Foundations of Integrated Assessment Modeling

A brief history with examples

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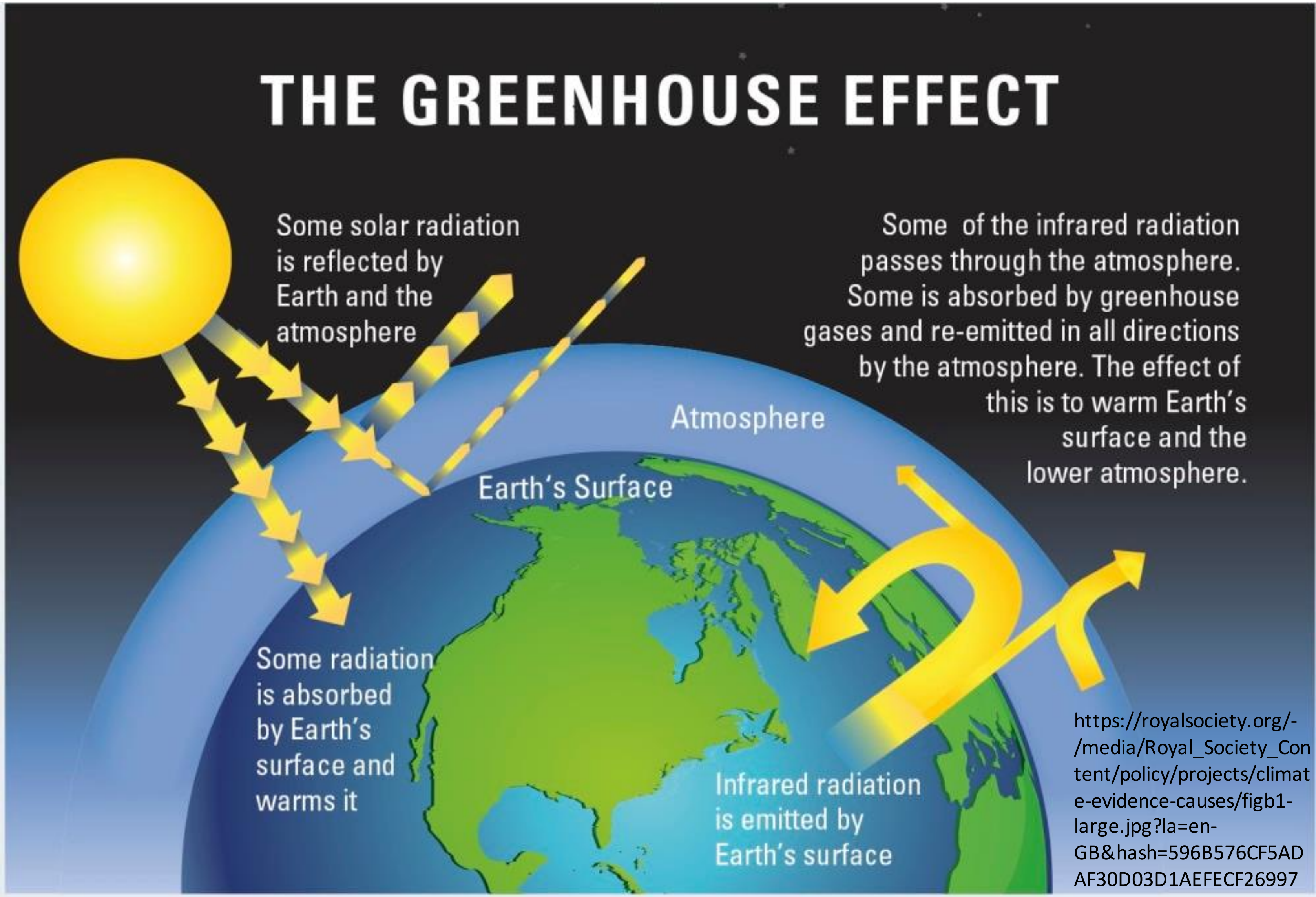
Foundations of Integrated Assessment

- *Today's Topics*
  - Some background stuff
  - Integrated assessment modeling (IAM) history
  - Highly detailed IAMs
  - Scenarios

CLIMATE BASICS

Climate Change

- Average Earth temperature ~15^{o}C (59^{o}F)
- Earth's black body temperature -23°C (-9.4^{o}F)
- Gases that change climate forcing include **H_2O**, CO_2, CH_4, N_2O, halons, short-lived forcers, and aerosols.
- **CO_2 is the most important human-generated GHG emitted**



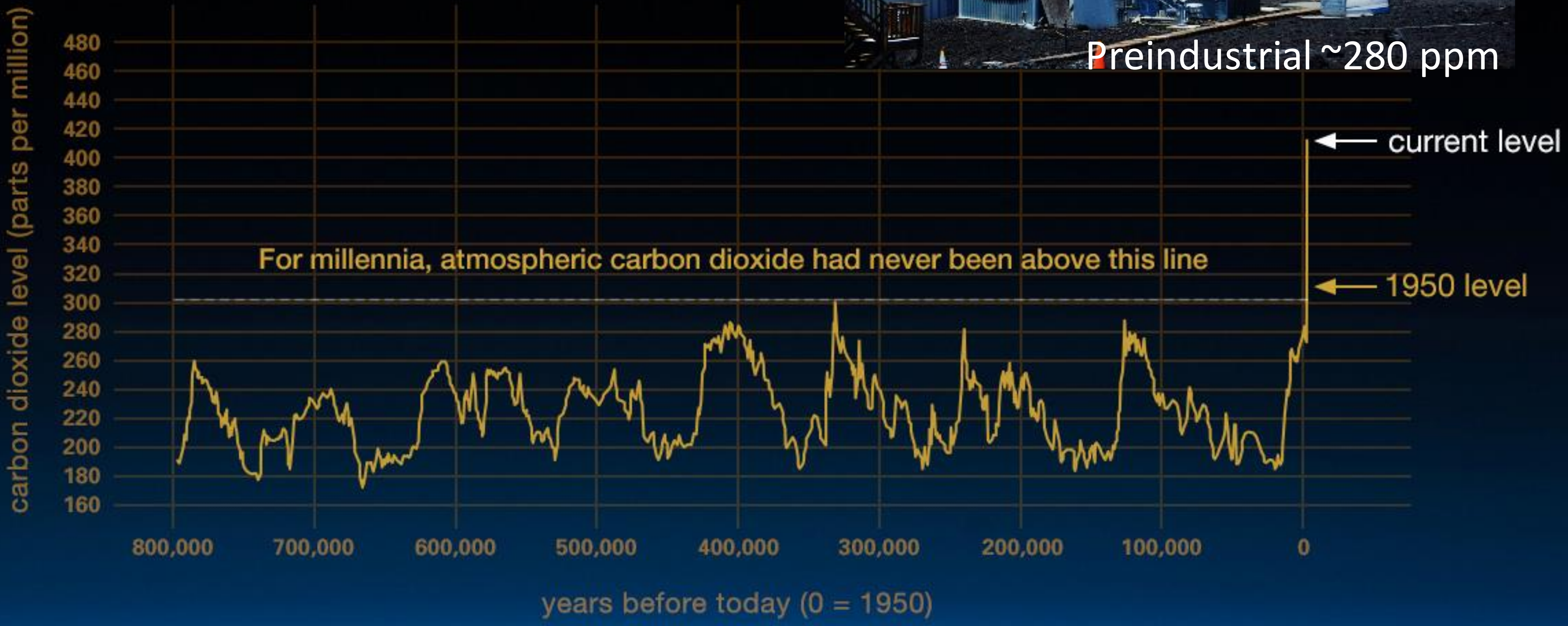
https://royalsociety.org/-/media/Royal_Society_Content/policy/projects/climate-evidence-causes/figb1-large.jpg?la=en-GB&hash=596B576CF5ADAF30D03D1AEFECF26997

CO_2 the last 800,000 years

CO_2 Jan 30 2023 **419.7 PPM** at NOAA's Mauna Loa Atmospheric Baseline Observatory

Preindustrial ~280 ppm

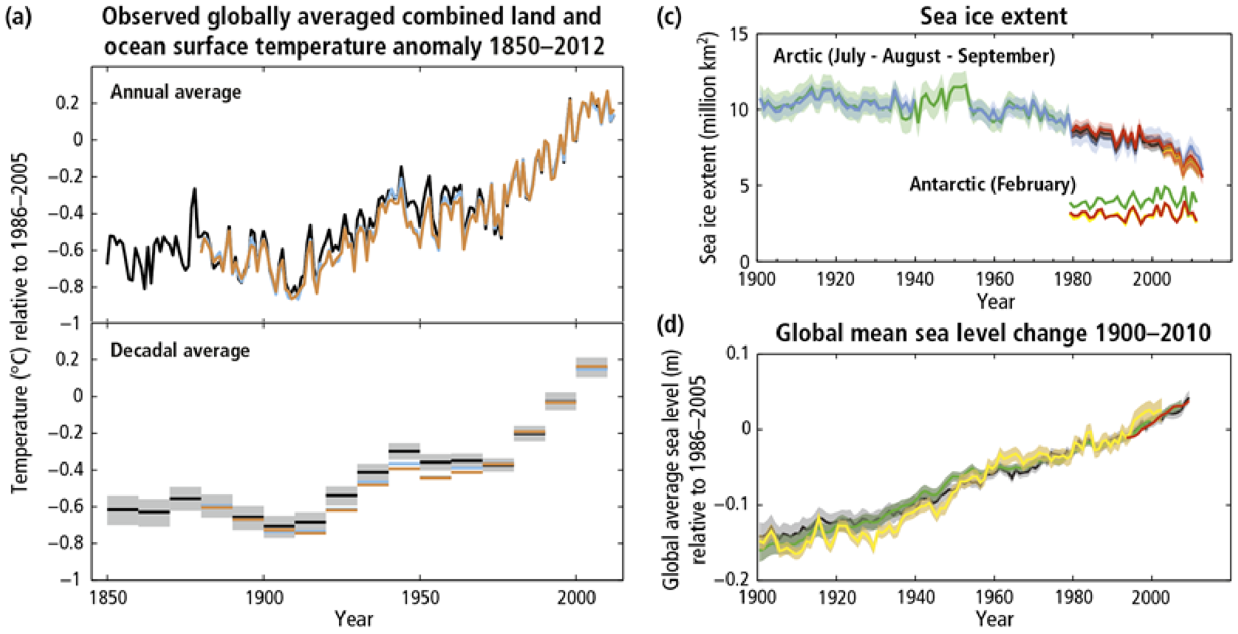
Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record.

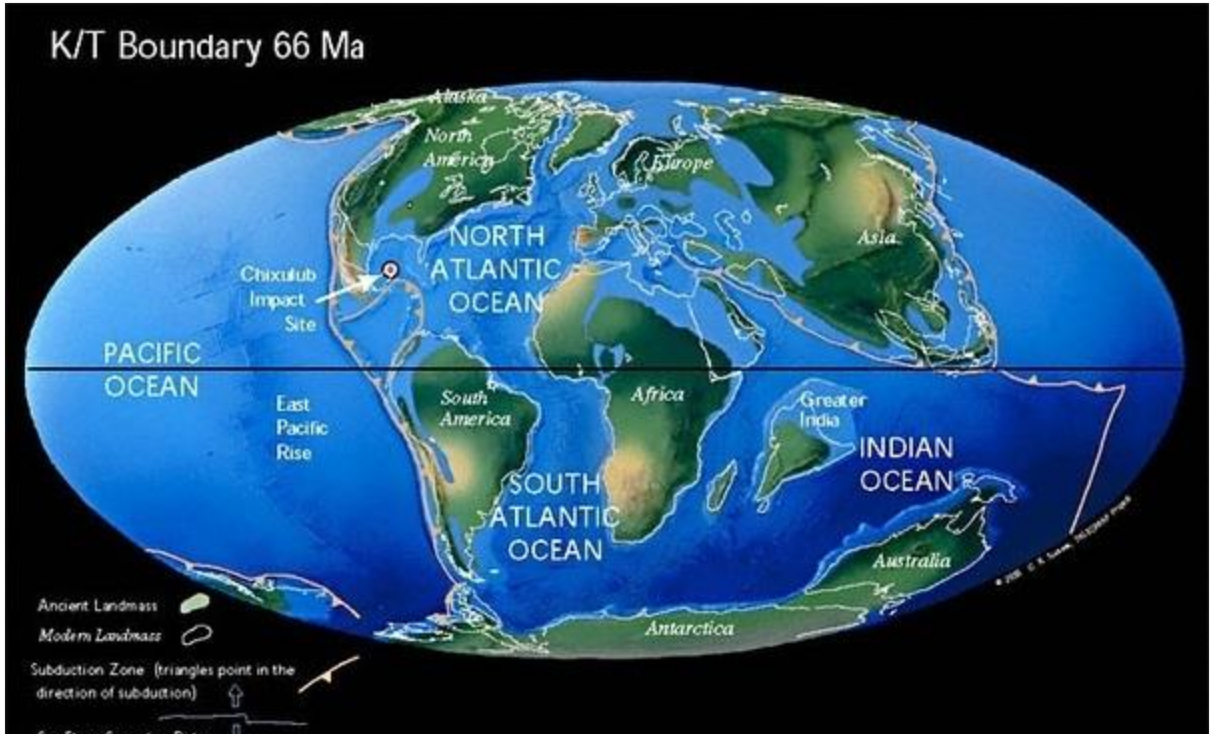


Source: https://climate.nasa.gov/news/2535/satellite-data-confirm-annual-carbon-dioxide-minimum-above-400-ppm/

ΔT ~1.0ºC (1.8ºF) Warming since 1850

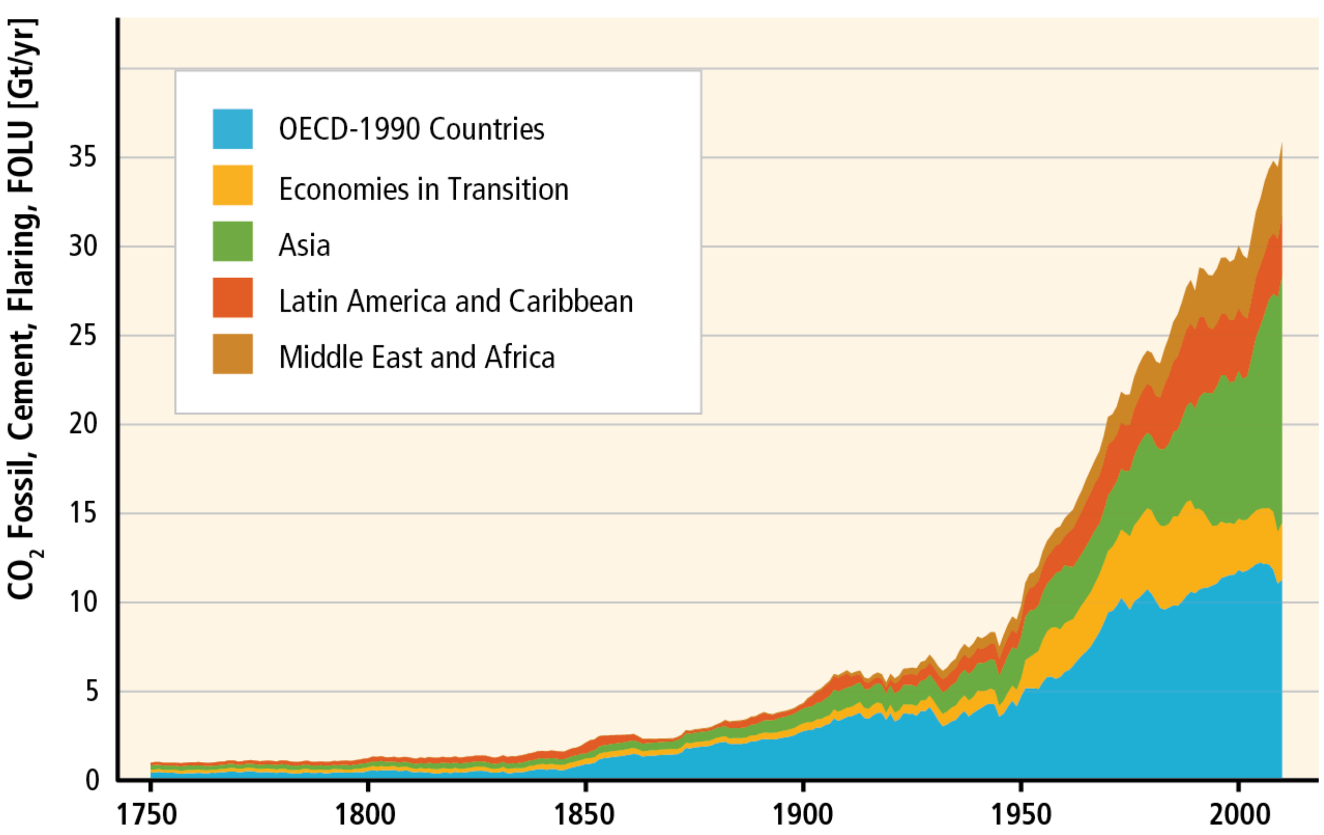
- Sea level rise 20cm (7.9in)
- Arctic sea ice reduction
- Sea levels were much higher when CO_2 concentrations where much higher and the Earth much warmer than today

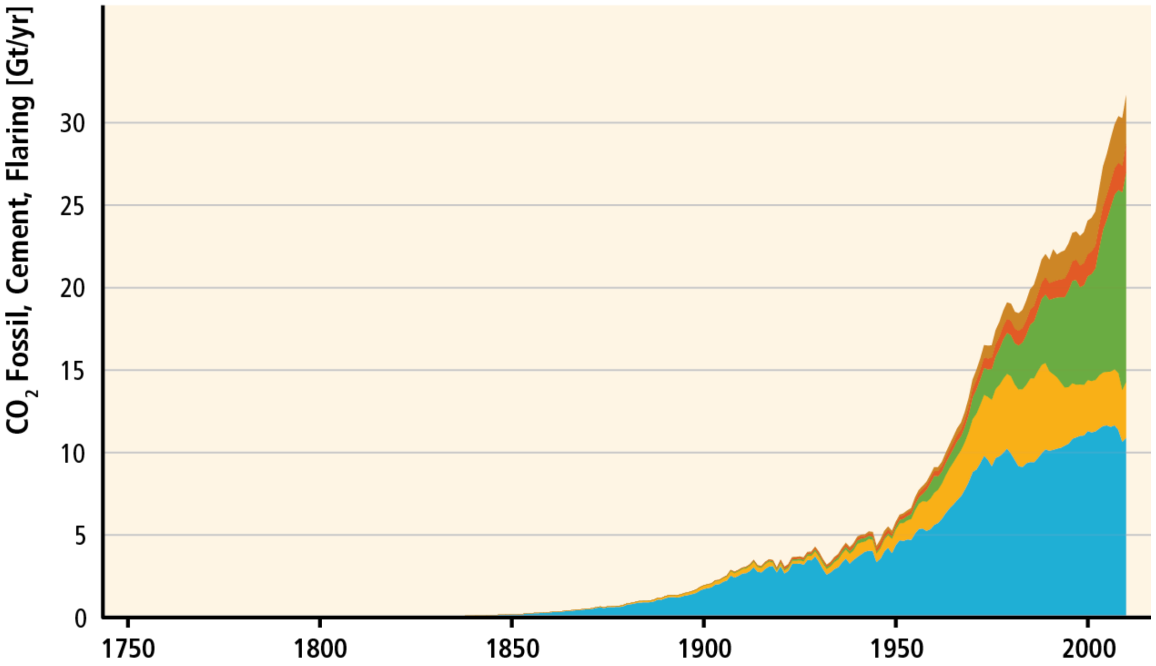




Source: https://qph.fs.quoracdn.net/main-qimg-a6fe08a52dd7b90cf59658764e295cd2-c

Fossil fuel and Land-use change emissions





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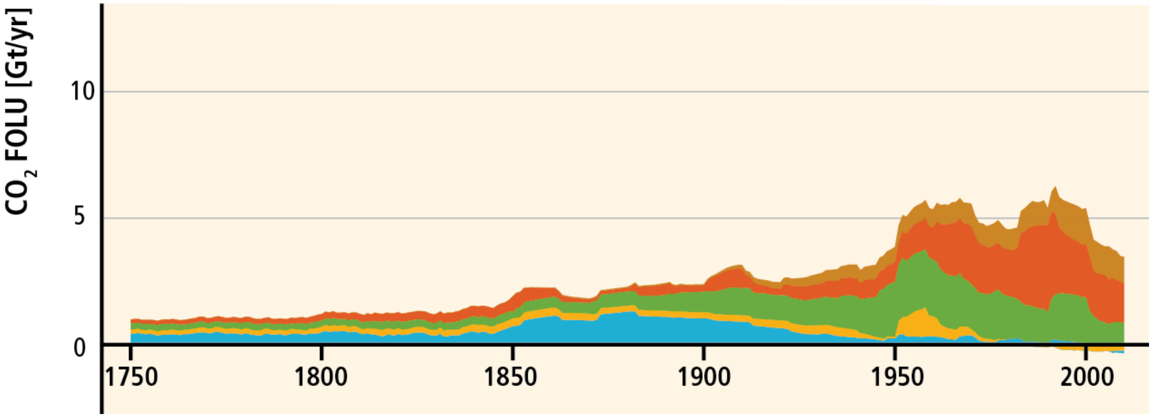
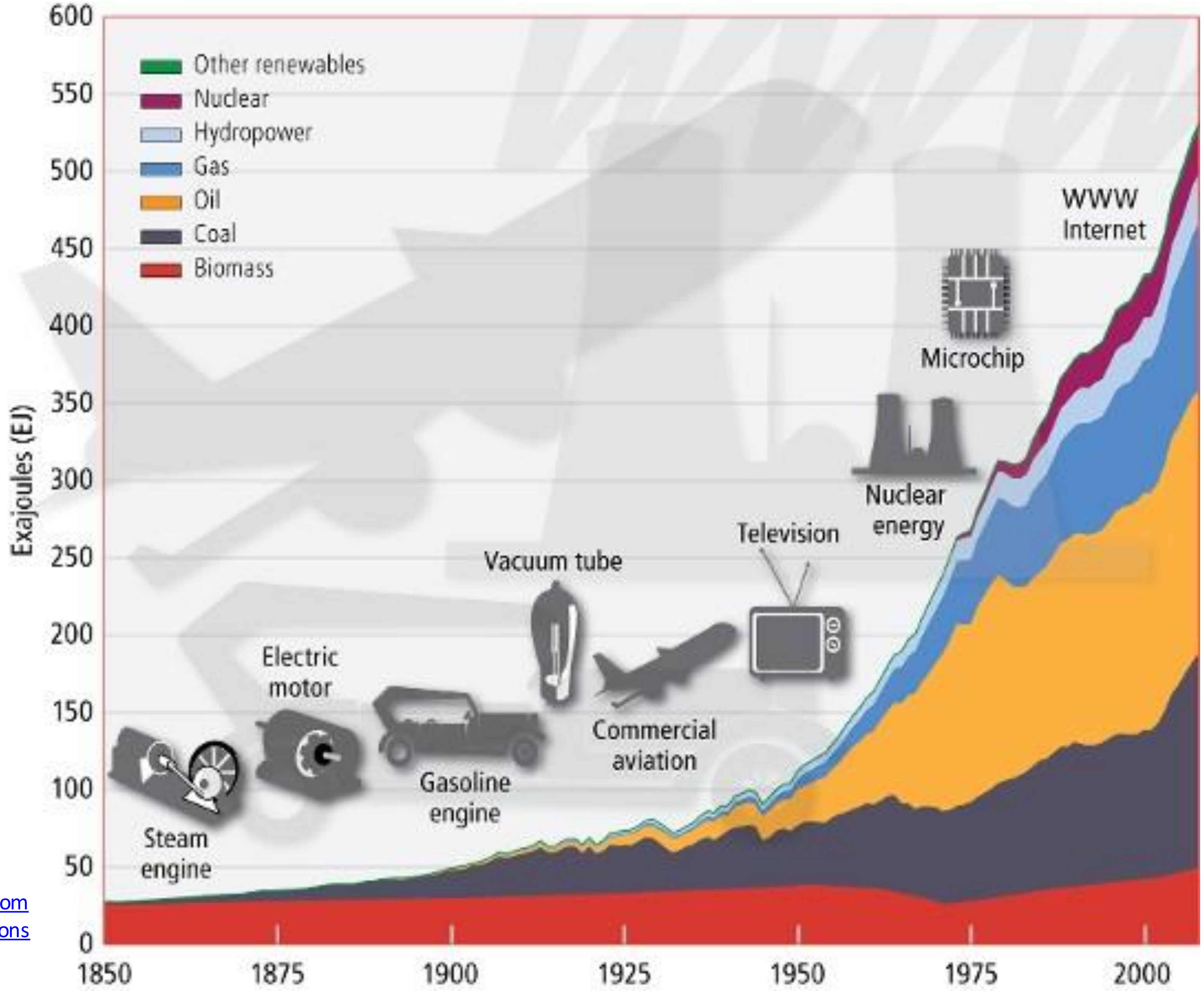
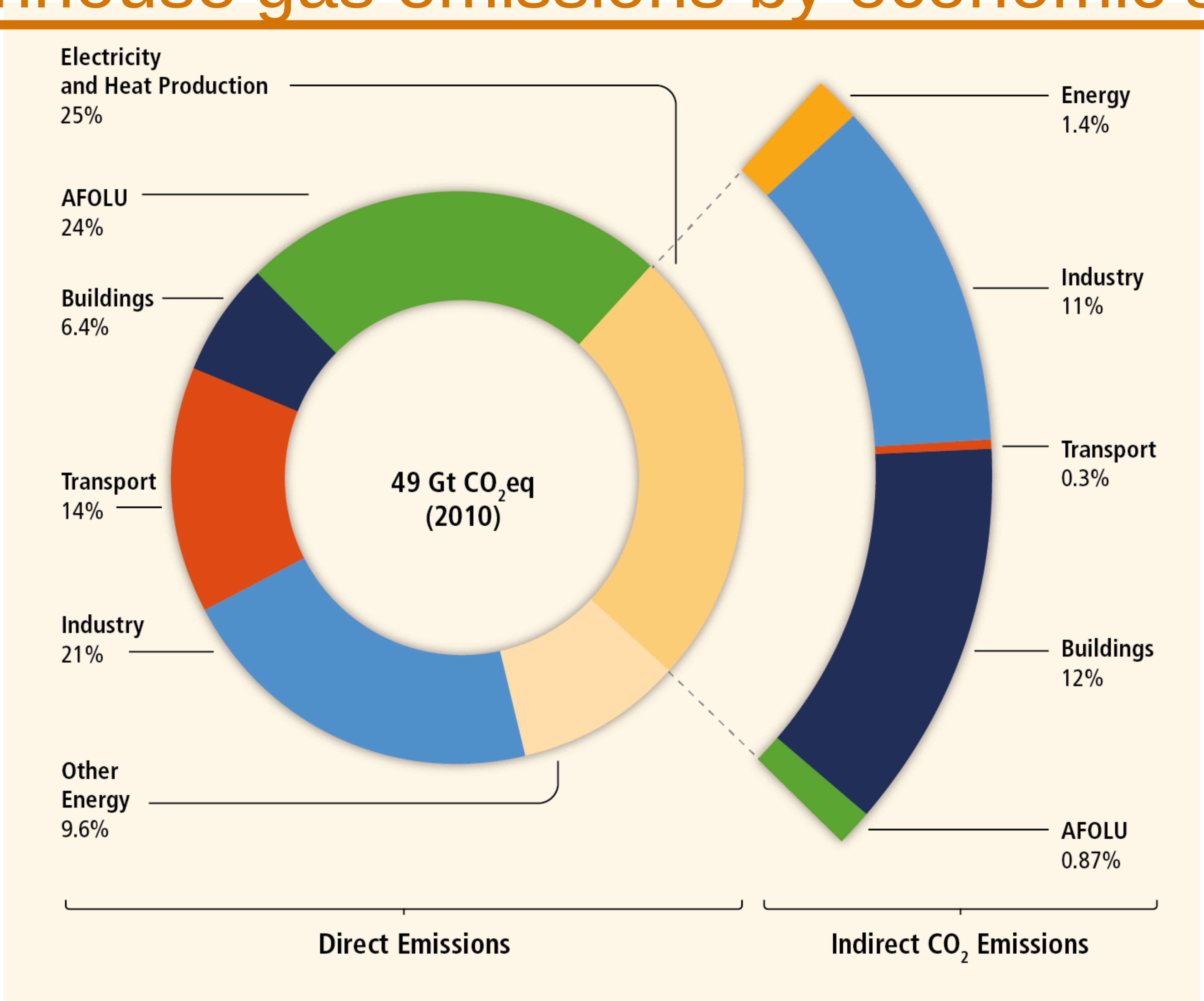


Source: https://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG3&f=Technical%20Summary



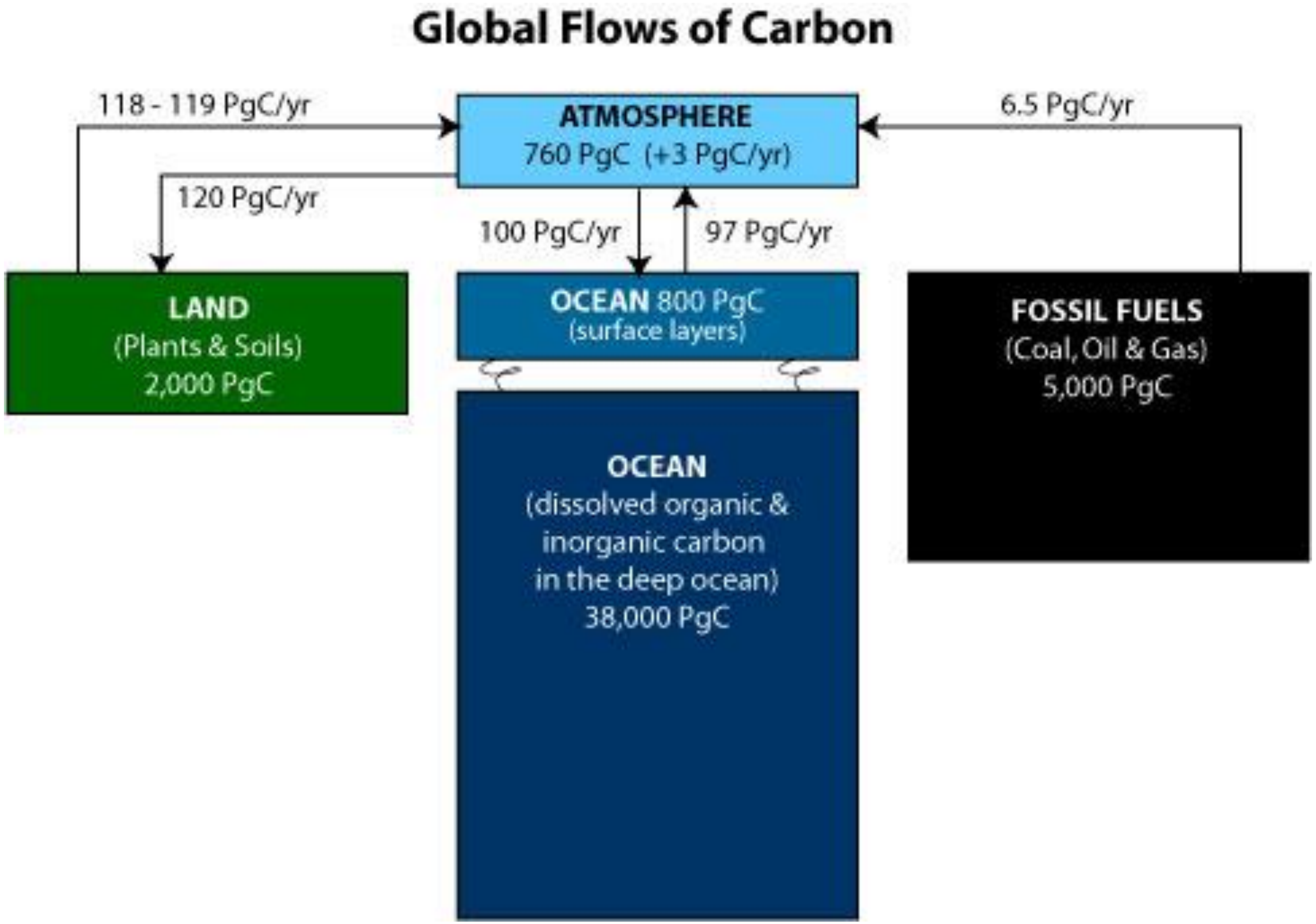
Source: http://www.iiasa.ac.at/web/home/resources/publications/options/Sustainable.en.html

Greenhouse gas emissions by economic sector



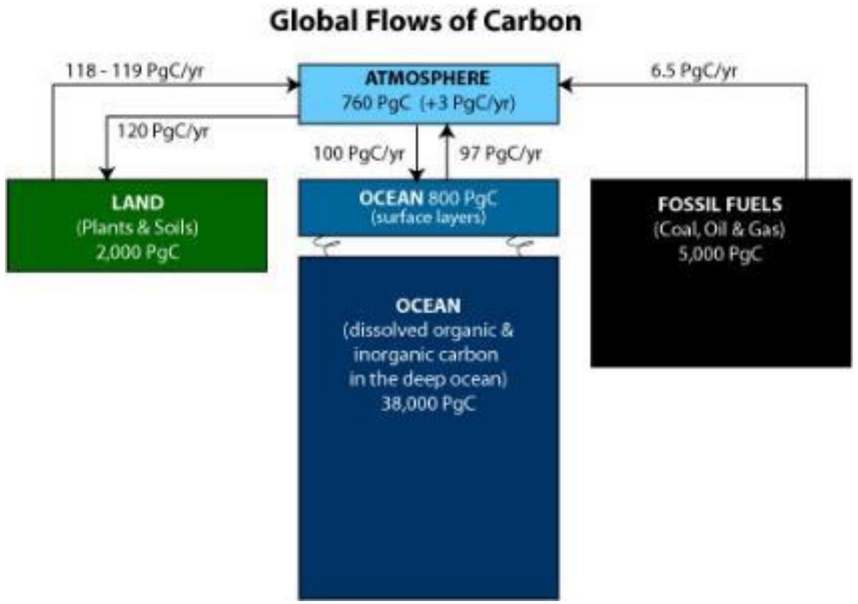
Source:
https://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG3&f=Technical%20Summary

Carbon Reservoirs

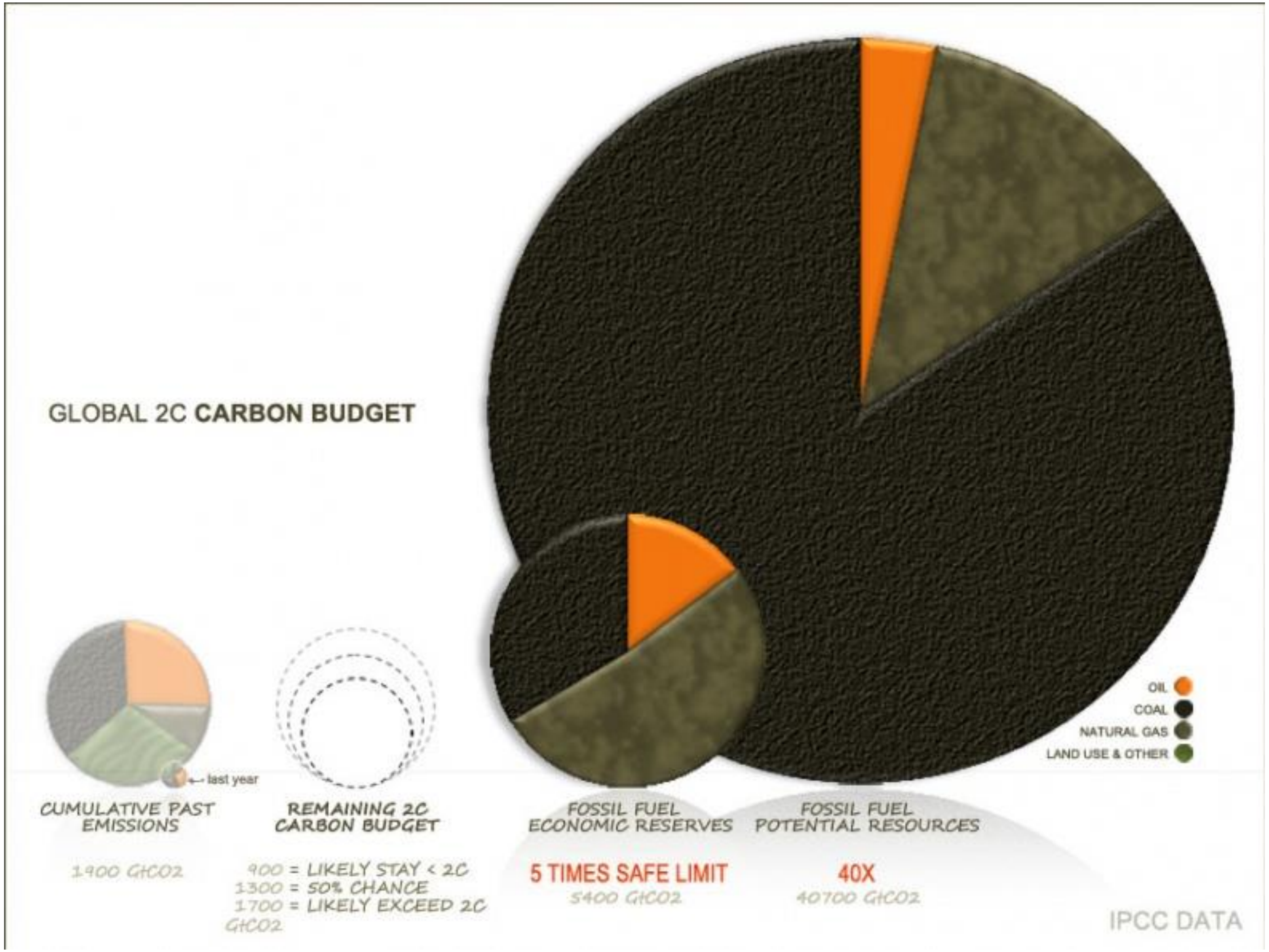


Source: https://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-carbon-cycle

Fossil Fuel Reserves versus Resources



Source: https://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-carbon-cycle



Source: https://www.nationalobserver.com/2015/05/14/news/climate-number-changes-everything

A brief comment of greenhouse gases

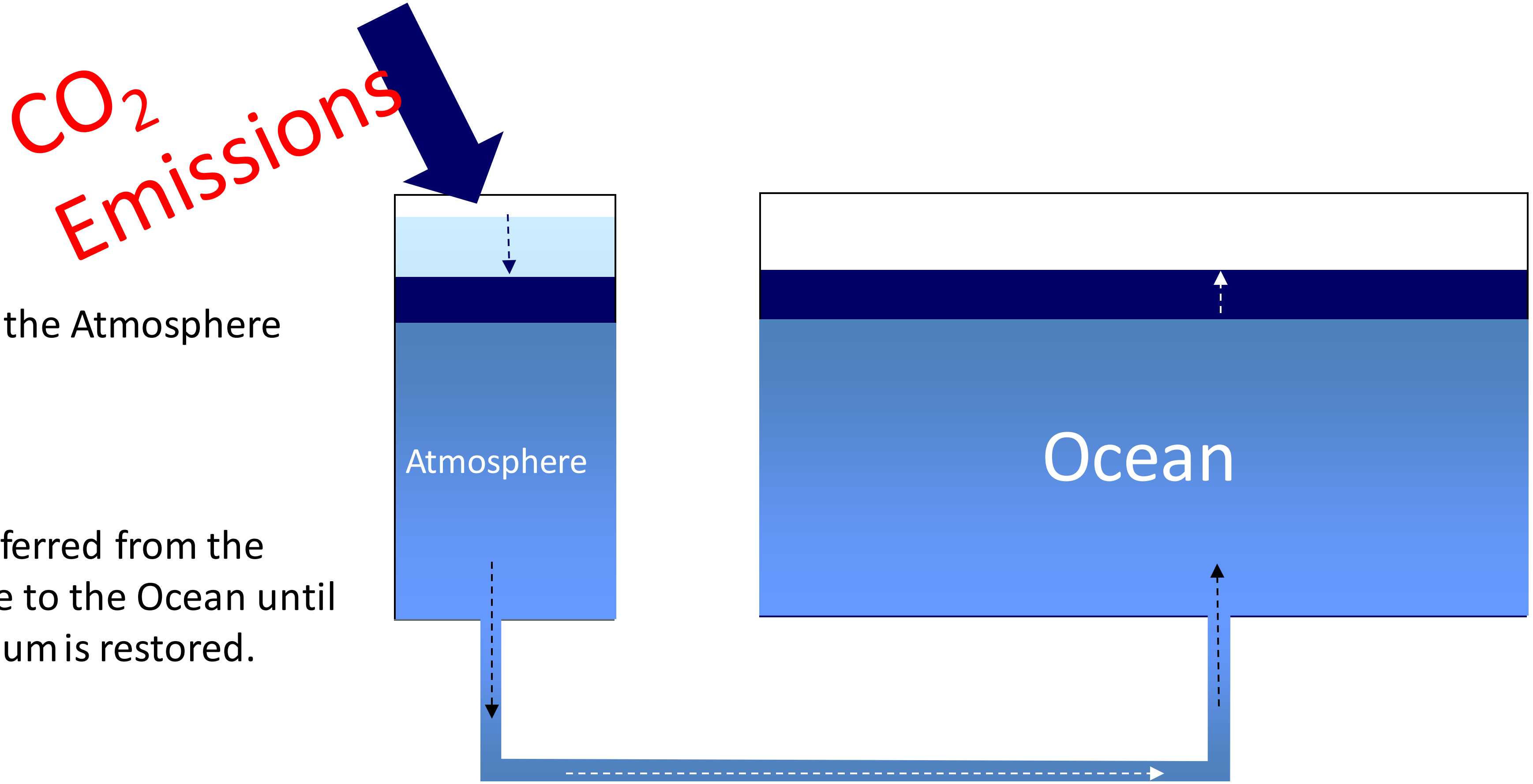
- Comparing greenhouse gas emissions is REALLY difficult.
  - CO_2 and the other gases behave differently

- Greenhouse gases fall into three categories
  - Short-lived species, with atmospheric sinks, e.g. CO, NO_x, CH_4, and N_2O.
    - For these gases constant emissions means constant concentration.
    - $C = \lambda E$, where λ is the inverse of the annual rate of atmospheric removal.
  - Very long lived species for which removal atmospheric rates are near zero, e.g. CFCs, and other manufactured gases.
    - For these gases concentrations rise linearly with emissions.
  - And then there's CO_2.

The Carbon Cycle

Cumulative emissions of CO_2 determine steady-state CO_2 concentrations.

Start with the Atmosphere and Ocean in Equilibrium.



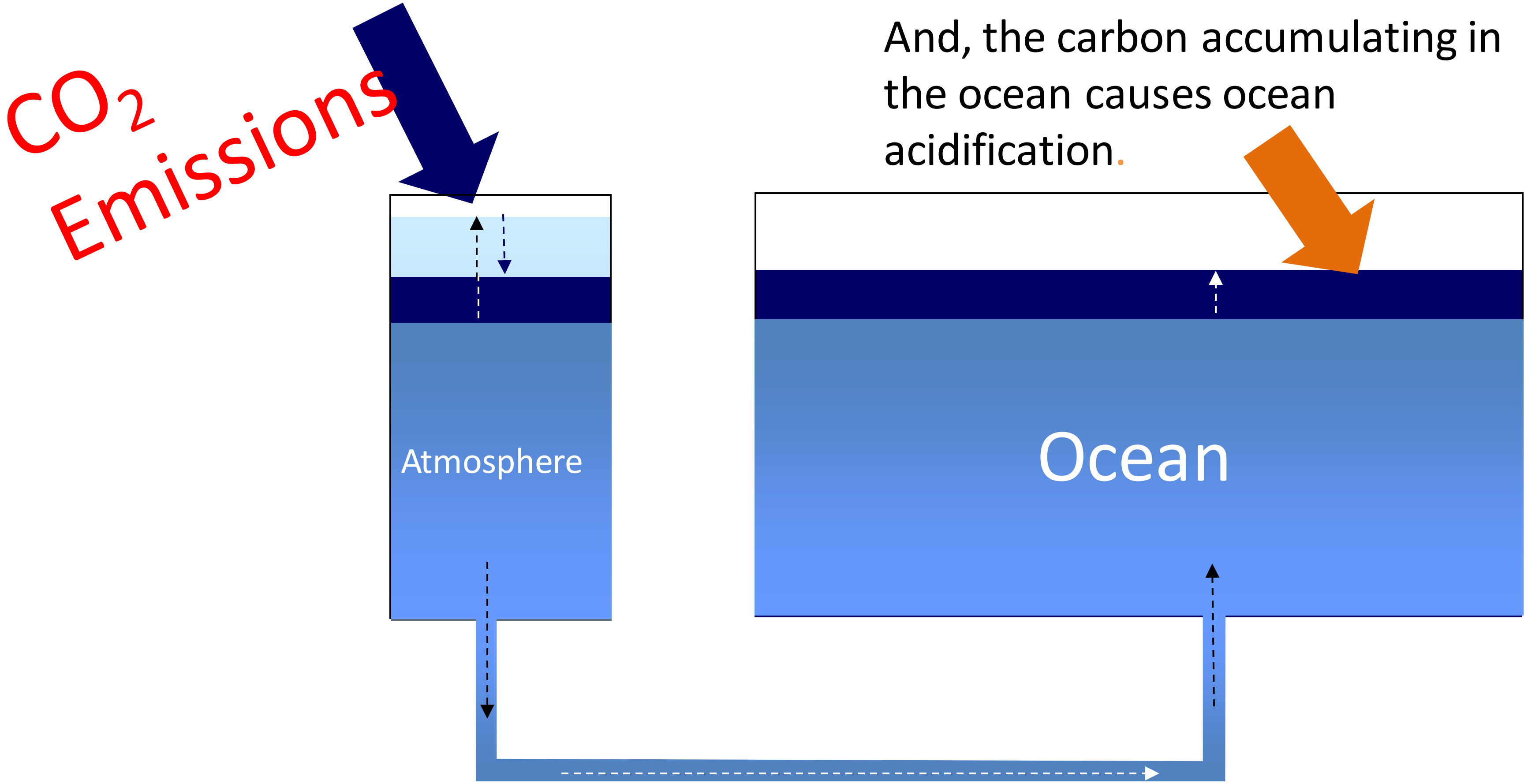
Add CO_2 to the Atmosphere

CO_2 is transferred from the Atmosphere to the Ocean until an equilibrium is restored.

The Carbon Cycle

In the long-run CO_2 emissions must approach zero.

And, the carbon accumulating in the ocean causes ocean acidification.



Climate Sensitivity and Average Earth Surface Temperature Change

- ***Climate Sensitivity*** is the change in the EQUILIBRIUM Earth surface temperature change following a doubling in the concentration of CO_2 or an equivalent change in another atmospheric constituent

Median Climate Sensitivity = **3^{o}C**

- Range is 1.5^{o}C to 4.5^{o}C (the same as it was 40 years ago in 1983)

INTEGRATED ASSESSMENT MODELING

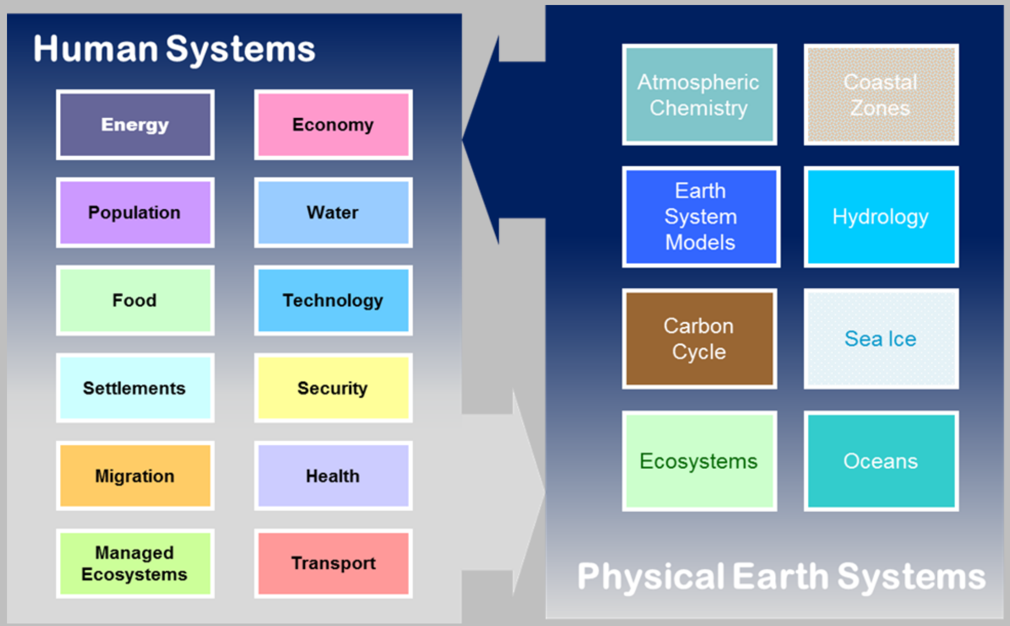
Integrated Assessment Models

IAMs integrate human and natural Earth system climate science.

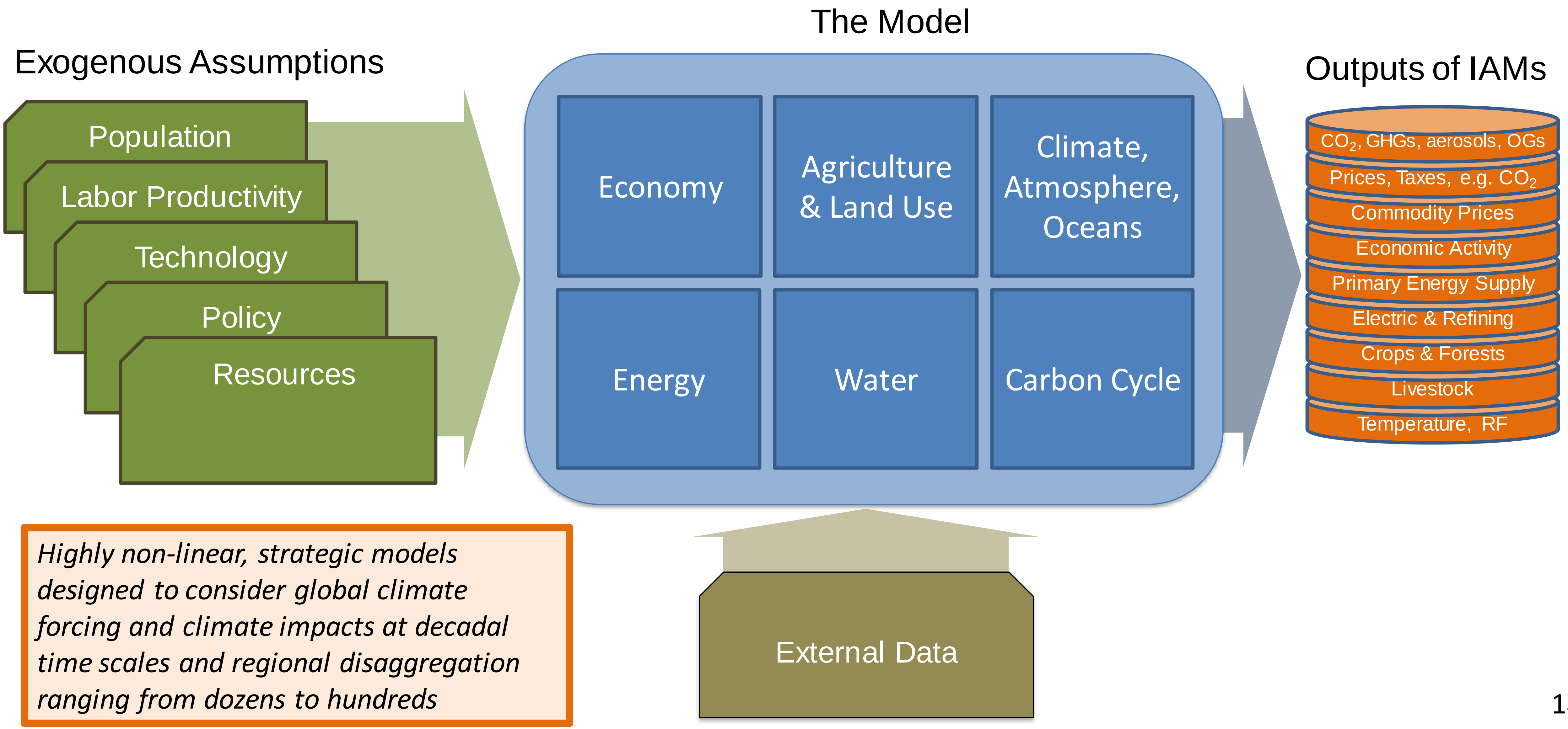
- IAMs provide insights that would be otherwise unavailable from disciplinary research alone.
- IAMs capture interactions between complex and highly nonlinear systems.
- IAMs provide natural science researchers with information about human systems such as GHG emissions, land use and land cover.

IAMs provide important, science-based decision support tools.

- IAMs support national, international, regional, and private-sector decisions.



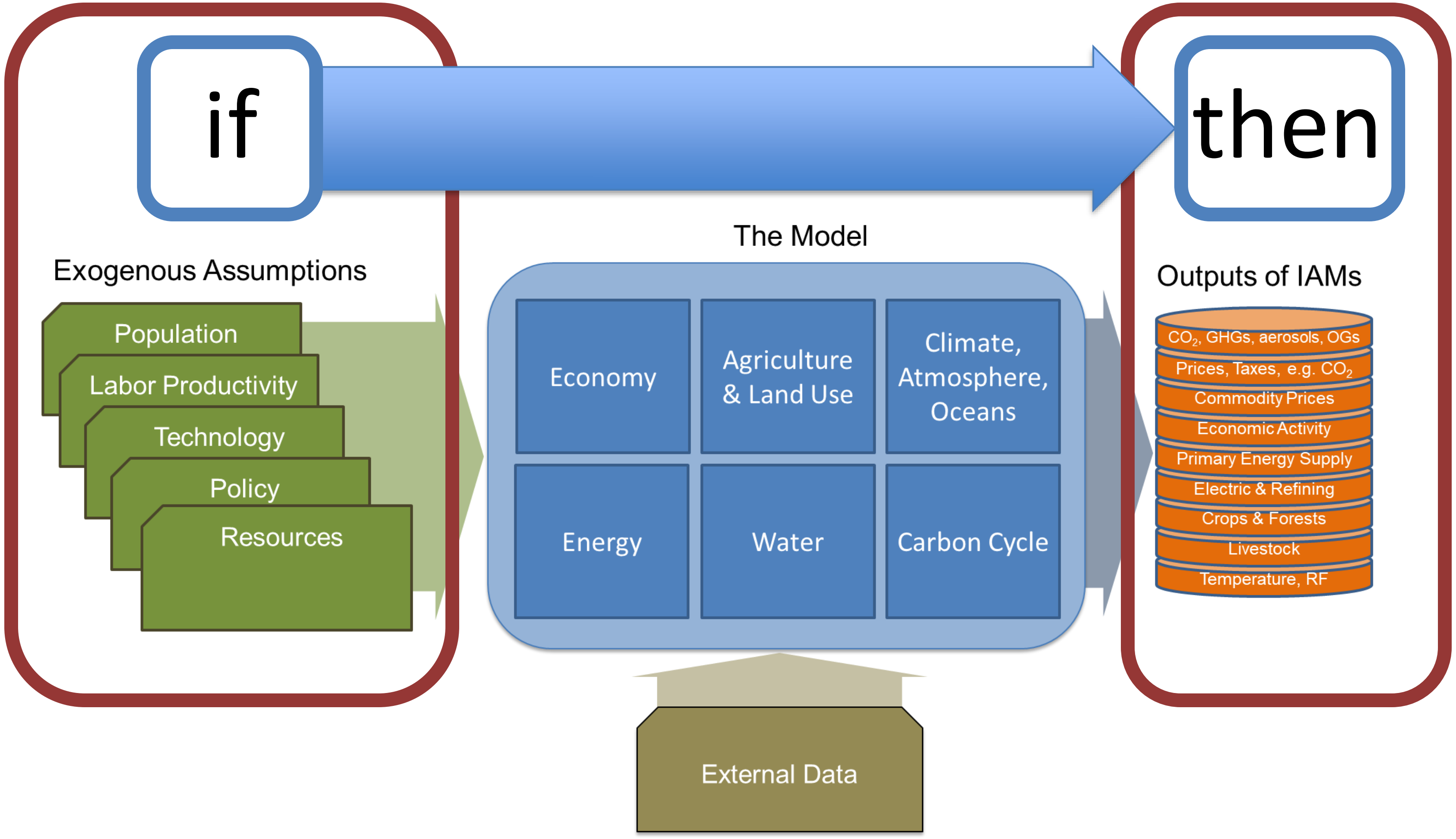
Integrated Assessment Models (IAMs) have external inputs and data, a representation of relevant systems and outputs



Highly non-linear, strategic models designed to consider global climate forcing and climate impacts at decadal time scales and regional disaggregation ranging from dozens to hundreds

Models and Scenarios

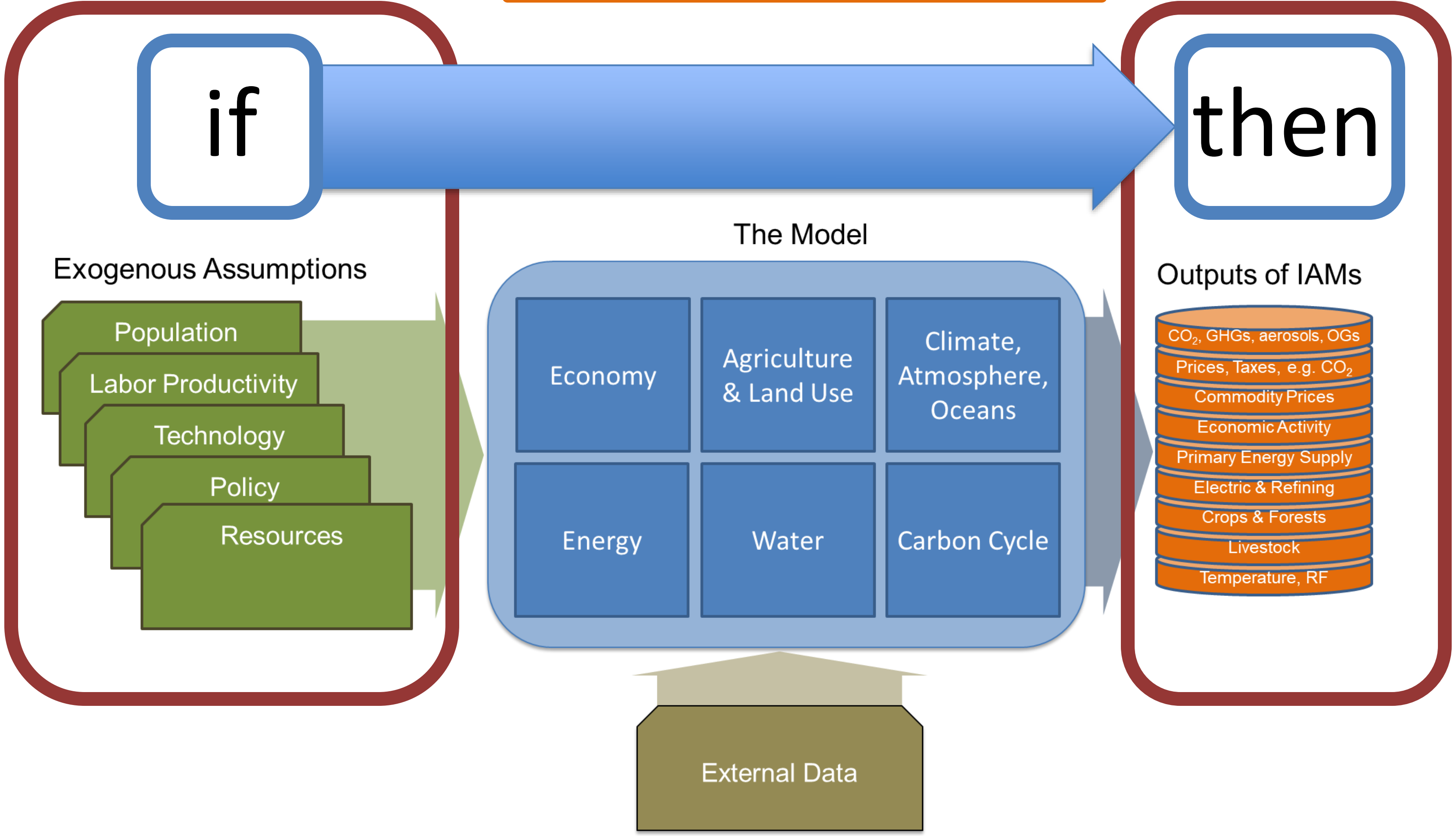
- **Models are structured relationships that produce conditional forecasts.**
- Scenarios are **<u>conditional</u>** forecasts.



Optimization Models

Optimization IAMs
- MESSAGE (IIASA)
- ReMIND (PIK)

- Some IAMs use an **optimization** structure. Doesn’t that mean they are NOT responsible for producing conditional forecasts.



Two Major Types of IAMS

- Integrated assessment models divide into two major branches:

- **Highly Aggregated Models**, where the central problem is determining the **social cost of carbon,** and

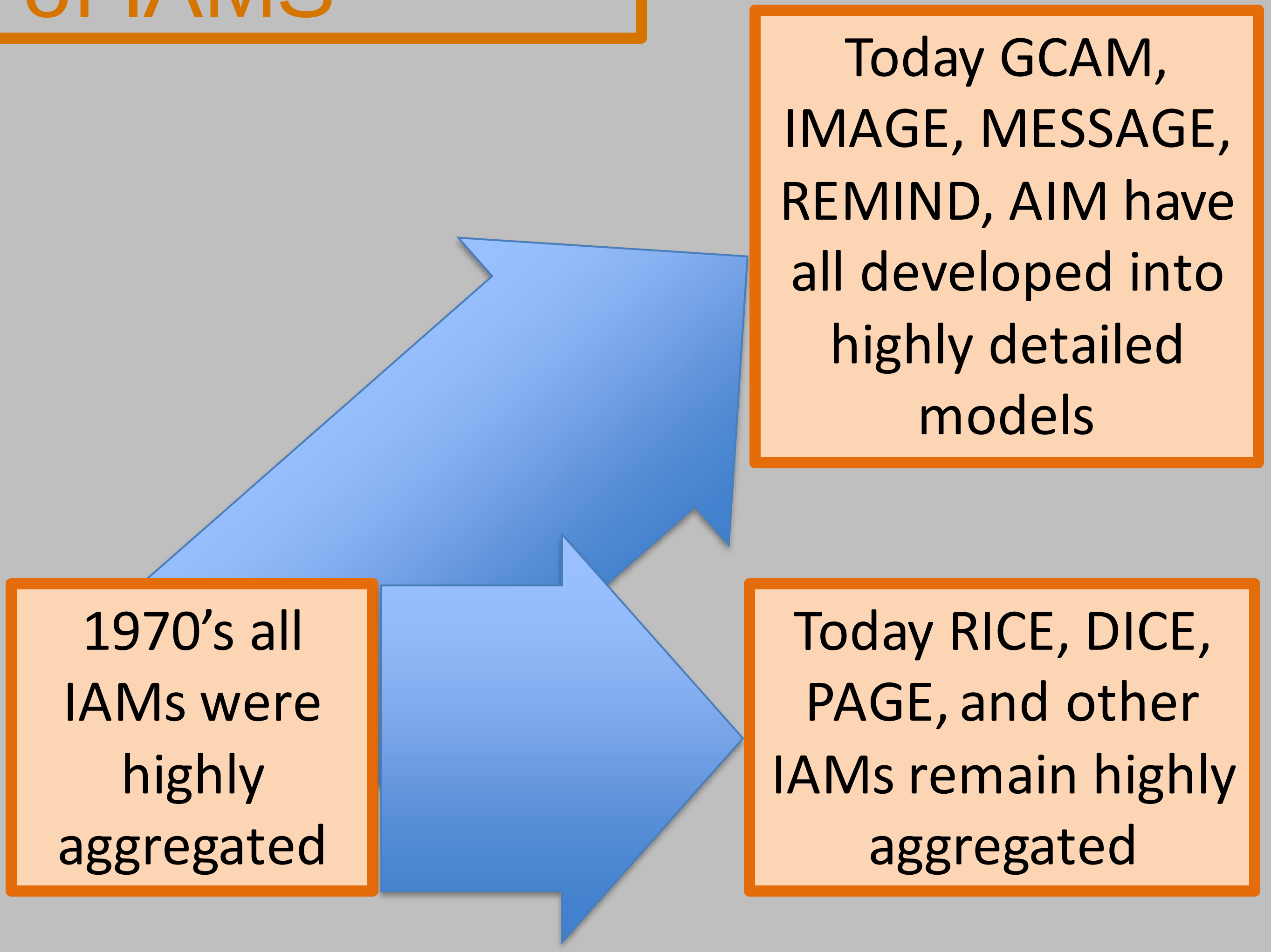
1970's all IAMs were highly aggregated

→

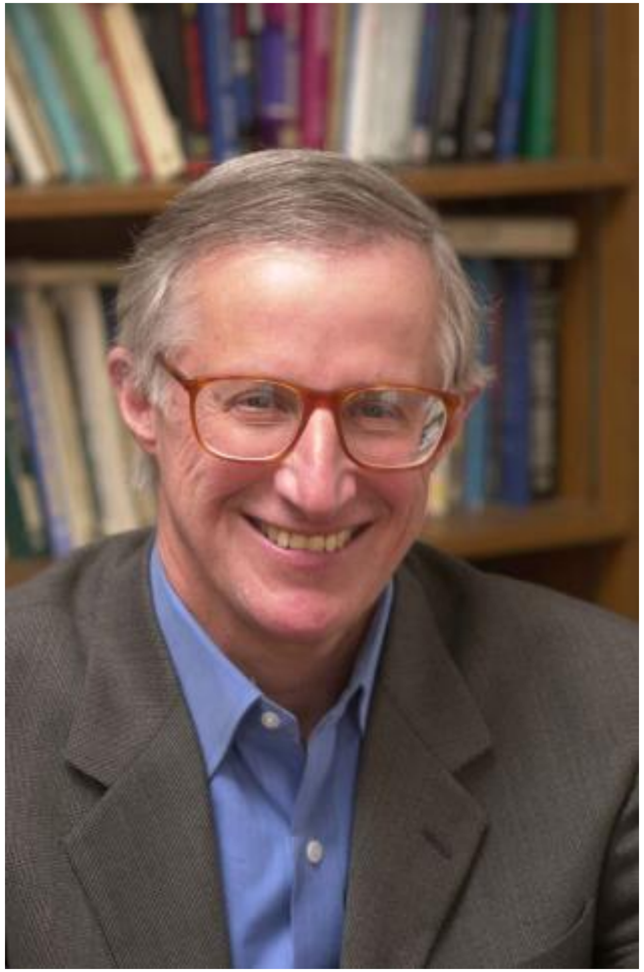
Today RICE, DICE, PAGE, and other IAMs remain highly aggregated

To Major Types of IAMS

- Integrated assessment models divide into two major branches:
- **Highly Aggregated Models**, where the central problem is determining the **social cost of carbon,** and
- **Highly Detailed Human-Earth System models**, whose primary problem is describing the detailed **interactions of human and physical Earth systems, in physical units**



Where did IAMs come from?



- Bill Nordhaus started it all
- 1979 The Efficient Use of Energy Resources , Yale University Press.
- In 2018, Bill won the Nobel Prize in Economics *“for integrating climate change into long-run macroeconomic analysis.”*
- That work was followed by the DICE model, which premiered in
- “Future Carbon Dioxide Emissions from Fossil Fuels,” with Gary Yohe, in National Research Council-National Academy of Sciences, ***Changing Climate***, National Academy Press, 1983.
- Dice is highly aggregated. It has 30 equations.
- http://www.econ.yale.edu/~nordhaus/homepage/Web-DICE-2013-April.htm

The DICE: the world in 30 Equations

Appendix A: DICE MODEL EQUATIONS

Total factor of Productivity (TFP)

$$A_g(t) = A_{g0} \times e^{[-A_{gd} \times 10 \times (t-1)]} \tag{A1}$$

$$A(t) = \frac{A(t-1)}{1 - A_g(t-1)} \tag{A2}$$

Labor

$$L(t) = L_0 \times \left(1 - L_g(t)\right) + L_A \times L_g(t) \tag{A3}$$

$$L_g(t) = \frac{e^{[L_{ga} \times (t-1)]} - 1}{e^{[L_{ga} \times (t-1)]}} \tag{A4}$$

Capital

$$K(t) = I(t-1) + (1 - \delta_K)^{10} \times K(t-1) \tag{A5}$$

$$I(t) = s(t) \times Q(t) \tag{A6}$$

Production Function

$$Y(t) = Y_0 \times \left(\frac{A(t)}{A_0}\right) \times \left(\frac{K(t)}{K_0}\right)^{\beta} \times \left(\frac{L(t)}{L_0}\right)^{1-\beta} \tag{A7}$$

$$Q(t) = \left(\Omega(t) - \Lambda(t)\right) \times Y(t) \tag{A8}$$

$$Q(t) = C(t) + I(t) \tag{A9}$$

Climate Change Damage

$$\Omega(t) = \frac{1}{1 + \Psi_1 \times T_{at}(t) + \Psi_2 \times T_{at}^{\Psi_3}(t)} \tag{A10}$$

$$T_{at}(t) = T_{at}(t-1) + \xi_1 \times \{F(t) - \xi_2 \times T_{at}(t-1) - \xi_3 \times [T_{at}(t-1) - T_{lo}(t-1)]\} \tag{A11}$$

$$T_{lo}(t) = T_{lo}(t-1) + \xi_4 \times [T_{at}(t-1) - T_{lo}(t-1)] \tag{A12}$$

$$F(t) = \Delta R_f \times log_2\left(\frac{M_{at}(t)}{M_{at}(1750)}\right) + F_{ex}(t) \tag{A13}$$

$$M_{at}(t) = E(t-1) + \phi_{11} \times M_{at}(t-1) + \phi_{21} \times M_{up}(t-1) \tag{A14}$$

$$M_{up}(t) = \phi_{12} \times M_{at}(t-1) + \phi_{22} \times M_{up}(t-1) + \phi_{32} \times M_{lo}(t-1) \tag{A15}$$

$$M_{lo}(t) = \phi_{23} \times M_{up}(t-1) + \phi_{33} \times M_{lo}(t-1) \tag{A16}$$

$$\xi_2 = \frac{\Delta R_f}{\Delta T} \tag{A17}$$

$$E(t) = E_{ind}(t) + E_{land}(t) \tag{A18}$$

$$E_{ind}(t) = \sigma(t) \times [1 - a(t)] \times Y(t) \tag{A19}$$

$$E_{land}(t) = E_0 \times 0.9^{t-1} \tag{A20}$$

$$\sigma(t) = \frac{\sigma(t-1)}{1 - \sigma_g(t)} \tag{A21}$$

$$\sigma_g(t) = \sigma_{g0} \times e^{[-10 \times \sigma_{gd} \times (t-1) - 10 \times \sigma_{ga} \times (t-1)^2]} \tag{A22}$$

$$F_{ex}(t) = F_{2000} + (F_{2100} - F_{2000}) \times (t-1) \tag{A23}$$

$$\Lambda(t) = \pi^{(1-\theta_2)}(t) \times \theta_1(t) \times a^{\theta_2}(t) \tag{A24}$$

Climate Change Abatement

$$\pi(t) = \varphi^{1-\theta_2}(t) \tag{A25}$$

$$\theta_1(t) = \left(\frac{P_b \times \sigma(t)}{\theta_2}\right) \times \left(\frac{P_r - 1 + e^{[-P_d \times (t-1)]}}{P_r}\right) \tag{A26}$$

Utility

$$U(t) = u(t) \times L(t) \tag{A27}$$

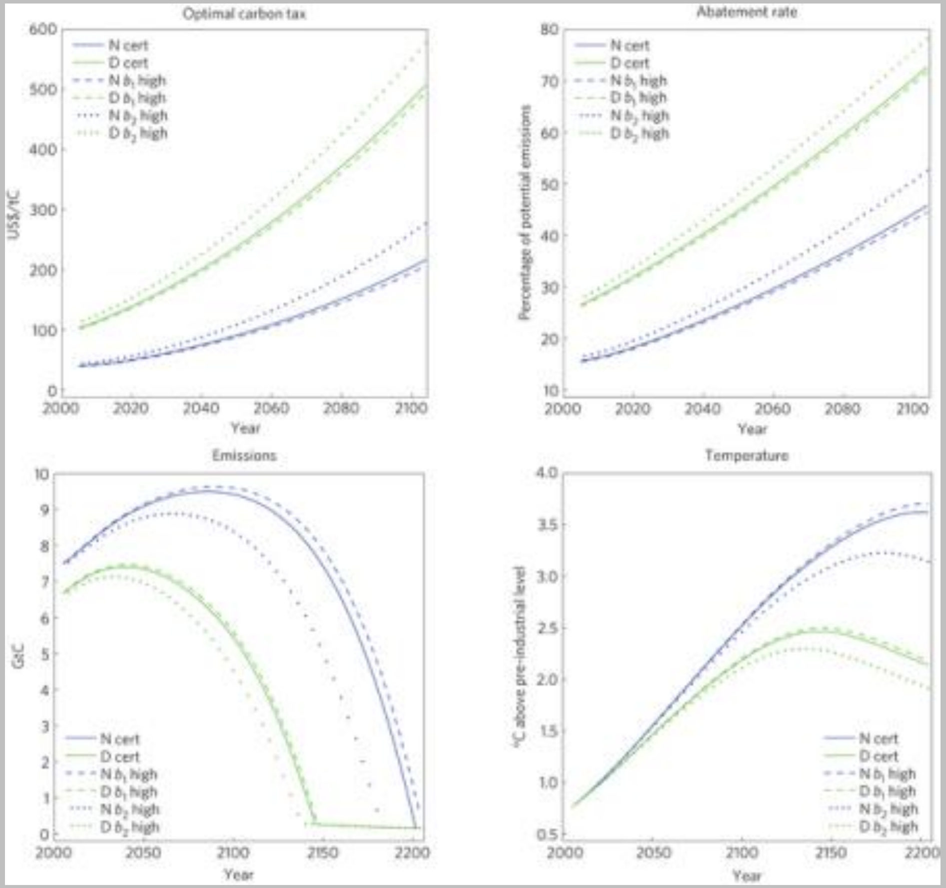
$$u(t) = \frac{c^{1-\alpha}(t)}{1 - \alpha} \tag{A28}$$

$$c(t) = \frac{C(t)}{L(t)} \tag{A29}$$

$$R(t) = \frac{R(t-1)}{(1 + \rho)^{10}} \tag{A30}$$

Nordhaus central problem is cost-benefit

- What is the socially optimal emissions path?
- What is the optimal global carbon tax?
- What is the optimal change in climate?
- How do you monetize climate damages, many of which do not pass through markets?
- How do you discount costs and benefits?



Source: Crost, Benjamin, and Christian P. Traeger. "Optimal CO2 mitigation under damage risk valuation." *Nature Climate Change* (2014).

The most important contribution highly aggregated IAMs make is defining the Social Cost of Carbon

The social cost of carbon (SCC) is an estimate, in dollars, of the economic damages that would result from emitting one additional ton of greenhouse gases into the atmosphere.

EPA estimates: \$120/tCO_2 (2.5%discount rate),
\$190/tCO_2 (2.0%discount rate),
\$340/tCO_2 (1.5%discount rate).
RFF estimate: \$185/tCO_2 (2.0%discount rate).

Highly aggregated IAMs have drawn the ire of critiques such as Robert Pindyck

These models [IAMs] have crucial flaws that make them close to useless as tools for policy analysis: certain inputs (e.g., the discount rate) are arbitrary, but have huge effects on the SCC estimates the models produce; the models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; and the models can tell us nothing about the most important driver of the SCC, the possibility of a catastrophic climate outcome. IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading.

Pindyck, Robert S.. 2013. "Climate Change Policy: What Do the Models Tell Us?." *Journal of Economic Literature*, 51(3):860-72.

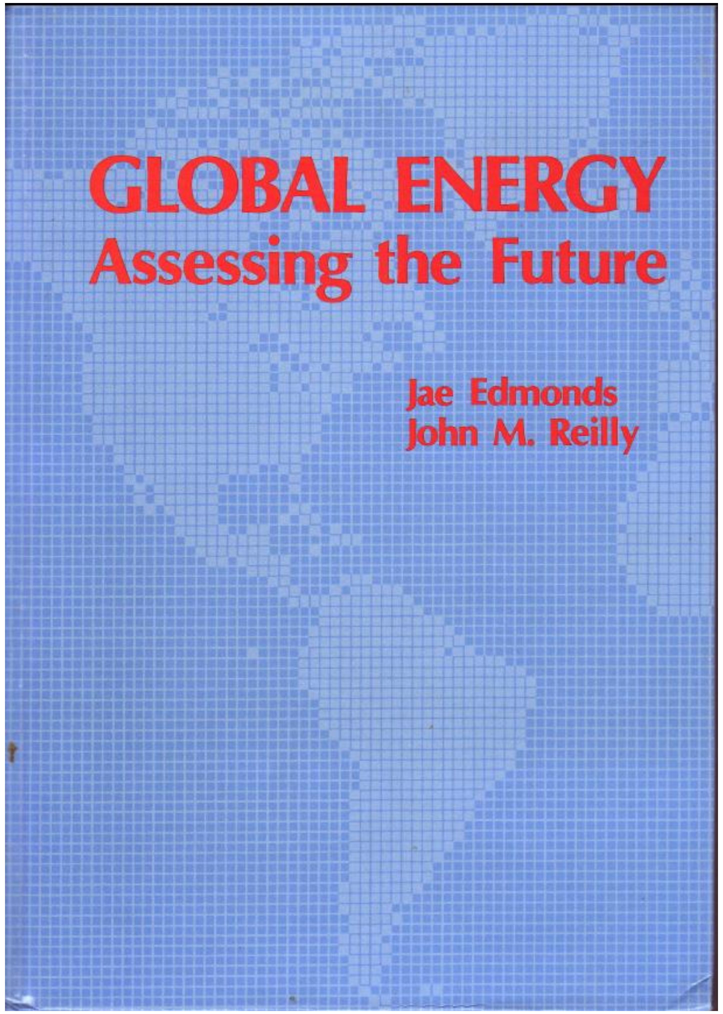
Researchers such as John Weyant have defended the field of integrated assessment

Researchers such as Weyant have pressed the case for IAMs, and particularly highly detailed IAMs as valuable research and policy support tools.

Weyant, J. “Some Contributions of Integrated Assessment Models of Global Climate Change” Review Of Environmental Economics And Policy, 2017; 11 (1): 115-137

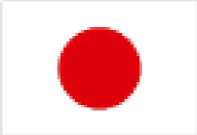
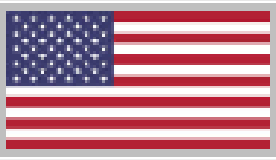
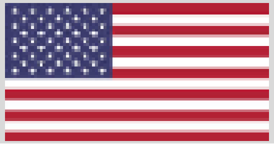
HIGHLY DETAILED IAMS

GCAM has its roots in the same time frame



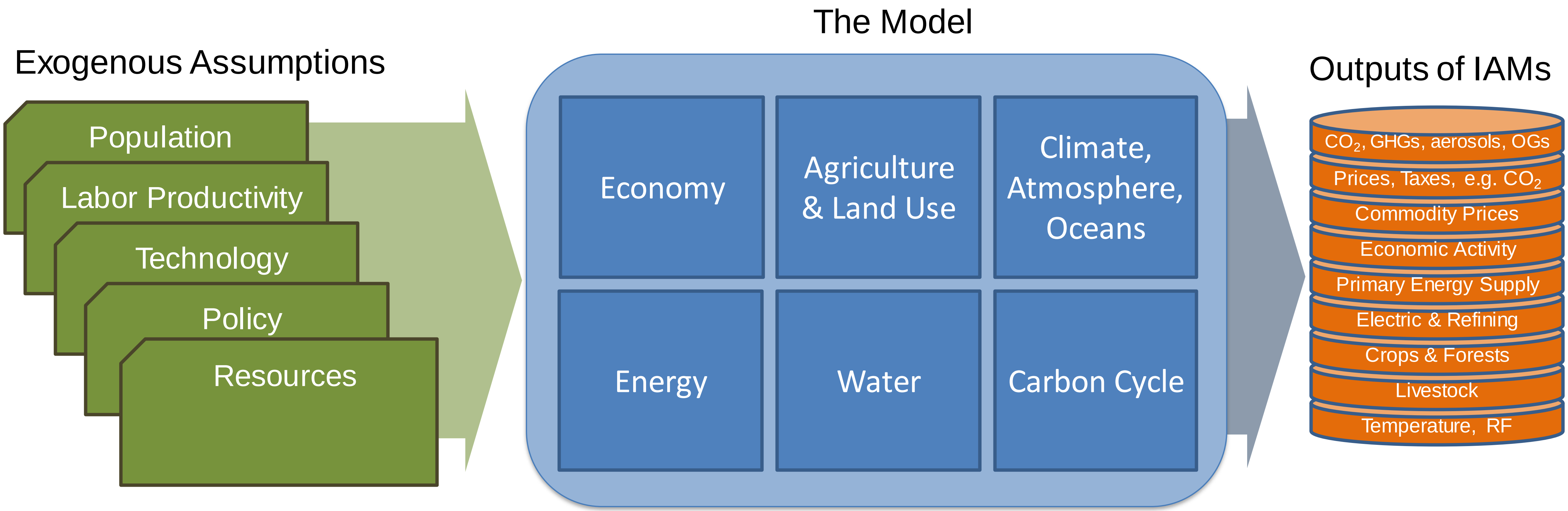
- The Global Change Assessment Model (GCAM) began in 1978.
- Jae Edmonds and John Reilly
  - Reilly was the director of the MIT IAM program until he retired in 2020.
- The original science question was would fossil fuel CO2 emissions continue to rise at 4.5%/yr? (which implied that CO2 concentrations would double around the year 2000)

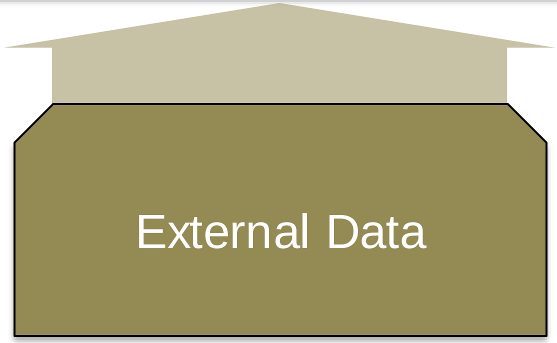
Highly detailed IAMs are developed by interdisciplinary teams

Model	Home Institution	
AIM Asia Integrated Model	National Institutes for Environmental Studies, Tsukuba Japan	
GCAM Global Change Assessment Model	Joint Global Change Research Institute, PNNL, College Park, MD	
IGSM Integrated Global System Model	Joint Program, MIT, Cambridge, MA	
IMAGE The Integrated Model to Assess the Global Environment	PBL Netherlands Environmental Assessment Agency, Bildhoven, The Netherlands	
MESSAGE Model for Energy Supply Strategy Alternatives and their General Environmental Impact	International Institute for Applied Systems Analysis; Laxenburg, Austria	
REMIND Regionalized Model of Investments and Technological Development	Potsdam Institute for Climate Impacts Research; Potsdam, Germany	

More are on the way

Fully developed IAMs include all of



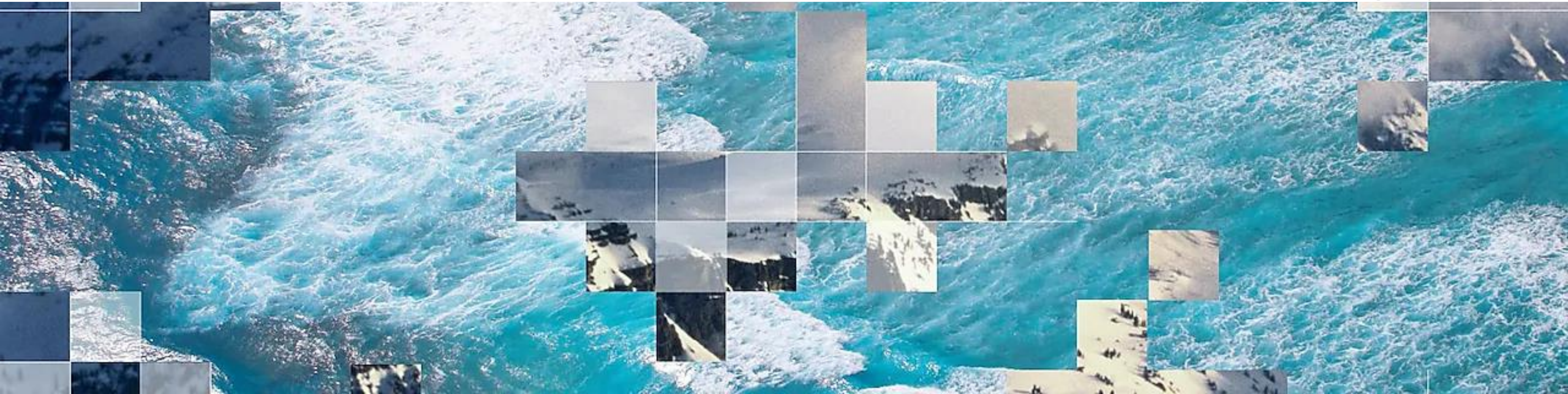


Highly non-linear, strategic models designed to consider global climate forcing and climate impacts at decadal time scales and regional disaggregation ranging from dozens to hundreds

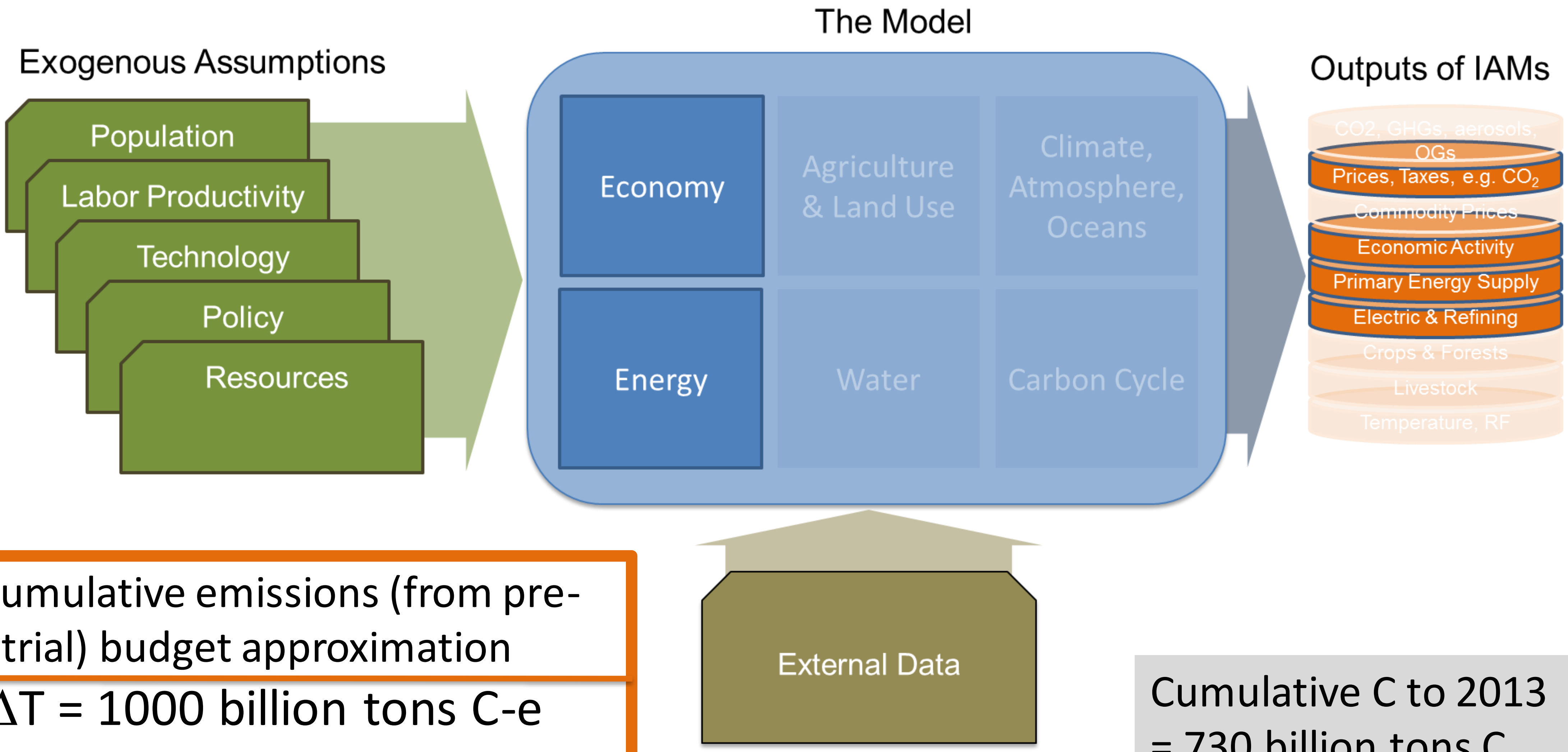
Scenarios are Produced by Models

- Models vary in complexity and detail
- You don’t need a full integrated assessment model (IAM) to be in the modeling business

Shell New Lenses Scenario



Energy models assume non-energy emissions and cumulative emissions budget



The cumulative emissions (from pre-industrial) budget approximation

2^{o}C ΔT = 1000 billion tons C-e

2^{o}C ΔT = 3667 billion tons CO_2-e

Cumulative C to 2013
= 730 billion tons C
= 2677 billion tons CO_2

SCENARIOS

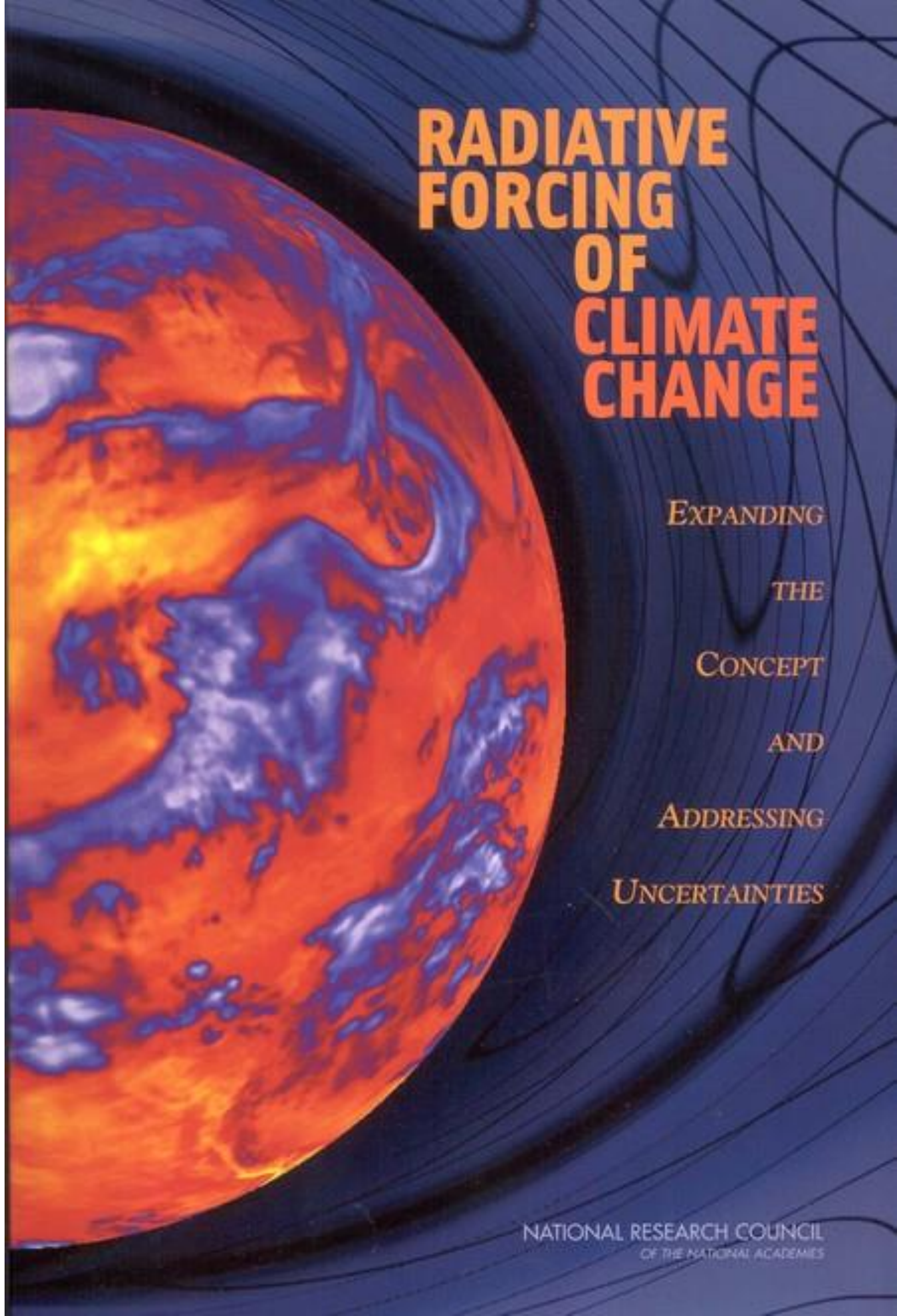
Concentrations to radiative forcing

- RF is the net change in the energy balance of the Earth system due to some imposed perturbation. It is usually expressed in watts per square meter averaged over a particular period of time and quantifies the energy imbalance that occurs when the imposed change takes place.

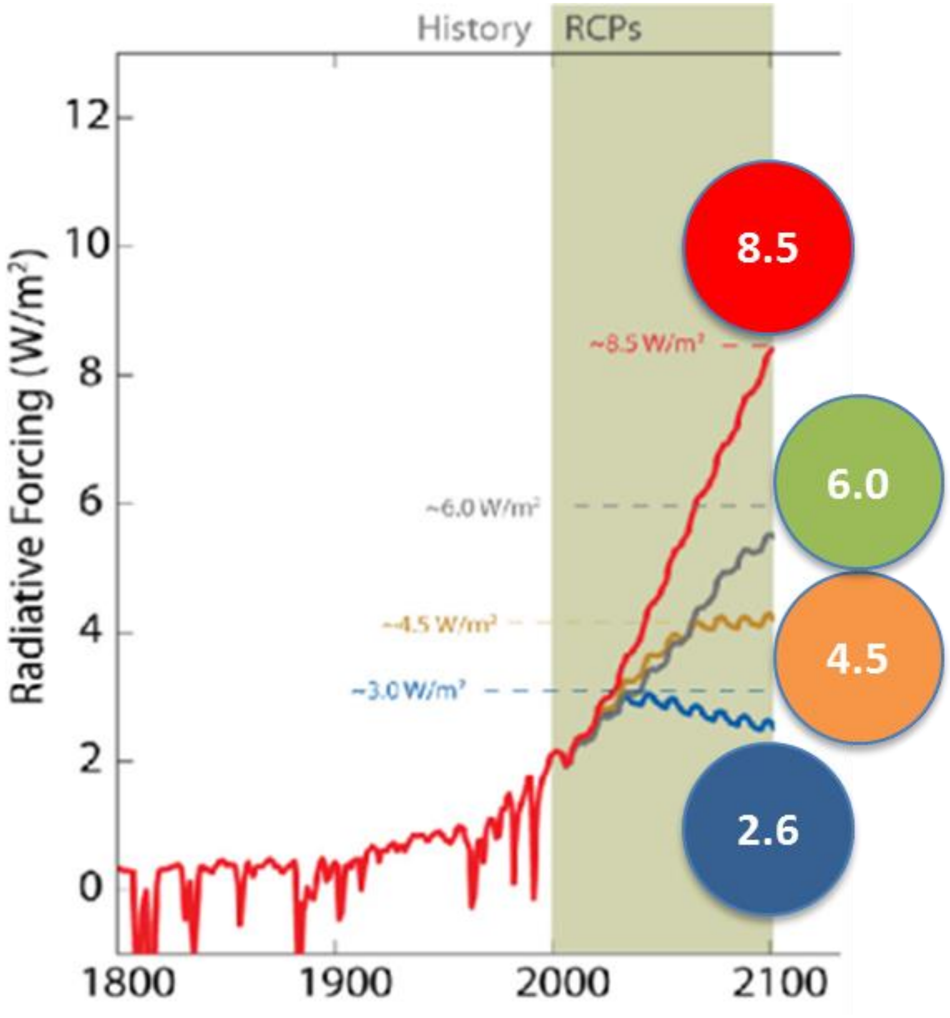
- Forcing is often presented as the value due to changes between two particular times, such as pre-industrial to present-day, while its time evolution provides a more complete picture.

Climate forcing from CO_2 Concentrations

$$\Delta F = 5.35 \ln(C/C_0)$$



The RCPs and Climate

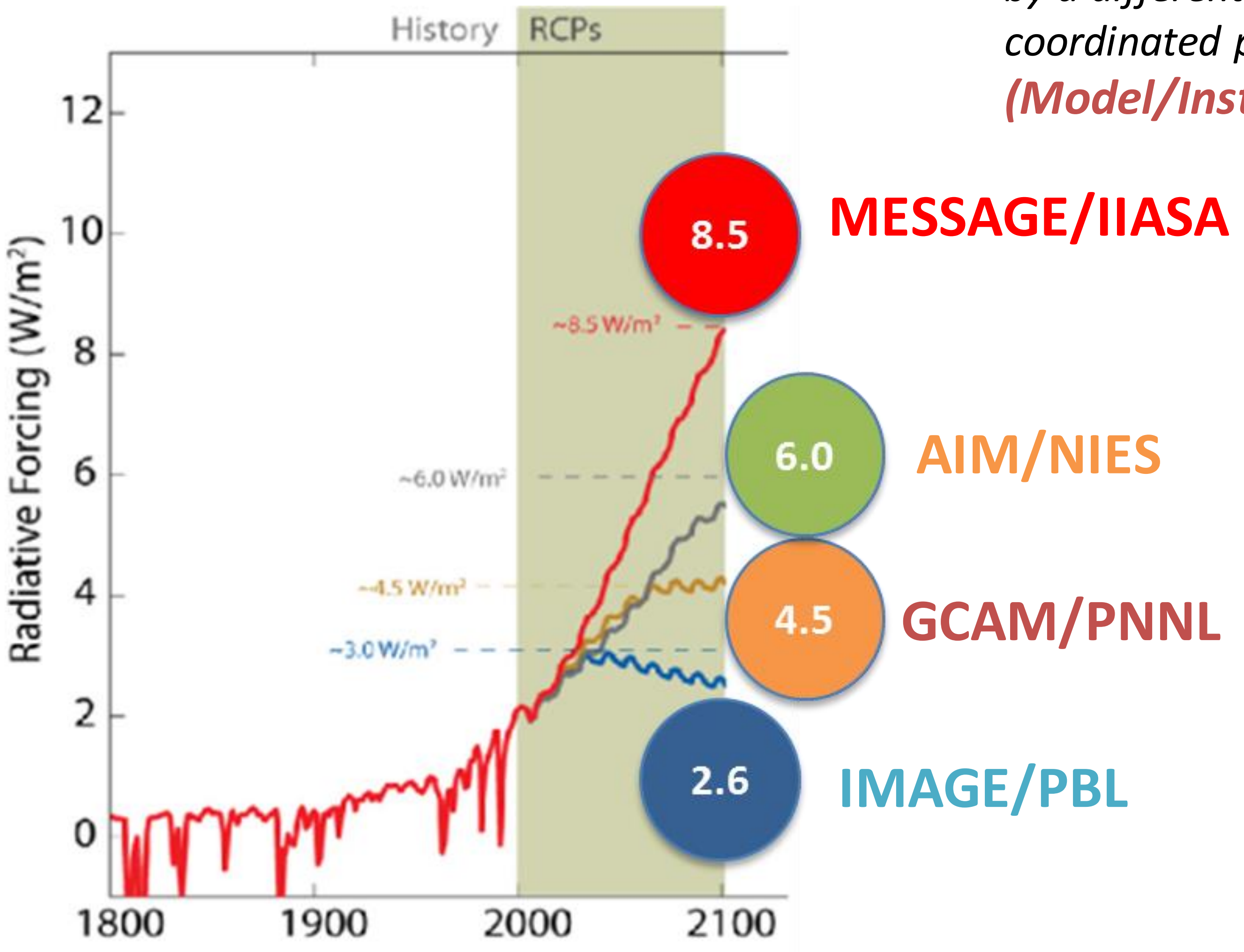


Scenarios are internally consistent representations of potential future developments.

- RCPs are defined in terms of "Radiative Forcing"
  - Units=Watts/Meter^2
  - Best thought of as an index
  - 0=preindustrial
- RCP 8.5 = Highest scenario in the literature and keeps rising
- RCP 6.0 = stabilize climate forcing
- RCP 4.5 = stabilize climate forcing
- RCP 2.6 = reduce climate forcing (2 degree scenario)

The RCPs and Climate

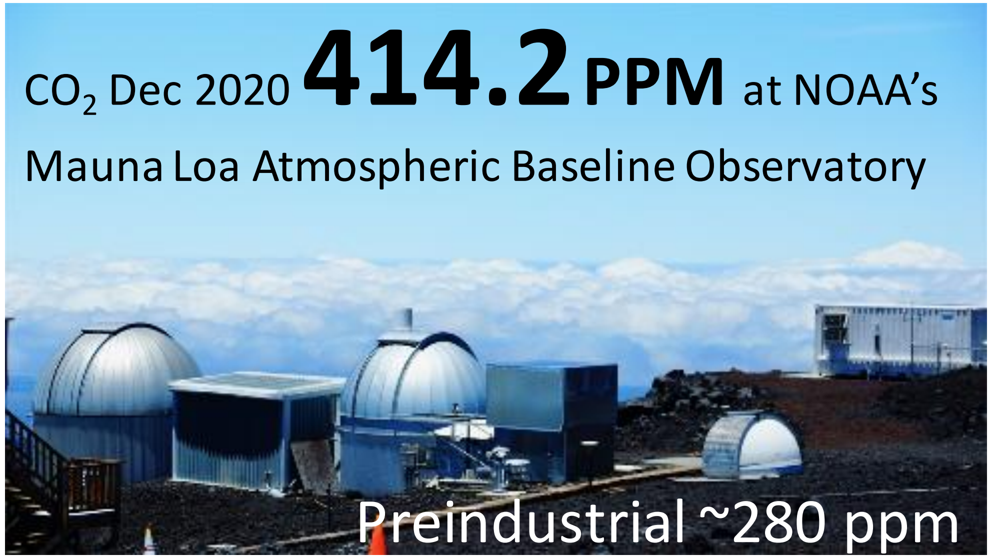
Each RCP was developed by a different model in a coordinated process.
(Model/Institution)



- Created by the Integrated Assessment Modeling Consortium (IAMC)
- For the intergovernmental Panel on climate change

Some handy equivalents

- CO_2 is measured in both tons of CO_2 and tons of C
- 3.667 ton CO_2 = 1 tons C
- \$1/tCO_2 = \$3.67/tC

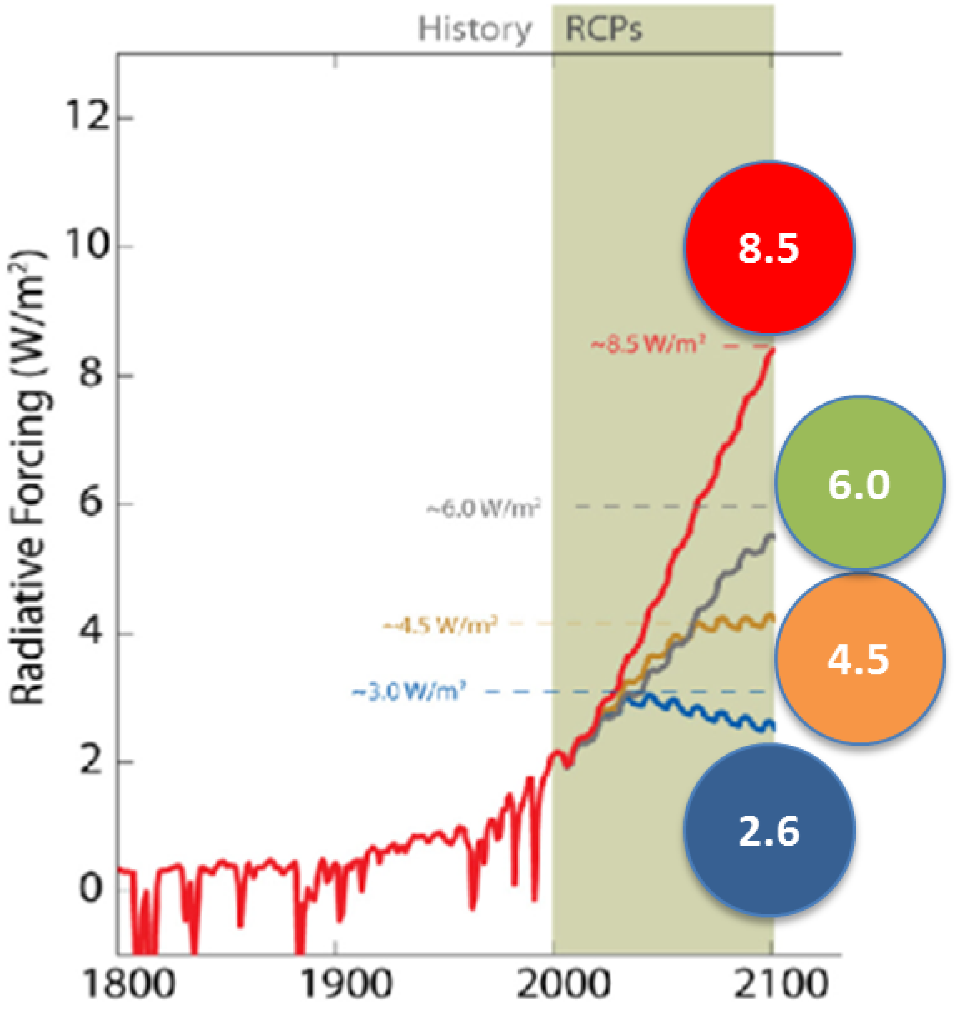


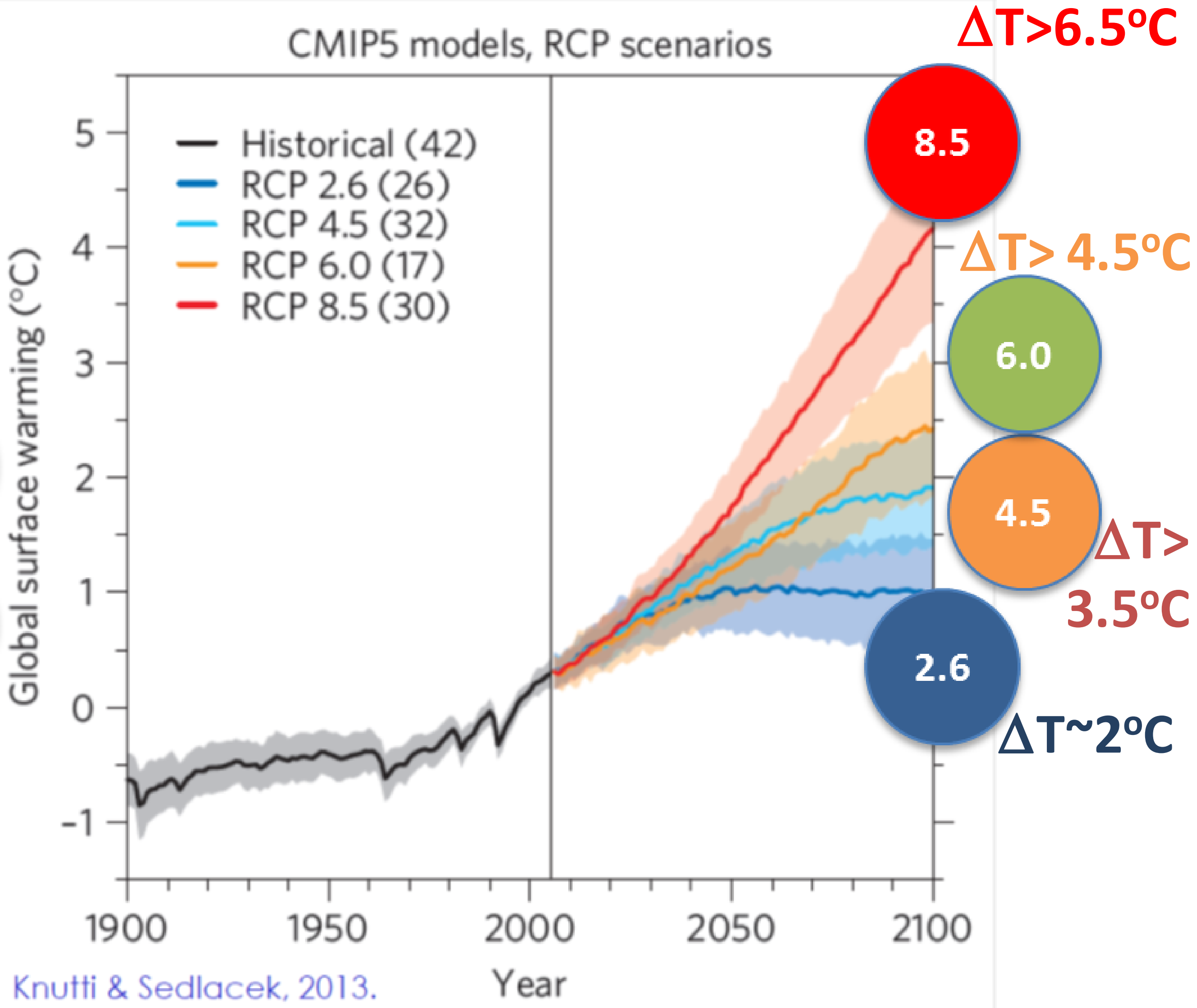
CO2-equivalent (ppm)	Radiative Forcing (W/m^2)	Avg. Global Temp. Change Long-term (ΔT)*
1360	8.5 (RCP)	6.8 ^oC
1030	7.0	5.6 ^oC
850	6.0 (RCP)	4.8 ^oC
650	4.5 (RCP)	3.6 ^oC
550	3.7	2.9 ^oC
450	2.6 (RCP)	2.1 ^oC
400	1.9	1.5 ^oC

* Assumes a climate sensitivity of 3^{o}C. Climate sensitivity is the number of degrees the planet would warm in the long term if the concentration of CO_2 doubled.

RCPs and Climate

Average Surface Long-term Temperature Change Compared to Pre-Industrial



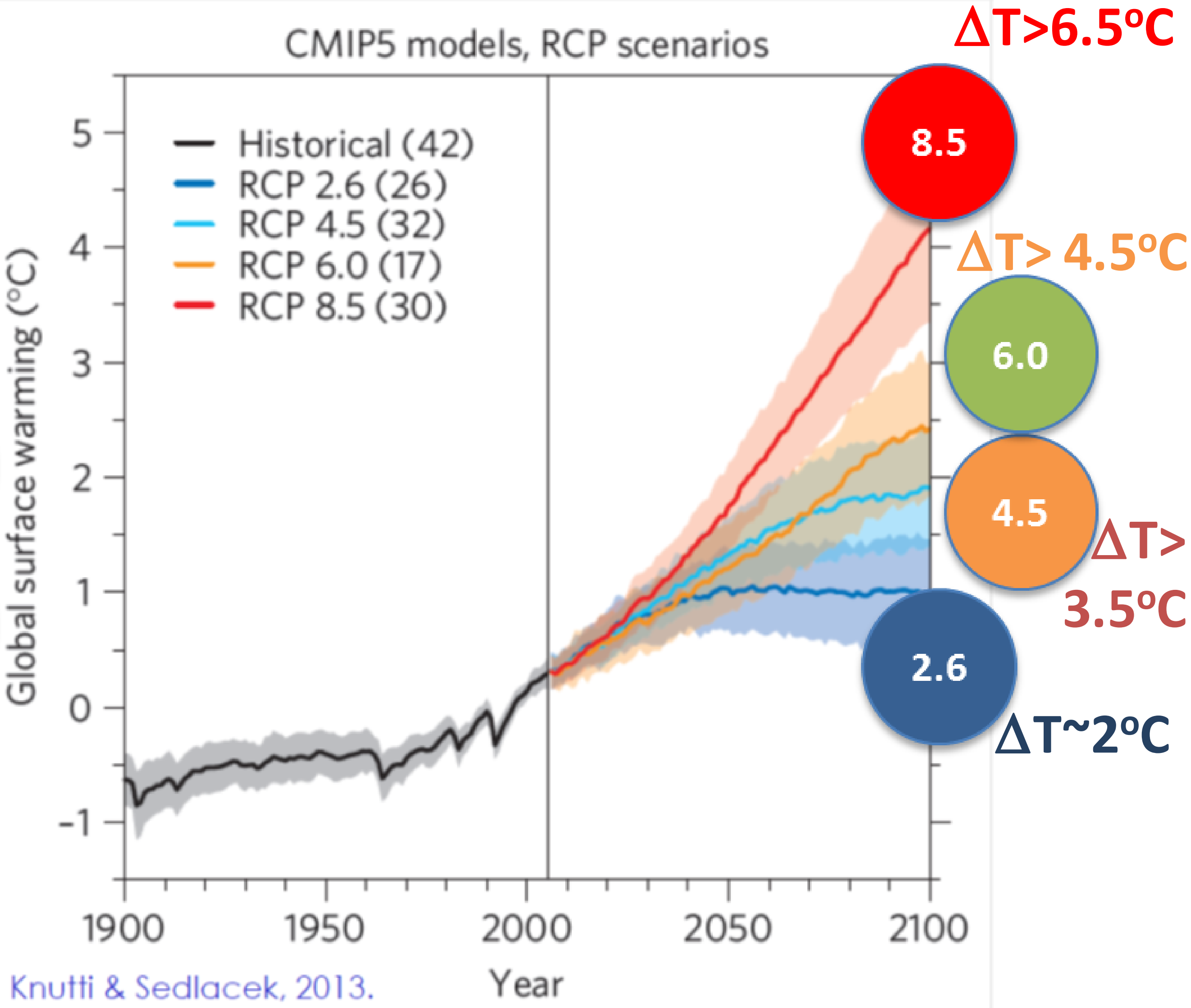


RCPs and Climate

Average Surface Long-term Temperature Change Compared to Pre-Industrial

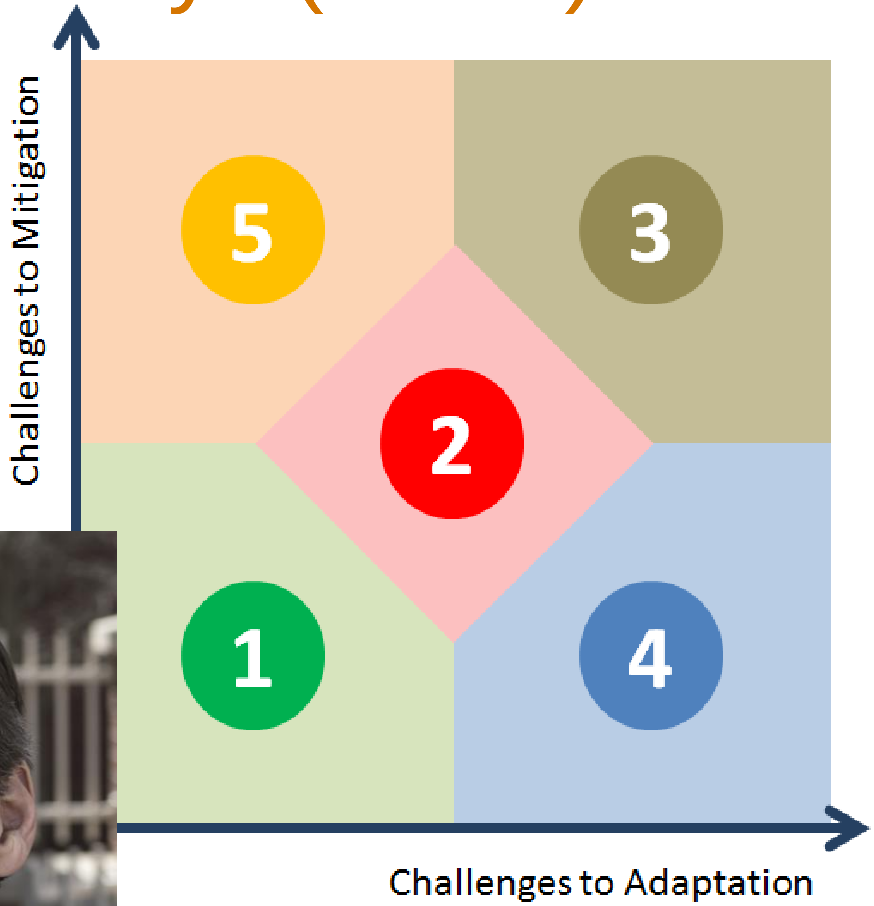
The climate simulations come from a different community—
climate modelers

CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project



Shared Socioeconomic Pathways (SSPs)

- SSPs are **Reference Scenarios**
- No new climate policies in the future
- Defined in terms of Challenges to Mitigation and Challenges to Adaptation
- Brian O'Neill (JGCRI) was one of the major architects



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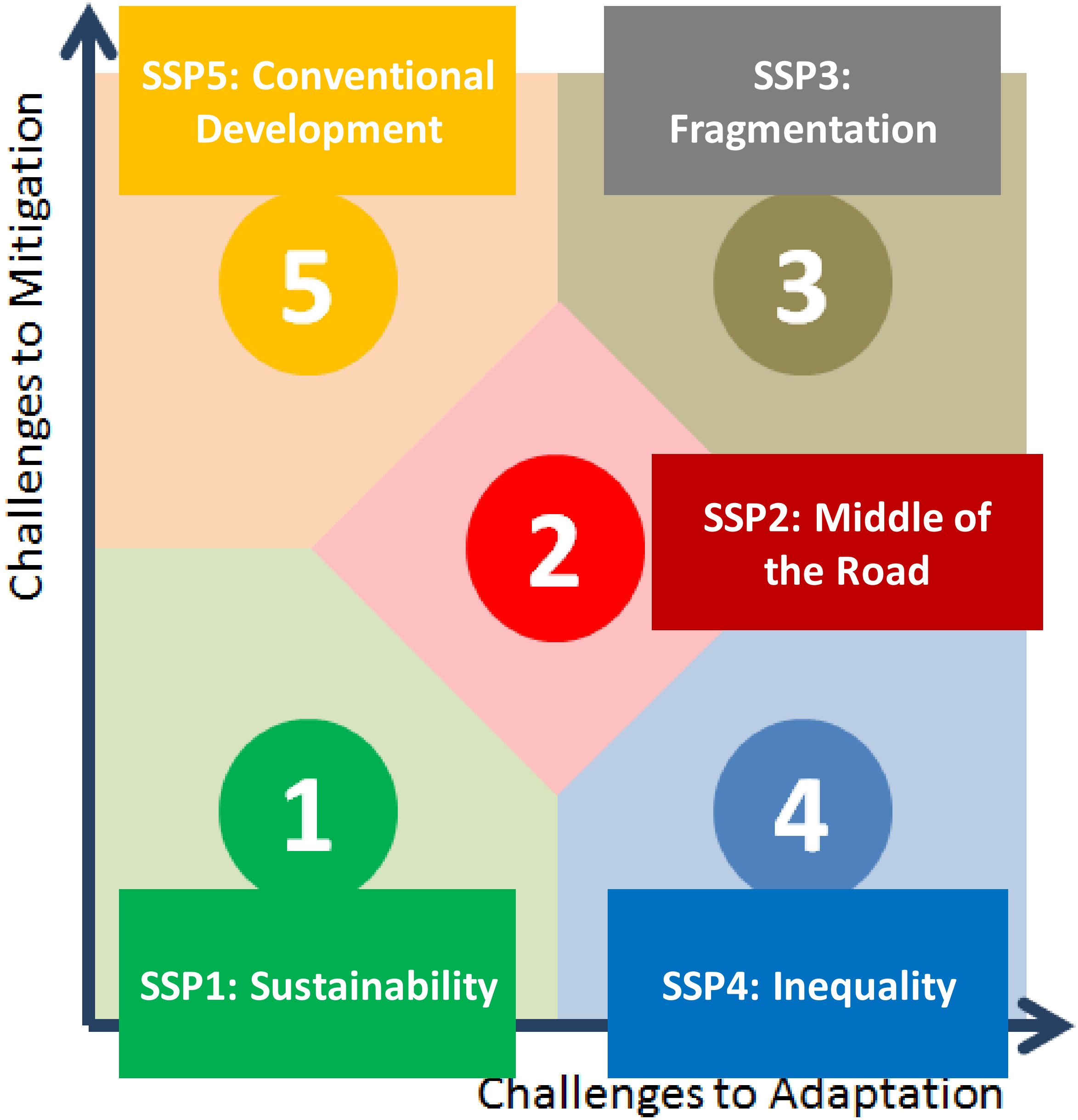
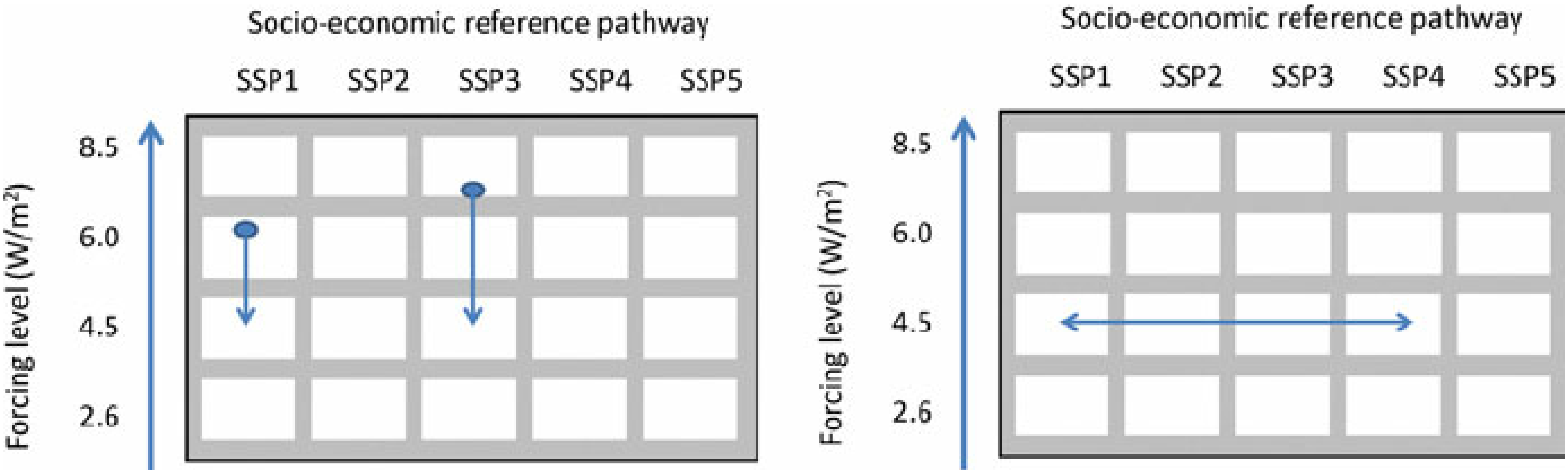
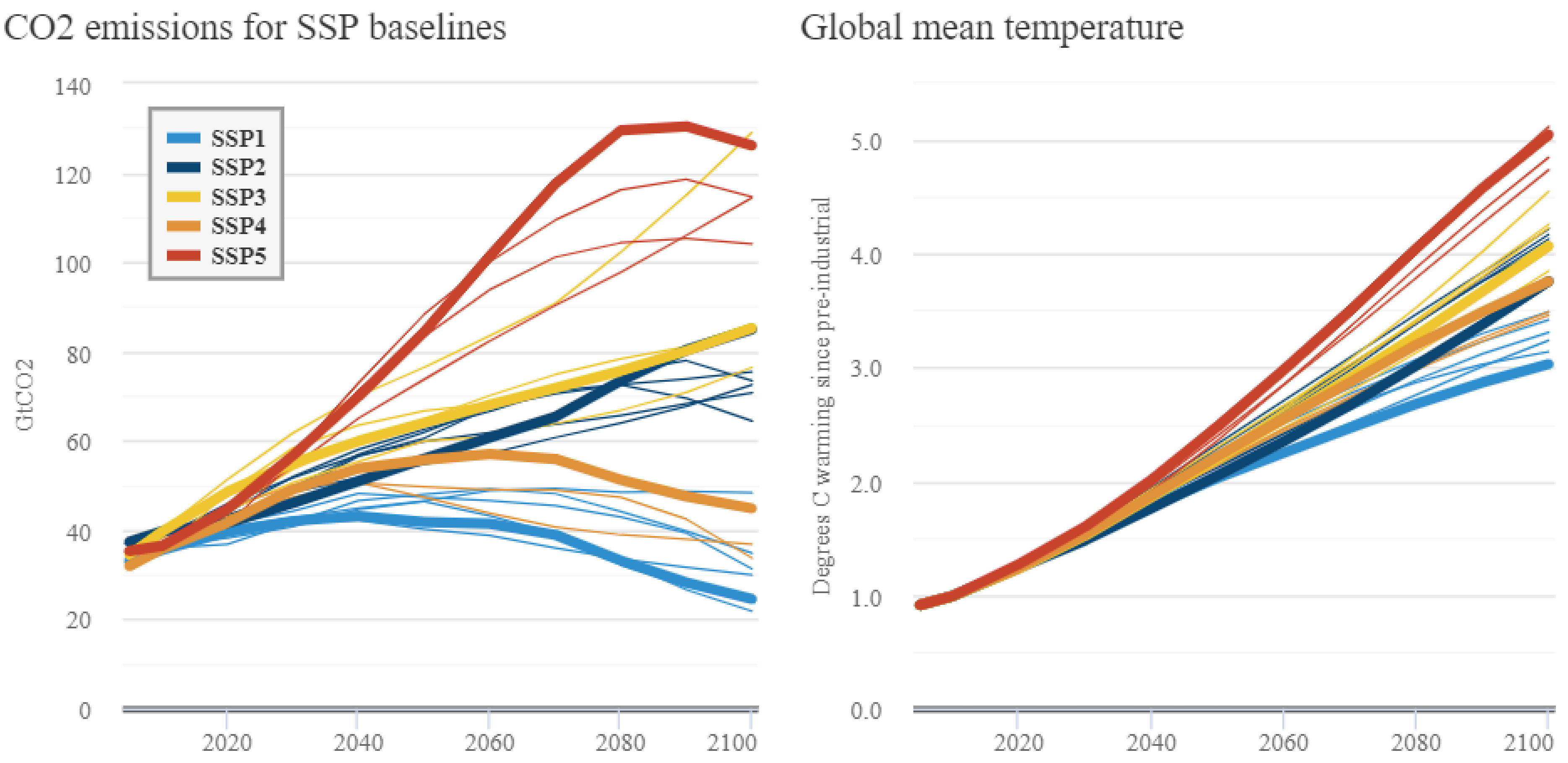


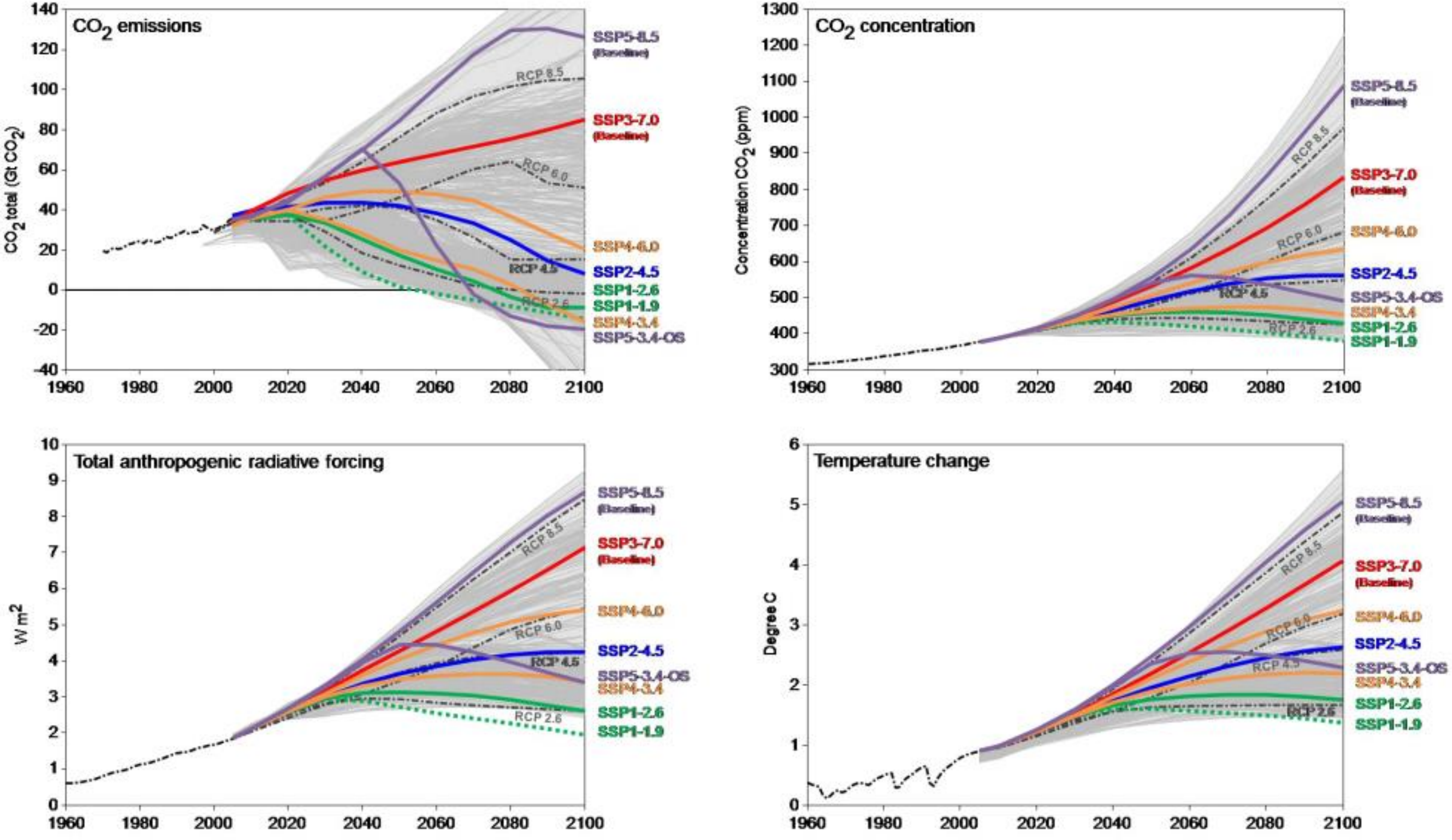
Combining SSPs with RCPs



Combining SSPs Emissions and Climate

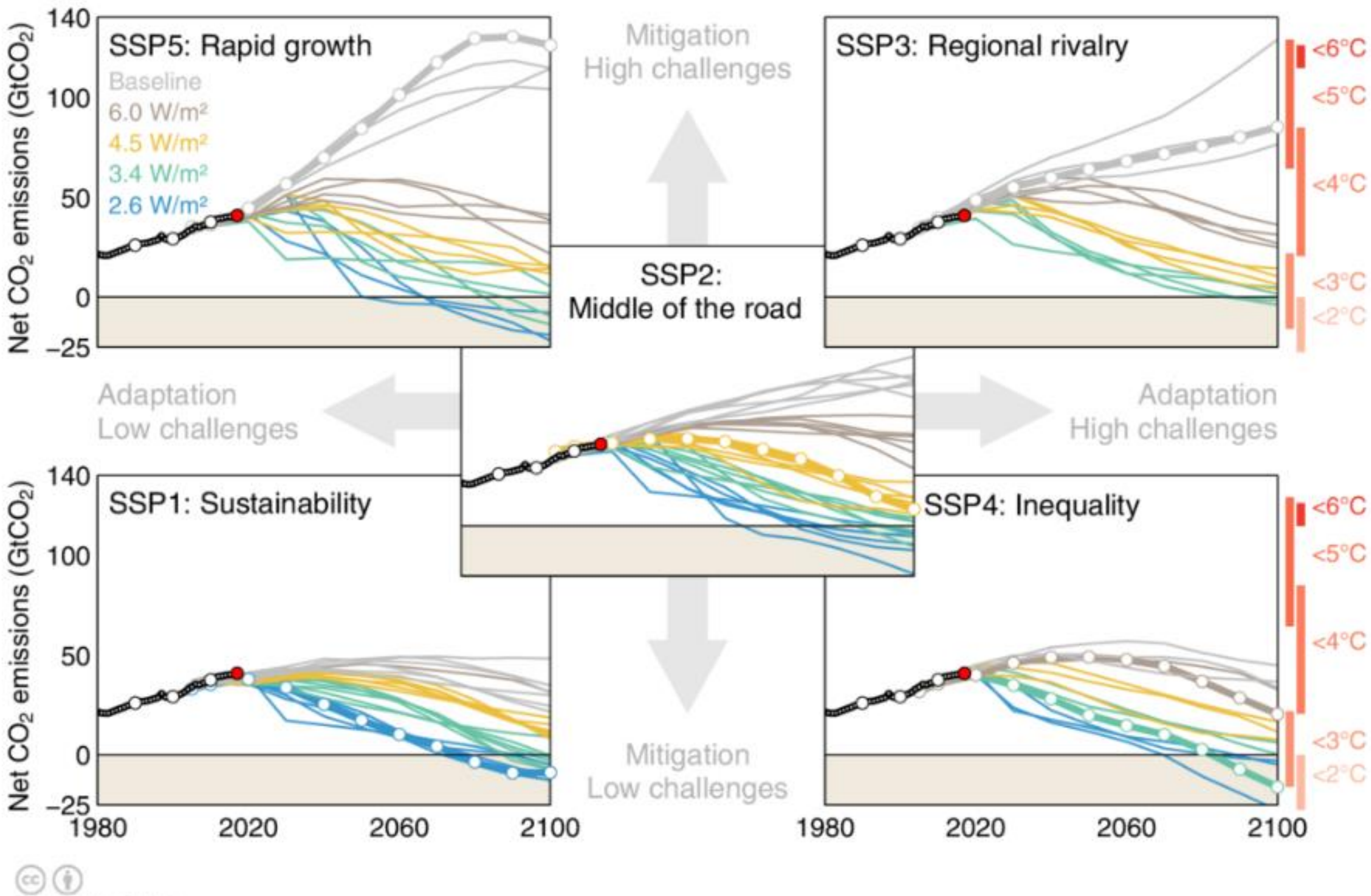


Combining SSPs Emissions and Climate



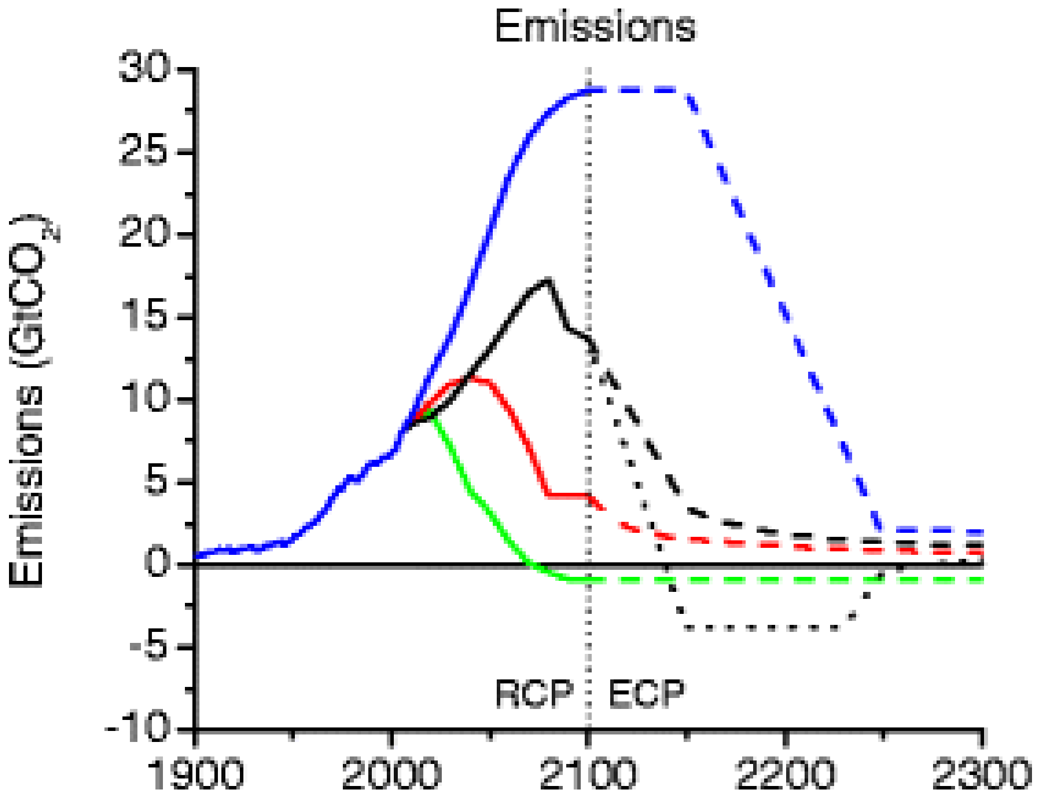
Source: Riahi et al, 2016

Limiting climate change to RCP levels in 5 SSP worlds



All CO2 EMISSIONS scenarios are alike—They all end at zero

- CO_2 has no atmospheric sink—it doesn't disappear
- Carbon that was removed from the atmosphere over millions of years, can only be partitioned between atmosphere, ocean and land
  - Atmosphere (~20% on average will remain permanently)
  - Oceans (~80% on average will end up in oceans)



Getting to Zero—Five strategy elements

- Energy efficiency—reduce demand for energy as much as economical
- Decarbonize power generation
  - Fossil fuel with CCS
  - Renewable power
  - Nuclear power
  - Bioenergy
  - Bioenergy with CCS
- Electrify Buildings and Industry
  as much as economical
- Decarbonize transport
  - Electrify
  - Biofuels
  - H2
- Halt deforestation/afforestation and continue improving crop yields

Source: http://www.energy.gov/science-innovation/energy-sources/renewable-energy/wind

DISCUSSION

A Cheat Sheet for IA

Energy Conversion (average values)

	Energy Content	Standard Unit	Practical Unit	Emission Coefficient
Coal	1 EJ	0.034 Gtce	0.038 bil short tons	27 TgC/EJ
Oil	1 EJ	0.024 Gtoe	0.175 bil. Barrel	20 TgC/EJ
Gas	1 EJ	27 bcm	984 bil cubic ft	14 TgC/EJ

Gtce = billion (10^9) metric tonnes of coal equivalent
Gtoe = billion (10^9) metric tonnes of oil equivalent
bcm = billion (10^9) cubic meters

1Quad = 10^{15} Btu = 1.055 Exajoules (EJ)
1 Exajoule (EJ) = 10^{18} joules
1 Terajoule (TJ) = 10^{12} joules
1 Gigajoule (GJ) = 10^9 joules

2005 Global Energy Use by Fuel

- Oil = 168 EJ/yr
- Gas = 99 EJ/yr
- Coal = 121 EJ/yr
- Traditional Bioenergy = 29 EJ/yr
- Commercial and Industrial Bioenergy = 20 EJ/yr
- Nuclear Power = 26 EJ/yr
- Hydro Power = 29 EJ/yr
- Wind Power = 1 EJ/yr
- Solar Power = <1 EJ/yr
- Geothermal Power = 1 EJ/yr

Carbon and Climate

Historical Atmospheric CO_2 Concentrations

Preindustrial Annual Average Atmospheric CO_2 = ~278 parts per million (ppm)

2005 Annual Average Atmospheric CO_2 = 380 parts per million (ppm)

2010 Annual Average Atmospheric CO_2 = 390 parts per million (ppm)

2012 Annual Average Atmospheric CO_2 = 394 parts per million (ppm)

Radiative Forcing and CO_2-e

2.6 Wm^{-2} = 450 ppm CO_2-e

4.5 Wm^{-2} = 650 ppm CO_2-e

6.0 Wm^{-2} = 850 ppm CO_2-e

8.5 Wm^{-2} = 1360 ppm CO_2-e

Atmosphere and Climate

Relationship between long-term steady-state radiative forcing and change in average Earth surface temperature assuming a climate sensitivity of 3.0°C/CO_2 doubling

2.6 Wm^{-2} = 450 ppm CO_2-e $\Rightarrow$ ΔT ~2.1°C

4.5 Wm^{-2} = 650 ppm CO_2-e $\Rightarrow$ ΔT ~3.6°C

6.0 Wm^{-2} = 850 ppm CO_2-e $\Rightarrow$ ΔT ~4.8°C

8.5 Wm^{-2} = 1360 ppm CO_2-e $\Rightarrow$ ΔT ~6.8°C

Emissions

- **Year 2005 CO_2 Equivalent (CO_2-e) Concentrations (estimated)**
  - Annual Average CO_2 equivalent (including all Kyoto Protocol Gases) = 433 ppm-e
  - Annual Average CO_2 equivalent (including all Kyoto Protocol Gases & CFCs) = 455 ppm-e
  - Annual Average CO_2 equivalent (including all Gases and Aerosols) = 382 ppm-e

- **Average DIRECT Carbon-Intensity of Energy Use by Fuel (estimated)**
  - Oil = ~20 KgC/GJ
  - **Gas = ~14 KgC/GJ**
  - Coal = ~27 KgC/GJ
  - Nuclear, Solar, Wind, Geothermal and other renewable energy forms = ~0 KgC/GJ

- **2010 Average DIRECT Carbon-Intensity of Energy Use for Selected Countries**
  - USA = ~16 KgC/GJ
  - China = ~24 KgC/GJ (Excluding traditional fuel use)
  - India = ~20 KgC/GJ (Excluding traditional fuel use)
  - Western Europe = ~15 KgC/GJ
  - Africa = ~15 KgC/GJ (Excluding traditional fuel use)

- **Carbon and CO_2**
  - 1 PgC = 1 Petagram carbon = 10^{15} grams C
  - 1 PgC = 1 Gigaton C = 1 GtC
  - 1 tonne C = 3.67 tonnes CO_2

- **Prices**
  - $\$1/tCO_2 = \$3.67/tC$