Climate Targets and Cost Effective Climate Stabilization Pathways

Joint EPS-SIF International School on Energy 2014
17-23 July 2014, Varenna, Italy

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Also Guest at

Potsdam Institute for Climate Impact Research (PIK)

P I K

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CLIMATE IMPACT RESEARCH

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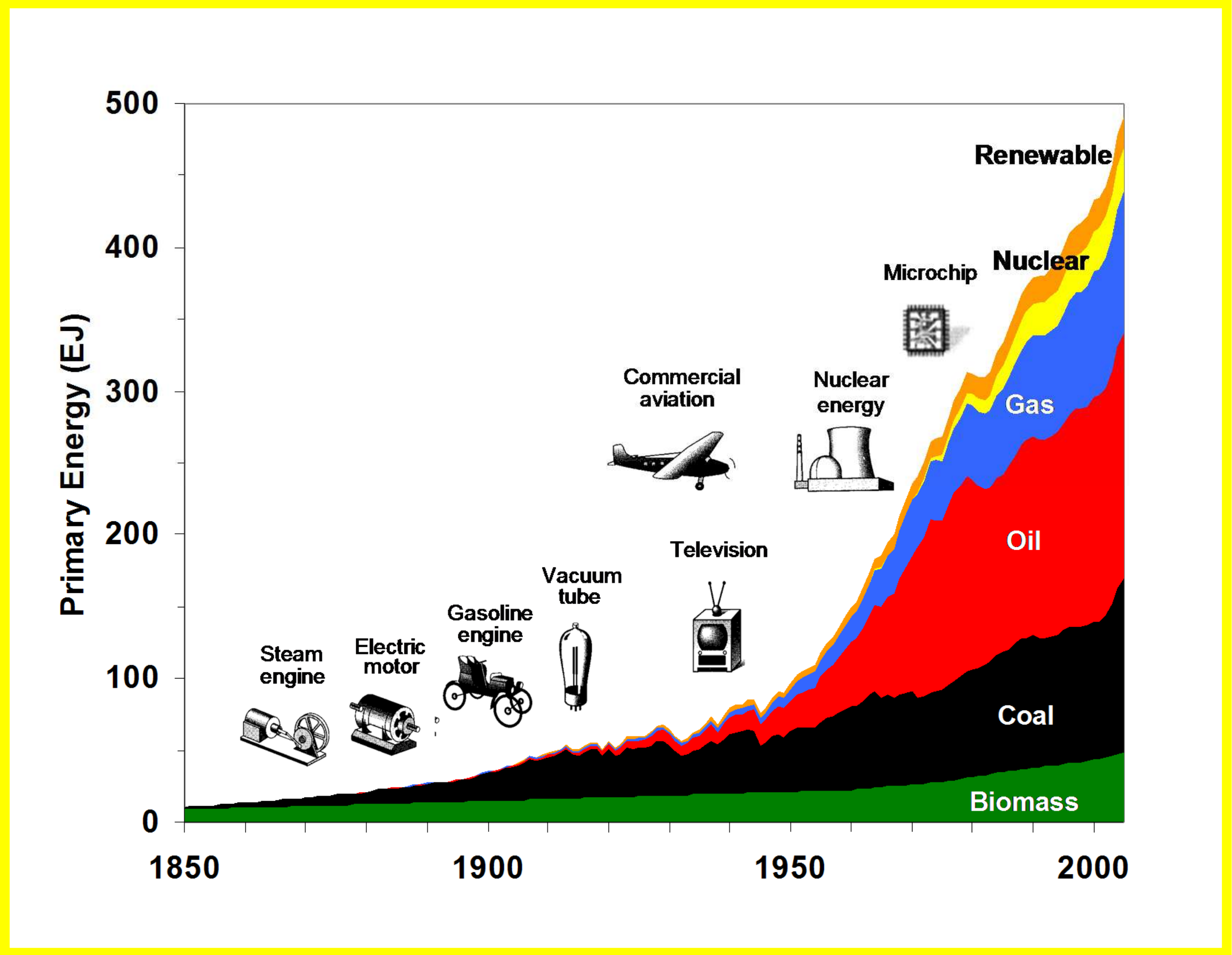
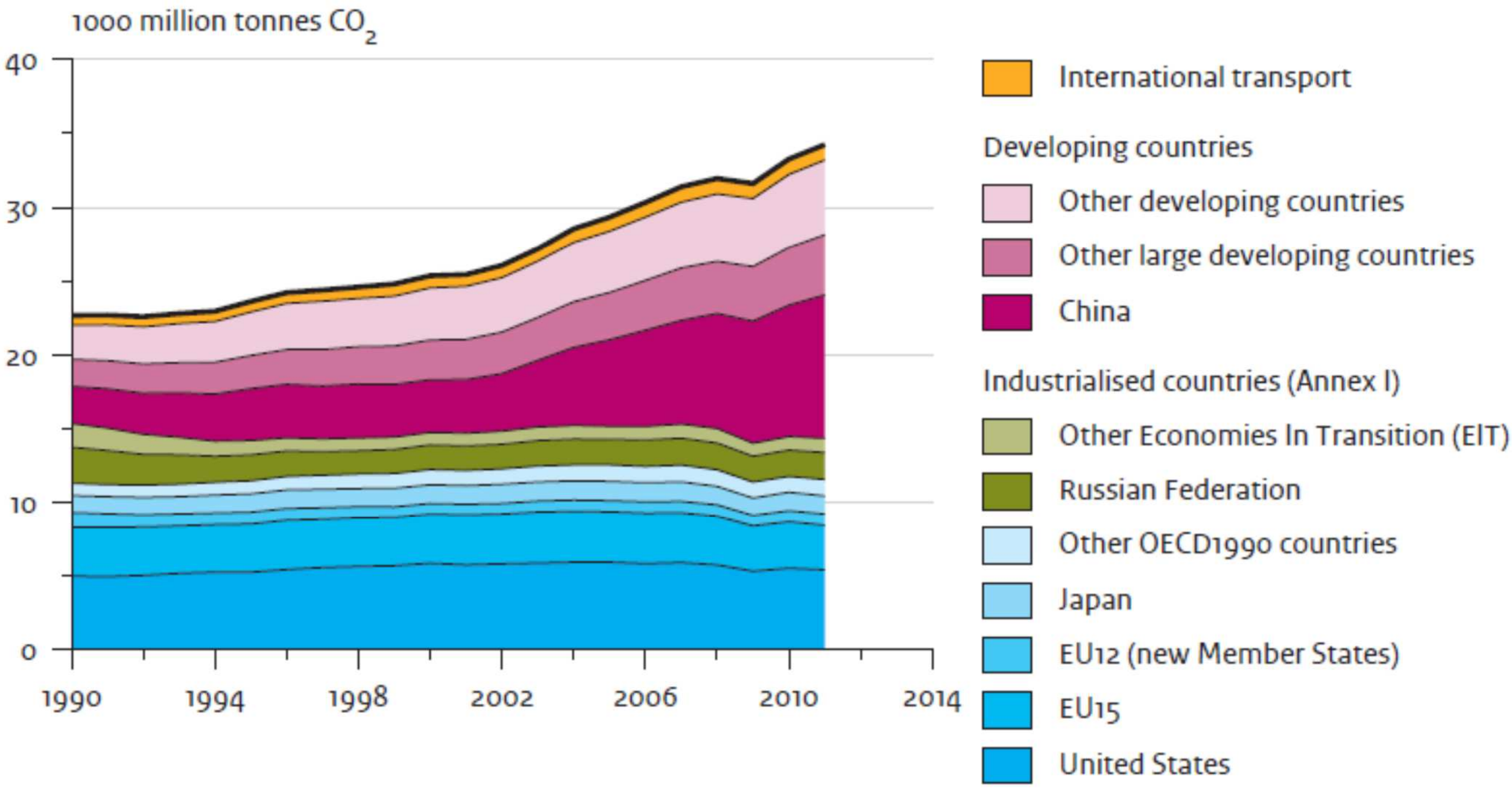
- Framing of the climate ‘problem’
- Two competing schools within climate economics:
  Cost benefit versus cost effectiveness analysis
- Integrated energy-climate-economic modelling

Global Primary Energy Consumption



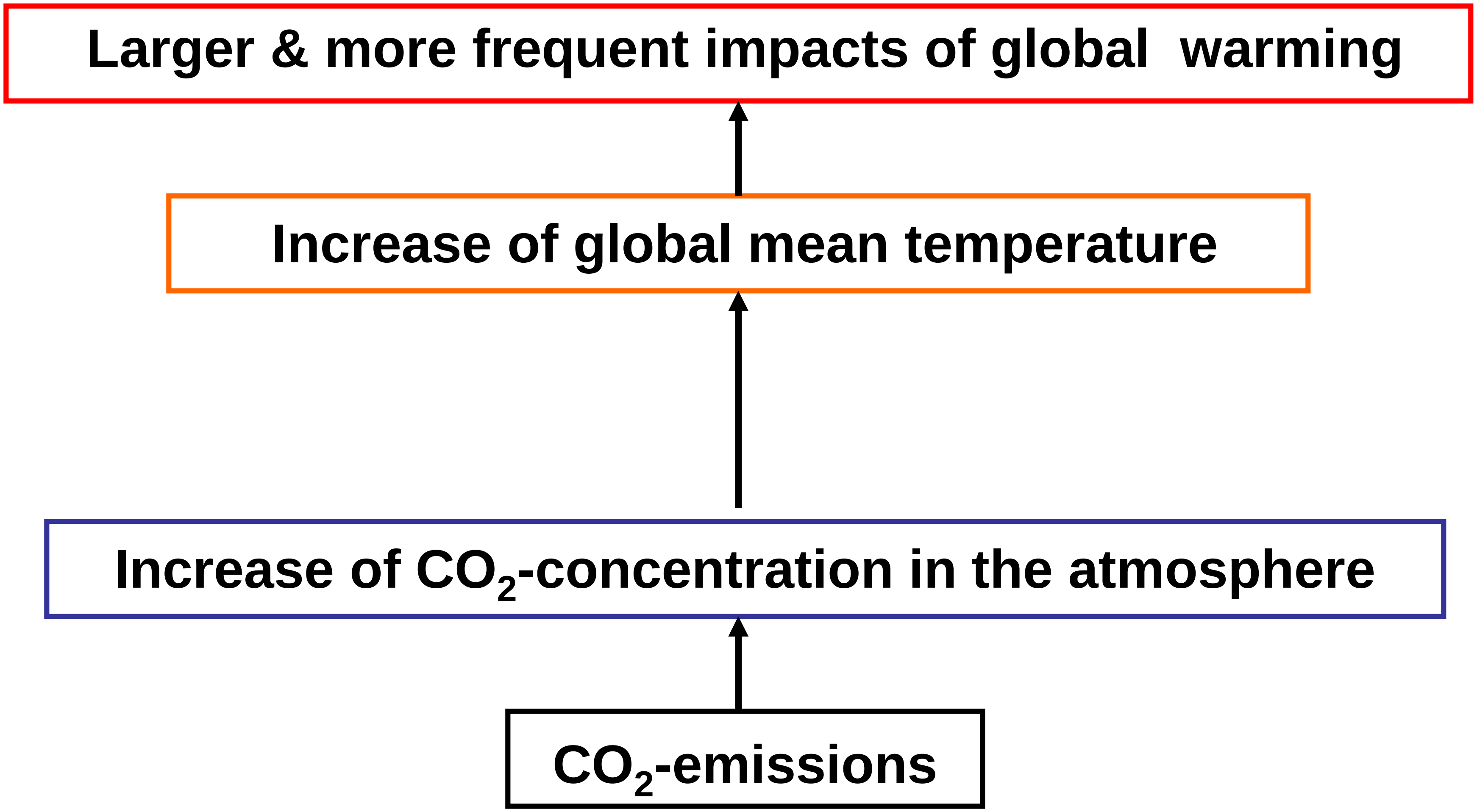
(Nakicenovic 2009)

Global CO_2-Emissions from Fossil Fuel Use and Cement Production



Olivier et al., 2012, Trends in Global CO_2 emissions.

Carbon Dioxide Impact Cascade

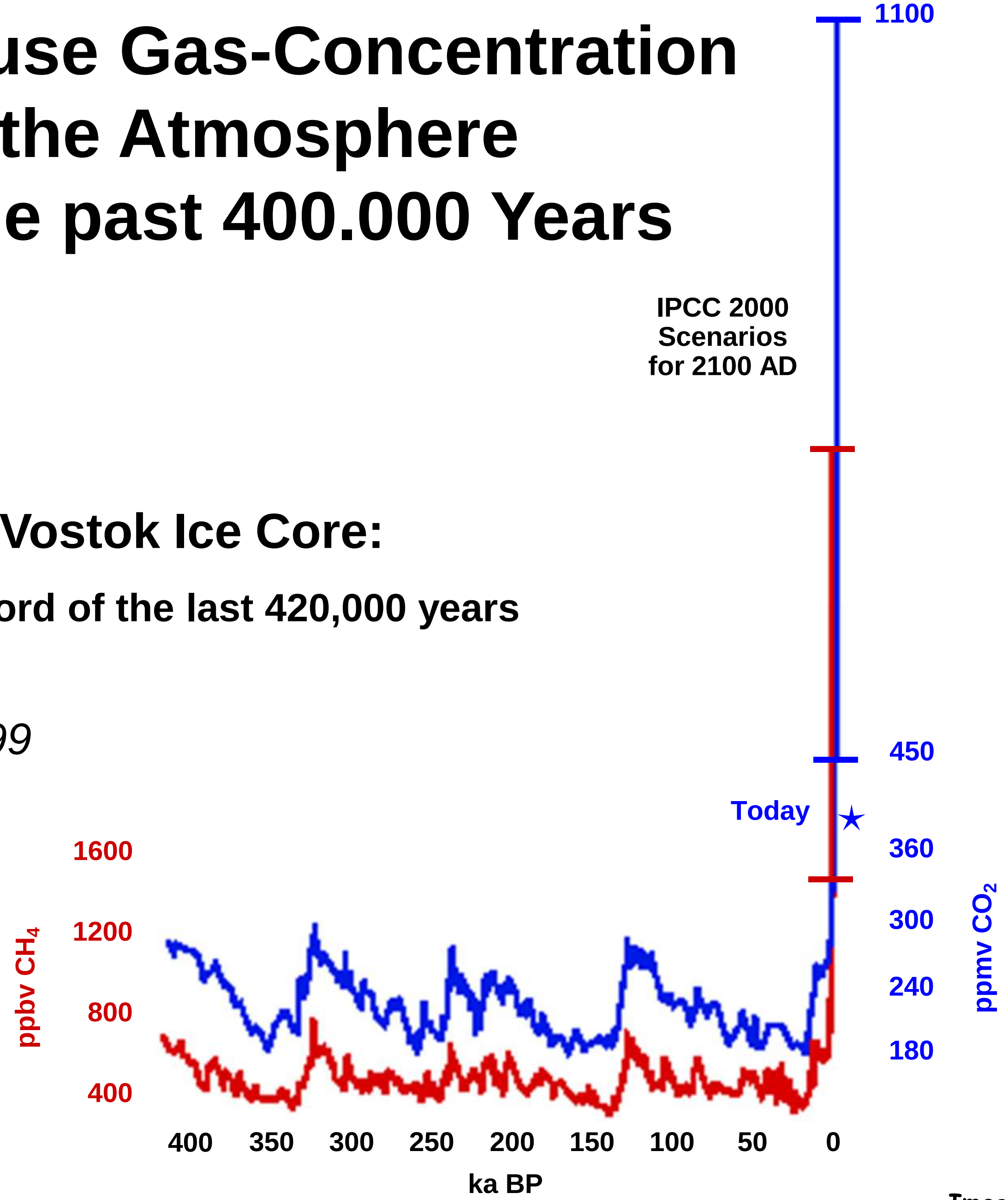


Greenhouse Gas-Concentration in the Atmosphere Over the past 400.000 Years

Vostok Ice Core:

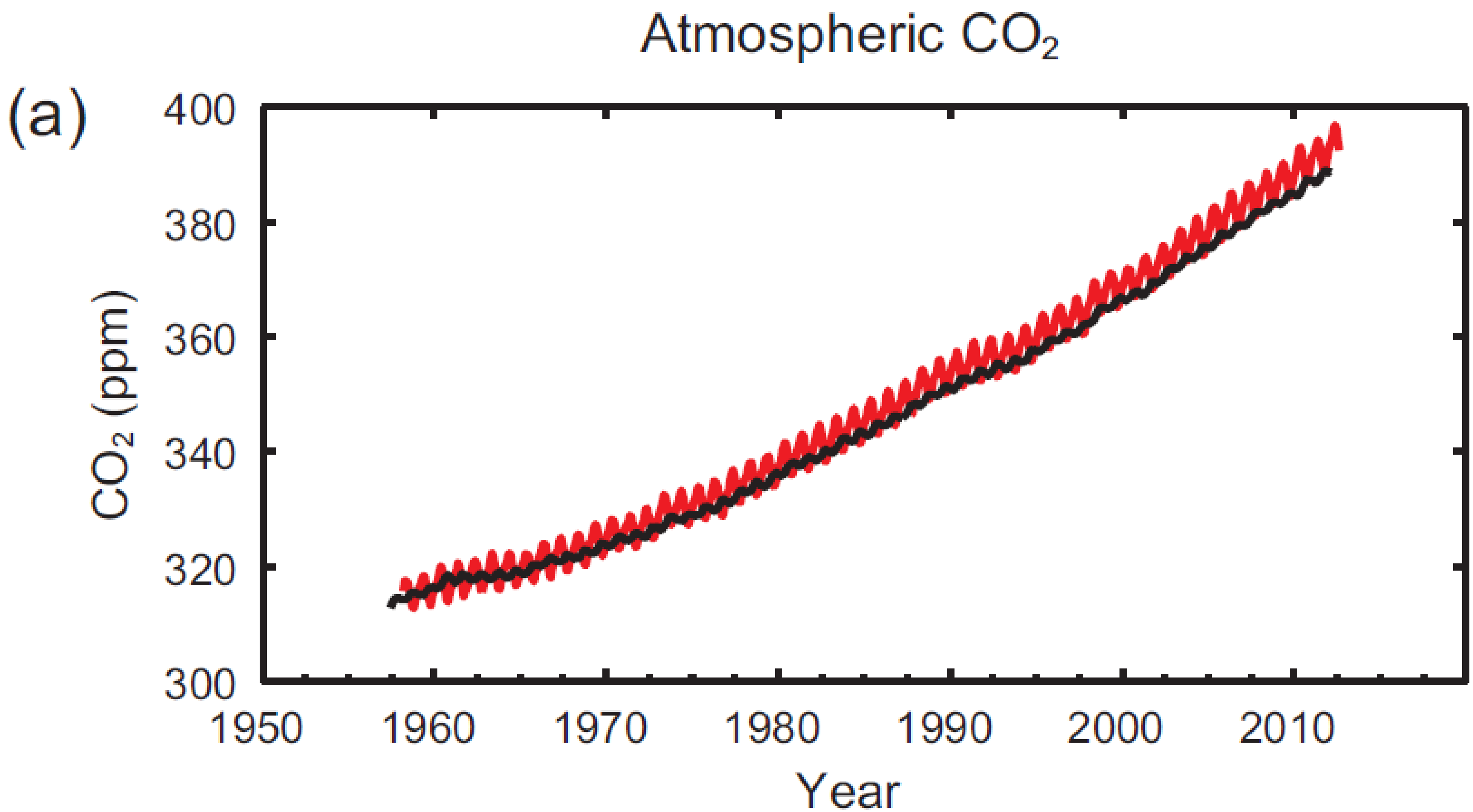
the record of the last 420,000 years

After Petit et al., 1999



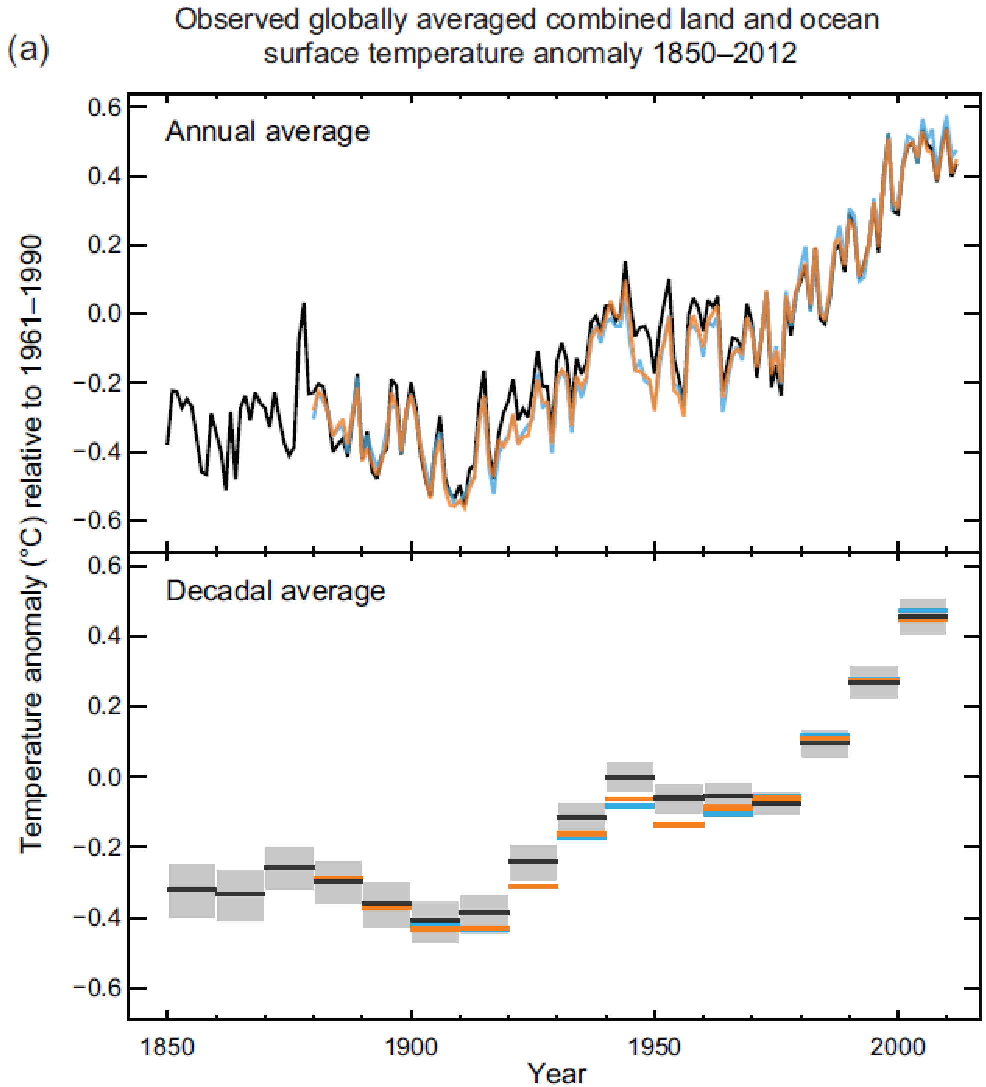
Images from WDCP/IPCC

Time Evolution of Atmospheric CO_2 Concentration



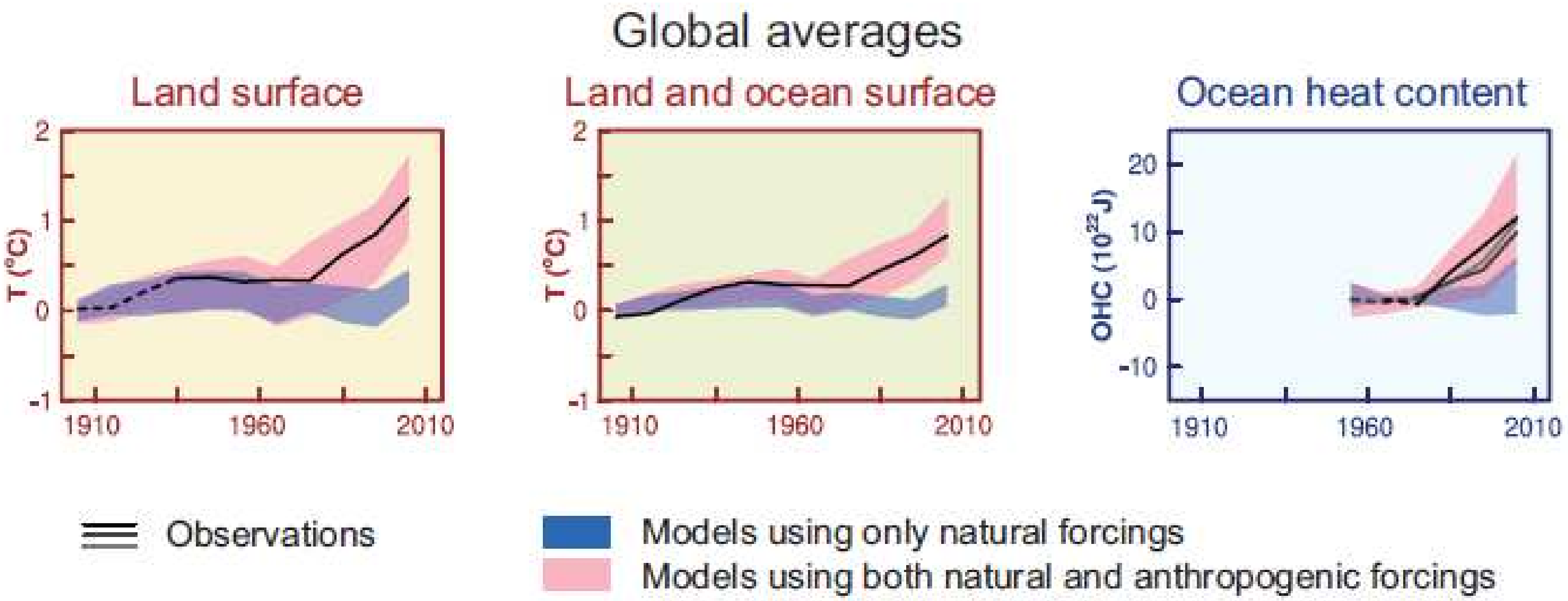
IPCC AR5 WG-I
SPM (2013)

Observed Global Mean Surface Temperature Change

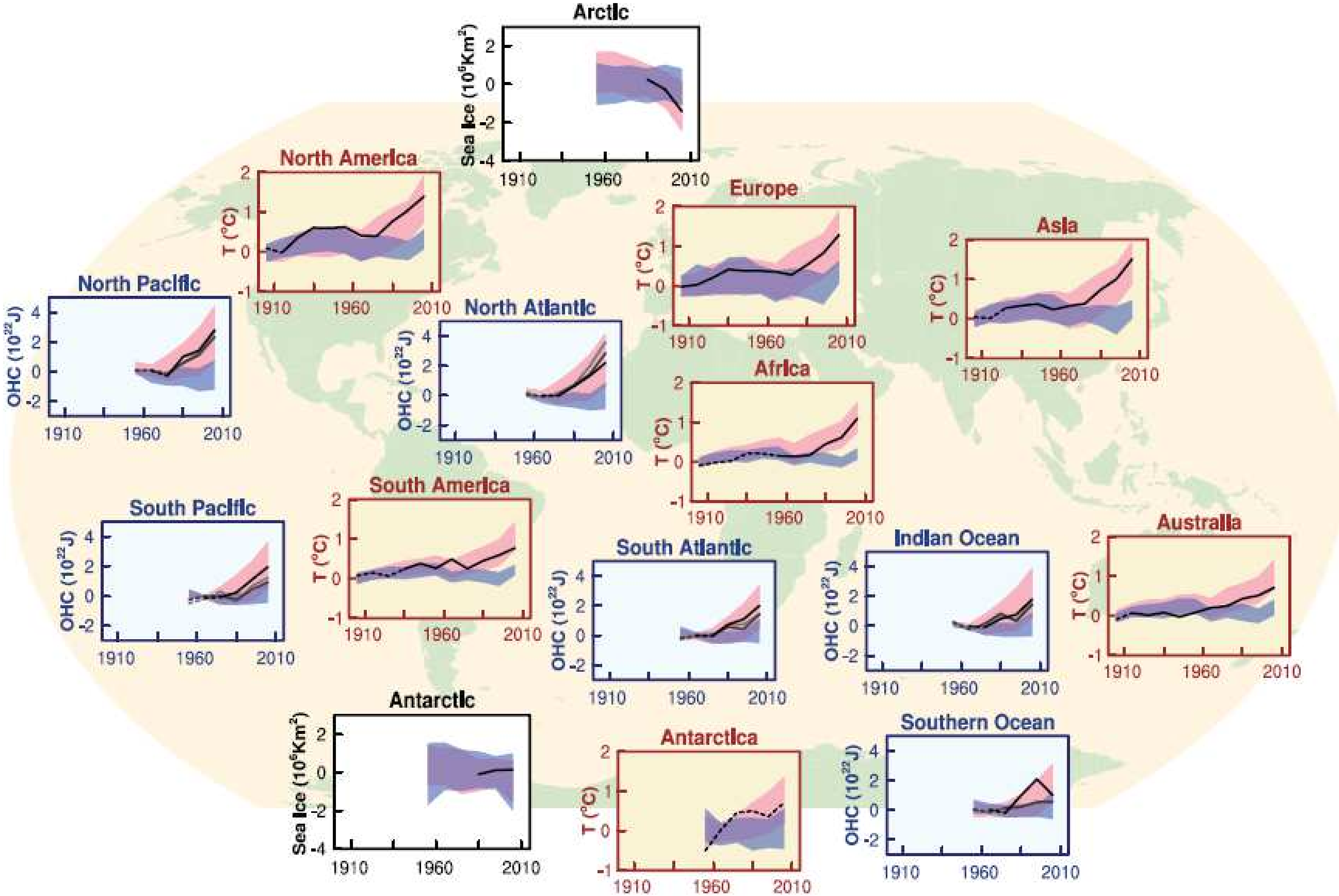


IPCC AR5 WG-I SPM (2013)

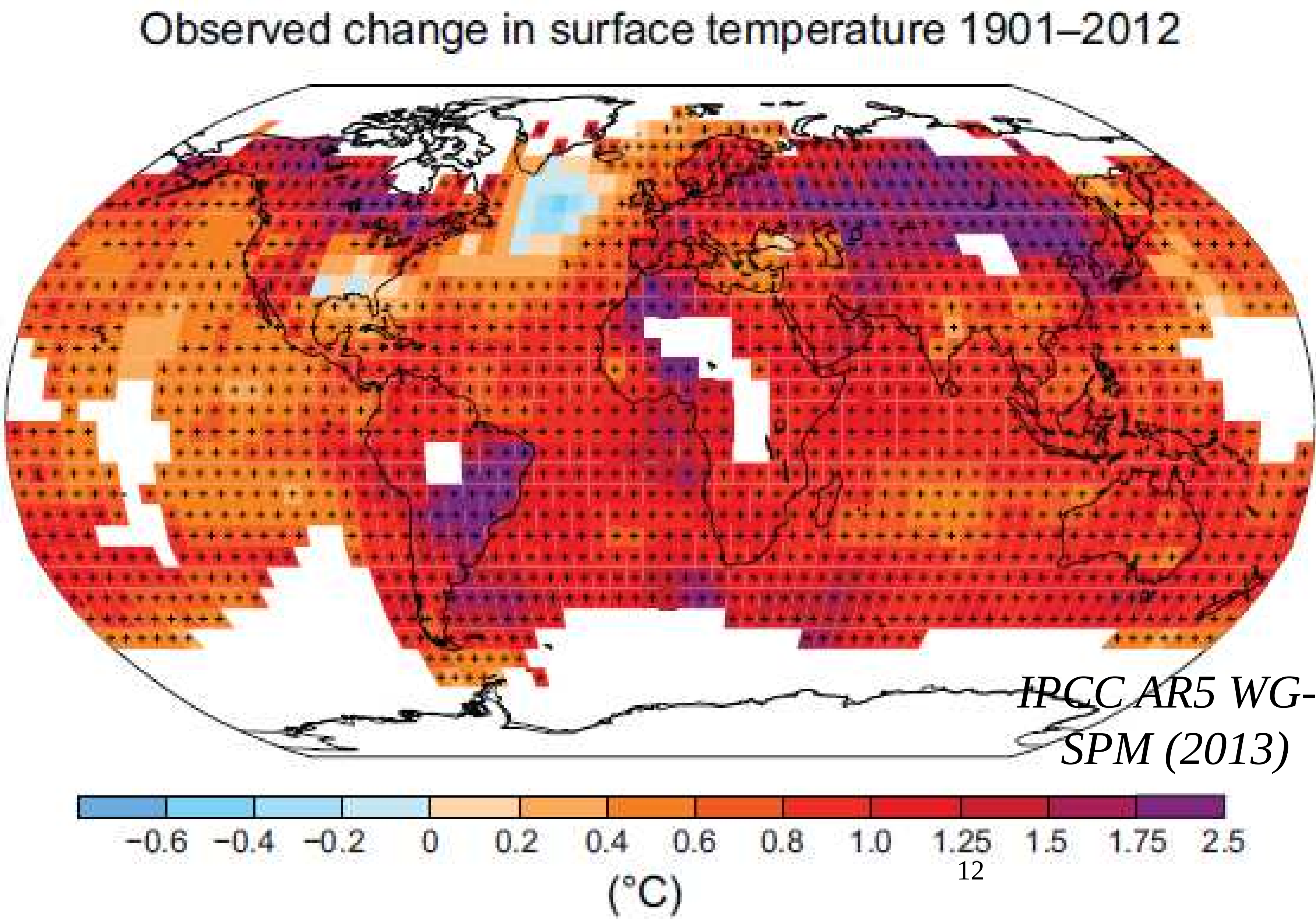
We cannot explain temperature rise without anthropogenic forcings



IPCC AR5 WG-I SPM (2013)



IPCC AR5 WG-I
SPM (2013)



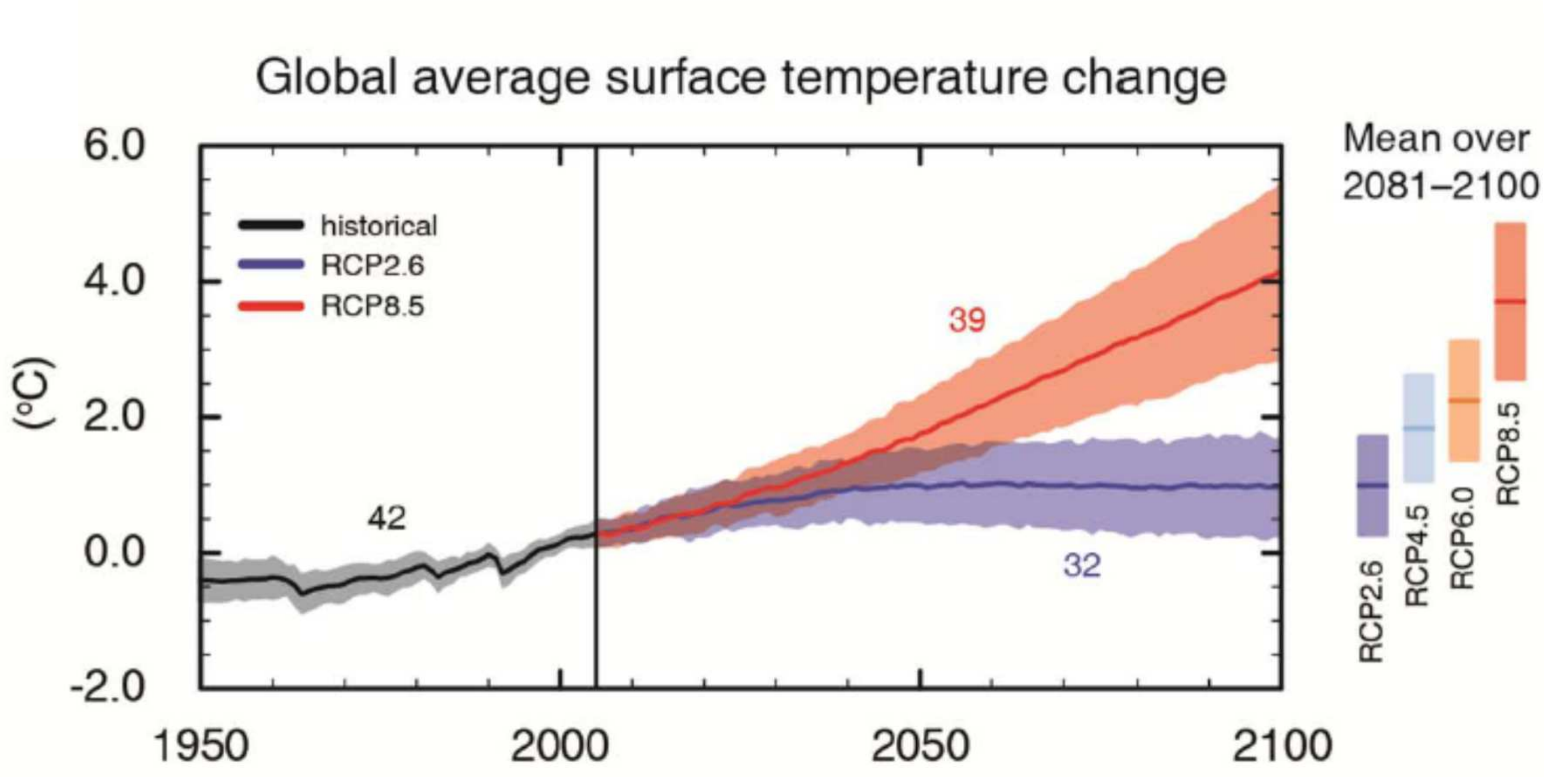
IPCC AR5 WG-I SPM (2013)

Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (see Figure SPM.6 and Table SPM.1). This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. {10.3–10.6, 10.9}

In this Summary for Policymakers, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Chapter 1 and Box TS.1 for more details).

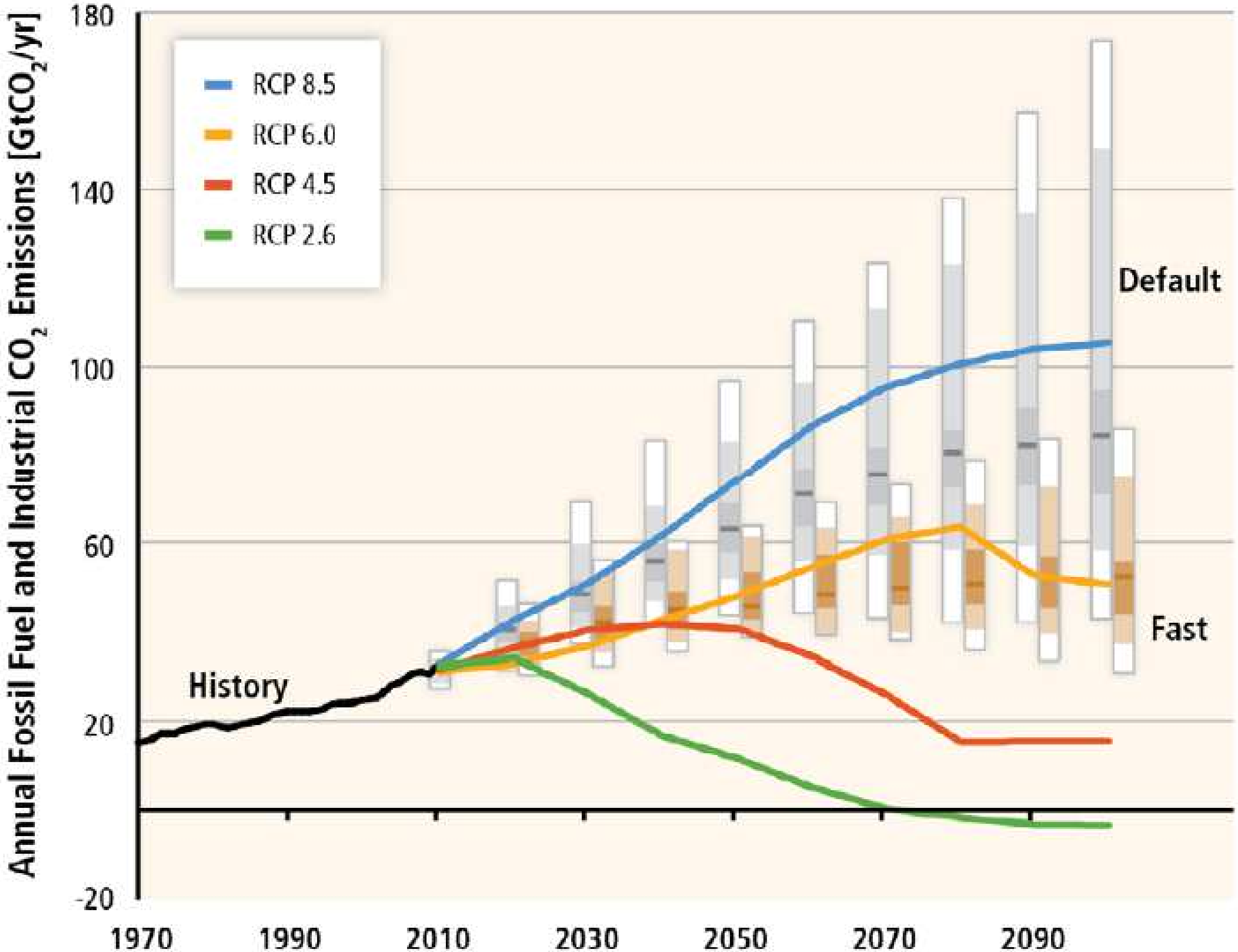
IPCC AR5 WG-I SPM (2013)

Future Temperature Rise:
Climate Policy´s Room for Manoeuvre



IPCC AR5 WG-I SPM

RCP = Representative Concentration Pathway



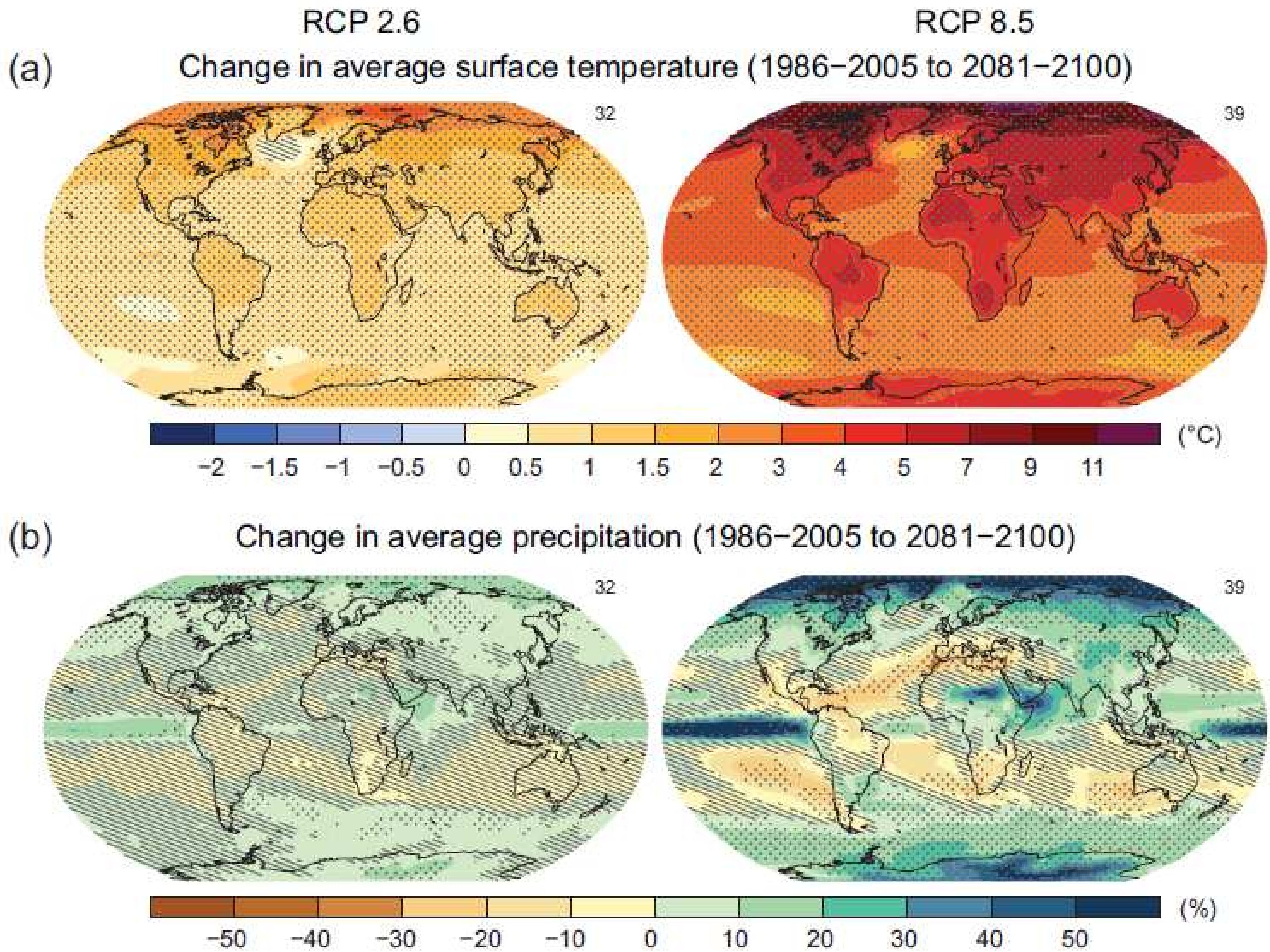
Two Lines of Argument behind Global Warming Mitigation Policies

- Explicitly projected impacts of global warming might be ‘too large’

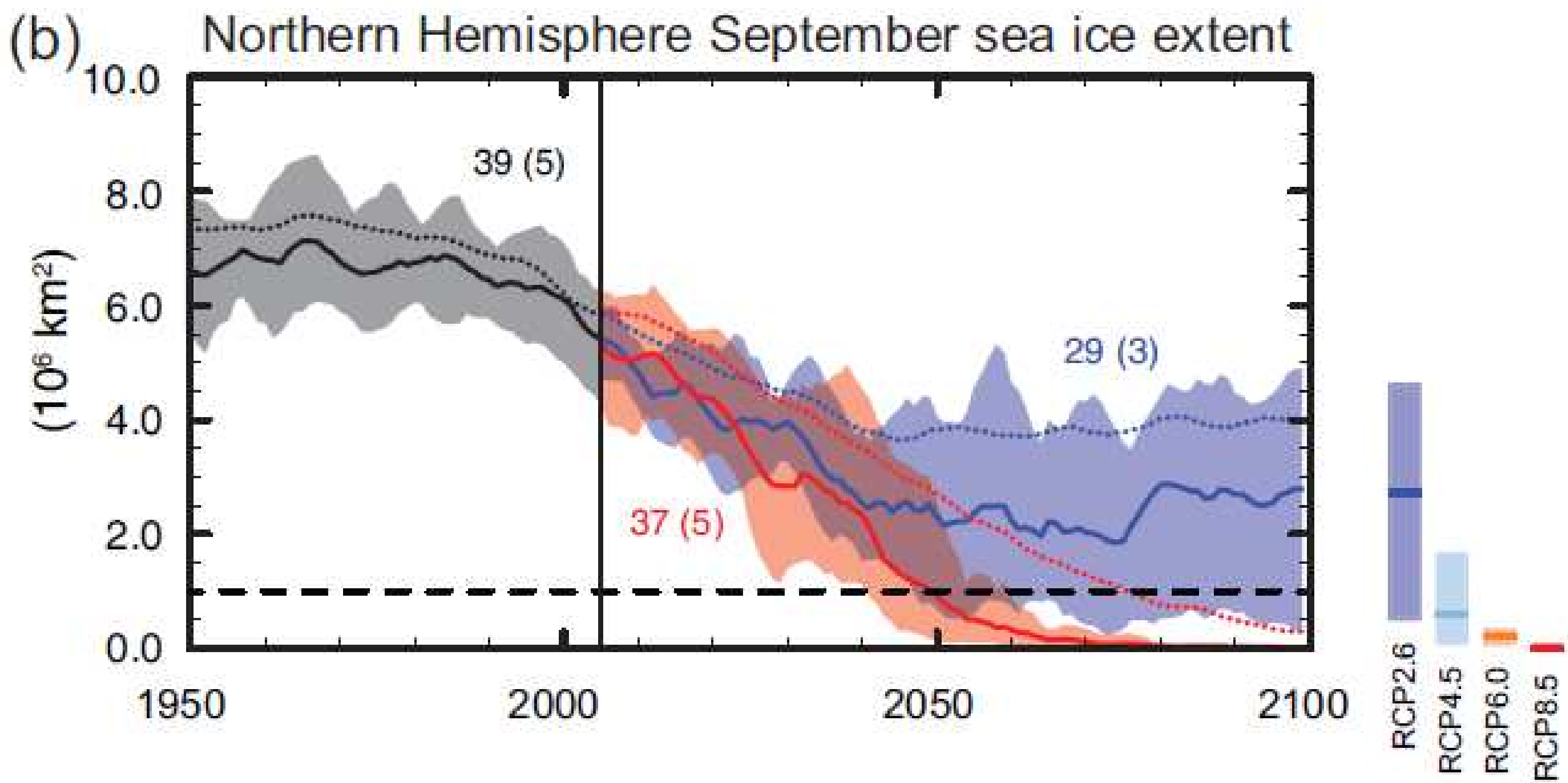
- Precautionary principle
  - beyond certain regimes knowledge too poor to weigh costs and benefits

A Selection of projected Impacts..

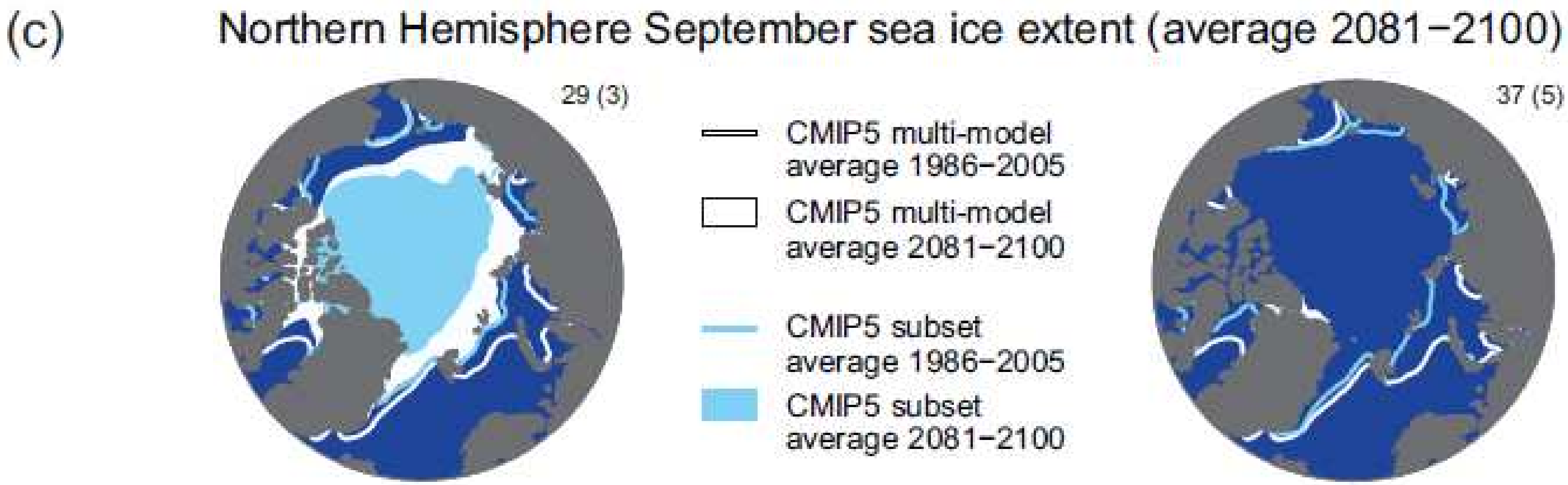
Projection := Prediction, conditioned on
future human intervention



IPCC AR5 WG-I SPM (2013)



IPCC AR5 WG-I SPM (2013)



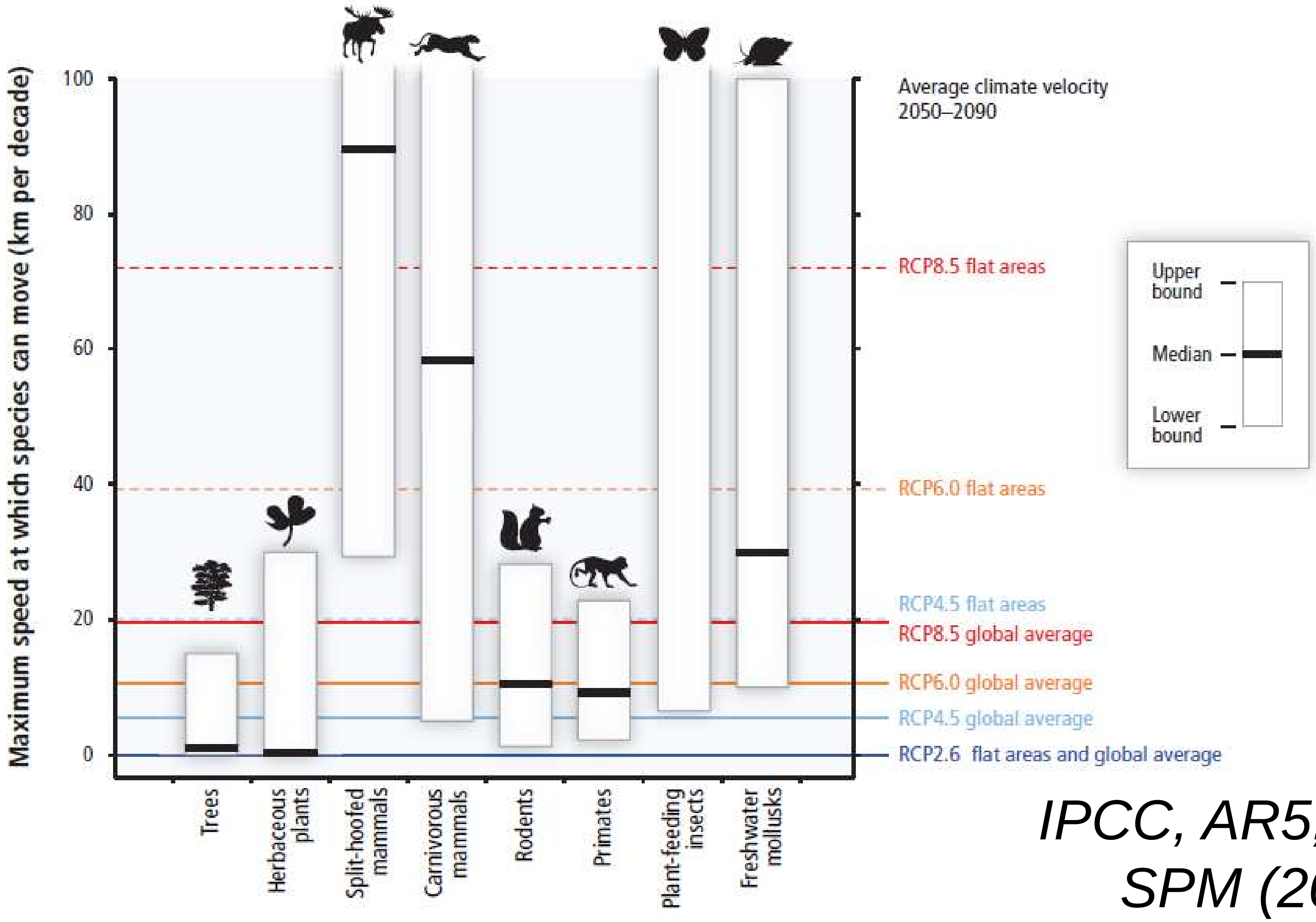
RCP 2.6

RCP 8.5

of the century. The CMIP5 multi-model mean is given in white colour, the projected mean sea ice extent of a subset of models (number of models given in brackets) that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea ice extent is given in light blue colour. For

IPCC AR5 WG-I
SPM (2013)

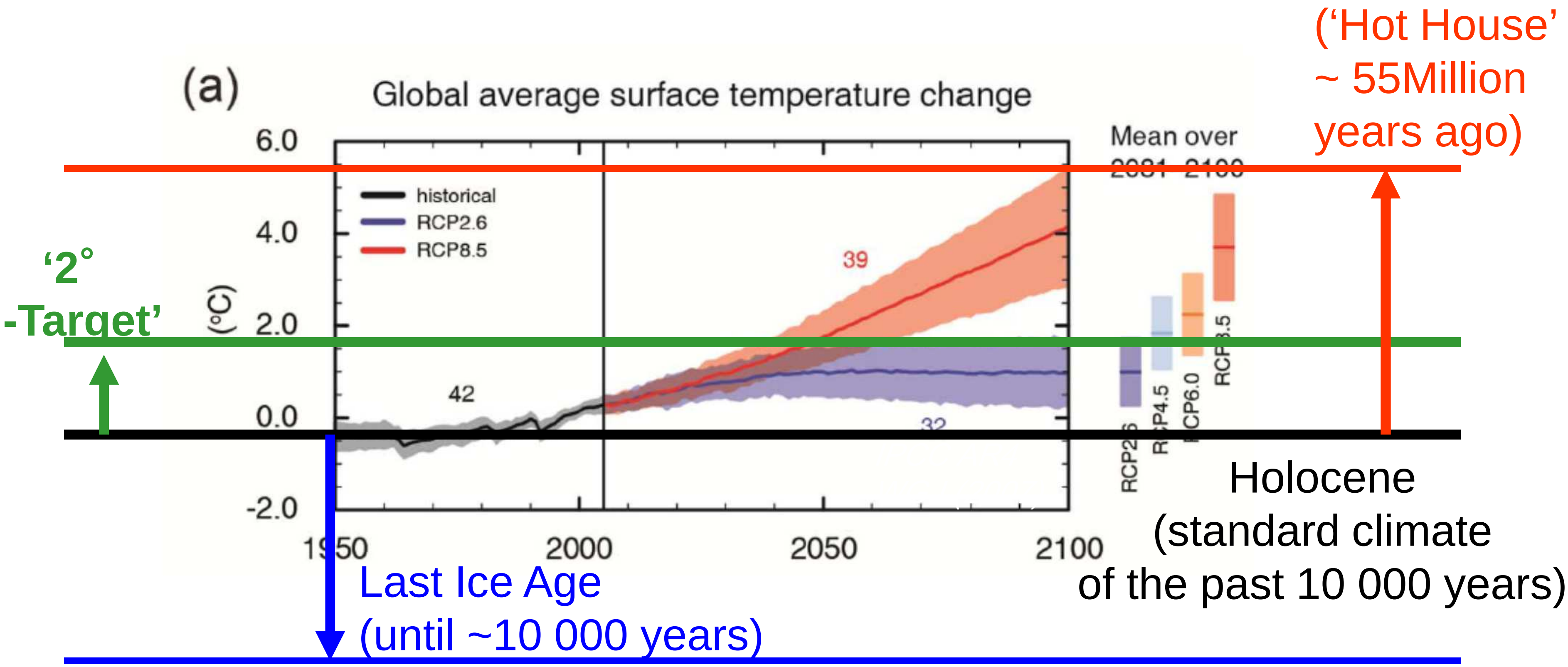
Velocity of Climatic Zones & Coping Capacities of Species



IPCC, AR5, WGII, SPM (2014)

Figure SPM.5 | Maximum speeds at which species can move across landscapes (based on observations and models; vertical axis on left), compared with speeds at which temperatures are projected to move across landscapes (climate velocities for temperature; vertical axis on right). Human interventions, such as transport or habitat fragmentation, can greatly increase or decrease speeds of movement. White boxes with black bars indicate ranges and medians of maximum movement speeds for trees, plants, mammals, plant-feeding insects (median not estimated), and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050–2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species with maximum speeds below each line are expected to be unable to track warming in the absence of human intervention. [Figure 4-5]

One possible interpretation of the Precautionary Principle:
Avoid Historic Dimension of Temperature Rise



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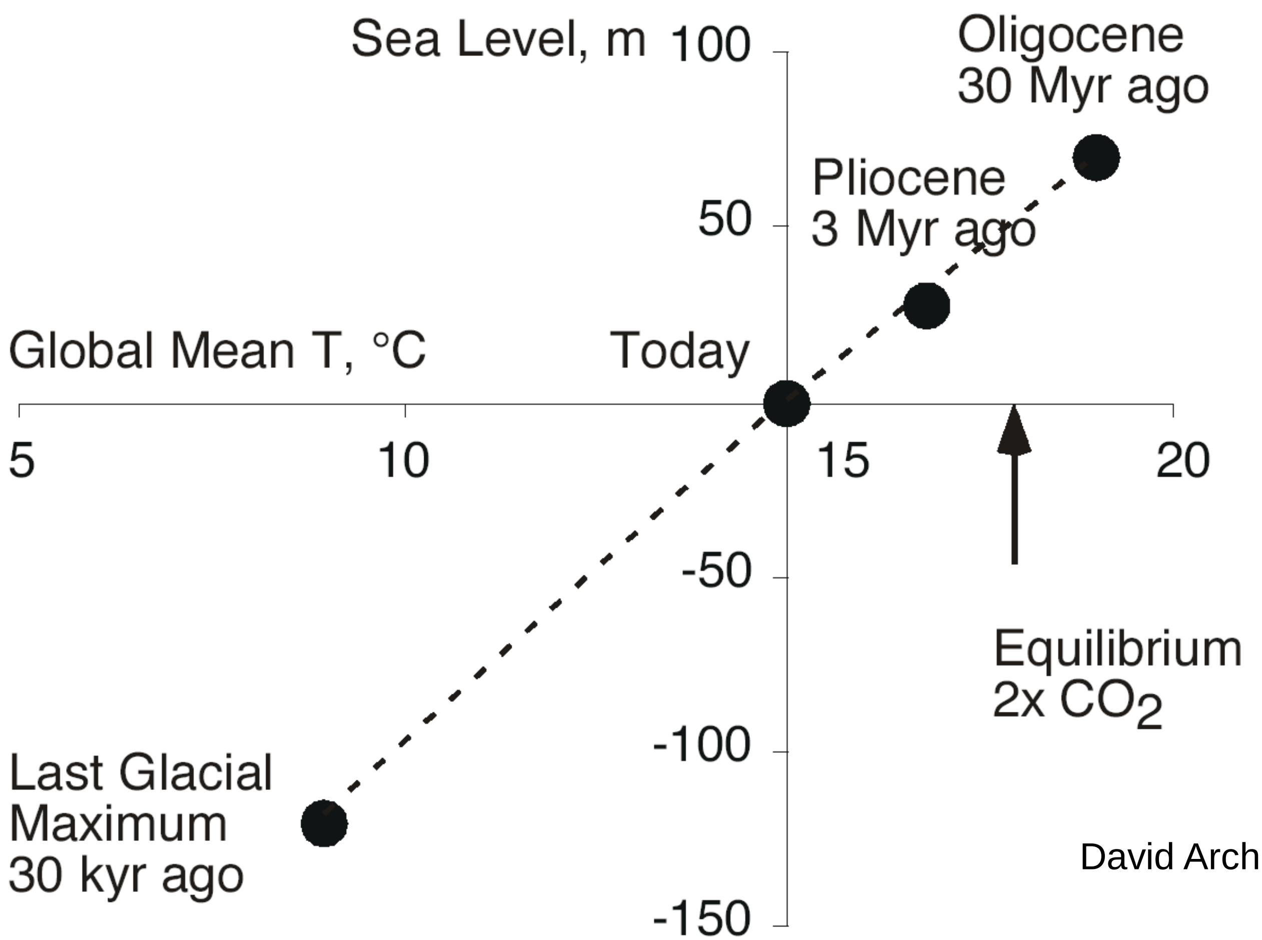
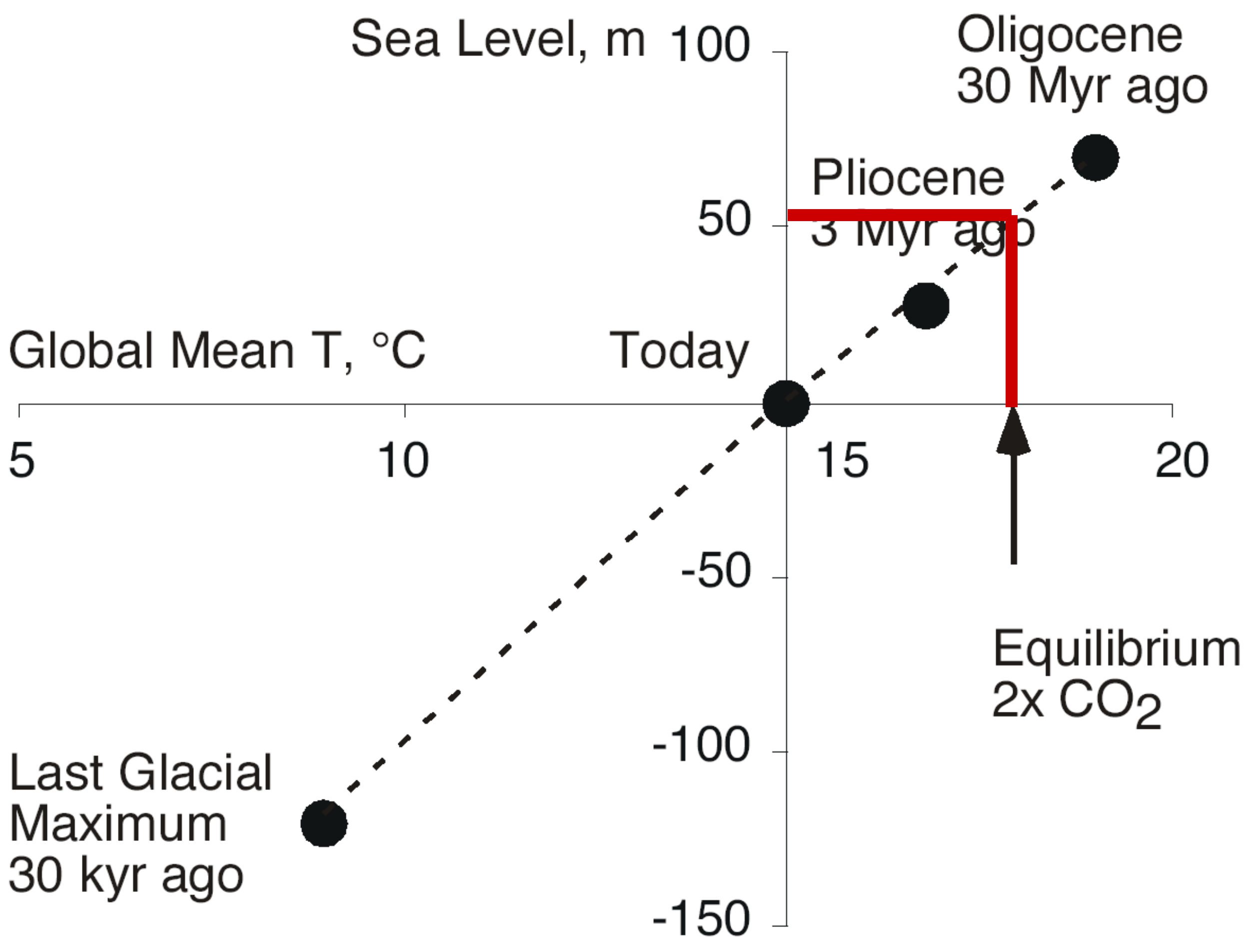
Past Sea Level vs. Temperature



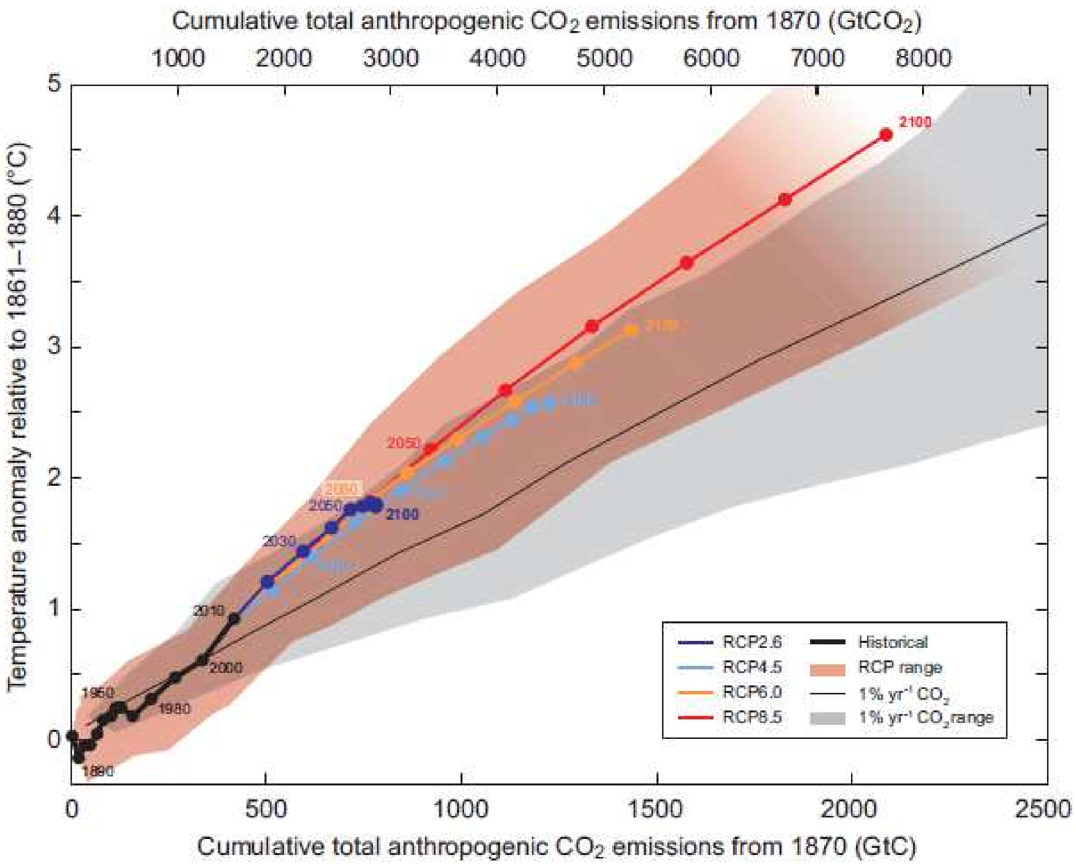
David Archer

Past Sea Level vs. Temperature



David Archer

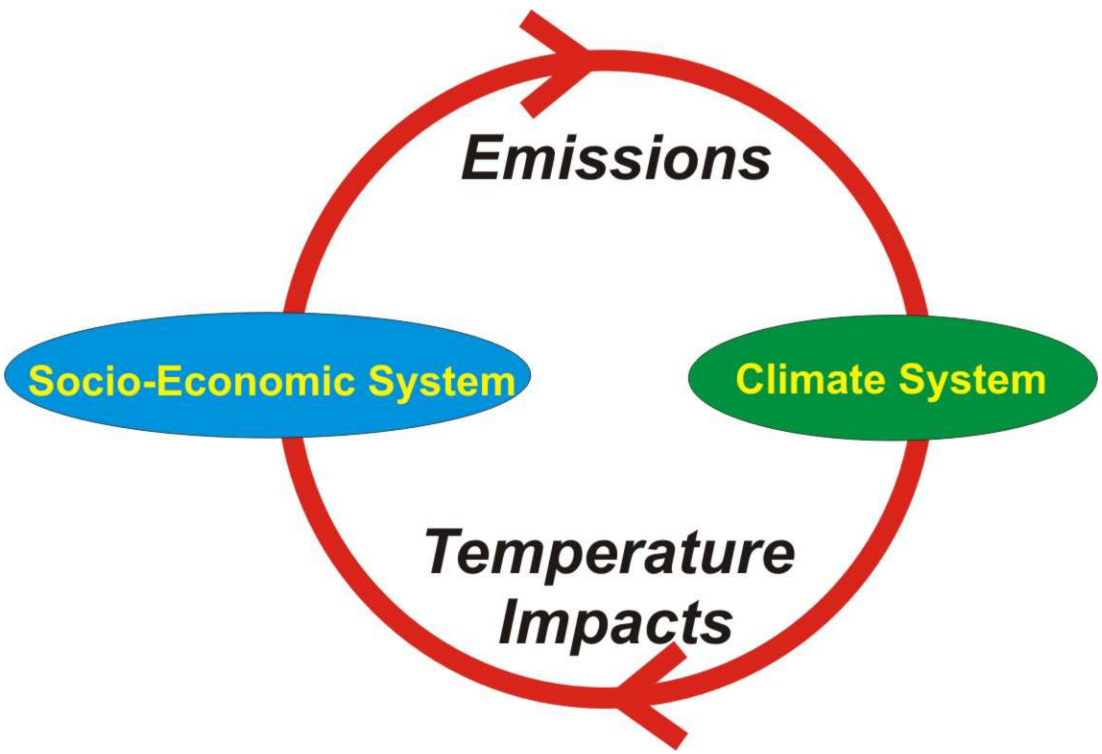
Carbon Emission Budget vs. Global Warming



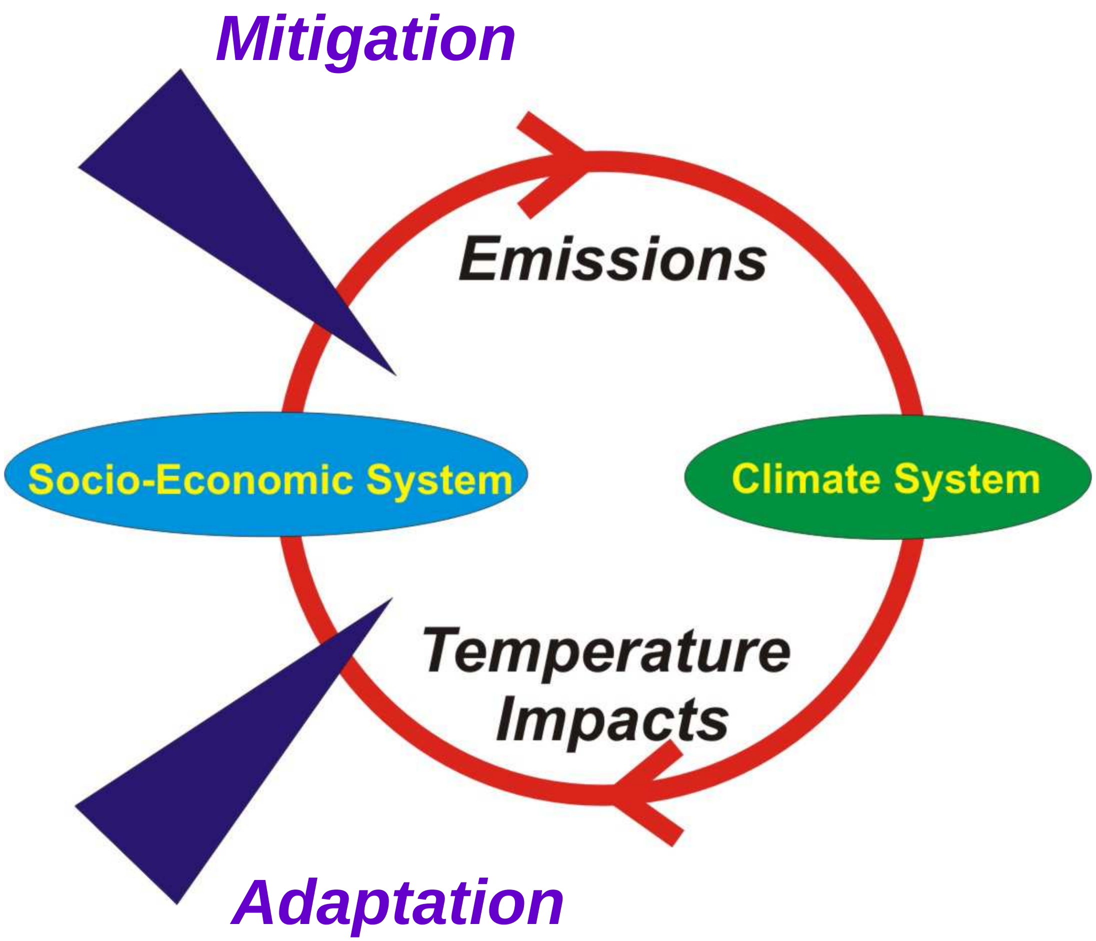
IPCC AR5 WG-I SPM (2013)

Figure SPM.10 | Global mean surface temperature increase as a function of cumulative total global CO_2 emissions from various lines of evidence. Multi-model results from a hierarchy of climate-carbon cycle models for each RCP until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are labeled for clarity (e.g., 2050 indicating the decade 2040–2049). Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The multi-model mean and range simulated by CMIP5 models, forced by a CO_2 increase of 1% per year (1% yr^{-1} CO_2 simulations), is given by the thin black line and grey area. For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature values are given relative to the 1861–1880 base period, emissions relative to 1870. Decadal averages are connected by straight lines. For further technical details see the Technical Summary Supplementary Material. {Figure 12.45; TS TFE.8, Figure 1}

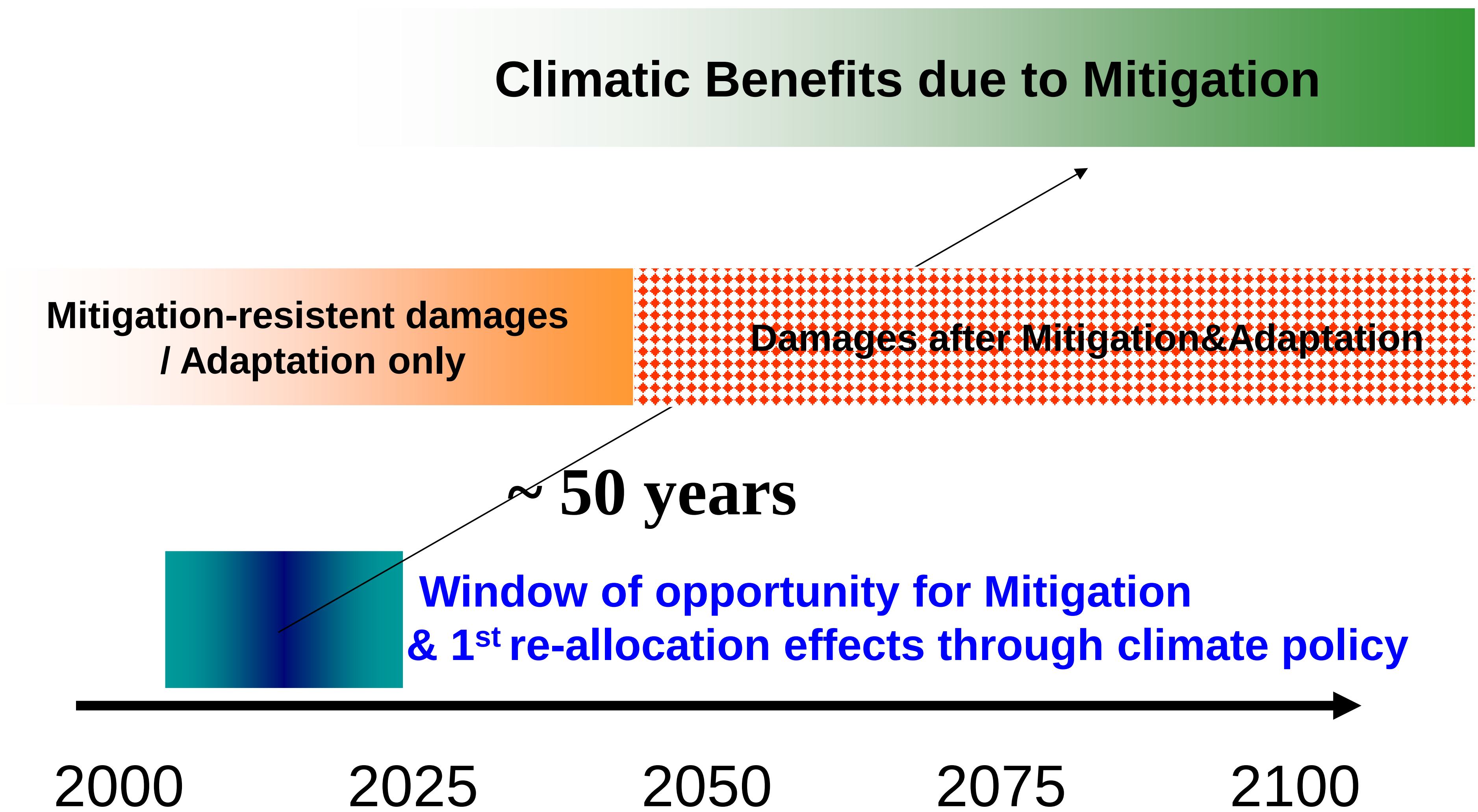
The Coupled Climate-Socioeconomic System



Climate Policies



Window of Opportunity for Mitigation Policy



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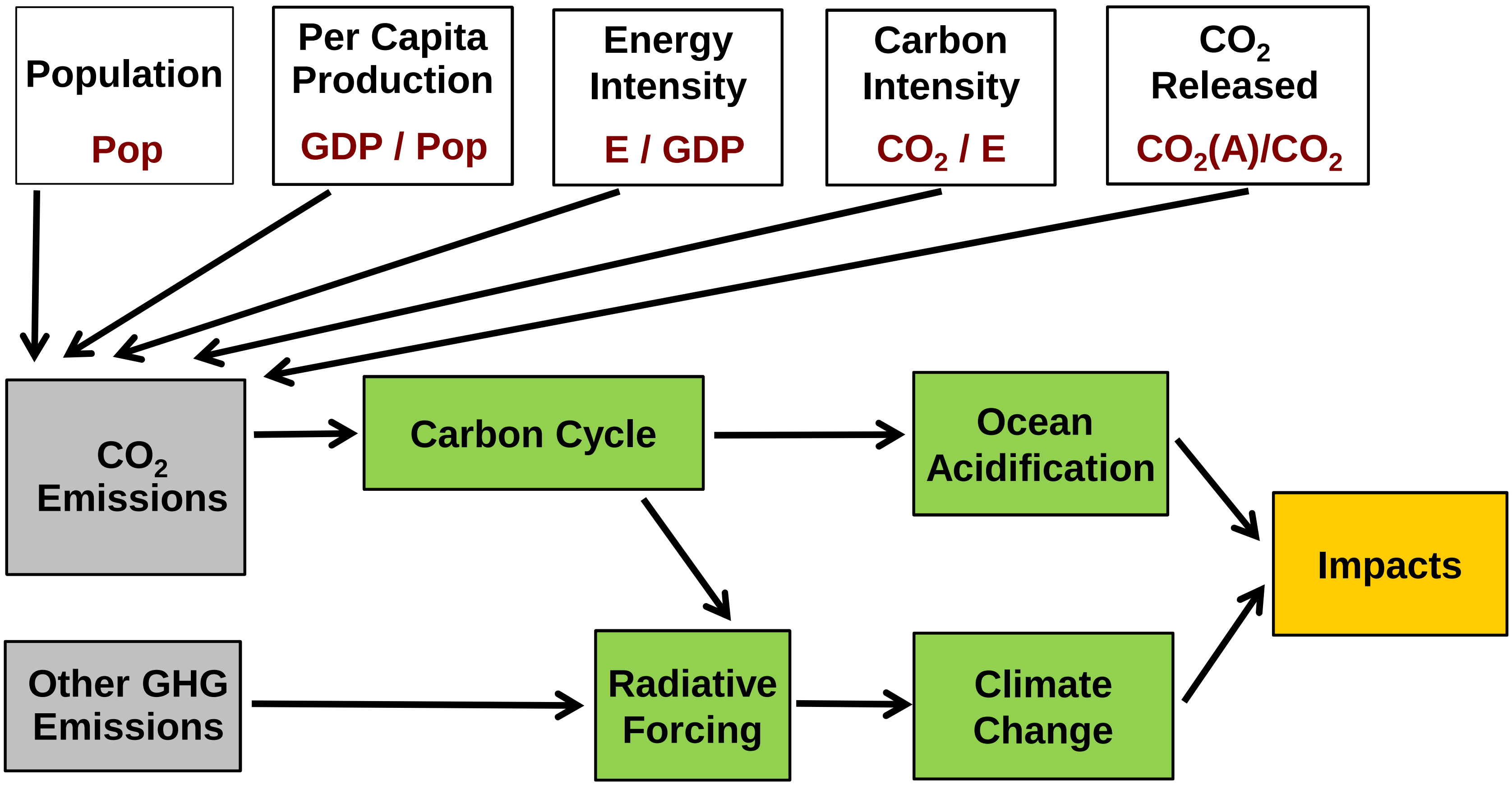
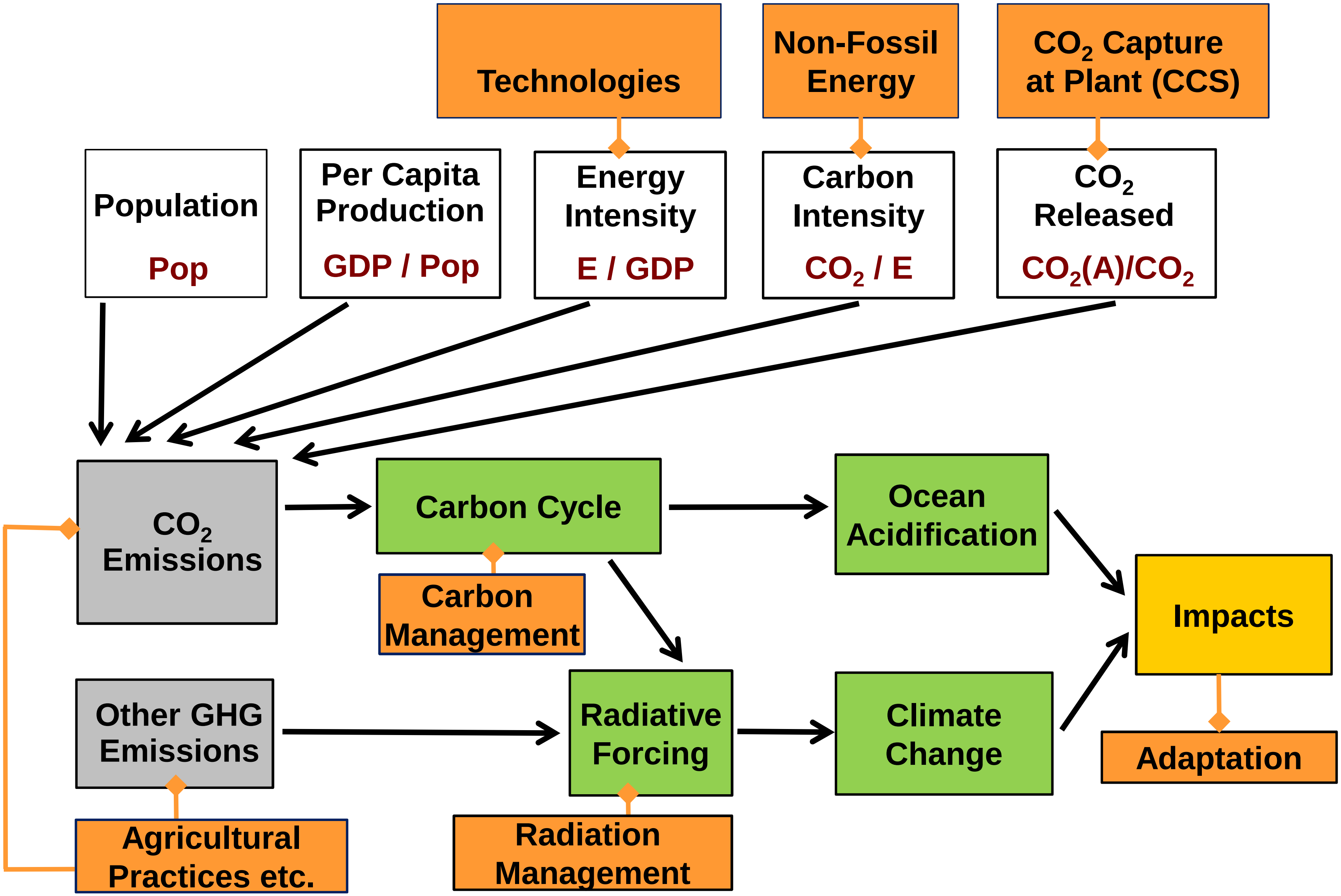
Driving Forces



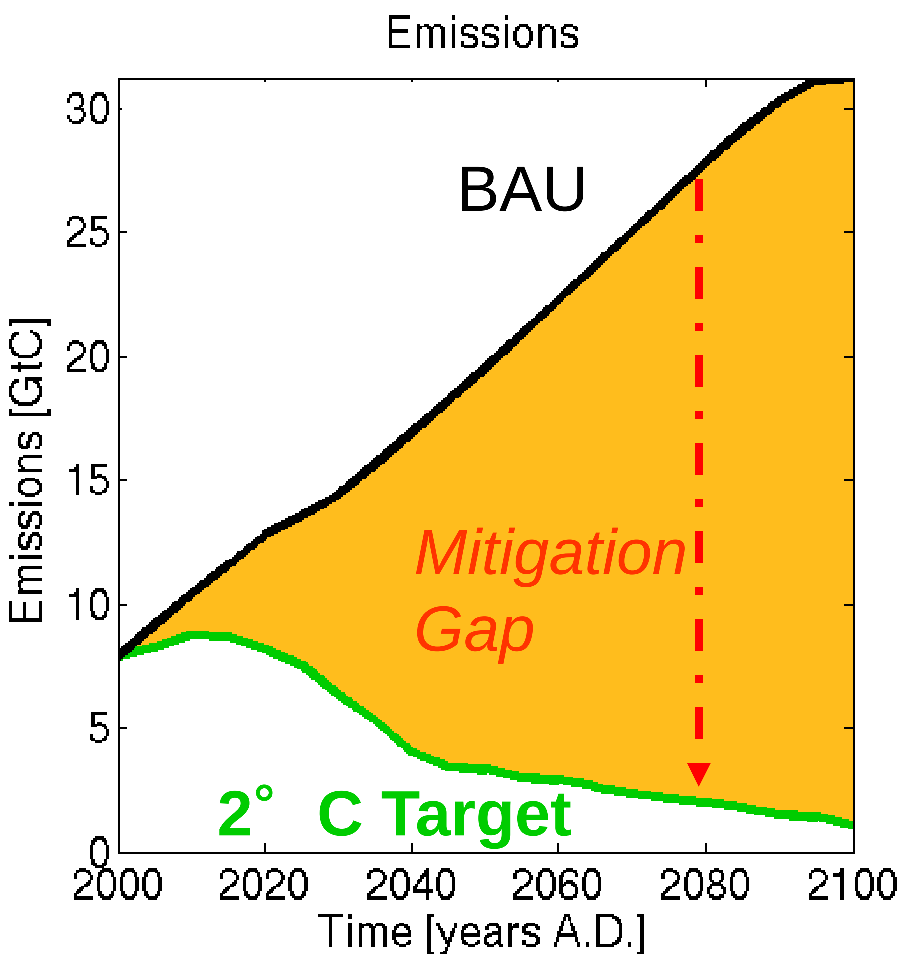
Assessing the Solution Space



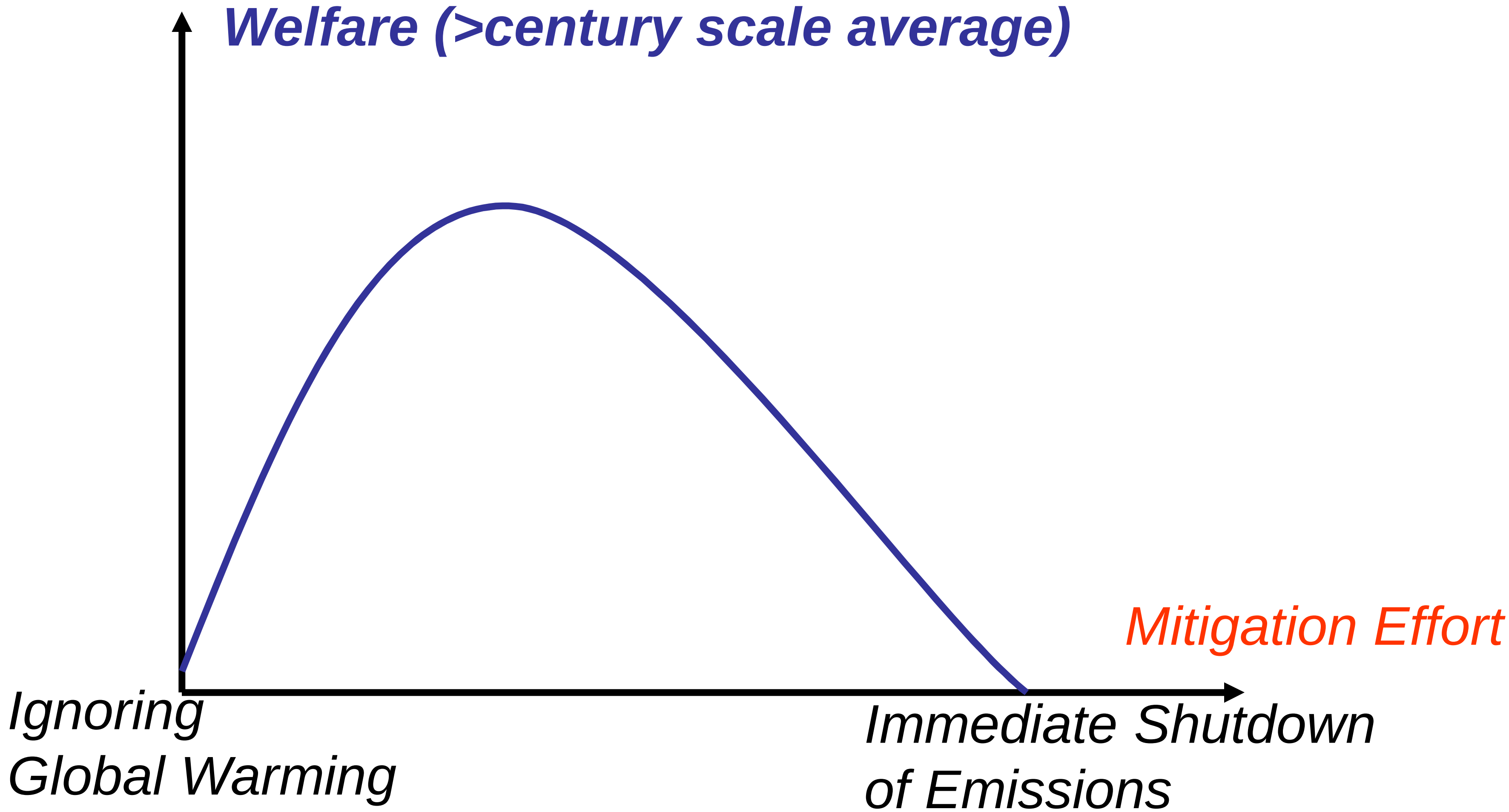
- For simplicity of didactics, we do not consider adaptation in the remainder of today’s lecture…

CO_2-Emissions

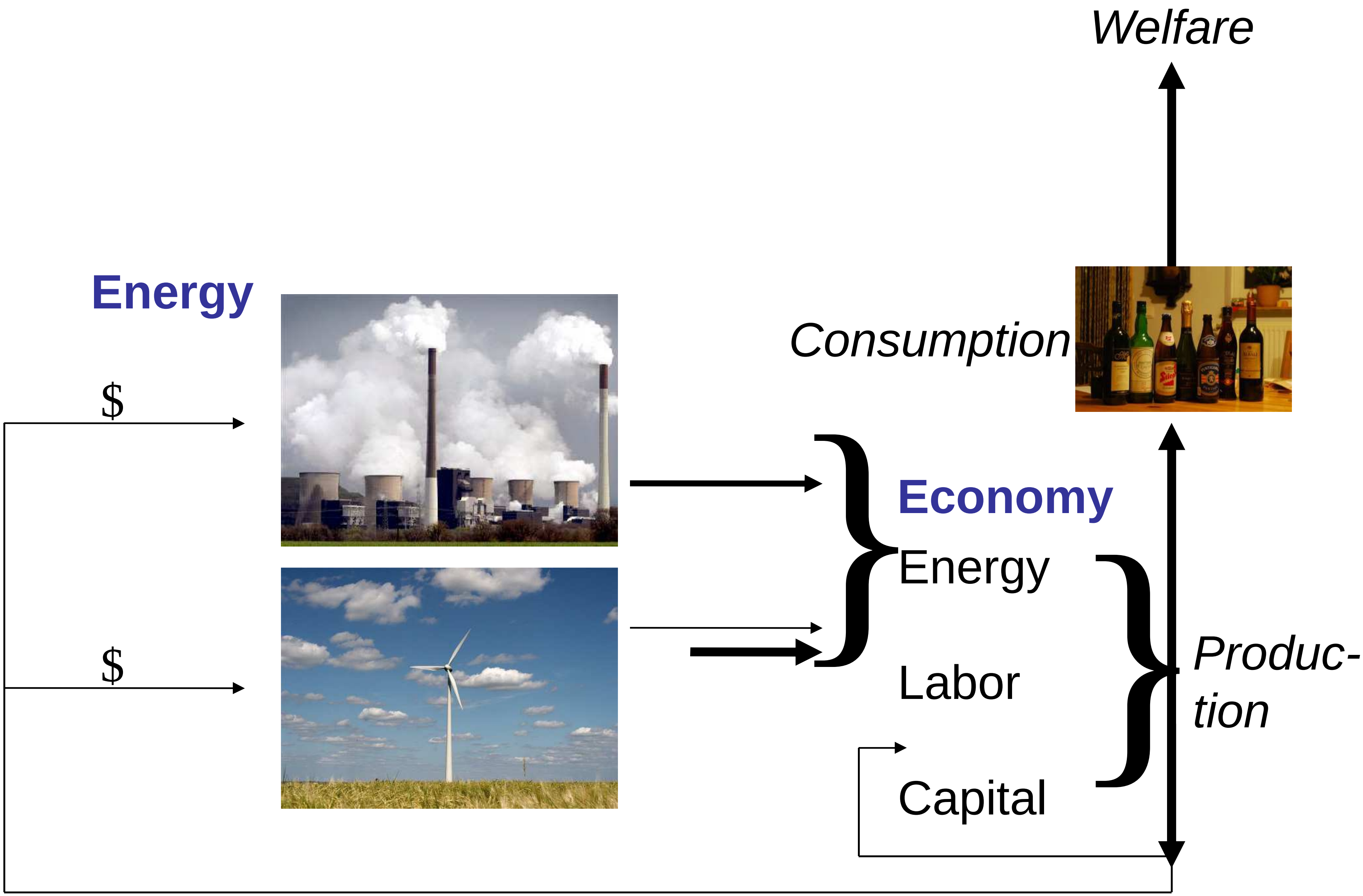
Business as Usual (BAU) vs 2° C-Target



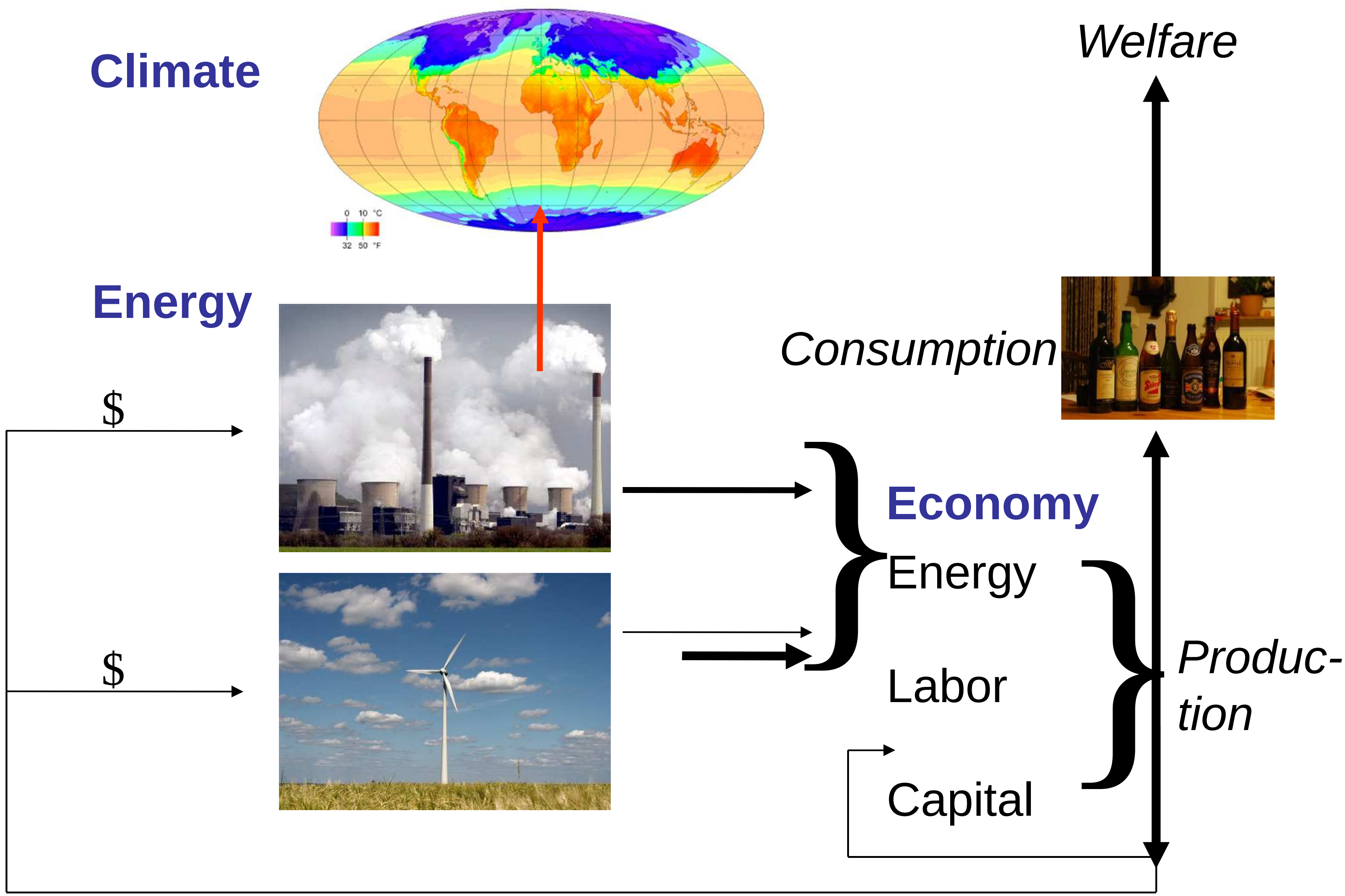
How much Mitigation is ‚Optimal‘?



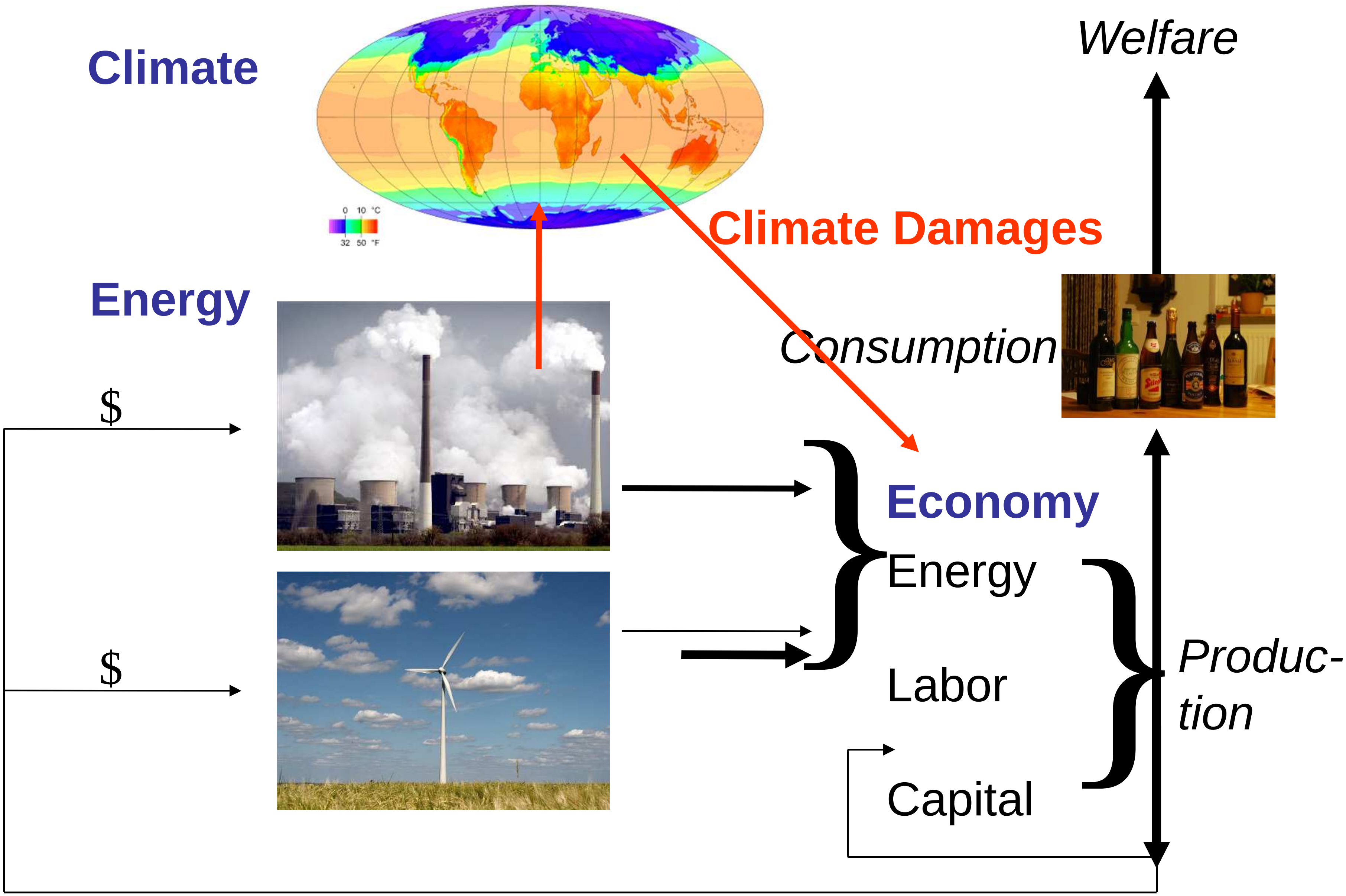
An interdisciplinary Optimisation Problem



An interdisciplinary Optimisation Problem



An interdisciplinary Optimisation Problem



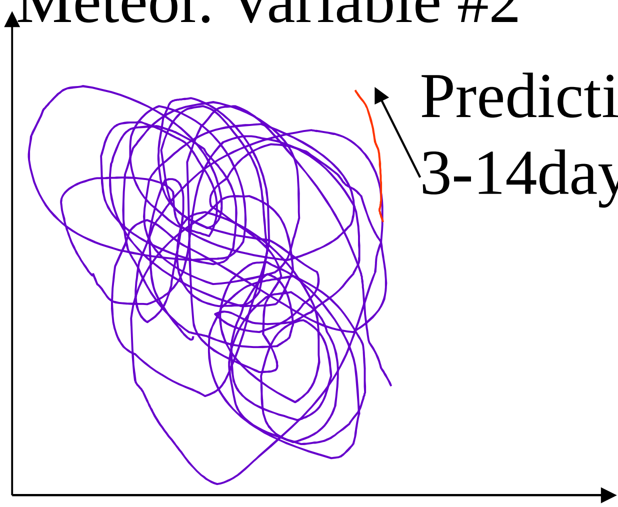
Side-Remark:
What can we predict?

	Atmosphere /Ocean Dynamics	**Biosphere Dynamics**	**Economic Entities**
Short-Term	Weather	Ecosystem behaviour (?)	Prices at Stock market
Long-Term (~100 yrs)	Climate	Carbon Cycle	Patterns & rates of economic growth

Weather Prediction vs Climate Projection

Meteor. Variable #2

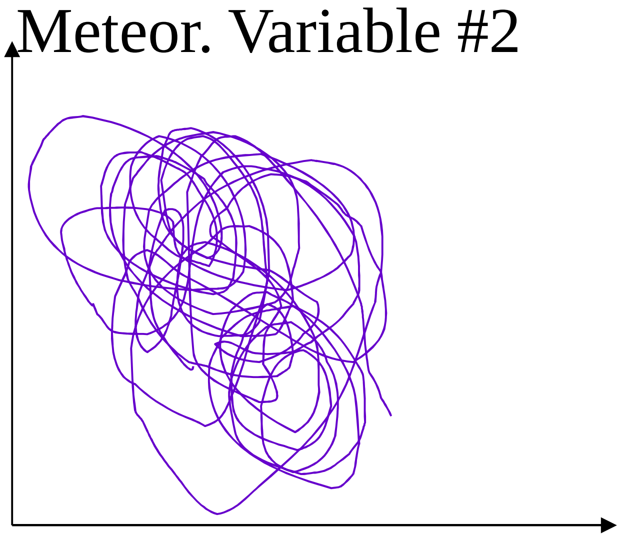
Predictive skill of weather prediction (‘forecast’): 3-14days



Meteor. Variable #1

Prediction of components of the system’s trajectory.

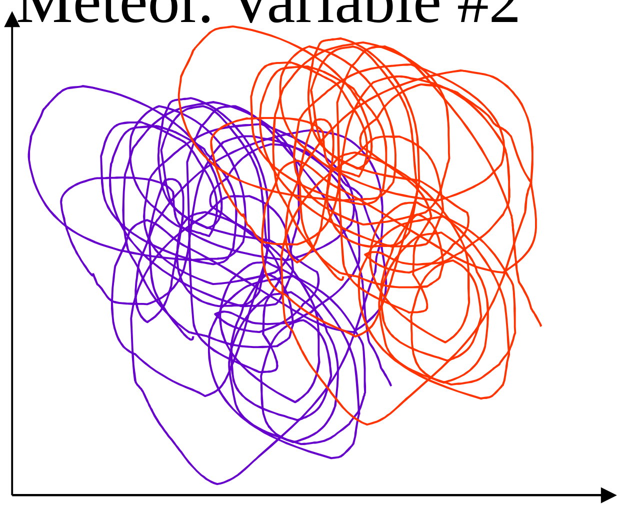
Weather Prediction vs Climate Projection



If this weather attractor is quasi-stationary, a collection of its statistical moments represents the *climate*.

Warning: many def's of climate circulating.

Weather Prediction vs Climate Projection



If we add eg CO_2 to the system and thereby change the boundary conditions, the climate changes.

Climate projection
:= prediction of climate change for a specified (and in most contexts anthropogenically-driven) change in boundary conditions.

The related (conditioned) predictive skill is orders of magnitude larger than the predictive skill of weather forecast.

How much mitigation is desirable?
Cost Benefit Analysis: The standard tool of environmental economics

Present-day mitigation costs

Future avoided damages

When to Invest How Much into which Energy Technology?

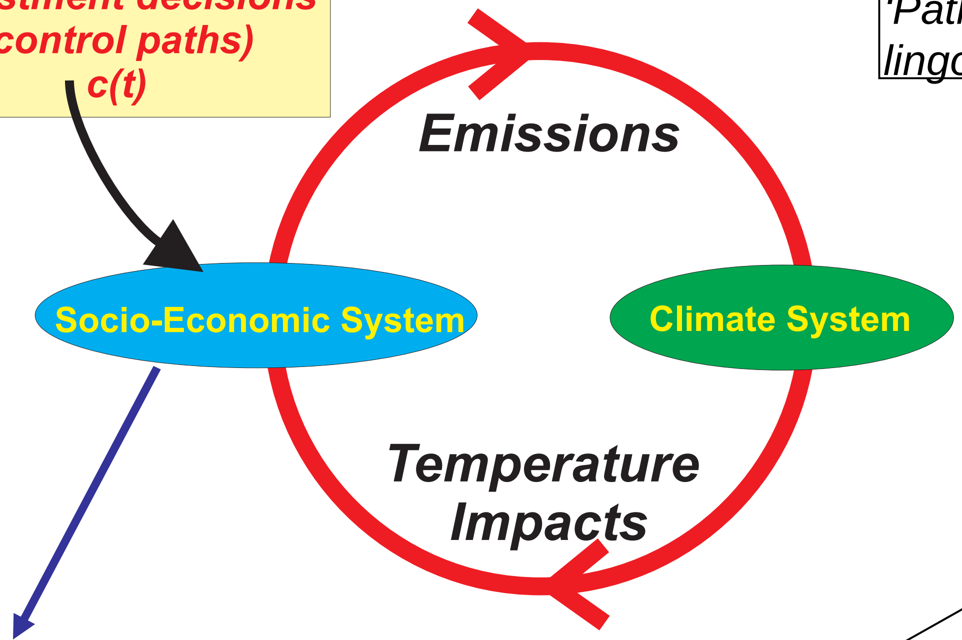
Phrasing as a Control Problem

Investments in

- **_Renewables_**
- **_Efficiency_**
- **_Fossil Fuels_**
- **_CCS_**

Investment decisions (control paths) c(t)

'Path'= Economists' lingo for 'time series'



'control path'

$$\text{Max!}_{(c(t_0),\dots,c(\infty))}\ \text{Welfare} := \int_{t_0}^{\infty} dt\ \boxed{\text{Utility}}(t)[(c(t_0),\dots,c(t))]\ \mathrm{e}^{-\rho t}$$

'Society's Material Basis for Happiness'

'Cost-Benefit-Mode'

Conceptual Difficulties

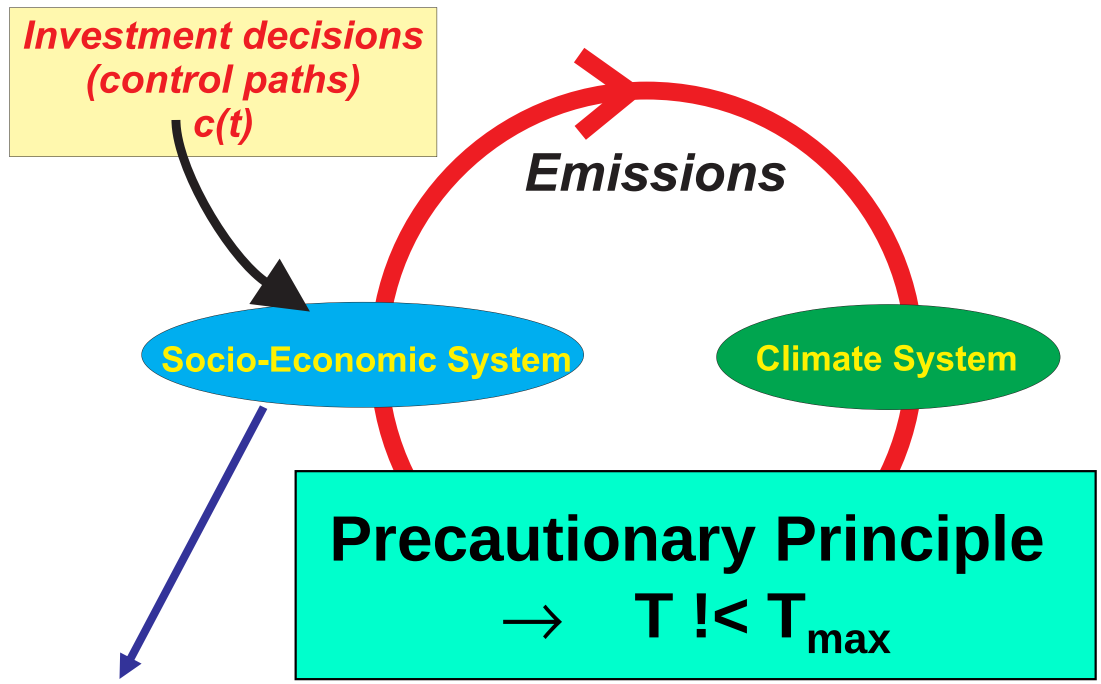
- Impacts poorly known
  - Often poor natural science/engineering knowledge (at least today)
  - Need for valuation of goods
- Need to weigh
  - Present mitigation costs … against …
  - Future avoided damages

- An easier & better-posed alternative? …

When to Invest How Much into which Energy Technology?
Phrasing as a Control Problem

Investments in

- ***Renewables***
- ***Efficiency***
- ***Fossil Fuels***
- ***CCS***



$$\mathrm{Max!}_{(c(t_0),\dots,c(\infty))}\ \mathrm{Welfare} := \int_{t_0}^{\infty} dt\ \boxed{\mathrm{Utility'}}(t)[(c(t_0),\dots,c(t))]\ \mathrm{e}^{-\rho t}$$

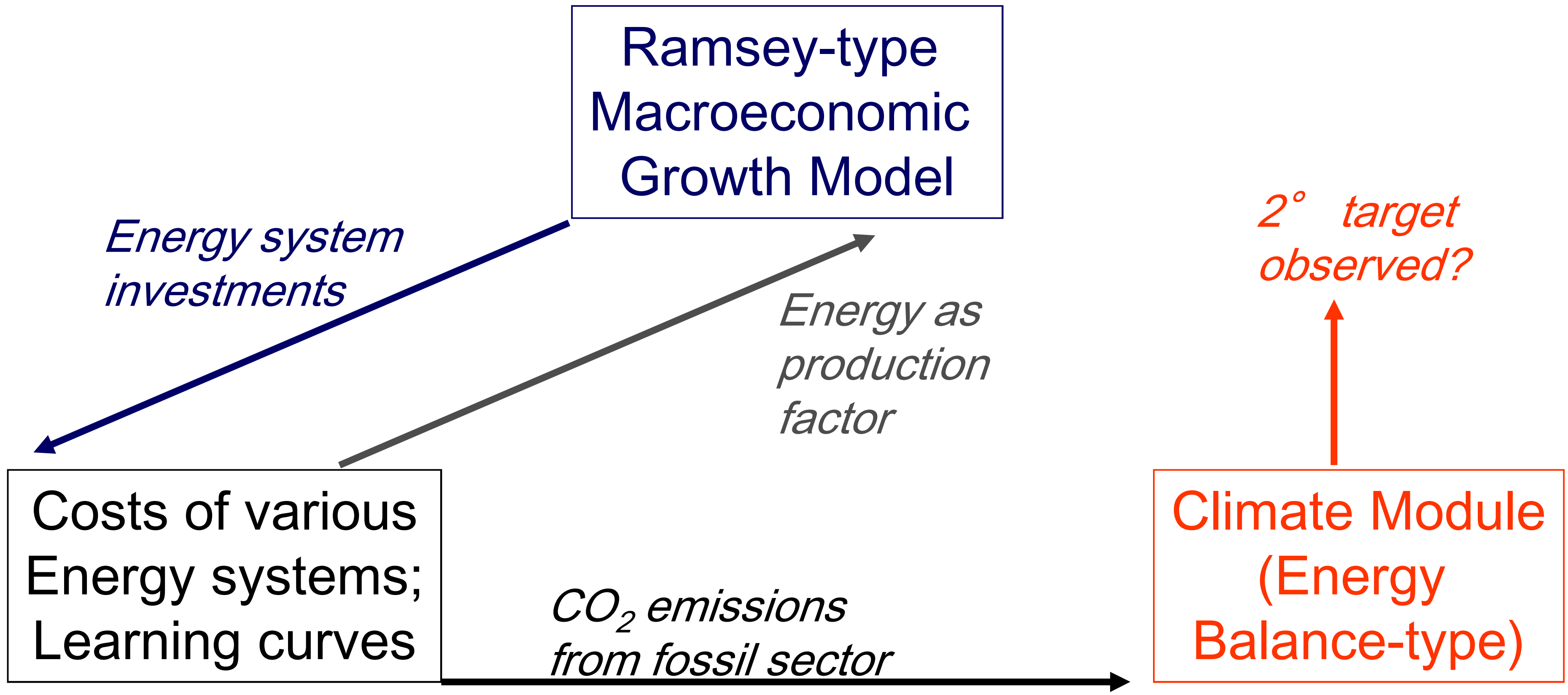
$$\text{subject to} \quad \forall_t\ T(t)[(c(t_0),\dots,c(t))] < T_{\max}$$

‘Cost-Effectiveness-Mode’

Our Research Question

- **When** to invest **how much** into **what energy** technology, given the 2° C (X° -)target?
- Options:
  - Renewable sources
  - Energy efficiency
  - Carbon capture & sequestration (CCS)
  - Nuclear
- ⇒ coupled economy – climate modules.

Costs of Climate Targets?
Our Model Setup



Edenhofer et al. (MIND / ReMIND; 2005-2012)

The simplest Climate Model

Control Variable

$$\dot{F} = E \quad (1)$$

$$\dot{C} = \beta E + \mathrm{B}F - \sigma C \quad (2)$$

$$\dot{T} = \mu \ln(c) - \alpha T \quad \text{with } c = \frac{C + C_{pi}}{C_{pi}} \quad (3)$$

Variable used for guardrail in CostEffectivenessAn.

Variables	
E	Anthropogenic CO_2 emissions [GtC a^{-1}]
F	Cumulative anthrop. CO_2 emissions [GtC]
C	Atmospheric CO_2 anomaly [ppmv]
T	Global mean temperature anomaly [^{o}C]

Initial conditions (year 1995, pi = preindustrial)

The simplest Climate Model

$$\dot{F} = E \quad (1)$$

$$\dot{C} = \beta E + \mathrm{B}F - \sigma C \quad (2)$$

Carbon Cycle

$$\boxed{\dot{T} = \mu \ln(c) - \alpha T \quad \text{with } c = \frac{C + C_{pi}}{C_{pi}} \quad (3)}$$

Temperature Equation

Variables

E	Anthropogenic CO_2 emissions [GtC a^{-1}]
F	Cumulative anthrop. CO_2 emissions [GtC]
C	Atmospheric CO_2 anomaly [ppmv]
T	Global mean temperature anomaly [^oC]

'anomaly' w.r.t. pi = preindustrial

Intertemporal Optimization as a key application of Utilitarism

- One application of 'Static Welfare:= average of individuals' utilities'

$$\text{Max! Welfare} := \int_{t_0}^{\infty} dt\ U(t)\ \mathrm{e}^{-\rho(t-t_0)}$$

'now'

- ρ := 'pure rate of time preference'
- If ρ=3% / year, you care about your children,
- If ρ=1% / year, you also care about your grand-children.

- Battle among economists: is ρ a normative or a positive (i.e. descriptive) parameter?
- When trying to interpret ρ as a descriptive parameter, in my view, this implies that the whole functional given above is also descriptive (at least with respect to the traditionally experienced incentive system).

Odysseus & the Sirens

http://vampirella91.de.tl/Drachen-und-Sirenen.htm

A highly desirable Property of this Welfare Functional

$$\text{Max! Welfare} := \int_{t_0}^{\infty} dt\; U(t)\; \mathrm{e}^{-\rho(t-t_0)}$$

'now'

This prescription is 'time-consistent':

Let {c*(t)} a control path that optimizes above welfare W ($[t_0,\infty[$).

Let $t_0<t_1$.

Then {c*} also optimizes W($[t_1,\infty[$).

Anticipated time-inconsistency: Odysseus & the Sirens

http://vampirella91.de.tl/Drachen-und-Sirenen.htm

This means:

- If boundary conditions stay the same, the decision-maker does not need to change her or his plans over time.

- A normatively very satisfying property of this decision rule.

- T C Koopmans showed necessary conditions for time-consitency.

Proof that Exponential Discounting implies Time-Consistency

$$
\begin{aligned}
\text{Max! Welfare}(t_0) \quad &:= \quad \int_{t_0}^{\infty} dt\, U(C(t))\, \mathrm{e}^{-\rho(t-t_0)} \\
&= \quad \int_{t_0}^{t_1} dt\, U(C(t))\, \mathrm{e}^{-\rho(t-t_0)} + \int_{t_1}^{\infty} dt\, U(C(t))\, \mathrm{e}^{-\rho(t-t_0)}
\end{aligned}
$$

Suppose the control path $\{c^*(t)\}_{t_0}^{\infty}$ steers the above functional into its optimum and it comes with a capital stock $K^*(t_1)$ that sets all the boundary conditions between the two integral periods. Then c^* also optimizes $\int_{t_1}^{\infty}$ (if it did not, another c would do a better job on $\int_{t_1}^{\infty}$, hence also on $\int_{t_0}^{\infty}$, and c^* could not be the optimum for $\int_{t_0}^{\infty}$). Then

$$
\begin{aligned}
\{c^*(t)\}_{t_1}^{\infty} &= \operatorname{argmax}_{\{c(t)\}} \int_{t_1}^{\infty} dt\, U(C(t))\, \mathrm{e}^{-\rho(t-t_0)} \\
&= \operatorname{argmax}_{\{c(t)\}} \mathrm{e}^{\rho(t_0-t_1)} \int_{t_1}^{\infty} dt\, U(C(t))\, \mathrm{e}^{-\rho(t-t_1)} \\
&= \operatorname{argmax}_{\{c(t)\}} \int_{t_1}^{\infty} dt\, U(C(t))\, \mathrm{e}^{-\rho(t-t_1)}
\end{aligned}
$$

But the latter integral is nothing else than that of a social planner who starts at t_1 with the capital stock $K^*(t_1)$ (the latter, because we assume, that in the first period the social planner had fulfilled her or his plan).

So a social planner who starts at t_1 would do exactly the same as one who started at t_0!

2 Interpretations of Technological Progress Leading to Cost Reduction

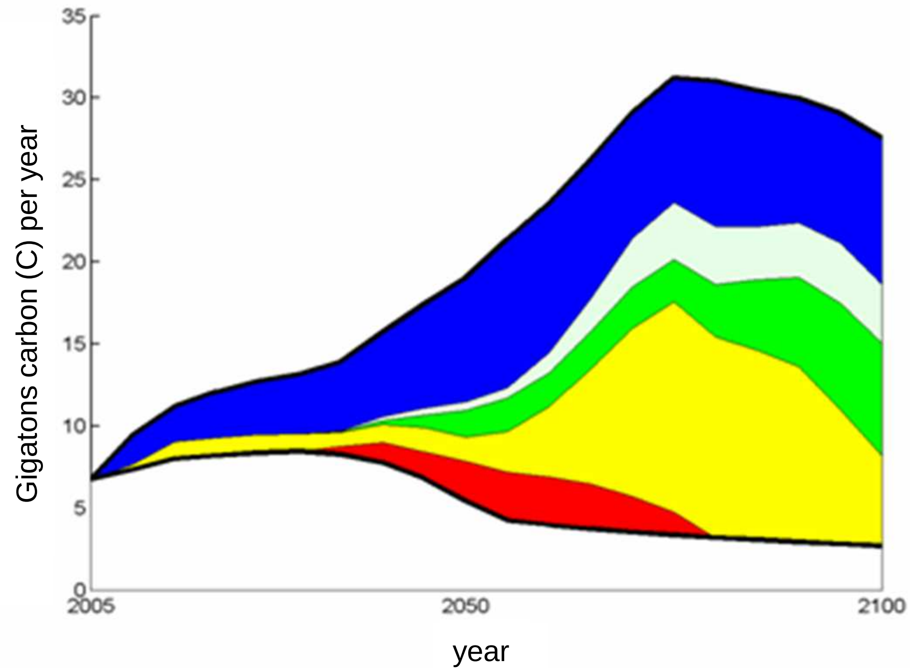
	Endogenous Technological Change	**Exogenous Technological Change**
Definition	Cost reduction primarily a function of **total installed capacity**	Cost reduction primarily a function of **time** (spill-over effects from overall technol. development)
Consequence for climate policy	Investment into new technologies can accelerate their cost reduction → early deployment?	Investment into new technologies does *not* accelerate their cost reduction → later deployment?

2 Interpretations of Technological Progress Leading to Cost Reduction

The following studies: ↓

	Endogenous Technological Change	**Exogenous Technological Change**
Definition	Cost reduction primarily a function of **total installed capacity**	Cost reduction primarily a function of **time** (spill-over effects from overall technol. development)
Consequence for climate policy	Investment into new technologies can accelerate their cost reduction → early deployment?	Investment into new technologies does *not* accelerate their cost reduction → later deployment?

Bridging the Mitigation Gap



Energy-induced emissions

- **nuclear**
- renewables
- biomass + CCS
- fossil + CCS
- efficiency

Coal/Oil/Nat.Gas cheap, pure time preference rate 1%

From REMIND-G (0D-Model)

Bruckner, Edenhofer, Held et al., 2009

Preliminary Summary

- It is extremely likely that anthropogenically caused global warming is unfolding.
- Unmitigated future warming might lead to temperature changes unprecedented for the past 50 million years.
- Coupled energy-climate economy models are used to project the costs of climate targets.
- Generically, the economic optimizer would choose an energy mix from renewables, energy efficiency increase, fossil fuels, mainly in combination with carbon capture & storage, nuclear.
- Tomorrow:
  - Costs of climate targets
  - Extra costs for eliminating energy options from the portfolio
  - Decision under uncertainty: Fundamental issues ..
  - Climate policy, IPCC, and its academia-policy interaction model

Literature on Lecture I

Introductions for 'interested non-experts':

- H. Held, Dealing with Uncertainty – From Climate Research to Integrated Assessment of Policy Options, in: Climate Change and Policy in: The Calculability of Climate Change and the Challenge of Uncertainty, Gramelsberger, Gabriele; Feichter, Johann (Eds.), ISBN 978-3-642-17699-9, 113-126, (2011).

- H. Held, Enabling systemic climate innovation, Public Service Review: European Science & Technology; **11**, 254-255 (2011).

- T. Bruckner, O. Edenhofer, H. Held, M. Haller, M. Lüken, N. Bauer, Robust Options to Combat Climate Change, in Global Sustainability – A Nobel Cause, Schellnhuber, H. J., M. Molina, N. Stern, V. Huber and S. Kadner (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, USA, ISBN-13:9780521769341, 189-204 (2010).

- H. Held, O. Edenhofer, Re-structuring the problem of Global Warming Mitigation: "Climate Protection" vs. "Economic Growth" as a false Trade-off. In: G. Hirsch Hadorn, H. Hoffmann-Riem, S. Biber-Klemm, W. Grossenbacher-Mansuy, D. Joye, C. Pohl, U. Wiesmann, E. Zemp (eds.), Handbook of Transdisciplinary Research. Heidelberg: Springer, 191-204, ISBN: 978-1-4020-6698-6 (2008).

Peer-reviewed model descriptions:

- O. Edenhofer, N. Bauer, E. Kriegler, The Impact of Technological Change on Climate Protection and Welfare: Insights from the Model MIND, Ecological Economics, 54 (2–3):277–292 (2005).

- G. Petschel-Held, Schellnhuber, T. Bruckner, F. L. Tóth, K. Hasselmann, The tolerable windows approach: theoretical and methodological foundations. Climatic Change 41, 303–331 (1999).

Literature on Lecture II

Peer-reviewed model intercomparison (state-of-the-art coupled energy-economy-carbon cycle models):

- G. Luderer, V. Bosetti, M. Jakob, M. Leimbach, J. C. Steckel, H. Waisman, O. Edenhofer, The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison, Climatic Change, DOI 10.1007/s10584-011-0105-x .

Peer-reviewed literature on Decision under Uncertainty in the climate context

- M. G. W. Schmidt, H. Held, E. Kriegler, A. Lorenz, Stabilization Targets under Uncertain and Heterogeneous Climate Damages, Environmental & Resource Economics, in press.

- A. Lorenz, E. Kriegler, H. Held, M. G. W. Schmidt, How to measure the importance of climate risk for determining optimal global abatement policies? Climate Change Economics, in press.

- A. Lorenz, M. G. W. Schmidt, E. Kriegler, H. Held, Anticipating Climate Threshold Damages, Environmental Modeling and Assessment, 17 (1), 163-175, DOI: 10.1007/ s10666-011-9282-2, in Special Issue on Modeling Uncertainty in Energy Policy and the Economics of Climate Change (2012).

- M. G. W. Schmidt, A. Lorenz, H. Held, E. Kriegler, Climate Targets under Uncertainty: Challenges and Remedies, Climatic Change Letters, 104 (3-4), 783-791, DOI 10.1007/s10584-010-9985-4 (2011).

- H. Held, E. Kriegler, K. Lessmann, O. Edenhofer, Efficient Climate Policies under Technology and Climate Uncertainty, Energy Economics 31, S50–S61 (contribution in C. Böhringer, T. P. Mennel, T. F. Rutherford (Guest Eds.): Technological Change and Uncertainty in Environmental Economics), doi:10.1016/j.eneco.2008.12.012 (2009).

- A. Lange, N. Treich, Uncertainty, learning and ambiguity in economic models on climate policy: some classical results and new directions. Climatic Change 89 (1): 7–21 (2008).

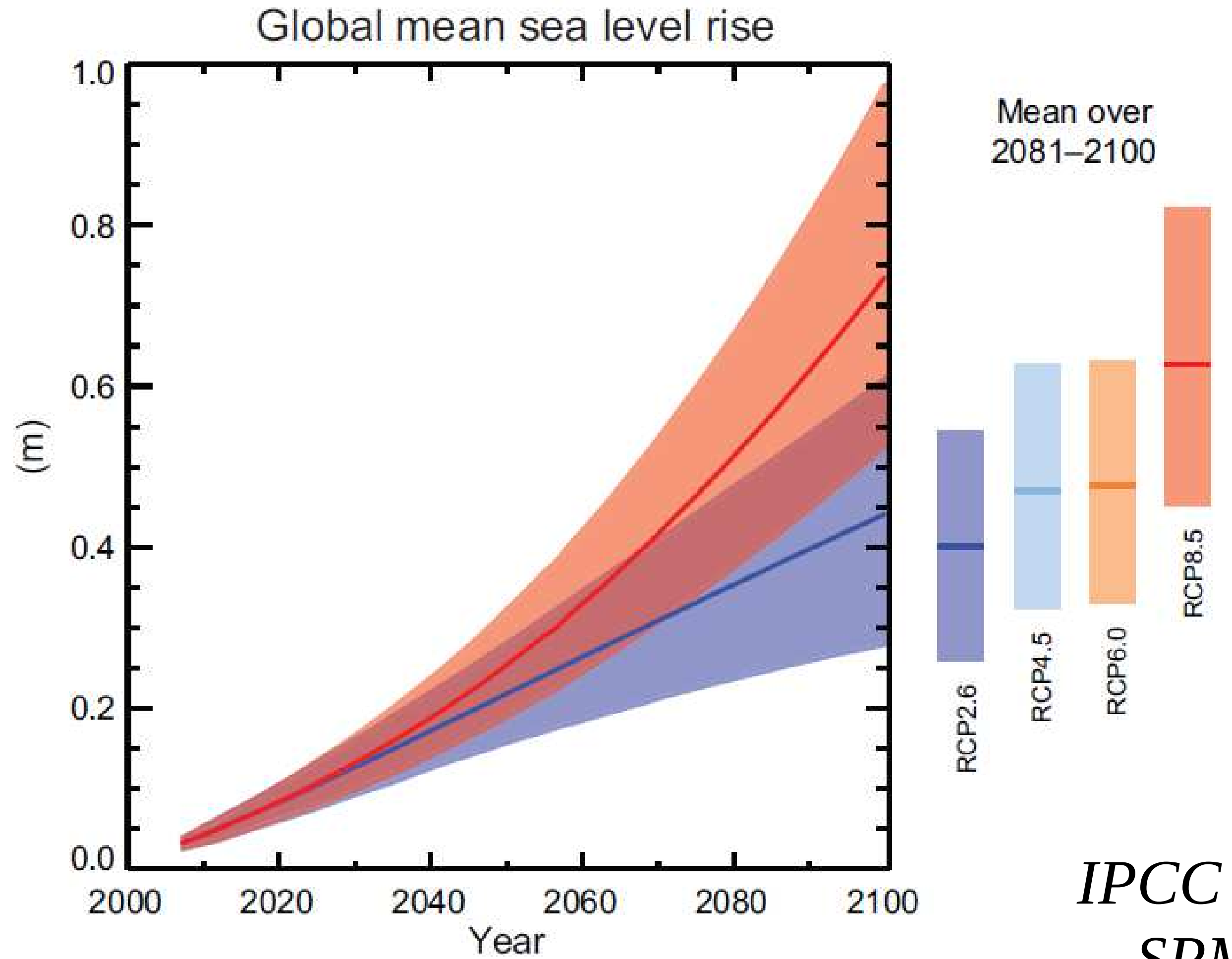
Literature on Lecture II (continued)

Peer-reviewed literature on CCS:

- Overview at: IPCC Special Report of CCS (2005).
- O. Edenhofer, H. Held, N. Bauer, A regulatory framework for carbon capturing and sequestration within the post-Kyoto process. In the peer-reviewed volume (**I**) by E. S. Rubin, D. W. Keith, C. F. Gilboy (eds.), Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (Vancouver, Canada, 5-9 September 2004). Amsterdam: Elsevier, 989-997 (2005).
- N. Bauer, O. Edenhofer, H. Held, E. Kriegler, Uncertainty of the role of carbon capture and sequestration within climate change mitigation strategies. In the peer-reviewed volume (**I**) by E. S. Rubin, D. W. Keith, C. F. Gilboy (eds.), Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (Vancouver, Canada, 5-9 September 2004). Amsterdam: Elsevier, 931-939 (2005).

Further literature on CCS & Climate Policy:

- K. Neuhoff, S. Dröge, O. Edenhofer, C. Flachsland, H. Held, M. Ragwitz, J. Strohschein, A. Türk and A. Michaelowa: Translating model results into economic policies RECIPE Working paper, available online at www.pik-potsdam.de/recipe (2009).
- H. Held, O. Edenhofer, CCS-Bonds as a superior instrument to incentivize secure carbon sequestration. Energy Procedia, 4559-4566, 1 (1) (2009).



IPCC AR5 WG-I SPM (2013)

Figure SPM.9 | Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed *likely* range is shown as a shaded band. The assessed *likely* ranges for the mean over the period 2081–2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line. For further technical details see the Technical Summary Supplementary Material {Table 13.5, Figures 13.10 and 13.11; Figures TS.21 and TS.22}