

# INTEGRATED ASSESSMENT MODELS

# INTRODUCTION

- Integrated Assessment Models (IAMs)  
approaches that integrate knowledge from two or more domains into a single framework

Economic Model + Geophysical Climate Model

- General Equilibrium
- Computerized simulations
- Literature more focused on results and applications: finding the cost of emissions (social cost of carbon)

- Origin in the energy models of 1970s and 1980s

Energy model + emissions and partial equilibrium



Energy system in a growth model and GE

- Nordhaus and Tobin (1972) “Is Growth Obsolete?”
- Nordhaus (1974) “Resources as a constraint for growth”

Greenhouse effect a much serious problem than scarcity of resources

Nordhaus (1980) first optimizing IAM - damage function

“The point emphasized in IAMs is that we need to have *at a first level of approximation* models that operate all the modules simultaneously.”

Nordhaus (2013:1077)

Very long list, and growing  
(there's even an IAM Consortium -webpage-)

Among them:

- DICE/RICE - Nordhaus
- FUND - Richard Tol
- PAGE - Chris Hope (Stern Review)
- Others: MERGE, GRACE,...

# ECONOMIC GROWTH AND CLIMATE (AER)

## Economic Growth and Climate: The Carbon Dioxide Problem

By WILLIAM D. NORDHAUS\*

In contemplating the future course of economic growth in the West, scientists are divided between one group crying "woe!" and another which denies that species' existence. One persistent concern has been that man's economic activities would reach a scale where the global climate would be significantly affected. Unlike many of the woe cries, this one, in my opinion, should be taken very seriously. The present article will first give a brief overview of the climatic implications of economic activity with special reference to carbon dioxide, and then will present possible strategies for control. A more complete report with references to the literature on climatic change is contained in Nordhaus (1976).

It is thought that the economic activities which most affect climate are agriculture and energy. Of these, the latter is probably more significant, is certainly more easily analyzed, and will be discussed here. In the energy sector, emissions of carbon dioxide, particulate matter, and heat are of significance for the global climate.

### 1. Energy and Climate

When we refer to climate, we usually are thinking of the average of characteristics of the atmosphere at different points of the earth, including the variabilities such as the diurnal and annual cycle. A more precise representation of the climate would be as a dynamic, stochastic system of equations. The probability distributions of the atmospheric characteristics is what we mean by climate, while a particular realization of that stochastic process is what we call the weather.

Recent evidence indicates that, even after several millennia, the dynamic processes which determine climate have not attained a stable

\*Cowles Foundation and Yale University.

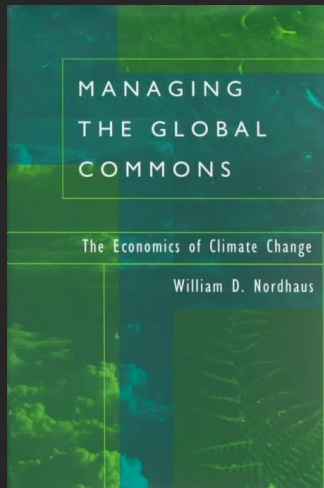
341

equilibrium. One of the more carefully documented examples is the global mean temperature which over the last 100 years has shown a range of variation of five-year averages of about  $0.6^{\circ}\text{C}$  (see Figure 1).

As what point is there likely to be a significant effect of man's activities on the climate? Many climatologists feel that it is prudent to consider as significant the changes witnessed in the last century—the  $0.6^{\circ}\text{C}$  range. Although the estimates are uncertain, it is probable that for carbon dioxide such a change would come with an increase of approximately 20 percent in atmospheric concentrations over preindustrial levels. According to recent projections, we shall probably reach this level in the 1985–90 period (W. S. Broecker). For other sources—heat and particulates—the effects appear considerably later and are also more controversial.

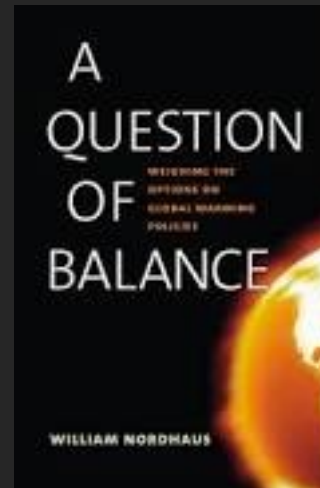
A brief overview of the interaction between carbon dioxide and the climate is as follows: combustion of fossil fuels leads to emissions of carbon dioxide into the atmosphere. Once in the atmosphere, the residence time appears to be very long, with approximately one-half of all industrial carbon dioxide still airborne. Because of the selective absorption of radiation, the increased atmospheric concentration is thought to lead to increased surface temperatures. The most careful study to date (S. Manabe and R. T. Wetherald) predicts that a doubling of atmospheric concentrations of carbon dioxide would eventually lead to a global mean temperature increase of  $3^{\circ}\text{C}$ . The predicted temperature increase by latitude indicates that there is considerable amplification at high latitudes. Figure 1 shows the predicted change in global mean temperature as a function of time, given the predicted emissions of carbon dioxide which we will discuss in the later part

## DICE-1994

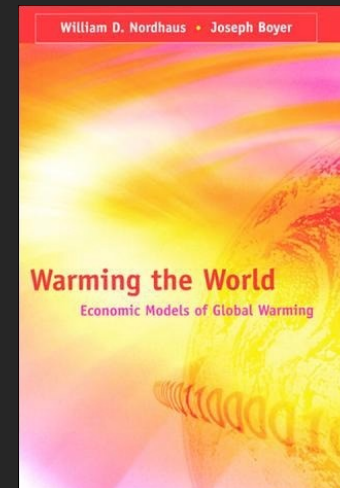


# DICE/RICE IN CONTEXT

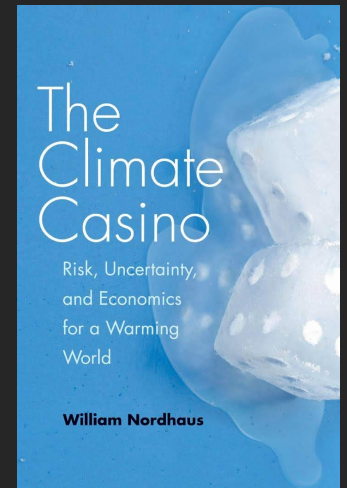
## DICE-2008



## RICE-2010



## DICE-2013



## 1977

## 1994

## 2008

## 2010

## 2015

## 1990

# ipcc

INTERGOVERNMENTAL PANEL ON  
climate change



## 1988

## JAMES HANSEN ET AL. NASA | MIT

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. D8, PAGES 9341–9364, AUGUST 20, 1988

## Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model



humberto.llavador@upf.edu

# DICE

Dynamic Integrated model of Climate and the Economy

## Latest versions (in GAMS code)

- DICE2016R2 in Nordhaus (2018, AEJ: Economic Policy)
- DICE2016R3 in Nordhaus (2019, AER)
- An Excel version DICE-2016R (derived from the GAMS version)
- User's Manual. Nordhaus and Sztorc (2013)
- Evolution in Nordhaus (2018, Climatic Change): DICE1992-2017
- Forthcoming DICE-2022

1. Objective functions - representative agent
2. Economic sectors
3. Geophysical sectors

Neoclassical growth model  
(Ramsey-Koopmans) incorporating  
an environmental process.



## A Objective: discounted sum of utilities

$$W = \sum_{t=1}^{T_{max}} R(t) V[C(t), L(t)] = \sum_{t=1}^{T_{max}} R(t) U[c(t)] L(t)$$

1. Constant elasticity utility function:  $U[c(t)] = \frac{c(t)^{1-\eta}}{1-\eta}$

$\eta$  = elasticity of the marginal utility of consumption

$\eta \rightarrow 0$ : consumption between generations are close substitutes

$\eta \rightarrow \infty$ : close complements

$$\eta = 1: U[c(t)] = \ln c(t)$$

2.  $R(t) = \frac{1}{(1+\rho)^t}$  discount factor ( $\rho$  = discount rate) represents the pure time preference.

## B Economic sectors

Standard neoclassical decisions about capital accumulation and production

- Initial endowments of capital and labor:  $L_0$  and  $K_0$
- Exogenous population and technological change (TFP) growth

$$L(t) = [1 + g_L(t)]L(t - 1), \text{ where } g_L(t) = \frac{g_L(t-1)}{1+\delta_L}$$

$$A(t) = [1 + g_A(t)]A(t - 1), \text{ where } g_A(t) = \frac{g_A(t-1)}{1+\delta_A}$$

Population and TFP growth decline over time.

## B Economic sectors: production function

### Cobb-Douglas production function

- Gross output (in the absence of damages and abatement)

$$Y(t) = A(t)K(t)^\gamma L(t)^{1-\gamma}$$

$$\text{TFP: } A(t) = [1 + g_A(t)]A(t-1), \text{ where } g_A(t) = \frac{g_A(t-1)}{1+\delta_A}$$

- Climate damages (as fraction of gross output):  $1 - \Omega(t)$
- Net output (net of climate damages)
$$\Omega(t)A(t)K(t)^\gamma L(t)^{1-\gamma}$$
- Abatement costs (fraction of net output devoted to abatement):  $\Lambda(t)$
- Output net of damages and abatement

$$Q(t) = (1 - \Lambda(t))\Omega(t)A(t)K(t)^\gamma L(t)^{1-\gamma}$$

B Economic sectors.  $Q(t) = (1 - \Lambda(t))\Omega(t)A(t)K(t)^\gamma L(t)^{1-\gamma}$

Damage function  $\Omega(t) = 1 - D(t)$

$$D(t) = \Psi_1 T(t) + \Psi_2 T(t)^2$$

Abatement costs  $\Lambda(t) = \theta_1(t)\mu(t)^{\theta_2}$

 Policy: emission abatement rate

Highly convex ( $\theta > 2$ ).

Calibrated so that the marginal cost of abatement equals the cost of an exogenous backstop technology at 100%

## B Economic sectors

Market clearing

$$Q(t) = C(t) + I(t)$$

$$Y(t) - \text{damages}(t) = C(t) + I(t) + \text{Abatement}(t)$$

Capital accumulation

$$K(t) = I(t) + \delta_k K(t-1)$$

Emissions are proportional to output

$$E(t) = E_{Ind}(t) + E_{Land}(t) = \sigma(t)(1 - \mu(t))Y(t) + E_{Land}(t)$$

Carbon intensity  
(exogenous and declines over time)

Policy

$$CCum \geq \sum_t E_{Ind}(t) \quad \text{Limit of total fossil fuel resources}$$

## C. Geophysical sector

I. Carbon cycle

emissions → carbon concentration

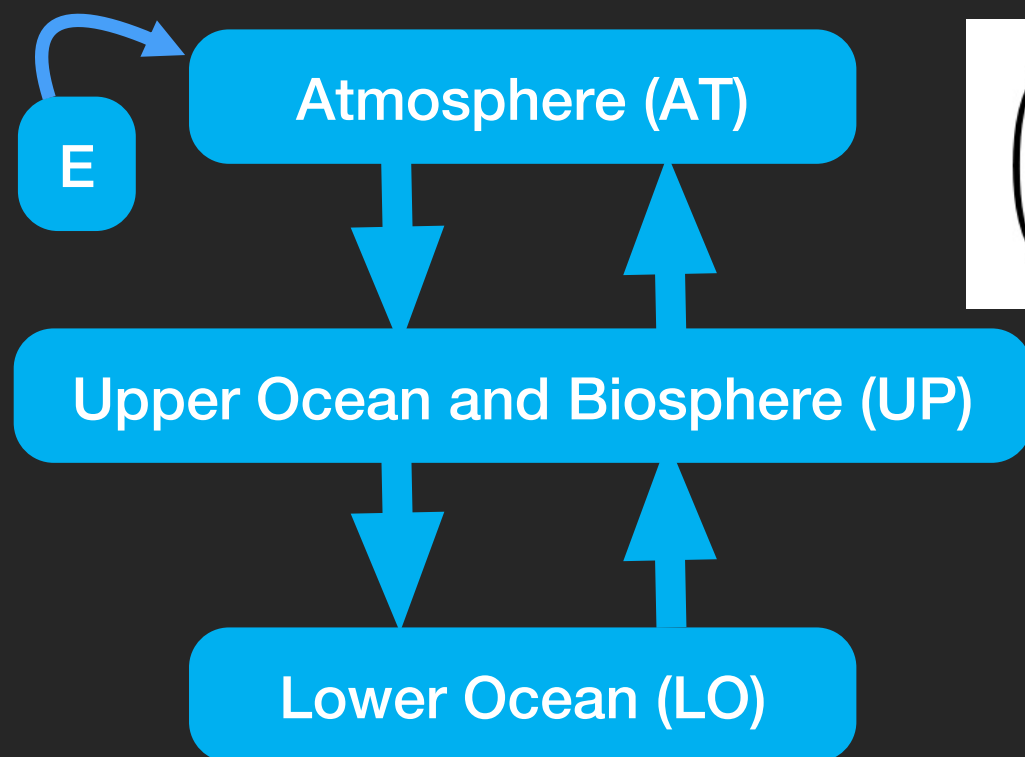
II. Radiative Forcing

warming impact

III. Temperature change

radiative forcing → temperature increase

**I. Carbon Cycle:** 3-reservoirs, linear system (Matrix representation in Machta, 1972)



$$\begin{pmatrix} M_{AT,t} \\ M_{UP,t} \\ M_{LO,t} \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} M_{AT,t-1} \\ M_{UP,t-1} \\ M_{LO,t-1} \end{pmatrix} + \begin{pmatrix} E_t + E_t^{Land} \\ 0 \\ 0 \end{pmatrix}$$

## C. Geophysical sector

I. Carbon cycle

emissions → carbon concentration

II. Radiative Forcing

warming impact

III. Temperature change

radiative forcing → temperature increase

II. Radiative forcing: observed relationship

$$F(t) = \eta \log_2 \frac{M_{AT}(t)}{M_{1750}} + F_{EX}(t)$$

Change in total forcing  
from atmospheric  
sources

Forcing from  
atmospheric  
concentration of CO<sub>2</sub>

Exogenous  
forcing

Climate sensitivity parameter: increase in  
forcing/temperature from doubling the stock of CO<sub>2</sub>

## C. Geophysical sector

- I. Carbon cycle      emissions → carbon concentration
- II. Radiative Forcing      warming impact
- III. Temperature change      radiative forcing → temperature increase

### III. Temperature change (warming), determining climate change damages

Higher radiative forcing warms the atmospheric layer, which then warms the upper ocean, gradually warming the deep ocean. The lags in the system are primarily due to the diffusive inertia of the different layers.

$$T_{AT}(t) = T_{AT}(t-1) + \{\xi_1[F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]]\}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)]$$

### Climate change damages

$$D(t) = \Psi_1 T_{AT}(t) + \Psi_2 [T_{AT}(t)]^2$$



## SUMMARY

$$\max W := \sum_{t=1}^T \beta^t L(t) \log c(t)$$

s.t.

**Objective: Discounted sum of utilities**

$$\left[1 - \Lambda(t)\right] \Omega(T(t)) Y[K(t), L(t)] = C(t) + I(t)$$

Abatement Damages Cobb-Douglas  
Production

**Economic  
growth model**

$$E(t) = \sigma(t) Y[K(t), L(t)]$$

Carbon intensity

Radiative  
force

$M_{AT}(t)$

Atmosphere

$M_{UP}(t)$

Surface

$M_{LO}(t)$

Deep ocean

**Climate Model**

Carbon concentration

## Results

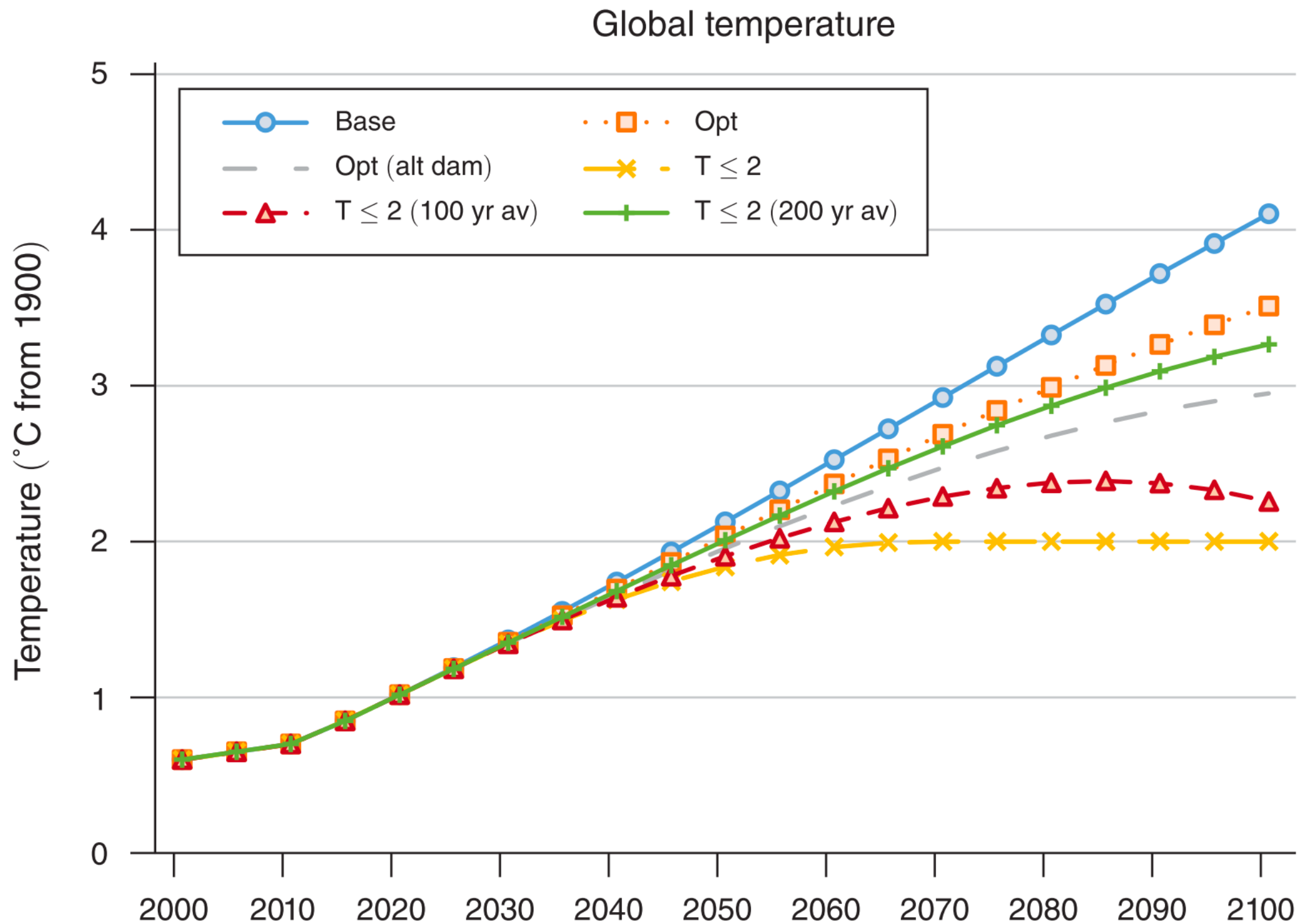


FIGURE 5. TEMPERATURE TRAJECTORIES FOR DIFFERENT OBJECTIVES

# Results

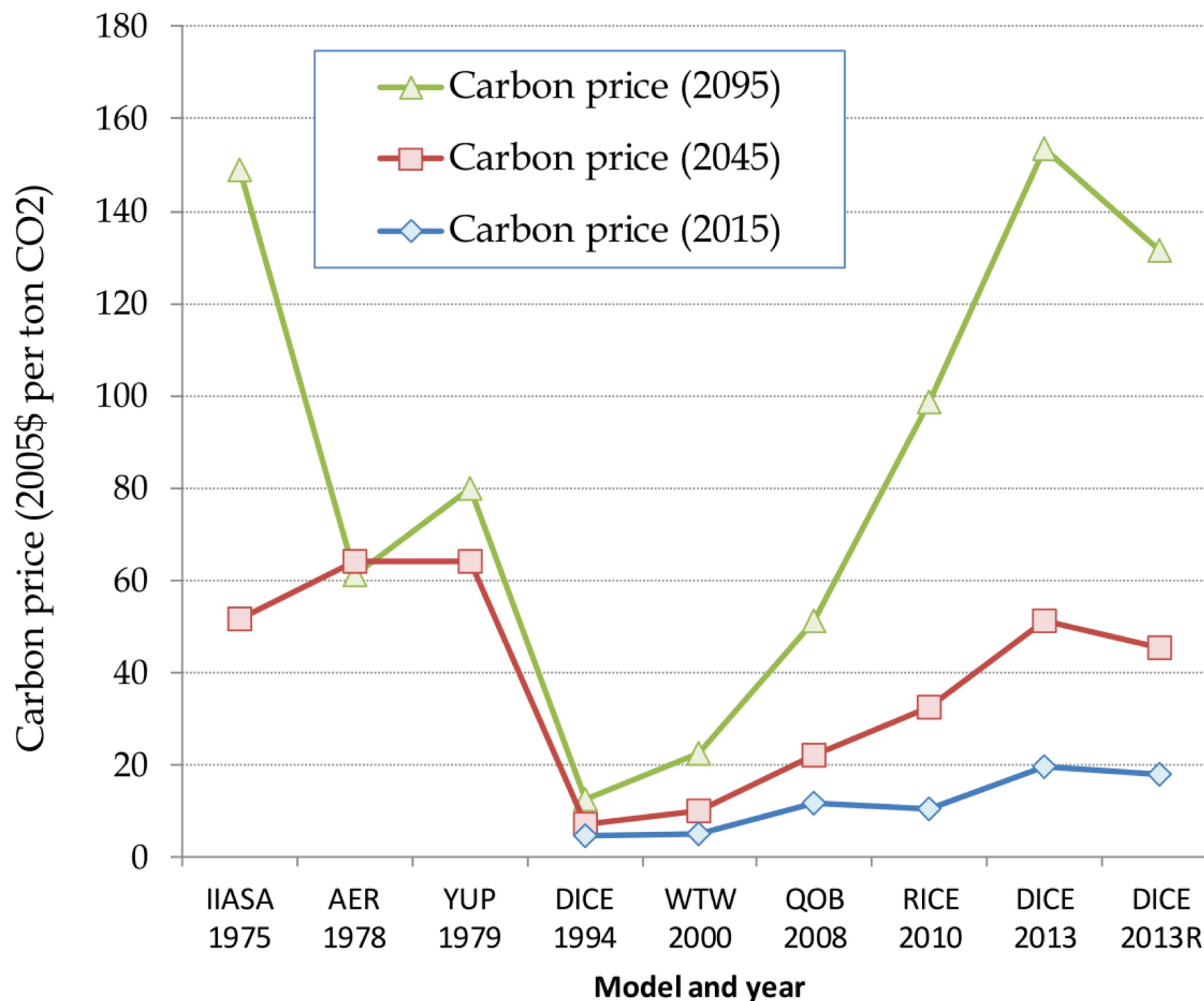
TABLE 1—SOCIAL COST OF CARBON ALTERNATIVE CONCEPTS,  
DICE 2016-R3 MODEL (2018\$)

	Social cost of carbon 2018\$ per ton of CO <sub>2</sub>			
	2015	2020	2050	2100
Base	37	45	108	304
Optimal	36	43	105	295
Optimal (alt dam)	91	108	249	584
T ≤ 2.5 (200yr)	41	49	123	379
T ≤ 2.0 (200yr)	49	59	153	511
T ≤ 1.5 (200yr)	69	84	226	776
T ≤ 2.5 (100yr)	76	93	260	755
T ≤ 2.0 (100yr)	130	158	413	1,013
T ≤ 1.5 (100yr)	236	279	682	1,191
T ≤ 2.5	95	118	361	477
T ≤ 2.0	225	275	749	459
T ≤ 1.5	NF	NF	NF	NF

*Notes:* *Base* = no controls. *Optimal* = cost-benefit maximum with base and alternative damage function. T ≤ 2.5 (200yr) = temperature limited 2.5°C for a 200-year average (and the parallel notation for different temperature limits and averaging periods). T ≤ 2.5 is temperature limited to 2.5°C as a hard constraint. In the table, “NF” indicates not feasible.

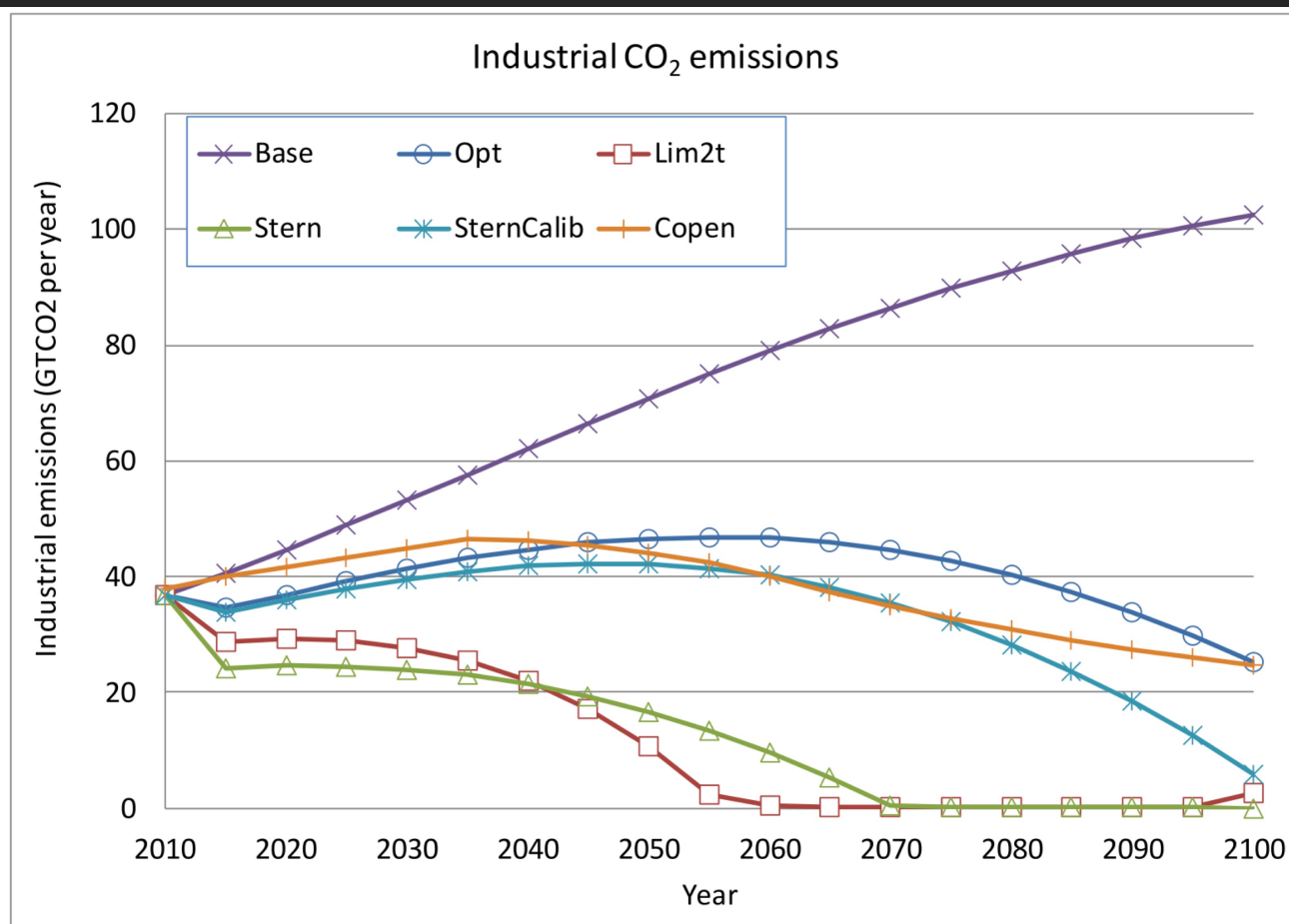
# Results

## Estimations have become more drastic over time



**Figure 15. Optimal carbon price, different vintages DICE/RICE models, 2005 \$ per ton CO<sub>2</sub> . Prices are for the indicated years.**

# THE RELEVANCE OF THE DISCOUNT RATE: NORDHAUS VS. STERN



Nordhaus: 1,5% annual

Stern: 0,1% annual

100 years

22%

90%

Figure 6. Projected emissions of CO<sub>2</sub> under alternative policies, DICE-2013R model

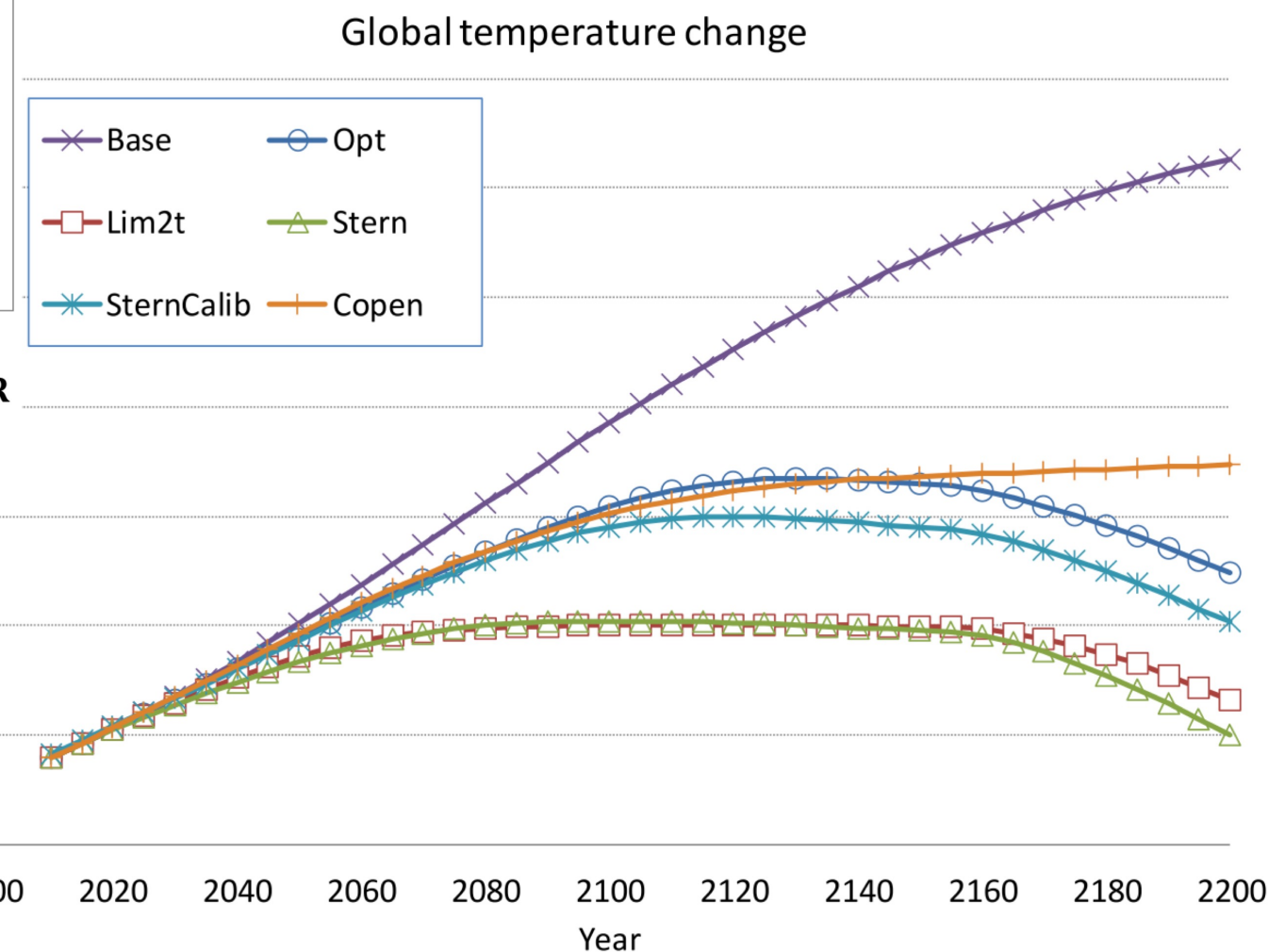


Figure 8. Global temperature increase (°C from 1900) under alternative policies, DICE-2013R model



# REFERENCES

- Nordhaus, W. (2013) Integrated economic and climate modeling. in *Handbook of Computable General Equilibrium Modeling* 1, 1069–1131 (Elsevier B.V., 2013).
- Nordhaus, W. (2018). Evolution of modeling of the economics of global warming: changes in the DICE model, 1992–2017. *Climatic Change*, 148(4), 623–640. <https://doi.org/10.1007/s10584-018-2218-y>
- Nordhaus, W. (2018) “Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies.” *American Economic Journal: Economic Policy* 10 (3): 333–60. <https://doi.org/10.1257/pol.20170046>
- Nordhaus, W. (2019) “Climate Change: The Ultimate Challenge for Economics.” *American Economic Review* 109 (6): 1991–2014. <https://doi.org/10.1257/aer.109.6.1991>
- Nordhaus, W., and P. Sztorc (2013) *DICE 2013R: Introduction and User’s Manual*. <http://acdc2007.free.fr/dicemanual2013.pdf>