# Review of modeling studies on health impacts and adaptation

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14 May 2012

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# 1. Introduction

Integrated assessment models (IAMs) of climate change are playing an increasingly important role in the analysis of climate policy. They were used to compute the headline result of the Stern Review that climate change would cause a welfare loss equivalent to a permanent income loss of 5-20% (Stern, 2007) and more recently to estimate the Social Cost of Carbon of \$21/t$CO_2$ that is now used in all US federal regulatory analysis (Interagency Working Group on Social Cost of Carbon, 2010). Naturally, this increase in importance leads to an increased desire to understand how these models come to their conclusions and on what studies they are based. I will contribute to this debate in a narrow way in this paper by reviewing how IAMs model health impacts from climate change.

For the purpose of this review I will divide IAMs into two groups: the first group contains models that compute the health impacts of climate change in physical units. I will call these models physical models for the purpose of this review. The output of such models will include the numbers of additional premature deaths due to climate change, the additional number of years people are sick due to climate change etc. The second group of models reports economic values as outputs, and I will call them economic IAMs in this review. In some models this is done by estimating physical impacts first and then multiplying those with unit value dollar estimates. A model might for example compute the additional deaths from a changing climate and then multiply that number with an estimate of the value of a statistical life. Other models skip the intermediate step of computing physical health impacts and have functional forms that relate changes in climate directly to monetary estimates of the loss in the health sector.

The number of economic IAMs is small, and for the purpose of this review I will only look at the three models that were used by the US interagency workgroup to estimate the social cost of carbon for US regulatory analysis.

# 2. Economic Integrated Assessment Models

## 2.1. DICE/RICE[1]

The DICE and RICE models, developed by Bill Nordhaus and collaborators, are probably the most widely used economic IAMs of climate change today. The original DICE model was developed in the early 90s. DICE is a global model and was soon accompanied by a regionally disaggregated variant called RICE (Nordhaus and Yang, 1996). Today both versions of the model are continually improved and updated and are known as the DICE/RICE model.

The damage equation in DICE/RICE does not distinguish between different types of impacts. Instead it is an estimate of the sum of individual impacts per year (and region for RICE). The functional form is

$$D_J(t) = \theta_{1,J}T(t) + \theta_{2,J}T(t)^2 \tag{1}$$

where $D_J(t)$ is the total impact from all impacts from climate change in region $J$ at time $t$ as a share of GDP. $T(t)$ is the increase in the globally and seasonally averaged temperature above 1990 at time $t$. $\theta_1$ and $\theta_2$ are parameters. The damage function in DICE has the same functional form but drops the distinction into separate regions and instead computes the global impact from rising temperatures.

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[1] The presentation is taken from Nordhaus and Boyer (2000). It appears that newer versions of DICE/RICE do not change anything about the health part of the impacts (Nordhaus, 2008; Nordhaus, 2010).

The adverse impact on health of climate change are a share of the impacts computed with this aggregate damage function in DICE/RICE. The models themselves contain no more specific information about health impacts.

Nordhaus and Boyer (2000) describes how the damage function in DICE/RICE is calibrated and that description clarifies what kind of health impacts are included in DICE/RICE and on what empirical study they are based. In general, DICE/RICE includes estimates of the effect of temperature changes on years of life lost from malaria, a number of tropical diseases[2], dengue fever and pollution. The empirical basis for the health impact calibration is Murray and Lopez (1996) which provides an estimate of the total number of years of life lost due to these diseases for separate regions of the world. Nordhaus and Boyer (2000) present three different methods to establish the effect of climate on these numbers and use an average to calibrate their impact function. Each year of life lost is then valued to be worth two years of per capita income, based on Tolley *et al.* (1994).

Adaptation is implicitly modelled by the use of an income elasticity (in the intermediate computation of impacts, not in the damage function used in DICE/RICE itself). The income elasticity of health impacts as a share of income is assumed to be 0, apparently based on an expert guess by the model developers.[3]

## 2.2. FUND

FUND is an integrated assessment model that was original developed by Richard Tol in the 90s and is now co-developed by David Anthoff and Richard Tol. FUND is continuously

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[2] They include trypanosomiasis, Chagas disease, schistosomiasis, leishmaniasis, lymphatic filariasis and onchocerciasis.

[3] Note that this amounts roughly to an income elasticity of 1 of the willingness to pay to avoid the impacts on health from higher temperatures when the willingness to pay is expressed in absolute dollars and not as a percentage.

improved, so that versions are released on regular intervals. My discussion concentrates on the latest version FUND 3.7.[4]

FUND has the most detailed modelling of health impacts of the three economic IAMs reviewed in this paper. It is the only of the three models that has an explicit representation of different types of health impacts and their valuation as part of the IAM itself. The economic health impacts are estimated in two steps: first, physical estimates of the impact of climate change on health outcomes are computed. Two metrics are used in the model: number of premature deaths per year and years of morbidity. Those estimates are multiplied with estimates of the economic unit harm (the value of a statistical life and value of a year of illness, respectively) to arrive at economic impacts from climate change.

Physical estimates are computed for the following channels in FUND: diarrhoea, malaria, Schistosomiasis, dengue fever, cardiovascular and respiratory mortality and mortality from tropical and extra tropical storms.

The next sections will describe how mortality and morbidity are valued in FUND, and then give a brief overview of the damage function for each health impact.

### *Health Valuation*

Deaths are valued using a region and time specific value of a statistical life. The VSL for a given region $r$ in year $t$ is computed as

$$VSL_{tr} = \beta \left( \frac{y_{tr}}{y_{vsl}} \right)^{\epsilon} \tag{2}$$

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[4] For the source code and more documentation see FUND's web page at www.fund-model.org.

here $\epsilon$ is the income elasticity of the VSL, set to 1 (see also Hammitt and Robinson, 2011), $y_{tr}$ is per capita income, $y_{vsl}$ is a normalisation constant and the parameter $\beta$ is calibrated such that the VSL is set to 200 times per capita income in each region (Cline, 1992).

Years of illness or morbidity are valued at as

$$VMORB_{tr} = \tau \left(\frac{y_{tr}}{y_{vmorb}}\right)^{\eta} \tag{3}$$

Again $\eta$ is the income elasticity that is set to 1, $y_{vmorb}$ is a normalisation constant and the parameter $\tau$ is calibrated such that a year of illness is valued at 80% of per capita income of the region at that time (Navrud, 2001).

*Diarrhoea*

Increasing temperatures are assumed to cause both additional deaths as well as additional years of morbidity from diarrhoea. Increases in wealth are a very strong counter force: it is assumed that diarrhoea cases decrease as regions grow wealthier.

The damage function for diarrhoea impacts has the following form:

$$D_{tr}^{d} = \mu_r^d P_{tr} \left(\frac{y_{tr}}{y_{0r}}\right)^{\epsilon} \left[\left(\frac{T_{tr}}{T_{0r}}\right)^{\eta} - 1\right] \tag{4}$$

Here $\mu_r^d$ is the rate of mortality from diarrhoea in region $r$ in the year 2000. The rate is taken from (WHO, 2000). $P_{tr}$ is population size. $y_{0r}$ is a normalization constant for region $r$ (namely per capita income in 1990). The income elasticity $\epsilon$ is -1.58, so that regions rapidly become less vulnerable to diarrhoea as their wealth increases. $T_{0r}$ is the absolute average pre-industrial temperature in region $r$, and $T_{tr}$ is the absolute average project temperature at time $t$ in region $r$. $\eta$ is set to 1.14 and controls the degree of non-linearity in the response to temperature increases. Both $\epsilon$ and $\eta$ are also estimated from data in WHO (2000).

Morbidity uses the same functional form with different values for the parameters. The income elasticity for morbidity is set to $\epsilon = -0.42$, and the parameter controlling the non-linearity of the temperature response to $\eta = 0.7$. The base rates for mortality and morbidity for each region are shown in the following table:

| Region | $\mu_r^d$ for mortality | $\mu_r^d$ for morbidity |
|---|---:|---:|
| **USA** | 41.154 | 1704.156 |
| **CAN** | 41.154 | 1704.156 |
| **WEU** | 14.551 | 631.878 |
| **JPK** | 8.896 | 166.292 |
| **ANZ** | 1.346 | 82.96 |
| **EEU** | 18.085 | 846.775 |
| **FSU** | 121.694 | 6734.631 |
| **MDE** | 29.799 | 166.214 |
| **CAM** | 161.717 | 643.001 |
| **LAM** | 168.068 | 649.877 |
| **SAS** | 229.167 | 896.137 |
| **SEA** | 135.411 | 630.93 |
| **CHI** | 33.091 | 400.604 |
| **MAF** | 414.929 | 989.751 |
| **SSA** | 3167.301 | 5706.631 |
| **SIS** | 252.443 | 1092.314 |

**Table 1: Diarrhea mortality and morbidity, expressed as (additional) deaths per million people, years of life lost per million people**

*Vector-borne diseases*

FUND models the impact of climate change on three vector borne diseases: dengue fever, schistosomiasis and malaria. Only changes in mortality are explicitly represented, changes in morbidity are modelled with fixed conversion factors from mortality cases. For dengue fever and malaria it is assumed that warming will cause more deaths, whereas increasing temperatures are assumed to decrease the cases of schistosomiasis. Again increases in wealth always decrease the number of deaths: as per capita income rises, impacts are assumed to fall even more rapidly than in the case of diarrhoea.

The damage function for vector borne diseases $v \in (\text{dengue}, \text{schisto}, \text{malaria})$ is

$$D_{tr}^{v} = P_{tr} D_{1990r}^{v} \alpha_r^{v} (T_t - T_{1990})^{\beta} \left(\frac{y_{tr}}{y_{1990r}}\right)^{\gamma} \tag{5}$$

Here $D_{1990r}^{v}$ is the baseline mortality in 1990 in region $r$ due to disease $v$ as a share of population. $\alpha_r^{v}$ is a parameter that specifies the increase in mortality as a fraction of baseline mortality for a 1° C increase in temperature. The values are the averages of Morita *et al.* (1994); Martens *et al.* (1995); Martin and Lefebvre (1995); Martens *et al.* (1997). $T_t$ is world average absolute temperature at time $t$. $\beta$ is a parameter that controls the non-linearity of the impact in warming, based on Martens *et al.* (1997) it is set to 1. The income elasticity $\gamma$ is set to -2.65 based on a regression of malaria mortality on income in Link and Tol (2004). The base rates for each diseases and the impact of warming are given in the following table:

| **Region** | $D_{1990r}^{dengue}$ | $\alpha_r^{dengue}$ | $D_{1990r}^{schisto}$ | $\alpha_r^{schisto}$ | $D_{1990r}^{malaria}$ | $\alpha_r^{malaria}$ |
|---|---|---|---|---|---|---|
| **USA** | 0 | 0.3534 | 0.007 | -0.1149 | 0.023 | 0.0794 |
| **CAN** | 0 | 0.3534 | 0.007 | -0.1149 | 0.023 | 0.0794 |
| **WEU** | 0 | 0.3534 | 0.02 | -0.1149 | 0.24 | 0.0794 |
| **JPK** | 0.125 | 0.3534 | 0.423 | -0.1149 | 2.358 | 0.0794 |
| **ANZ** | 0 | 0.3534 | 0.037 | -0.1149 | 0.069 | 0.0794 |
| **EEU** | 0 | 0.3534 | 0.012 | -0.1149 | 0.377 | 0.0794 |
| **FSU** | 0 | 0.3534 | 0.003 | -0.1149 | 0.133 | 0.0794 |
| **MDE** | 0.286 | 0.3534 | 4.229 | -0.1149 | 24.113 | 0.0794 |
| **CAM** | 0.508 | 0.3534 | 1.235 | -0.1149 | 2.913 | 0.0794 |
| **LAM** | 0.541 | 0.3534 | 1.217 | -0.1149 | 3.09 | 0.0794 |
| **SAS** | 6.896 | 0.3534 | 0.898 | -0.1149 | 48.413 | 0.0794 |
| **SEA** | 2.072 | 0.3534 | 0.629 | -0.1149 | 22.129 | 0.0794 |
| **CHI** | 0.593 | 0.3534 | 1.43 | -0.1149 | 8.987 | 0.0794 |
| **MAF** | 1.089 | 0.3534 | 7.474 | -0.1149 | 458.133 | 0.0794 |
| **SSA** | 0.351 | 0.3534 | 8.275 | -0.1149 | 1414.284 | 0.0794 |
| **SIS** | 1.01 | 0.3534 | 1.296 | -0.1149 | 116.586 | 0.0794 |

**Table 2: Baseline mortality $D$ is given as deaths per million, impact of 1° warming $\alpha$ is a fraction of baseline impact**

*Cardiovascular and respiratory mortality*

Respiratory mortality is assumed to increase as temperatures rise. It is assumed that only the fraction of the population that lives in urban areas is affected by this. Therefore regions grow more vulnerable over time as urbanization is assumed to increase with increases in wealth. A cap is imposed on the additional numbers of deaths due to temperature related respiratory conditions, the cap is set to 5% of the base rate of respiratory diseases in the population. The base rate of respiratory diseases is assumed to increase as the share of people over 65 increases.

For cardiovascular diseases warming temperatures are good and bad news, as death rates are worsened both by extreme cold (which will be reduced by rising temperatures) and extreme warms (which will increase with global warming). Increases in mortality due to heat are again assumed to be limited to the urban population, so that societies grow more vulnerable over time to this channel as urbanization is assumed to increase. Decreases in mortality due to a reduction in extreme colds is assumed to affect the whole population. Changes in mortality are again limited to 5% of the base rate of cardiovascular disease cases in the population. The base rate is assumed to increases in the share of people over 65. Increases and decreases in cardiovascular death rates due to rising temperatures are estimated separately for the population over and below 65.

The core damage function for all respiratory and cardiovascular impacts is a simple quadratic function:

$$D_{tr}^{c} = \alpha_{r}^{c} T_{t} + \beta_{r}^{c} T_{t}^{2} \tag{6}$$

$D_{tr}^{c}$ is the additional deaths due to climate change as a share of the size of the affected population group for disease $c$. $\alpha$ and $\beta$ are parameters that are specific for each disease and region. The equation is computed five times for the five different values $c$ can take: respiratory, cardio heat over 65, cardio cold over 65, cardio heat under 65 and cardio cold under 65. For respiratory diseases $D_{tr}^{c}$ is multiplied with population $P_{tr}$ and the urbanization share $U_{tr}$ to arrive at absolute casualty numbers. For heat impacts on cardiovascular diseases (6) is computed with different parameter values for the population over and below 65, then that share is multiplied with the urban population over and under 65 respectively to arrive at absolute impact numbers in terms of additional deaths. For cold impacts on cardiovascular disease (6) is again computed with different parameter values for the population over and below 65, and then that share is multiplied with the entire population size over and below 65 respectively. That is cold impacts, which are always beneficial due to reduced death rates, are not limited to the share of the population that lives in cities. As described before, the such estimated impact numbers are finally capped to 5% of the base rate of each diseases.

The empirical basis for the calibration of the impact functions is the literature review and meta study by Martens (1998), who presents estimates of the impact of a 1.16° C warming on heat and cold related cardiovascular death rates and heat related respiratory diseases for 17 countries. Tol (2002) extrapolates these findings to the rest of the world.[5] The actual parameter values used are present in the following tables:

| **Region** | **resp** | **card heat 65+** | **card cold 65+** | **card heat 65-** | **Card cold 65-** |
|---|---:|---:|---:|---:|---:|
| **USA** | 0.9452 | 34.9374 | -161.4521 | 1.0988 | 151.6768 |
| **CAN** | -1.9284 | 27.328 | -205.4176 | 1.0705 | 195.6424 |
| **WEU** | -0.765 | 25.757 | -145.9539 | 0.4022 | 19.2327 |
| **JPK** | 0.4185 | 8.2986 | -33.683 | 1.0356 | 65.5934 |
| **ANZ** | 0.2579 | 18.8372 | -91.0606 | 0.4493 | 67.1775 |
| **EEU** | -1.2946 | 29.6249 | -201.8789 | 0.6119 | 61.484 |
| **FSU** | 1.5277 | 36.4415 | -190.3936 | 0.6468 | -3.4422 |
| **MDE** | 5.6711 | 50.5493 | -136.8033 | 1.0931 | -2.4508 |
| **CAM** | 3.8894 | 44.7697 | -54.1635 | 0.9144 | -0.6855 |
| **LAM** | 1.0893 | 33.7621 | -78.4126 | 0.5893 | 16.6942 |

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[5] See also Bosello *et al.* (2006); Ackerman and Stanton (2007); Bosello *et al.* (2007) for further discussions of the empirical basis used in FUND.

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|---|---|---|---|---|---|
| **SAS** | 10.2485 | 74.5092 | -80.232 | 1.6317 | -1.6072 |
| **SEA** | 4.8562 | -18.7223 | 12.0899 | 0.8545 | -0.6838 |
| **CHI** | 4.4083 | 82.0355 | -66.6796 | 0.7565 | 81.1077 |
| **MAF** | 5.198 | 50.4842 | -102.4339 | 1.0409 | -1.9826 |
| **SSA** | 3.6196 | 43.4397 | -49.97 | 0.8682 | -1.0407 |
| **SIS** | 4.1354 | 16.9938 | -10.4503 | 1.0227 | 1.6035 |

**Table 3: Values for the linear parameter $\alpha$**

| Region | resp | card heat 65+ | card cold 65+ | card heat 65- | Card cold 65- |
|---|---|---|---|---|---|
| **USA** | 0.4342 | 1.7285 | 2.8314 | 0.0471 | -155.1251 |
| **CAN** | 0.4342 | 1.7285 | 2.8314 | 0.0471 | -199.0906 |
| **WEU** | 0.4341 | 1.7966 | 2.8279 | 0.0467 | -21.7191 |
| **JPK** | 0.4342 | 0.7493 | 1.2018 | 0.0559 | -67.185 |
| **ANZ** | 0.4342 | 1.7286 | 2.8314 | 0.047 | -68.9576 |
| **EEU** | 0.4342 | 1.7531 | 2.8314 | 0.047 | -65.2217 |
| **FSU** | 0.4342 | 1.7285 | 2.8314 | 0.0471 | 0.0473 |
| **MDE** | 0.4194 | 1.7011 | 2.7443 | 0.0452 | 0.0457 |
| **CAM** | 0.4342 | 1.662 | 2.7085 | 0.0471 | -0.484 |
| **LAM** | 0.4335 | 1.7535 | 2.8094 | 0.047 | -18.2021 |
| **SAS** | 0.4342 | 1.7378 | 2.8314 | 0.047 | 0.0473 |
| **SEA** | 0.4339 | -0.6683 | -1.1081 | 0.0411 | 0.0413 |
| **CHI** | 0.4319 | 1.2095 | 2.0193 | 0.0474 | -84.8815 |
| **MAF** | 0.4341 | 1.7096 | 2.8314 | 0.0471 | 0.0473 |
| **SSA** | 0.411 | 1.6578 | 2.6771 | 0.044 | 0.0448 |
| **SIS** | 0.2522 | 0.4223 | 0.5138 | 0.0324 | -2.3428 |

**Table 4: Values for quadratic parameter $\boldsymbol{\beta}$**

### *Tropical and Extratropical storms [DRAFT]*

Increases in tropical and extratropical storms are projected to increase death rates in FUND. Again, it is assumed that an increase in wealth is a counter balance to that, so that societies grow less vulnerable as their per capita income levels increase.

The damage function for tropical storms is given as

$$TM_{tr} = \beta_r P_{tr} \left(\frac{y_{tr}}{y_{1990r}}\right)^{\eta} [(1 + \delta T_{tr})^{\gamma} - 1] \tag{7}$$

Where $TM_{tr}$ is additional deaths, $\beta_r$ is a parameter, $\eta$ is the income elasticity of impacts set to -0.5, $\delta$ is a parameter that indicates how much wind speeds will increase per degree warming and set to 0.04, $\gamma = 3$ because the power of the wind in the cube of its speed.

The damage function for extratropical storms is given as

$$ETM_{tr} = \beta_r P_{tr} \left(\frac{y_{tr}}{y_{1990r}}\right)^{\eta} \delta_r \left[\left(\frac{C_t}{C_{pre}}\right)^{\gamma} - 1\right] \tag{8}$$

Where $ETM_{tr}$ is additional deaths, $\beta$ is a parameter, $\eta$ is the income elasticity set to -0.5, $C_t$ is atmospheric CO2 concentrations at time $t$, $C_{pre}$ is atmospheric CO2 concentrations at pre-industrial levels, $\gamma = 1$ is a parameter and $\delta_r$ is the storm sensitivity of region $r$. Note that this formulation should not indicate that extratropical storm impacts depend on CO2 concentrations in a physical sense, instead this formulation was picked because the underlying studies expressed these relationships in terms of CO2 concentrations.

## 2.3. PAGE

PAGE is an integrated assessment model developed by Chris Hope. PAGE2002 (Hope, 2006) was used to compute the headline impact figures of the Stern Review (Stern, 2007). PAGE09 is a major update of PAGE and the newest version of the model (Hope, 2011).

The damage function in PAGE does not separate out health impacts, just like DICE and RICE. The damage function parameters are calibrated to the results of three other aggregate impact studies whose results were reviewed in Smith *et al.* (2001). The three studies are (Mendelsohn *et al.*, 2000), which does not include an estimate of health impacts; Nordhaus and Boyer (2000), which includes health impacts as described in another section; and Tol (1999), which is based on an older version of FUND than described in this paper that includes the monetized impacts from heat and cold stress and malaria.

## 3. Conclusion

At this stage the three economic IAMs discussed in this paper differ both in what types of health impacts are represented, their general approach of representing health impacts and how they model adaptation of health impacts.

Given that PAGE’s impact function is more a meta damage function that spans the estimates derived both in FUND and DICE/RICE, it does not contain any health impact category that would not be represented in one of the two other IAMs. DICE/RICE includes health impacts from pollution that are not represented in FUND, and some of the tropical diseases accounted for in DICE/RICE are also not included in FUND’s damage estimate. Impacts on respiratory and cardiovascular diseases, diarrhoea and deaths from tropical and extratropical storms are health impact categories that are included in FUND but not in DICE/RICE. Both FUND and DICE/RICE cover impacts on malaria, Schistosomiasis and dengue fever.

In spirit, both DICE/RICE and FUND model adaptation via income elasticities. Adaptation is not modelled as an explicit decision by agents to engage in certain activities to reduce the harmful impacts of climate change. At the same time the impact estimates in principle take into account that vulnerability to many health impacts strongly depends on wealth in addition to climatic conditions. In FUND those income elasticities are represented directly in the main model and therefore e.g. pick up changes in assumption about economic growth for different scenarios of socio-economic development. The income elasticities are not included in the main DICE/RICE model, but instead are only used in the intermediate computation of impacts that forms the basis for the calibration of the aggregate damage functions used in the IAM itself.

Both FUND and DICE/RICE use a willingness to pay approach to attach economic values to physical casualty estimates. Again, this step is explicitly part of the IAM model for FUND and implicitly used in the computation of the underlying data that is used to calibrate the DICE/RICE damage function. At the same time FUND and DICE/RICE use different physical units to estimate health impacts, and therefore also use different specific economic values. DICE/RICE is based on a years-of-life-lost calculation, whereas FUND uses a value of a statistical life approach for additional mortality and a years of morbidity approach for increases in disease years.

The empirical basis for health impacts in both FUND and DICE/RICE is thin, with a lot of extrapolation across both time and space by the original model authors. In some cases the underlying studies just estimate base rates for various diseases, and the authors of the IAMs estimated simple equations that relate increases in temperature to changes in health outcomes. In other cases the impact functions are based on studies that already explicitly estimate the effect of climate change on health outcomes.

The list of potential improvements to the representation of health impacts in IAMs is long. The methods of valuing deaths and morbidity could be updated with new empirical insights into differences between developed and developing countries (Hammitt and Robinson, 2011), each model could be extended to cover at least all health impact areas that the other models cover and additional impact types could be included. In general, more empirical studies that explicitly focus on the impact of climate change on health outcomes would lend credibility to the impact estimates of IAMs. Studies in developing countries would in particular be helpful.

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