Climate Modeling for Economists

ECON 482/ECON 530 Lectures

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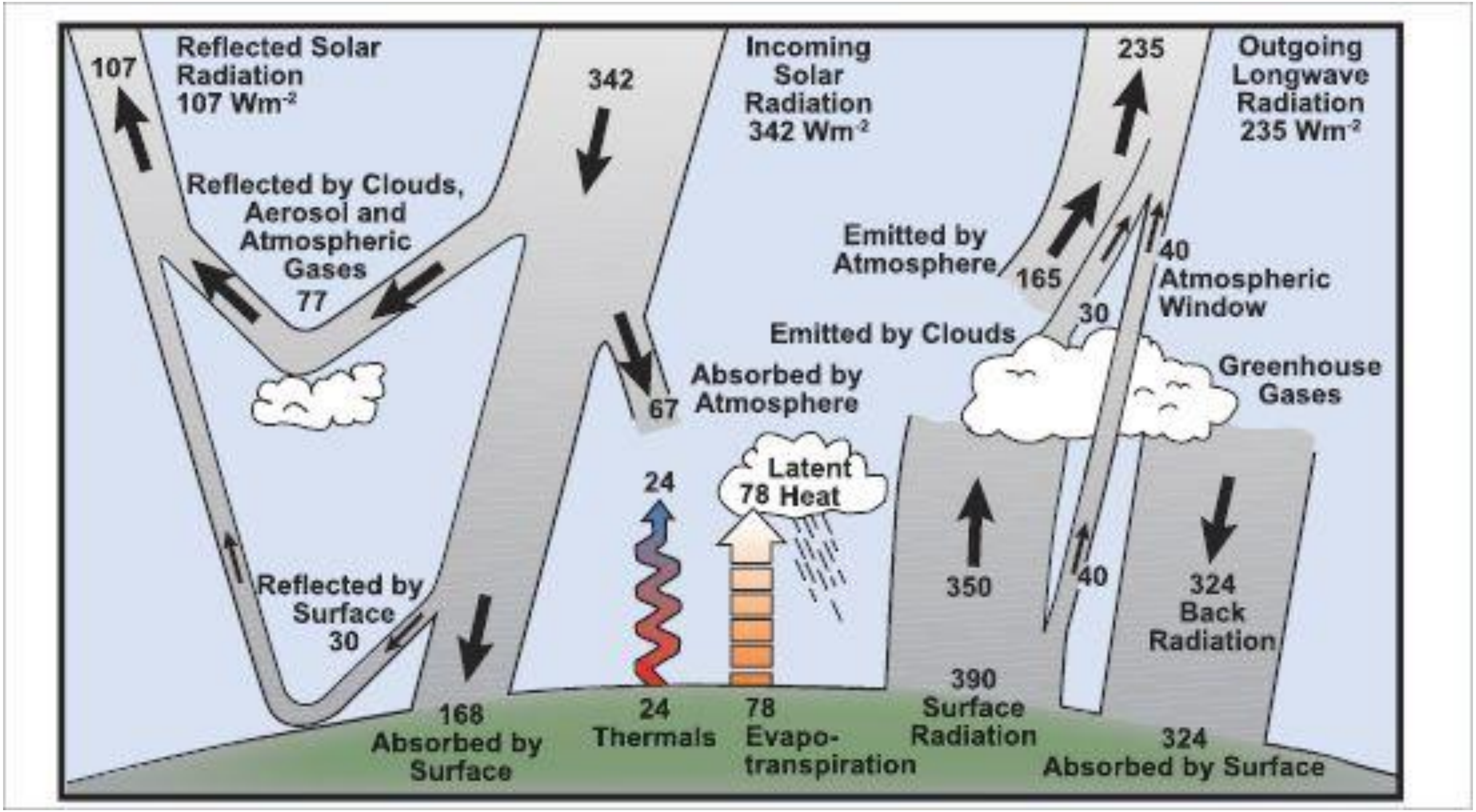
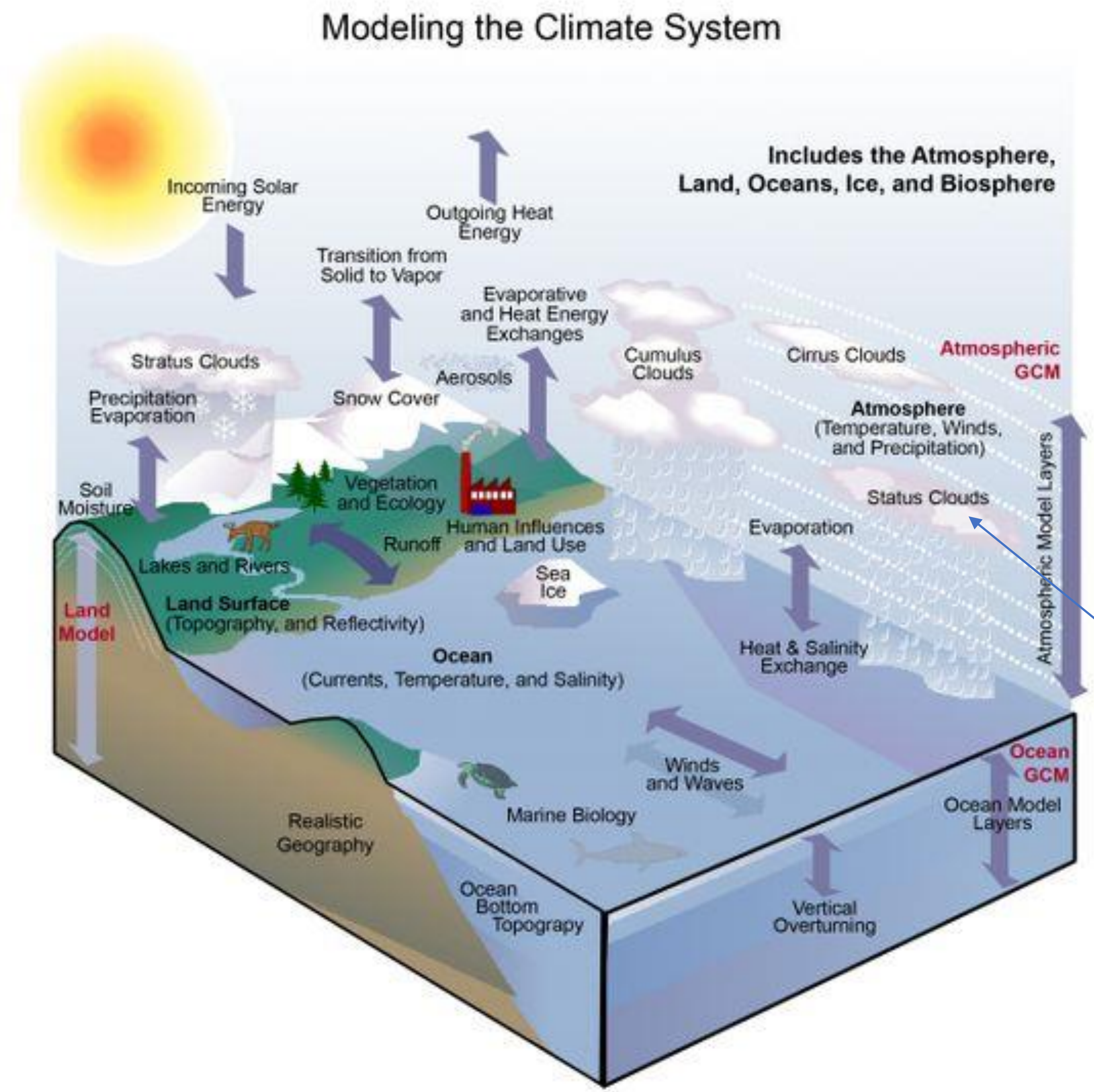
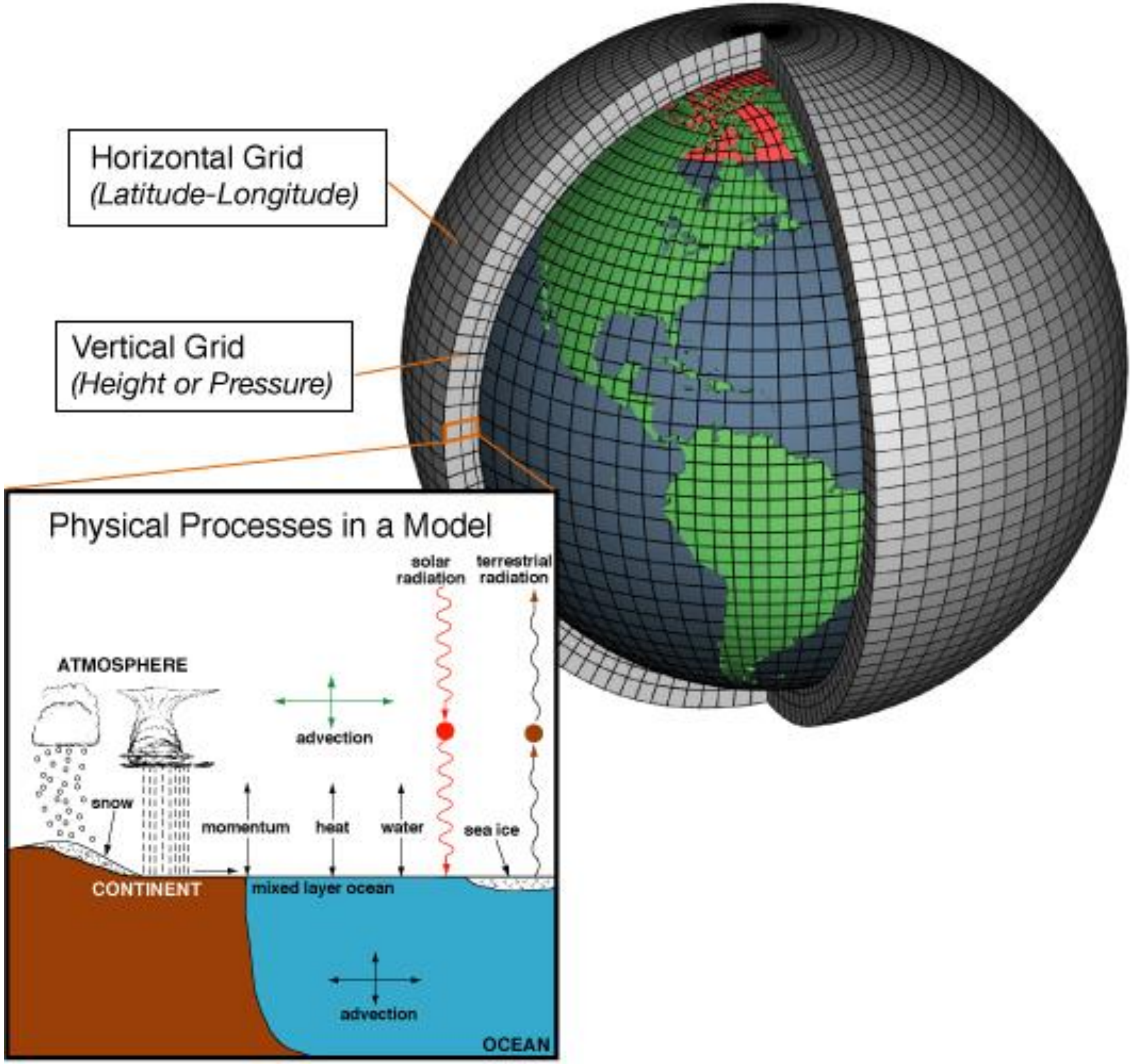


Simple zero-dimensional, energy-balance climate model



Complex climate model requiring millions of equations

Spelling error? Not status clouds but stratus clouds.



NOAA Model

https://www.climate.gov/

Uncertainties/contention regarding climate change

1. Projected increase in average global temperatures (McKitrick and Christy 2018; Lewis and Curry 2018; Hourdin et al. 2017; Millar et al. 2017);
2. Regional changes in climate that might be expected (Pielke 2018; Lomborg 2007);
3. Contribution to global warming of human activities (e.g., burning of fossil fuels, land use changes) versus that of natural factors (e.g., CO_2 release from oceans, changes in the sun's activities) (McKitrick & Michaels 2004, 2007; de Laat & Maurellis 2004, 2006; Khilyuk & Chilingar 2006; McKitrick & Nierenberg 2011; de Larminat 2016, 2019; Zharkova et al. 2019; Frank 2019; Richard 2019); and
4. Potential damages from future climate change, which, in turn, constitute the benefits of mitigating (avoiding) it. This is seen in the controversy concerning estimates of the social cost of carbon (SCC), which depends on estimates of expected damages from global warming (Auffhammer 2018; Dayaratna et al. 2017; Pindyck 2013).
5. Underlying assumptions and parameterizations used in climate models (incl. RCPs)

Translating climate projections into economic policy variable proceeds in three steps

1. Storylines are developed and used to determine future emissions of CO_2 (recalling that other greenhouse gases are included in this measure as used here). Storylines are then converted into emissions scenarios using one or more IAMs.
   - IMAGE (2.6), MiniCAM (4.5), AIM (6.0), MESSAGE (8.5)
2. Emissions scenarios are translated into future climate scenarios using various climate models.
3. Finally, IAMs that differ from those employed in step 1 are used to determine the economic impact of climate change. These IAMs are used to **derive optimal policies** for mitigating (or perhaps adapting to) global warming.
   - DICE model (Nordhaus)
   - FUND model (Tol)

Integrated Assessment Models for Policy

1. William Nordhaus' Dynamic Integrated Climate and Economics (DICE) model (Nordhaus 2013, 2018a)
2. Richard Tol's Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model (Tol 2014)
3. Policy Analysis of the Greenhouse Effect (PAGE) (Hope 2006).
    - Proprietary: not open source

- DICE model is the simplest to work with as it is a constrained optimization model written in GAMS. FUND is written in Matlab and constitutes a simulation model.
- Each IAM has a carbon-climate-temperature module (i.e., a climate model) imbedded in it.

Physics of climate models

- Stefan-Botzmann law gives the flux density (*F*) or irradiance from any blackbody:

$$F(\mathrm{T}) = \sigma\, \mathrm{T}^4\ [\mathrm{W} \cdot \mathrm{m}^{-2}]$$

where $\sigma = 5.67\times10^{-8}\ \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-4}$ is Stefan-Boltzmann constant, T is temperature.

- Earth is not a blackbody: clouds, snow, ice, etc. reflect the sun's rays (energy) back to space – known as **albedo**
- Solar energy flux varies with the distance from the sun according to:

$$S_0 = \sigma\, T_{sun}^4 \frac{r_{sun}^2}{d_{ES}^2},$$

where d_{ES} is distance Earth to sun. Average surface (but not core) temperature of the sun is 5,780 degrees Kelvin (K), the radius of the sun is 695,500 km, and the average d_{ES} = 149.6 million km, then S_0 = 1,367.8 W per m^2.

- Incident solar radiation over the Earth's surface varies with d_{ES}, tilt of Earth's axis, etc.
- ¼ of Earth's surface exposed to the sun at any time =>

average radiation = $342\ \mathrm{W} \cdot \mathrm{m}^{-2}$

Physics of climate models (cont)

- Easy to show that: $S_0 = 4\,\sigma\,\mathrm{T}^4$ [W · m^{-2}]
- The total radiative forcing historically consists of anthropogenic, volcanic and solar contributions (de Larminat 2019):

$$F = F_{anth} + F_{volc} + F_{sol}.$$

- Anthropogenic radiative forcing for double CO_2 is:

$$f_{2\times CO2} \approx 3.7\ \mathrm{W \cdot m^{-2}} \approx 5.35\ \ln(2)\ \mathrm{W \cdot m^{-2}}.$$

- The anthropogenic *a priori* forcing factor is then given by

$$f_{anth,t} = f_{2\times CO2} \times \frac{ln\left(\frac{\mathrm{CO}_{2,t}}{\mathrm{CO}_{2,base}}\right)}{ln(2)},$$

where $CO_{2,base}$ is the pre-industrial (base) level of atmospheric $CO_2 \approx 270$ ppm.

Forcings and Feedbacks

- Feedbacks are crucial for determining the anthropogenic impact on average global temperature.
- Any forcing or perturbation can have positive or negative feedbacks. Example:
  - If a perturbation causes temperatures to fall, more snow and ice are likely; snow and ice lead to an albedo reflecting sunlight back to space, thereby enhancing the original cooling. This constitutes a positive feedback because it further reduces the original reduction in temperature.
  - Warming effect of increased atmospheric CO_2 will tend to reduce snow and ice, thereby reducing the Earth's albedo and increasing its temperature.
- A warmer atmosphere holds more water vapor – a potent GHG that amplifies initial warming due to CO_2 and other trace GHGs.
- To determine the impact of human emissions of CO_2 on climate, related feedbacks must be taken into account as they either amplify or dampen the forcing from adding CO_2 into the atmosphere.

Global Mean Radiative Forcings, 1750 to 2011

Source	RF (W/m^2)	Range (W/m^2)[a]
Total anthropogenic forcing	+2.30	[+1.10, +3.30]
Well-mixed GHGs (CO_2, CH_4, N_2O, CFC, halocarbon)	+2.83	[+2.54, +3.12]
Aerosol-radiation interaction[b]	–0.45	[–0.95, +0.05]
Aerosol-cloud interaction	–0.45	[–1.20, +0.00]
Troposphere ozone	+0.40	[+0.20, +0.60]
Stratosphere ozone	–0.05	[–0.15, +0.05]
Stratosphere water vapor	+0.07	[+0.02, +0.12]
Surface albedo (land use)	–0.15	[–0.25, –0.05]
Surface albedo (black carbon aerosol on snow & ice)	+0.04	[+0.02, +0.09]
Combined contrails & contrail-induced cirrus	+0.05	[+0.02, +0.15]
Solar irradiance	+0.05	[+0.00, +0.10]

[a] Effective radiative forcing (ERF) is used rather than radiative forcing (RF) where they differ, because ERF has been shown to be a better indicator of the global mean surface temperature (GMST) response and is emphasized by the IPCC (2013, p.53 of Technical Summary).

[b] Biomass burning is neutral, although in previous reports it was negative and then slightly positive in AR4 (IPCC 2007).

Source: IPCC (2013, Table 8.6, p.696).

Forcings and Feedbacks

- With the CO_2 forcing, the system will eventually achieve a new (higher) equilibrium temperature given by (McGuffie and Henderson-Sellers 2005; Spencer 2010):

$$\frac{dT_m}{dt} = \frac{1}{C_m}(F - \lambda\, T_m),$$

where T_m is the temperature departure from a long-term average or from equilibrium (°C); dt represents the time step; C_m is the effective heat capacity of system component m (energy needed to heat surface of a mass unit of a substance by 1°C); F is the net radiative forcing [$\mathrm{W \cdot m^{-2}}$]; and λ is the total feedback parameter [$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$]

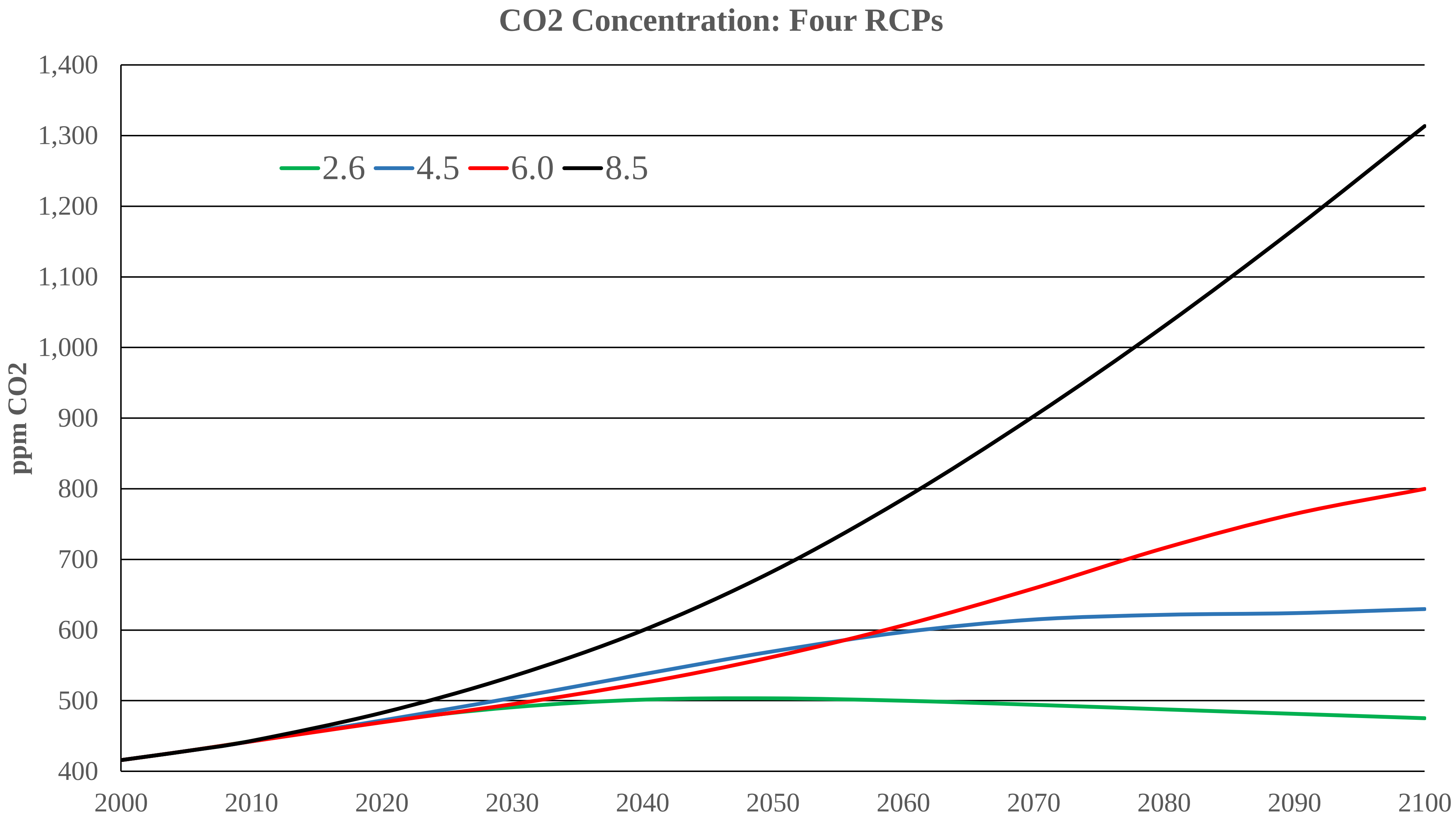
- Rewrite this in Euler's discrete form as follows (A refers to atmosphere):

$$T_{m,t+1} - T_{m,t} = (\Delta t\, / C_A)\,(F_t - \lambda\, T_{m,t}),$$

Representative Concentration Pathways (RCP)

- For its 2014 report (AR5), the IPCC developed RCPs that superseded the storylines developed in the IPCC's *Special Report on Emission Scenarios* (2000).
- These describe various climate futures, all of which are considered possible.
- Four RCPs that depend on the concentration of CO_{2e} in the atmosphere rather than emissions per se. These are based on radiative forcings assumed for 2100:
  - RCP2.6 assumes 2.6 W/m^2
  - RCP4.5 (4.5 W/m^2)
  - RCP6 (6.0 W/m^2)
  - RCP8.5 (8.5 W/m^2)
- Additional RCPs are being developed for AR6, including a RCP9.1 scenario.
- RCPs are now being augmented by the SSPs to provide flexible descriptions of possible futures within each RCP.

Question: Why is the RCP8.5 chosen as the business-as-usual scenario?



Shared Socioeconomic Pathways (SSP): Five Narratives or Storylines

- SSP1: “Sustainability: Taking the Green Road”
  - Low challenges to mitigation and adaptation
  - A world of sustainably focused growth and equality
- SSP2: “Middle of the Road”
  - Medium challenges to mitigation and adaptation
  - A world where trends broadly follow historical patterns
- SSP3: “Regional Rivalry: A Rocky Road”
  - High challenges to mitigation and adaptation
  - A world of resurgent nationalism
- SSP4: “Inequality: A Road Divided”
  - Low challenges to mitigation and high challenges to adaptation
  - A world of ever increasing inequality
- SSP5: “Fossil-fueled Development: Taking the Highway”
  - High challenges to mitigation and low challenges to adaptation
  - A world of rapid and unconstrained growth in economic output and energy use

Energy Balance Model (EBM)

- A simple zero-dimensional EBM is just as capable of predicting future trends in global average surface temperatures as a more-complicated global climate model. Even with a simple EBM, assumptions need to be made regarding four parameters that are found in all climate models:
    1. Depth of the ocean layer assumed to impact heat storage;
    2. Transfer of heat between the ocean and the atmosphere;
    3. Feedback parameters determining whether, when temperatures rise as a result of some forcing, the warming is reduced (negative feedback) or enhanced (positive feedback); and
    4. Initial temperature departure from the norm (i.e., the temperature anomaly), which affects the sequence of temperature projections from a climate model because, without additional forcing, temperatures should trend toward the norm.
- The values of these parameters are not known with certainty, but yet have a profound effect on outcomes.

A simple, single-layer climate model

- Recall: $T_{m,t+1} - T_{m,t} = (\Delta t / C_A)\,(F_t - \lambda\, T_{m,t})$
- For C_A=3.1403 × 10^8 J · K^{-1} · m^{-2}, an ocean depth of 75 m and an annual time step (86,400 s · day^{-1} × 365 days), we get:

$$T_{m,t+1} - T_{m,t} = 0.100424 \times (F_t - \lambda\, T_{m,\mathrm{t}}).$$

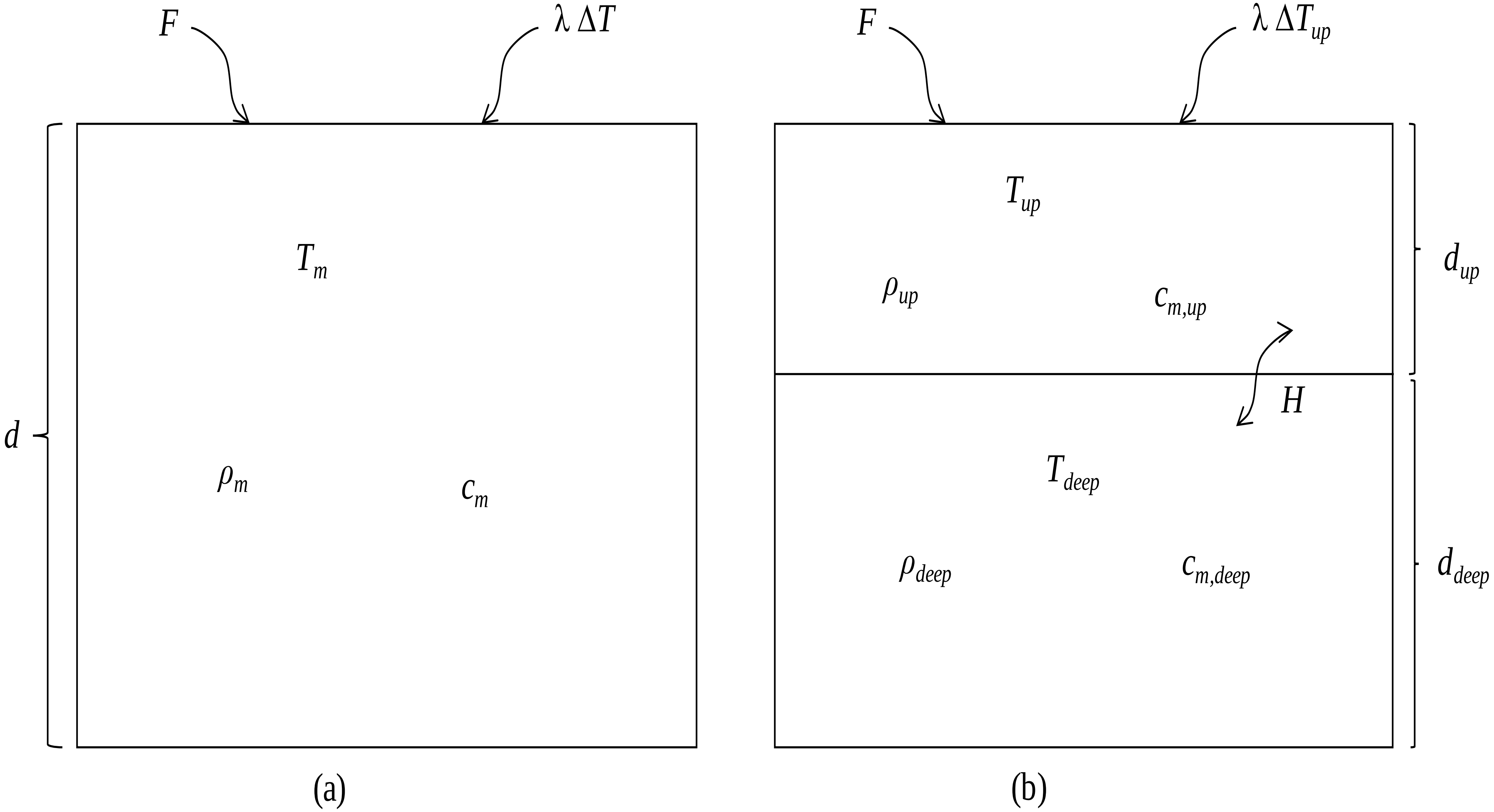
- Then, given a forcing *F* and feedback *λ*, the temperature anomaly evolves on an annual time step as follows (for component *m* – the atmosphere):

Period 1: $T_{m,1} = T_{m,0} + 0.100424 \times [F_0 - \lambda\, T_{m,0}]$

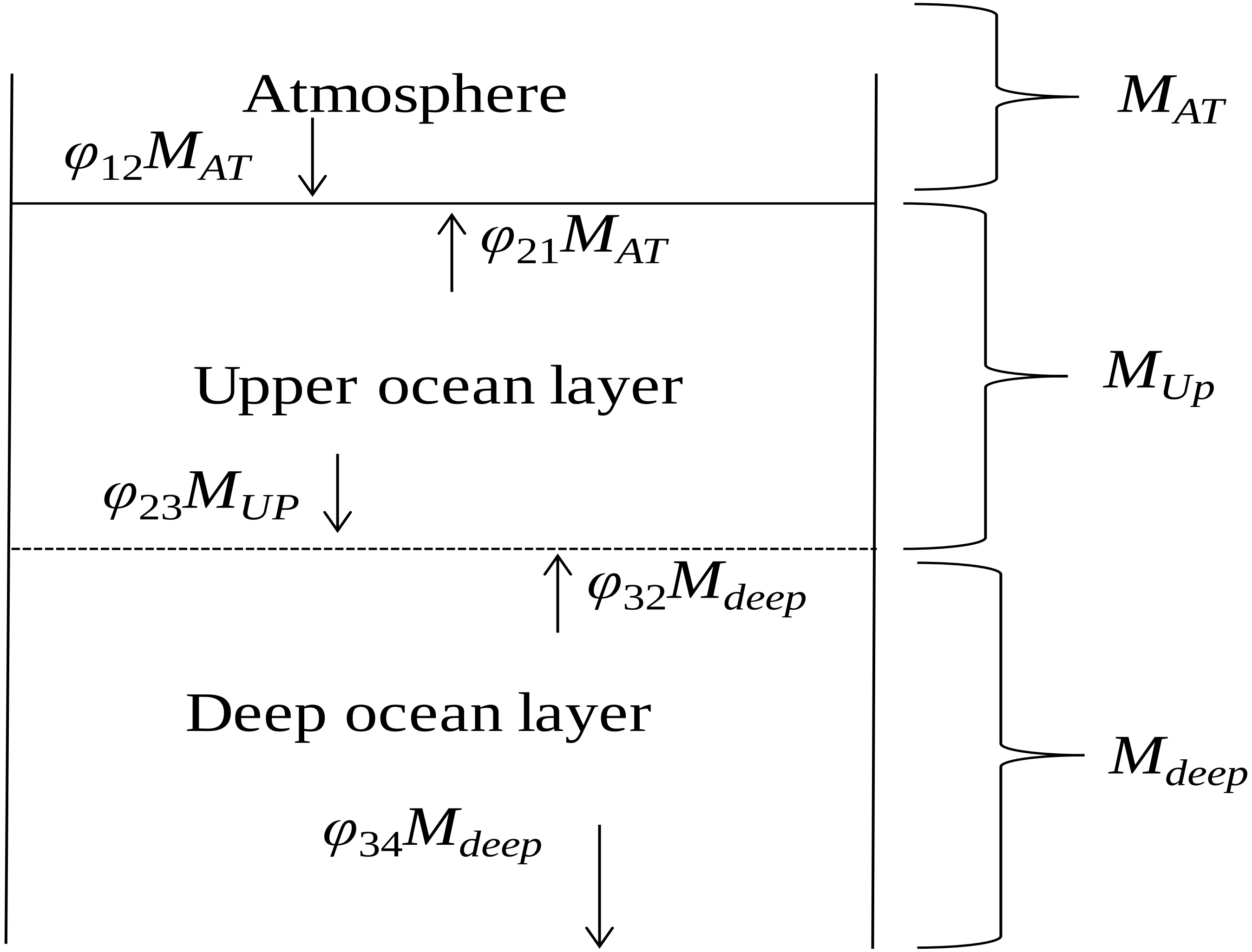
Period 2: $T_{m,2} = T_{m,1} + 0.100424 \times [F_1 - \lambda\, T_{m,1}]$

…

Period *N*: $T_{m,N} = T_{m,N-1} + 0.100424 \times [F_{N-1} - \lambda\, T_{m,N-1}]$



(a) Single Layer Climate Model (b) Two-Layer Climate Model



Atmosphere

$\varphi_{12}M_{AT}$

$\varphi_{21}M_{AT}$

Upper ocean layer

$\varphi_{23}M_{UP}$

$\varphi_{32}M_{deep}$

Deep ocean layer

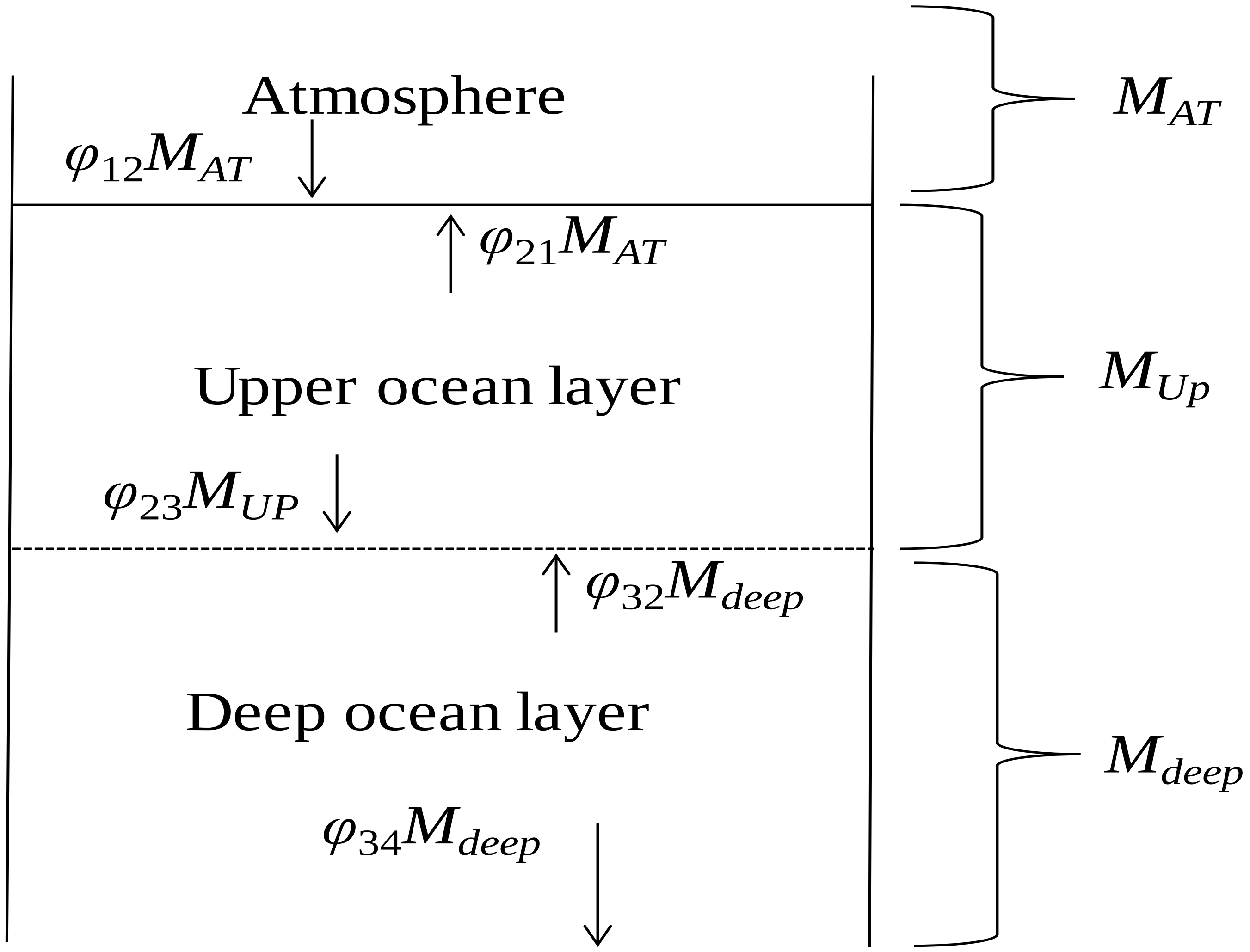
$\varphi_{34}M_{deep}$

M_{AT}

M_{Up}

M_{deep}

Carbon Cycle in the DICE Model (*M* refers to carbon)



Atmosphere

$\varphi_{12}M_{AT}$

$\varphi_{21}M_{AT}$

Upper ocean layer

$\varphi_{23}M_{UP}$

$\varphi_{32}M_{deep}$

Deep ocean layer

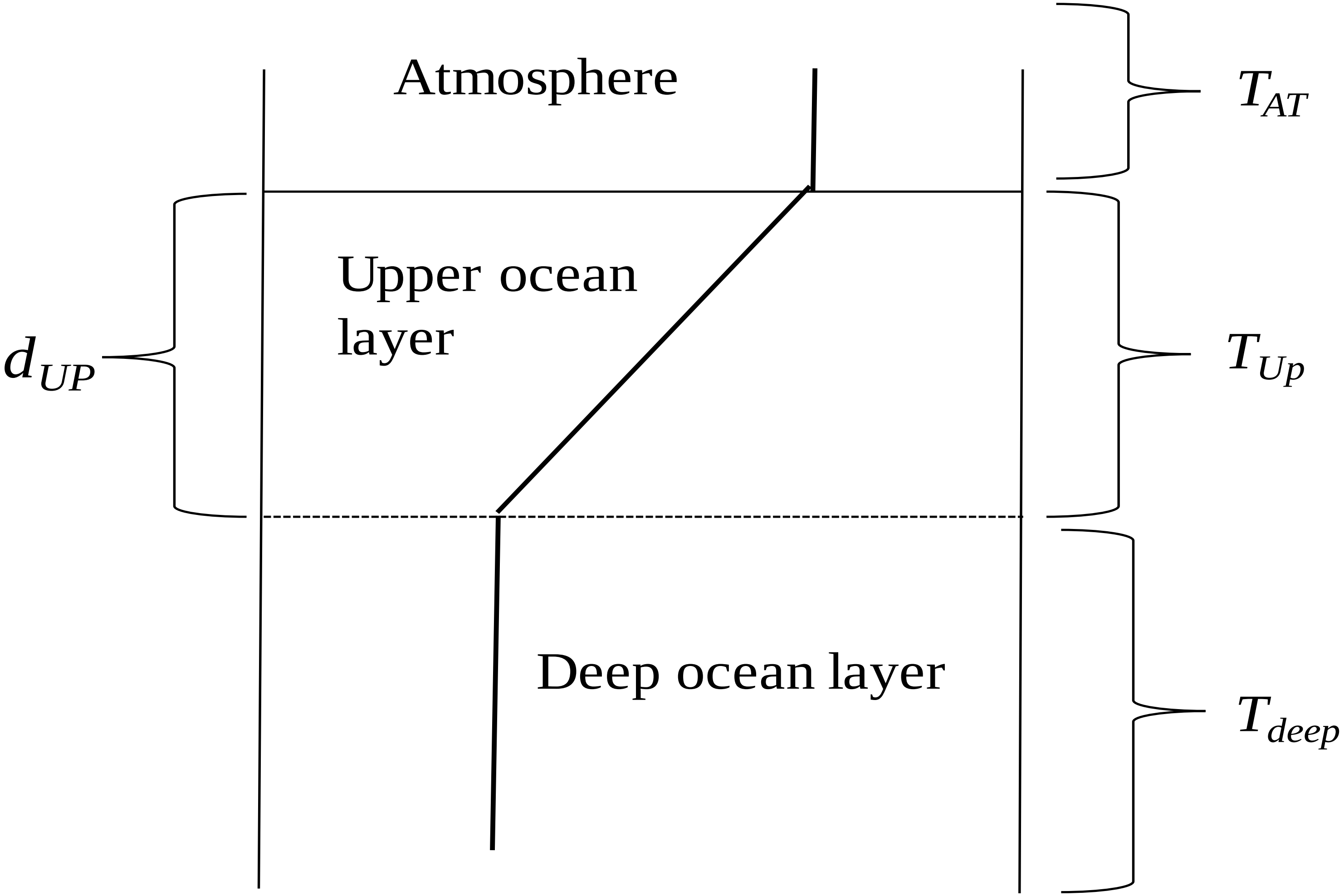
$\varphi_{34}M_{deep}$

M_{AT}

M_{Up}

M_{deep}

Carbon Cycle in the DICE Model (M refers to carbon)



Atmosphere

T_{AT}

Upper ocean layer

d_{UP}

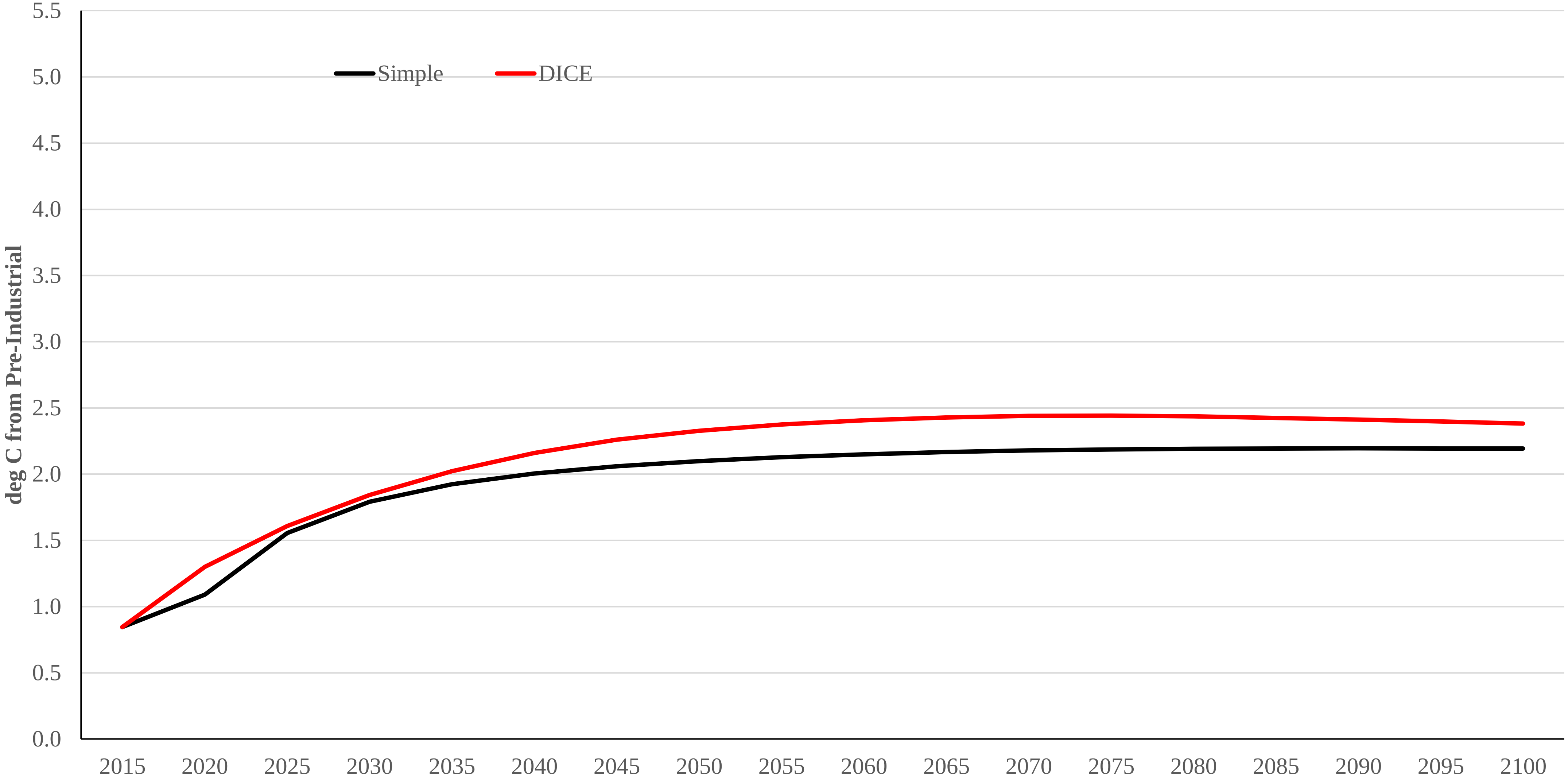
T_{Up}

Deep ocean layer

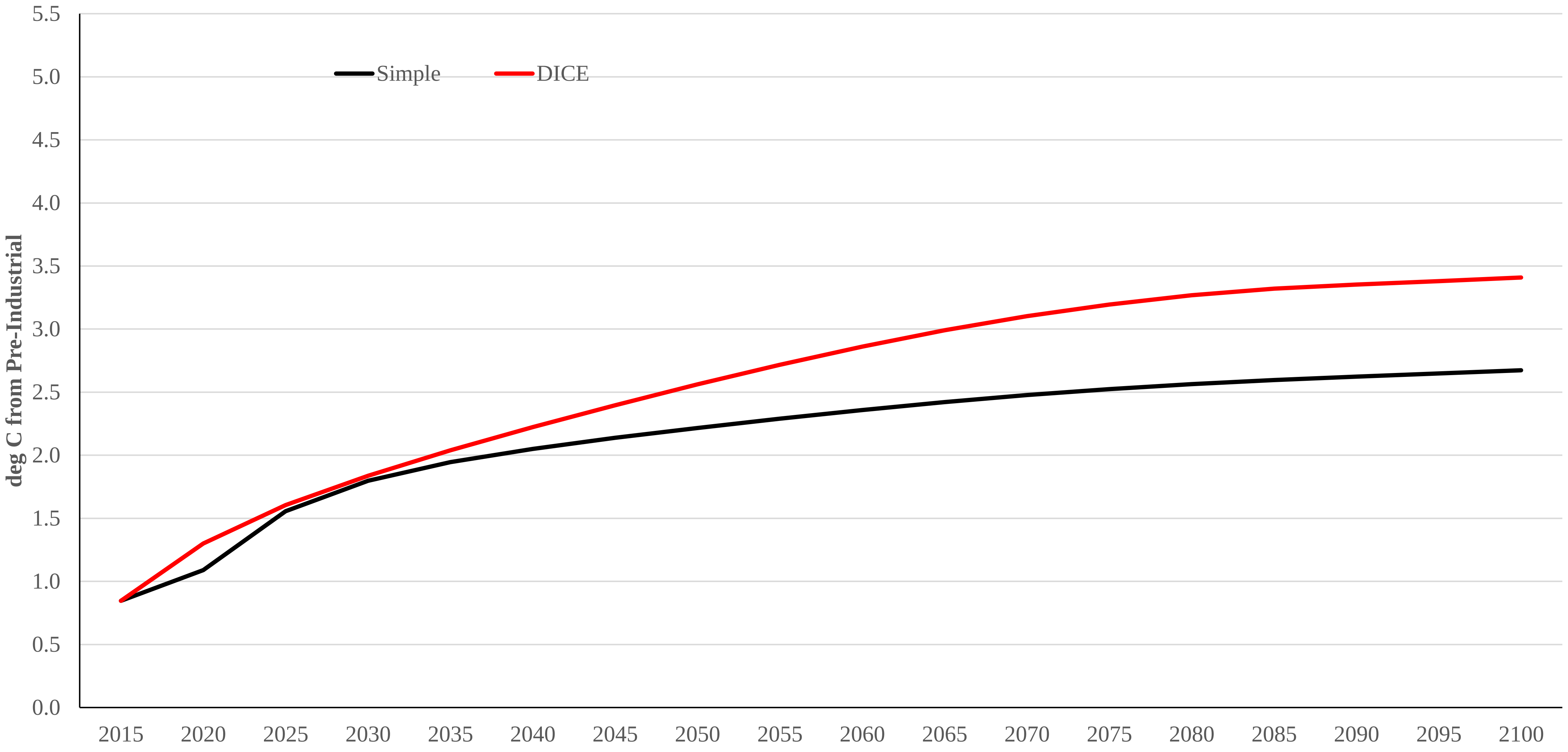
T_{deep}

Temperature Component in the DICE Model

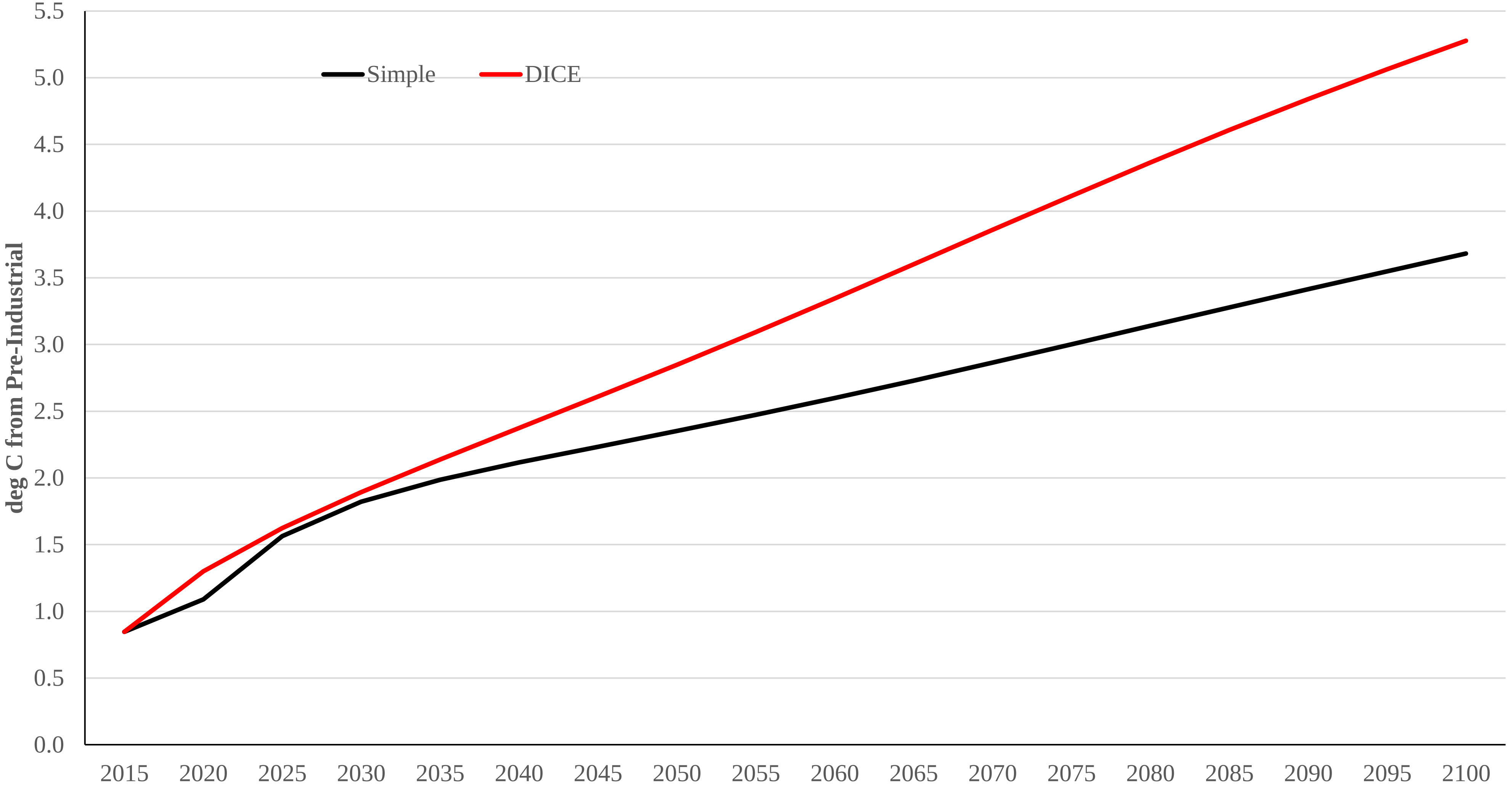
RCP2.6: Projected Temperature Anomalies, 2015-2100 (5-year steps)



RCP4.5: Projected Temperature Anomalies, 2015-2100 (5-year steps)



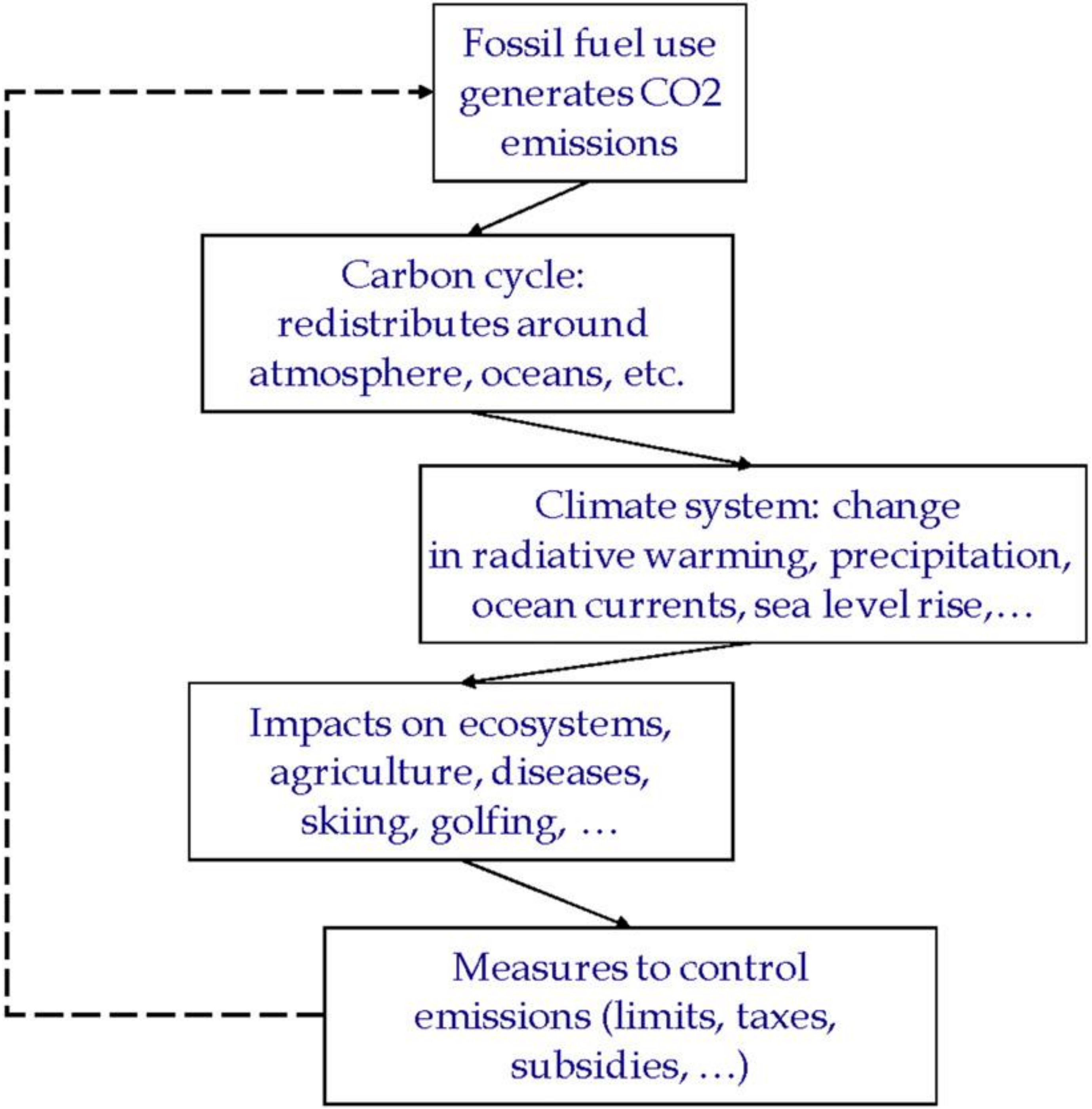
RCP8.5: Projected Temperature Anomalies, 2015-2100 (5-year steps)



Energy Modeling Forum (EMF)

- Headed by John Weyant
- Included the following IAMs:
  - PACE, IMAGE, MRN-NEEM, GTEM, MiniCAM, SGM, IGSM, WITCH, ADAGE, GEMINI, POLES, IGEM, MESSAGE, FUND, ETSAP-TIAM, MERGE, DART.
- These are large models:
  - Not unusual for models to have 40,000 or more lines of code written in Fortran and C within the same model
  - For the most part, models are not transparent; thus, unavailable to others
  - Models clearly focused on energy sector in great detail, with much less detail regarding other sectors of the economy
  - Even FUND (which is open access and originally written in Matlab) is becoming more difficult for non-initiates to run

Description of DICE Model



Fossil fuel use generates CO2 emissions

Carbon cycle: redistributes around atmosphere, oceans, etc.

Climate system: change in radiative warming, precipitation, ocean currents, sea level rise,…

Impacts on ecosystems, agriculture, diseases, skiing, golfing, …

Measures to control emissions (limits, taxes, subsidies, …)

Schematic flow chart of a full IAM for climate change science, economics and policy

Objective of DICE Model: Maximize Social Welfare Function

$$W = \sum_{t=1}^{T_{max}} U(c_t, L_t) R_t$$

where *W* is discounted sum of the population-weighted utility of per capita consumption; *c* is per capita consumption; *L* is population; R(t) is the discount factor; and

$$U(c_t, L_t) = L_t \, [c_t^{(1-\alpha)}/(1-\alpha)]$$

where α is the elasticity of the marginal utility of per capita consumption – the extent of substitutability of the consumption of different years or generations. If α is close to zero, the consumption of one generation and another are close substitutes; if α is high, they are not close substitutes.

$R_t = (1+\rho)^{-t}$ where ρ is the pure rate of social time preference that weights the utilities of future generations.

How the objective is written in GAMS:

From the previous slide, the utility/social welfare function is:

$$U(c_t, L_t) = L_t\,[c_t^{(1-\alpha)}/(1-\alpha)]$$

However, in practice the following form is used in the DICE model:

$$\{[c_t^{(1-\alpha)} - 1]/\,(1-\alpha)\} - 1$$

((C(T)*1000/L(T))**(1-elasmu)-1)/(1-elasmu)-1

Other Economic Variables

Output: $Q_t = [1 - A_t]\, B_t K_t^{\gamma} L_t^{(1-\gamma)}/(1+D_t)$

where Q_t is output net of damages and abatement at time t; A_t represents climate abatement costs; B_t is total factor productivity; K_t is capital stock and services; and D_t represents climate damages.

Damage functions:

Two damage functions are specified by Nordhaus as follows:

1. $D_t = \delta_1\, T_t^{atm} + \delta_2\, SLR_t + \delta_2\, M_t^{atm}$ (RICE – regional model)
2. $D_t = d_1\, T_t^{atm} + d_2\, (T_t^{atm})^2$ (DICE model)

T_t^{atm} refers to the atmospheric (surface) temperature, SLR_t to sea level rise, and M_t^{atm} to the carbon dioxide in the atmosphere (e.g., measured in ppm).

Determination of the parameters is difficult and includes estimated damages to major sectors such as agriculture, cost of sea-level rise, adverse impacts on health, non-market damages, CO_2 fertilization, and estimates of the potential costs of catastrophic damages

Abatement costs and standard accounting equations

Abatement costs:

$$A_t = \theta_1\, Q_t\, u_t^{\theta_2}$$

This specification says that abatement costs are proportional to output and an increasing function of the emissions reduction rate, u_t. It allows for inclusion of various assumptions about abatement costs.

Accounting:

$Q_t = C_t + I_t$ (output equals consumption plus investment)

$c_t = C_t/L_t$ (per capita consumption where L is population)

$K_t = I_t + (1 - \delta_K)\, K_{t-1}$ (change in the capital stock over time)

CO_2 emissions and control

- CO_2 emissions are projected as a function of total output, a time-varying emissions-output ratio, and an emissions-control rate.
- Uncontrolled industrial CO_2 emissions are given by a level of carbon intensity, σ_t, times output. Actual emissions are then reduced by one minus the emissions-reduction rate, u_t. The emissions-reduction rate is the control variable:

$$E_t^{ind} = \sigma_{\mathrm{t}} (1 - u_t) B_t K_t^{\gamma} L_t^{(1-\gamma)}$$

- Finally, there is a limit to the availability of fossil fuels, measured in terms of carbon release and denoted *CL*. It is assumed that carbon fuels are efficiently allocated over time to produce optimal Hotelling rents:

$$\mathrm{CC} \geq \sum_{t=1}^{T_{max}} E_t^{ind}$$

- Finally, total emissions are given by:

$$E_t = E_t^{ind} + E_t^{land} \ ,$$

where E_t^{ind} are endogenously determined industrial emissions and E_t^{ind} are exogenously determined emissions from land (viz., deforestation)

Carbon Cycle

Climate system consists of atmosphere, upper ocean and deep (lower) ocean. Carbon flux equations for each component in terms of carbon sources & sinks (Gt CO_2).

$$\frac{dA}{dt} = e(t) + \psi_{12}U - \psi_{21}A$$

$$\frac{dU}{dt} = \psi_{21}A + \psi_{23}D - (\psi_{21} + \psi_{12})U$$

$$\frac{dD}{dt} = \psi_{32}U - \psi_{23}D$$

where e(t) is rate of emissions (Gt $CO_2 \cdot s^{-1}$); A, U, and D represent carbon in atmosphere, upper ocean & deep ocean reservoirs; ψ_{ij} parameters describe rate of carbon exchange from reservoir i to reservoir j (in s^{-1}). Integrated solution for carbon in a given reservoir is an exponential decay with ‘residence time’ of $\tau_{ij} = 1/\psi_{ij}$.

Carbon cycle in DICE model

The discretized form of the equations on the previous slide as used in DICE:

$$A_t = E_{t-1} + (1 - \varphi_{21}) A_{t-1} + \varphi_{12} U_{t-1}$$
$$U_t = (1 - \varphi_{12} - \varphi_{32}) U_{t-1} + \varphi_{21} A_{t-1} + \varphi_{23} D_{t-1}$$
$$D_t = (1 - \varphi_{23}) D_{t-1} + \varphi_{32} U_{t-1}$$

R_t is total carbon in a given reservoir ($R = A$, U or D) at time t, and R_{t-1} and E_{t-1} are the reservoir values and total emissions in the previous time step.

For a timestep, Δt, $\varphi_{ij} = \psi_{ij} \Delta t$ is fraction of carbon transferred between reservoirs; $(1 - \varphi_{ij})$ represents the proportion of carbon retained to next period. $0 \leq \varphi_{ij} \leq 1, \forall i,j$.

Values of the parameters used in DICE2016 and in earlier versions of DICE are found in the table on the next slide. There, I retain terms written as φ_{ii} in Nordhaus' notation. The φ_{ij} values must be scaled by Δt when using different model timesteps; however, ψ_{ij} values are independent of the timestep used.

These values do not need to be defined, as they are simply equal to $(1–\varphi_{ij})$.

Parameter	DICE 2016R2	DICE 2013	DICE 2008	Current
		General		
$F_{2\times \mathrm{CO2}}$	3.6813	3.8	3.8	3.7
ECS	3.1	2.9	3.2	2.0
		Damage function		
a_1 (intercept)	0	0	0	
a_2 (quadratic term)	0.00236	0.00267	0.0028388	
a_3 (exponent)	2.0	2.0	2.0	
		Carbon module		
φ_{11}	0.88	0.912	0.810712	0.9
φ_{21}	0.12	0.088	0.189288	0.1
φ_{12}	0.196	0.052267	0.097213	0.0033
φ_{22}	0.797	0.945233	0.852787	0.9917
φ_{32}	0.007	0.0025	0.05	0.0050
φ_{23}	0.11433	0.038329	0.003119	0.0015
φ_{33}	0.98857	0.961671	0.996881	0.9975
		Temperature module[a]		
$c_1 = \frac{\Delta t}{C_{up}}$	0.1005	0.098	0.208	(3.0767, 0.0973)[b]
β	0.0880	0.088	0.31	0.008 [1.3]
$c_2 = \frac{\beta \Delta t}{C_{deep}}$	0.0250	0.025	0.05	0.00034

Parameter Values used in the DICE Model, Past and Current

Temperature Module in DICE Model

Temperature flux between the atmosphere and deep ocean depends on the gradient in the upper ocean (see previous slide) and thereby the depth of the upper ocean. Temperature in each period is given by the following equations:

$$T_t = T_{t-1} + \frac{\Delta t}{C_{up}} [F_{t-1} - \lambda\, T_{t-1} - \beta\, (T_{t-1} - T_{t-1}^{deep})]$$

$$T_t^{deep} = T_{t-1}^{deep} + \frac{\beta \Delta t}{C_{deep}} (T_{t-1} - T_{t-1}^{deep})$$

where T is the increase in atmospheric temperature in ^{o}C since 1900; $\lambda = \frac{F_{2\times CO_2}}{ECS}$; T^{deep} is the increase in lower ocean temperature in ^{o}C; F_t is the increase in radiative forcing (W/m^2) from 1900 in period t.

$F_{2\times CO2}$ = 3.44 W/m^2 but, more often, 3.7 W/m^2

Increase in radiative forcings

The relationship between greenhouse gas accumulations and increased radiative forcing is derived from empirical measurements and climate models

$$F_t = \eta\ [\log_2(M_t^{atm}/M_b^{atm})] + F_t^{EX}$$

where F_t is the change in total radiative forcings of greenhouse gases since base year b, taken to be 1750. The first term refers to the forcing due to CO_2, while F_t^{EX} *refers to* exogenous forcings. From the DICE model, it seems $\eta = 1/\log_2$

The DICE model uses a time step of five years ($\Delta t = 5$), although it can be reformulated to be at one-year time step.