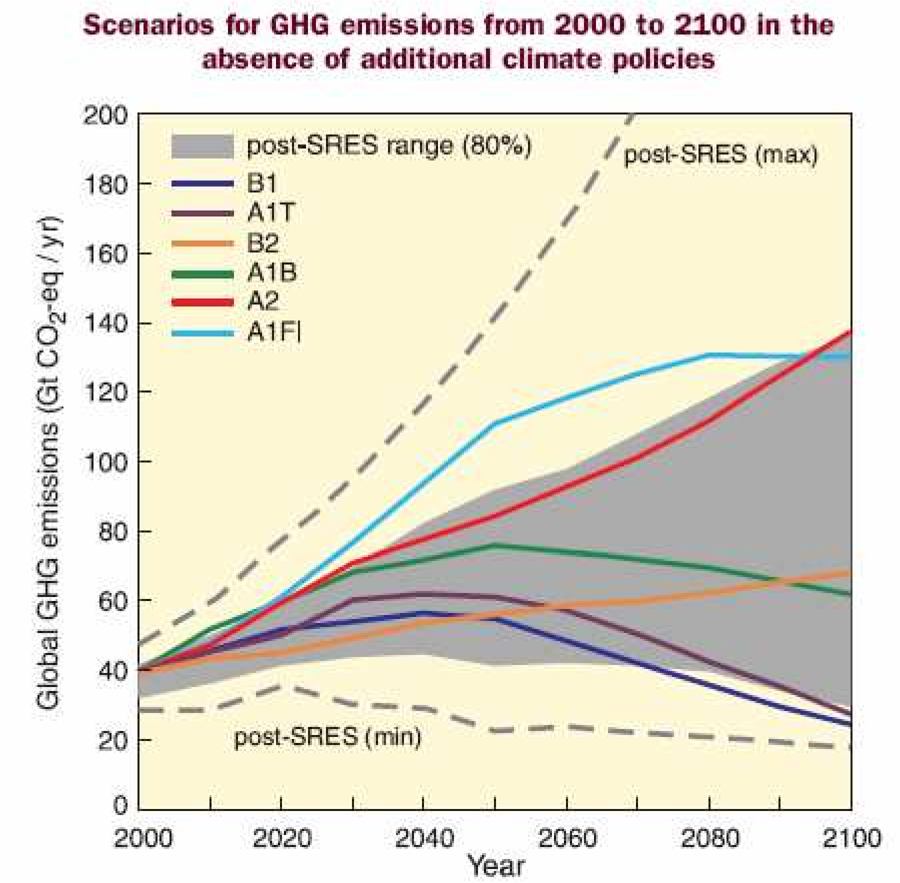



*Figure 3.1. Global GHG emissions (in $GtCO_2$-eq per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (coloured lines) and 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include $CO_2$, $CH_4$, $N_2O$ and F-gases. {WGIII 1.3, 3.2, Figure SPM.4}*

## 4. Damage and abatement costs

For damage and abatement costs we take of course the same equations and parameters as in Deliverable D.12.1, although the following minor modifications are necessary to adapt it to a dynamic context. In particular the damage cost at time t increases in proportion to the global world product GWP

$$C_{dam}(t) = GWP(t)\,\rho(\Delta T_{stab})^{\theta} \quad . \qquad (2)$$

We assume exponential growth of GWP(t) with a rate of $r_{GWP}$ = 2%/yr.

For the abatement cost we keep the time independent formulation of Deliverable D.12.1, even though cost reductions due to learning should be included in a more complete model. One modification is, however, necessary since for the emissions scenarios WRE350 and WRE450 the required reduction of emissions during certain years is larger than the range of validity of Eq.14 of Deliverable D.12.1. Therefore we replace that equation by

$$\frac{dC_{ab}}{d(-E)} = Min[\alpha\left(\frac{E-\beta}{E_s}\right)^{\gamma}, dC_{ab}/d(-E)_{\max}] \quad , \qquad (3)$$

where $dC_{ab}/d(-E)_{max}$ is the marginal abatement cost of the most expensive technology (sometimes called "backstop technology") that would be used in practice and that could be implemented at a sufficiently large scale; for example, photovoltaics (with storage) and nuclear are possible backstop options.

## 5. Discounting and time horizon

As for discounting, the general consensus in recent years has been that long term costs should be discounted at a rate much lower than the conventional social discount rate, in order not to disadvantage future generations. Examples of such long term discounting are the Bluebook rates of the UK DEFRA and the discounting procedure of Weitzman. In the present report we apply the discounting procedure of Rabl [1996] which is quite similar in its results. Rabl showed that the discount rate preferred by future generations is equal to the growth rate of GWP/capita - appropriate since global warming affects mostly future generations. That rate equal to

$$r_{dis} = r_{GWP} - r_{pop} \qquad (4)$$

where is the growth rate of the world's population, estimated as approximately $(10/6)^{(1/100)}$ = 0.5% averaged between 2000 and 2100. Thus we take a discount rate of $r_{dis}$ = 1.5%/yr.

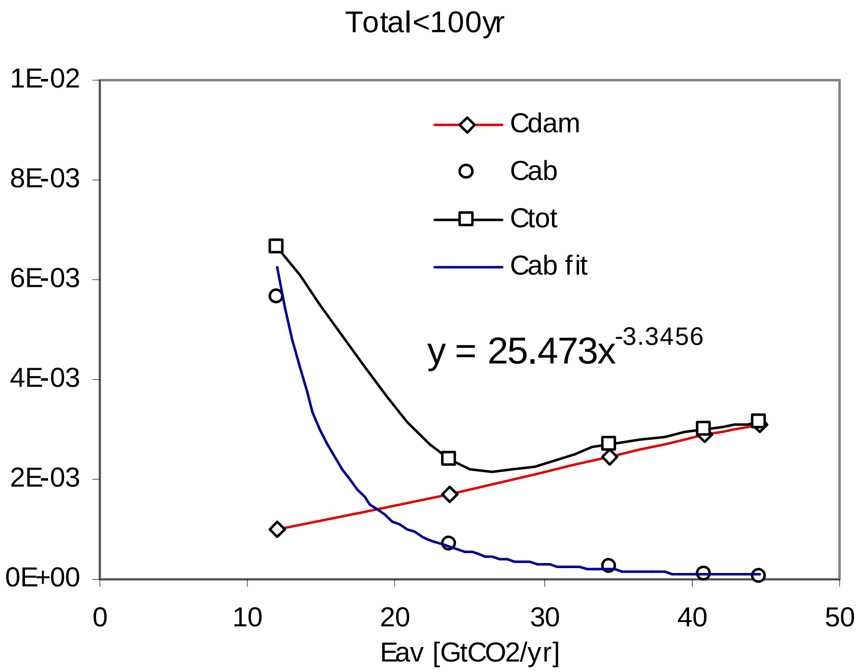
We also need to choose the time horizon for the analysis. Ideally it should be long enough for the temperature increase ΔT to reach steady state (stabilized) conditions. Fig.3 indicates that it should be at least 150 yr. Predicting costs over such a long time span is of course more than problematic. For that reason we have considered two cutoffs, 2100 and 2150.

## 6. Results

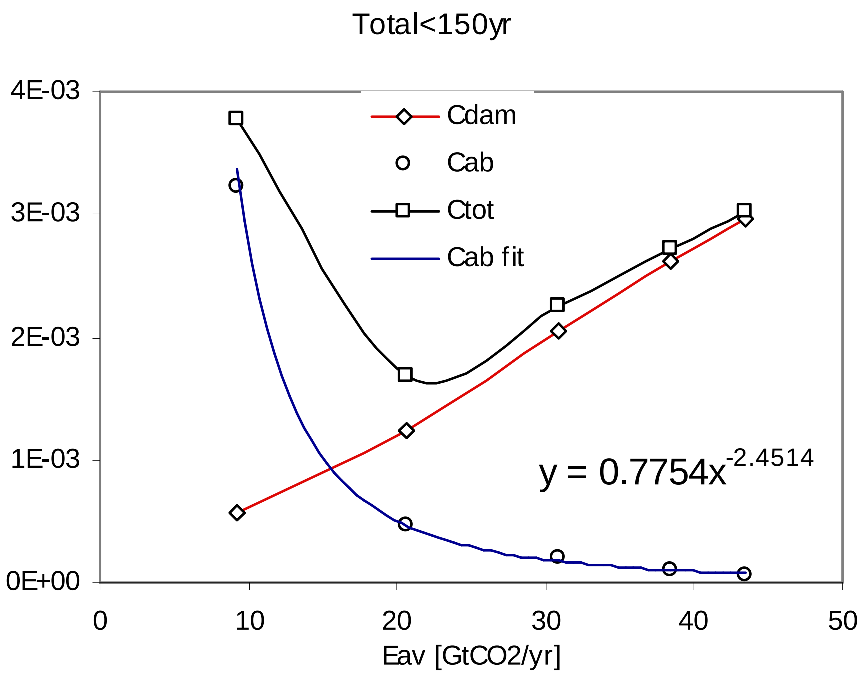
With the concentration data of Wigley et al [1996] we can calculate the costs only for the five discrete emission scenarios, whereas we really need the costs as a continuous function of the emissions. To fill this gap we use the Add Trendline feature of Excel to fit interpolating functions to the present value of the costs, as function of the average emissions $E_{av}$ of the respective WRE scenarios (averaged over the respective time horizons). The results are shown in Fig.5, for a cutoff of 100 yr and 150 yr in part a) and part b), respectively.

Fig.5. Damage cost $C_{dam}$ and abatement cost $C_{ab}$ (present values) for a cutoff of 100 yr and 150 yr, plotted as function of the average emissions of the WRE scenarios during these periods.

a)




b)




The equations of the fits are shown in Table 1. With these fits it is easy to find the optimal average emission level $E_{av,opt}$ by minimizing the total cost $C_{ab}(E_{av}) + C_{dam}(E_{av})$ as function of $E_{av}$. The result is $E_{av,opt}$ = 25.6 $Gt_{CO2}$/yr for the 100 yr horizon and $E_{av,opt}$ = 19.2 $Gt_{CO2}$/yr for the 150 yr horizon. Expressed as % of the corresponding average BAU emissions (25.6/47.1 for 100 yr and 19.2/53.0 for 150 yr) the emissions should be reduced to 54% and 36% of BAU for the respective horizons of the analysis. The calculated reduction is greater for a longer time horizon and the 150 yr cutoff is the minimum to approximate steady state conditions; thus the latter is more appropriate for comparison with the static analysis. The reduction to 36% of BAU is very close to the 34% reduction from $E_s$ = 25.7 $Gt_{CO2}$/yr to 8.7 $Gt_{CO2}$/yr that we calculated with the static model of Deliverable D2.1., thus confirming the validity of the latter.

Table 1. The equations of the interpolating functions in Fig.5.

| Time horizon | $C_{ab\ fit}$ | $C_{dam\ fit}$ |
|---|---|---|
| 100 yr | $C_{ab\ fit} = 25.473\ E_{av}^{-3.3456}$ | $C_{dam\ fit}$ = 9E-08 $E_{av}^{2}$ + 6E-05 $E_{av}$ + 0.0002 |
| 150 yr | $C_{ab\ fit} = 0.7754\ E_{av}^{-2.4514}$ | $C_{dam\ fit}$ = 3E-07 $E_{av}^{2}$ + 6E-05 $E_{av}$ - 6E-06 |

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