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CLIMATE, CLIMATIC CHANGE,
AND SOCIETY (CLICCS)

Climate Targets: Are They Feasible and Is a Dynamically Consistent Interpretation Possible?

Quantum Universe VIDEO Colloquium
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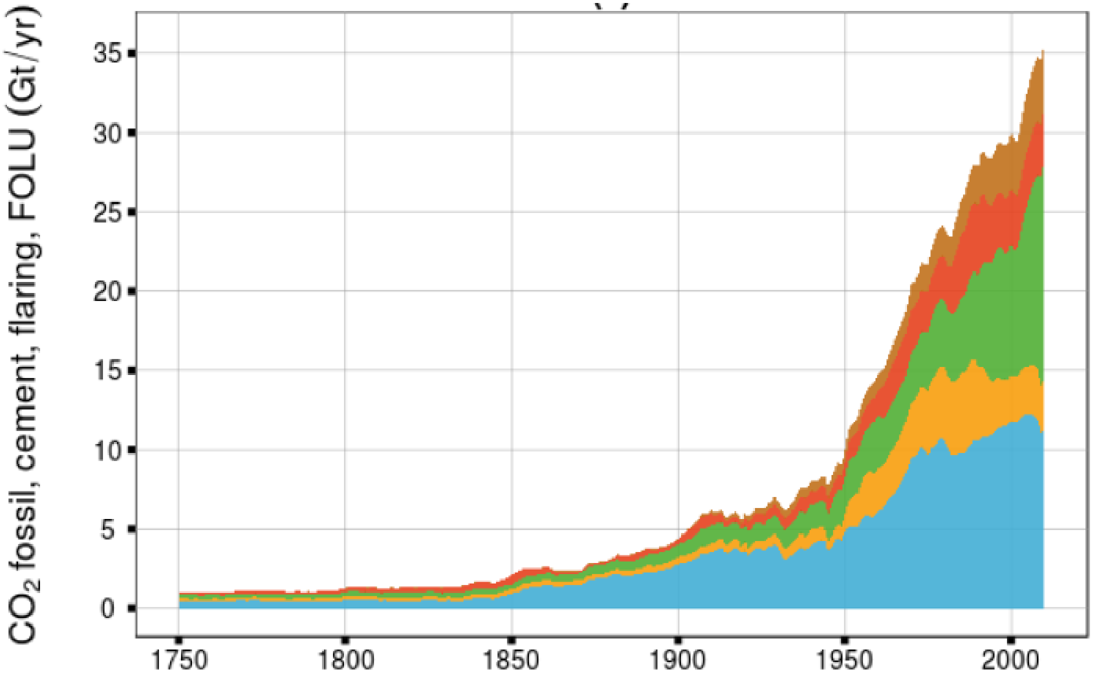
- Two major approaches in climate economics:
  'facts-based' vs. precaution-oriented decision-making
- Cost risk analysis: The best from both decision-analytic schools?
- The persistent gap between climate targets and action

Globale Greenhouse Gas Emissions on the Rise

Dis-entangling w.r.t. country groups



Asian Contribution

OECD-Contribution

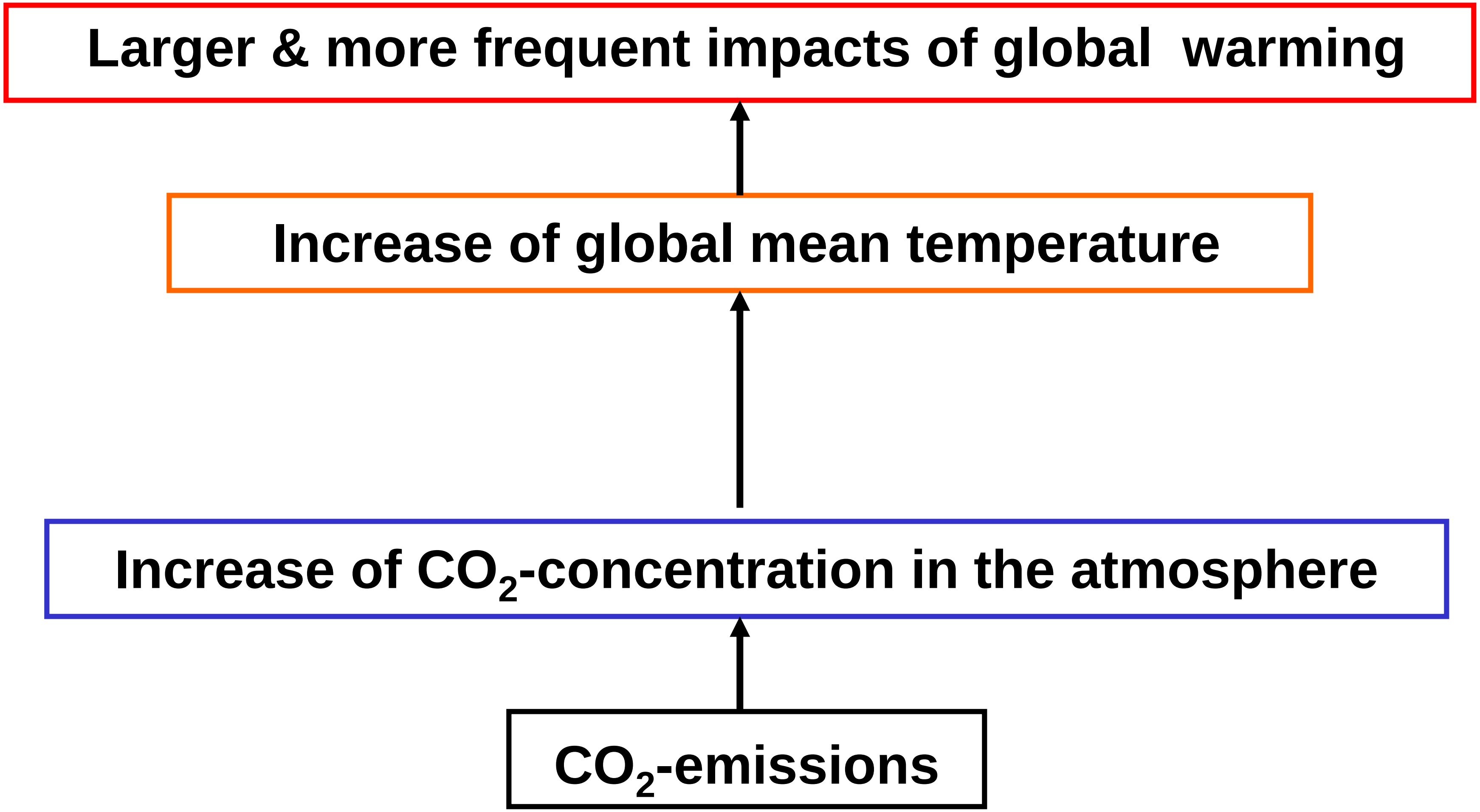
IPCC AR5 WGIII, Fig. TS.2a (2014)

- Currently driven by growth in Asia,

- formerly by OECD

Carbon Dioxide Impact Cascade

(a First Order Approximation)



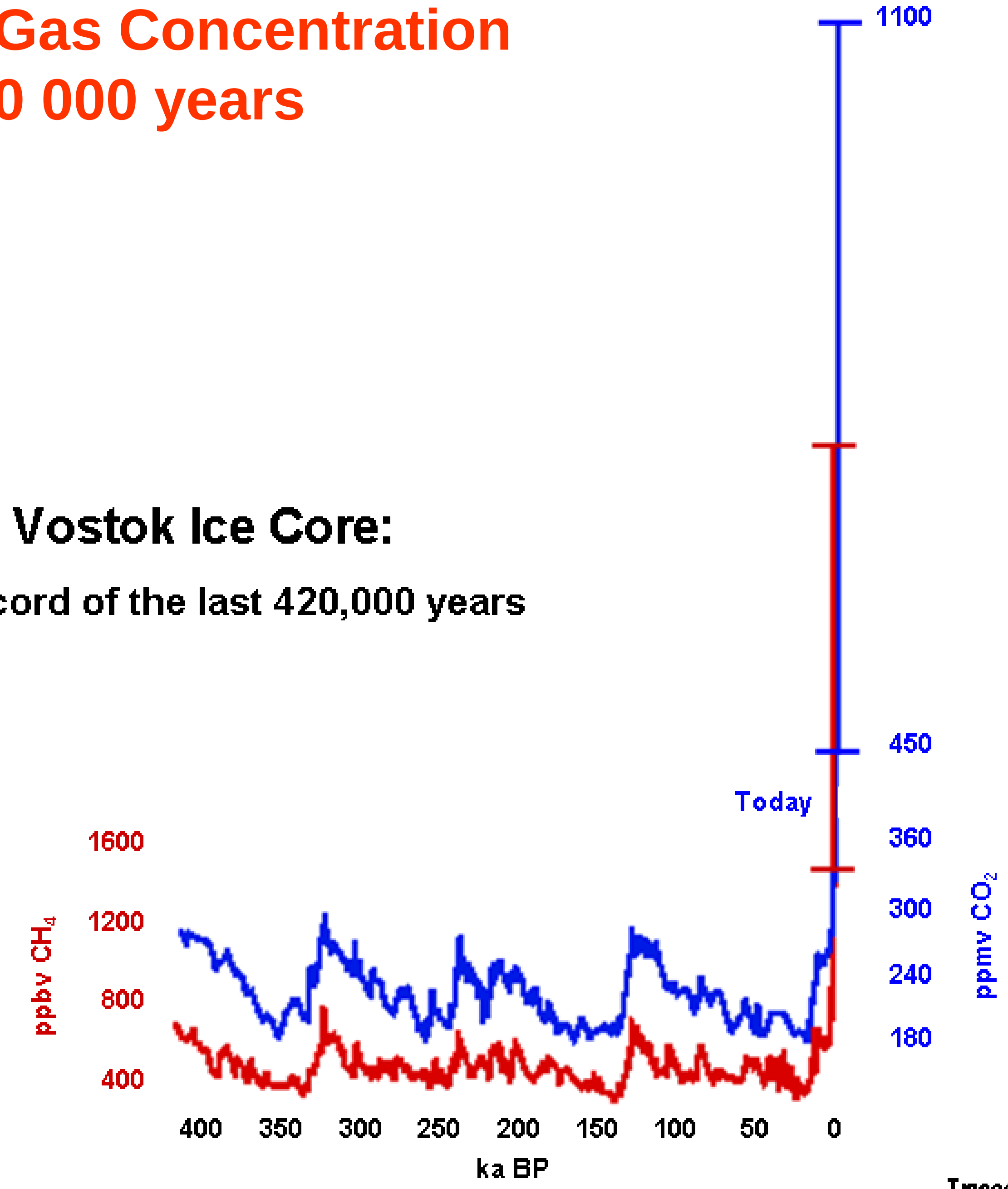
Larger & more frequent impacts of global warming

Increase of global mean temperature

Increase of CO_2-concentration in the atmosphere

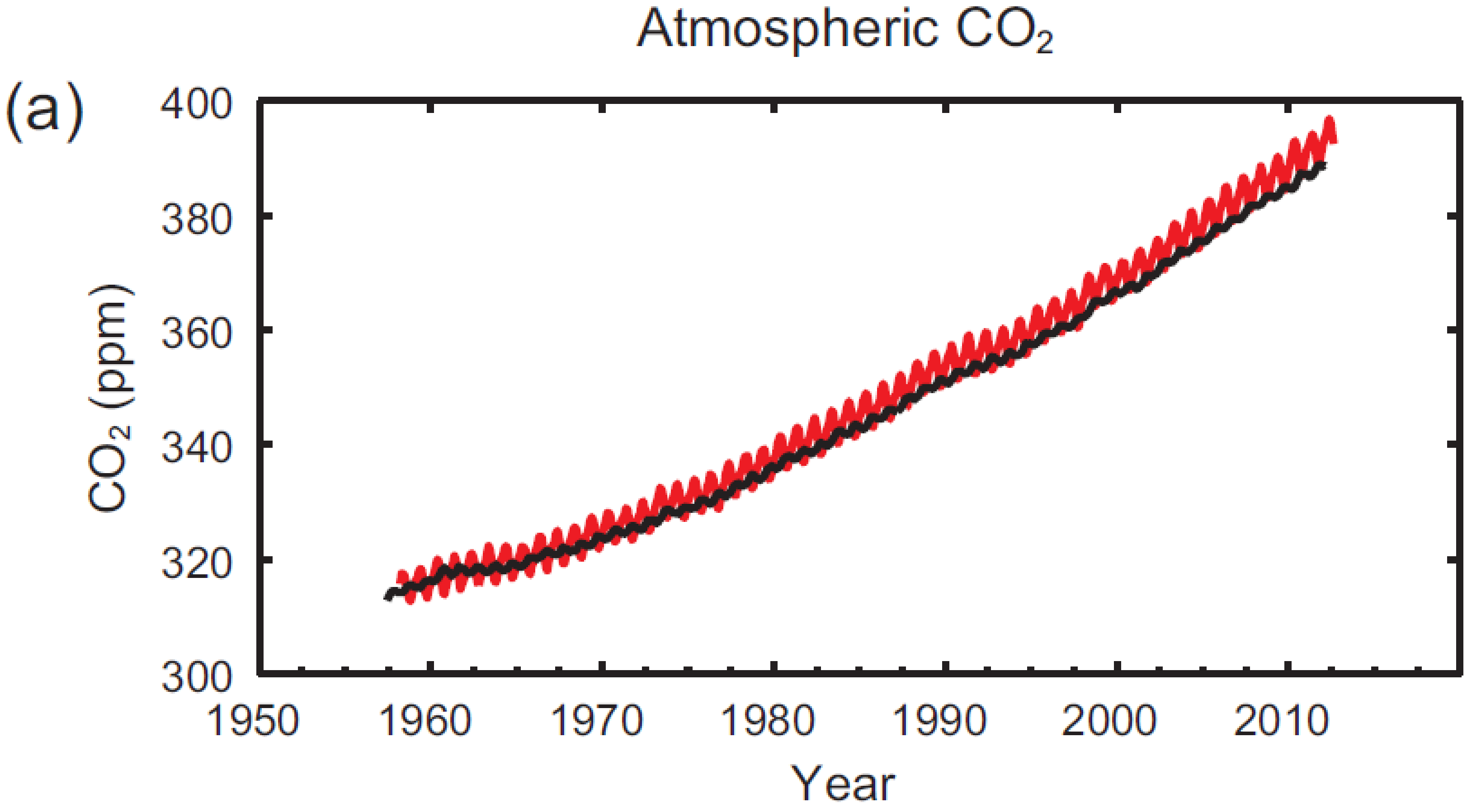
CO_2-emissions

Greenhouse Gas Concentration of the last 400 000 years



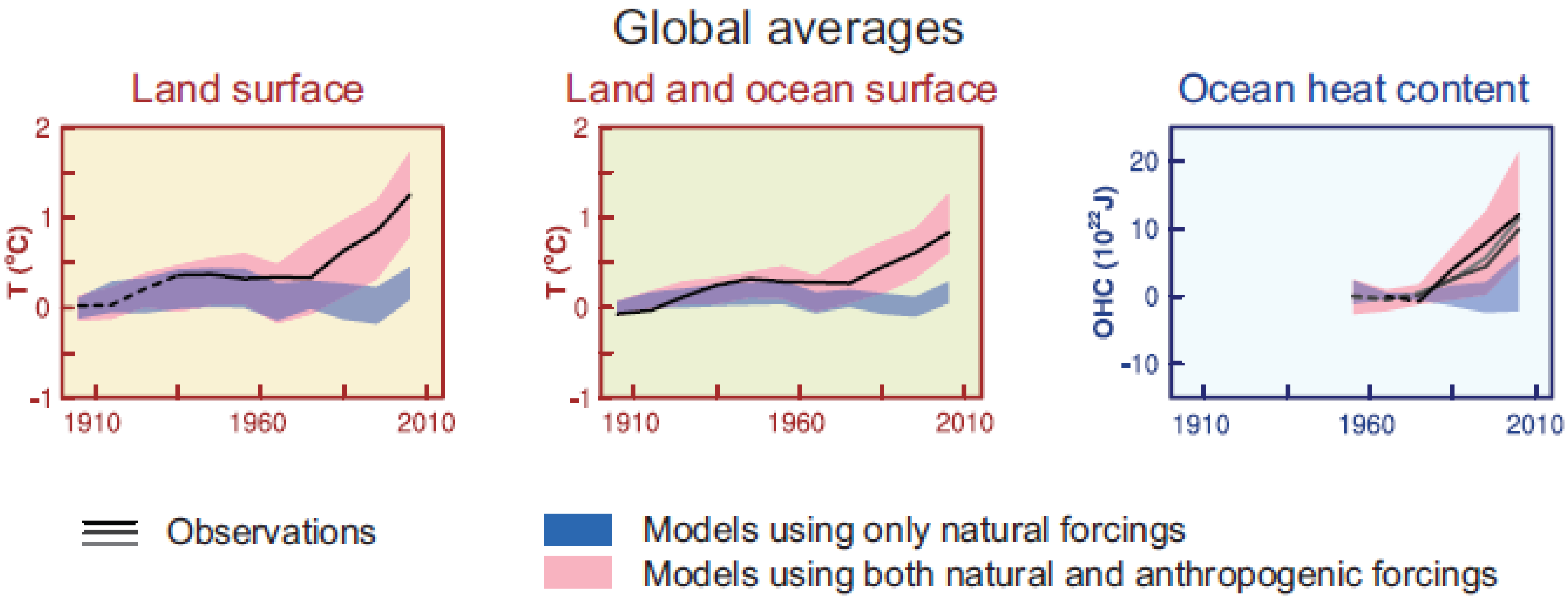
Images from WDCP/IPCC

Time Evolution of Atmospheric CO_2 Concentration

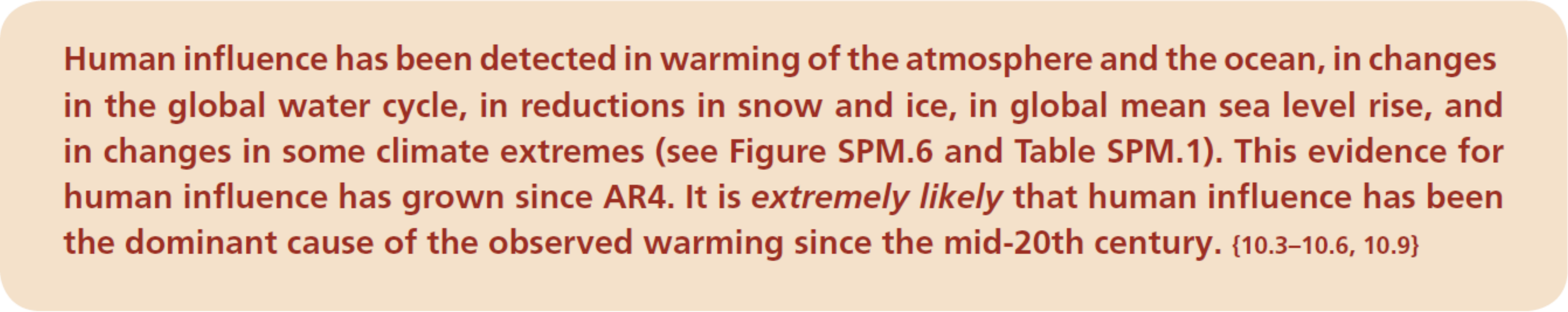


IPCC AR5 WG-I
SPM (2013)

We cannot explain temperature rise without anthropogenic forcings.



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}

‘extremely likely’ := significance level $\geq$ 95%

IPCC AR5 WG-I SPM (2013)
IPCC Uncertainty guidance notes (2010)

Interpretation

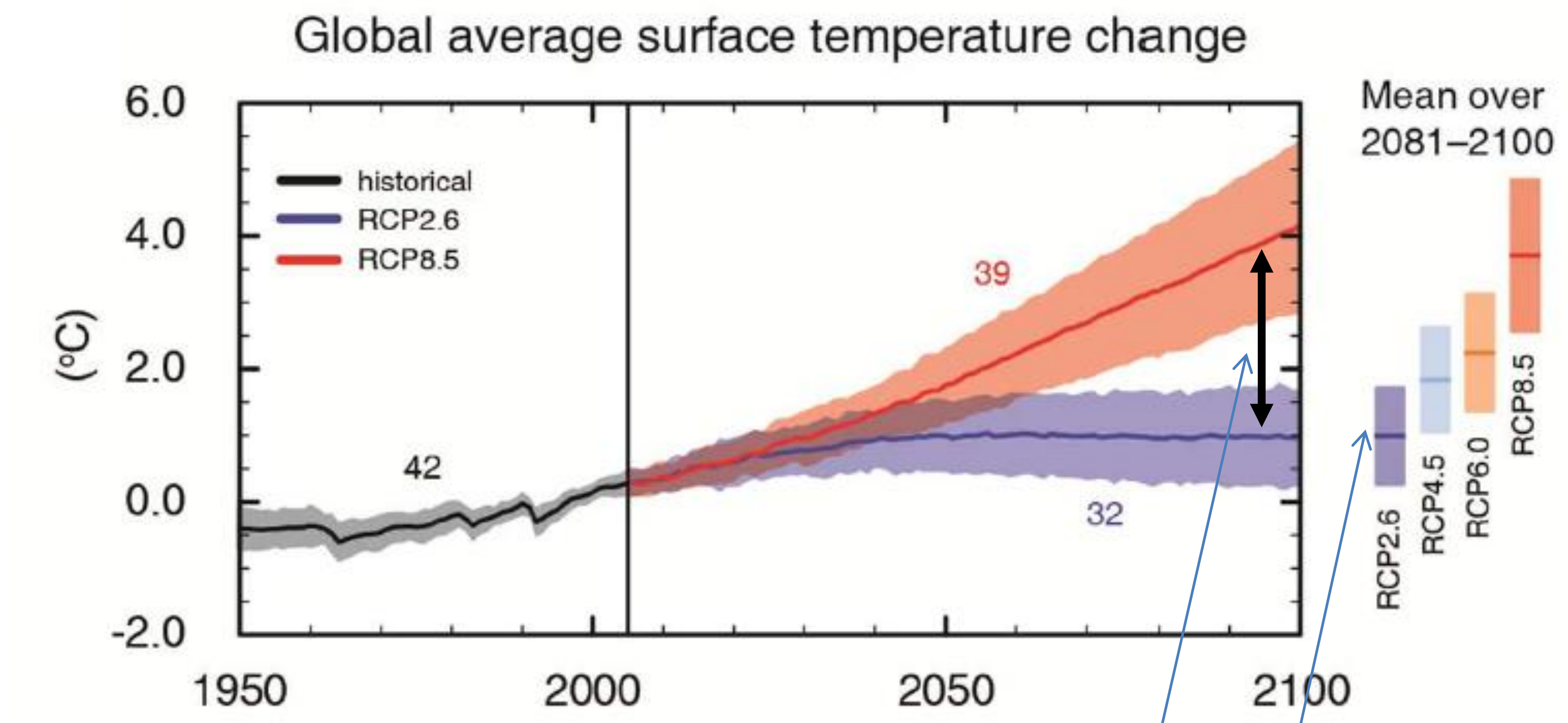
- Spatio-temporal response patterns, induced by competing drivers
  - CO_2 and other greenhouse gases (anthrop.)
  - SO_2 (anthrop.)
  - Ozone (anthrop.)
  - Natural sources

  are determined.
- Climate's covariance properties are determined.
- The observed warming signal is linearly regressed to those patterns.
- Confidence ellipsoids in pattern scaling coefficient space are derived from an F - statistic.
- 95% refer to the significance with which the null hypothesis, global warming is a natural phenomenon, is rejected.

A Remark on Climate Models

- Based on hydrodynamics
- Require additional assumptions in order to parameterize unresolved sub-scale processes.
- State-of-the-art coupled atmosphere-ocean general circulation models: 10^8 … 10^9 ordinary differential equations

Future Temperature Rise: Maneuvering Space and Uncertainty



- What policy could influence
- Climate science residuary uncertainty

IPCC AR5 WG-I SPM

Why Might Society Care About Global Warming?

Some of the Projected Consequences

Two Lines of Argument Behind Global Warming Mitigation Policies

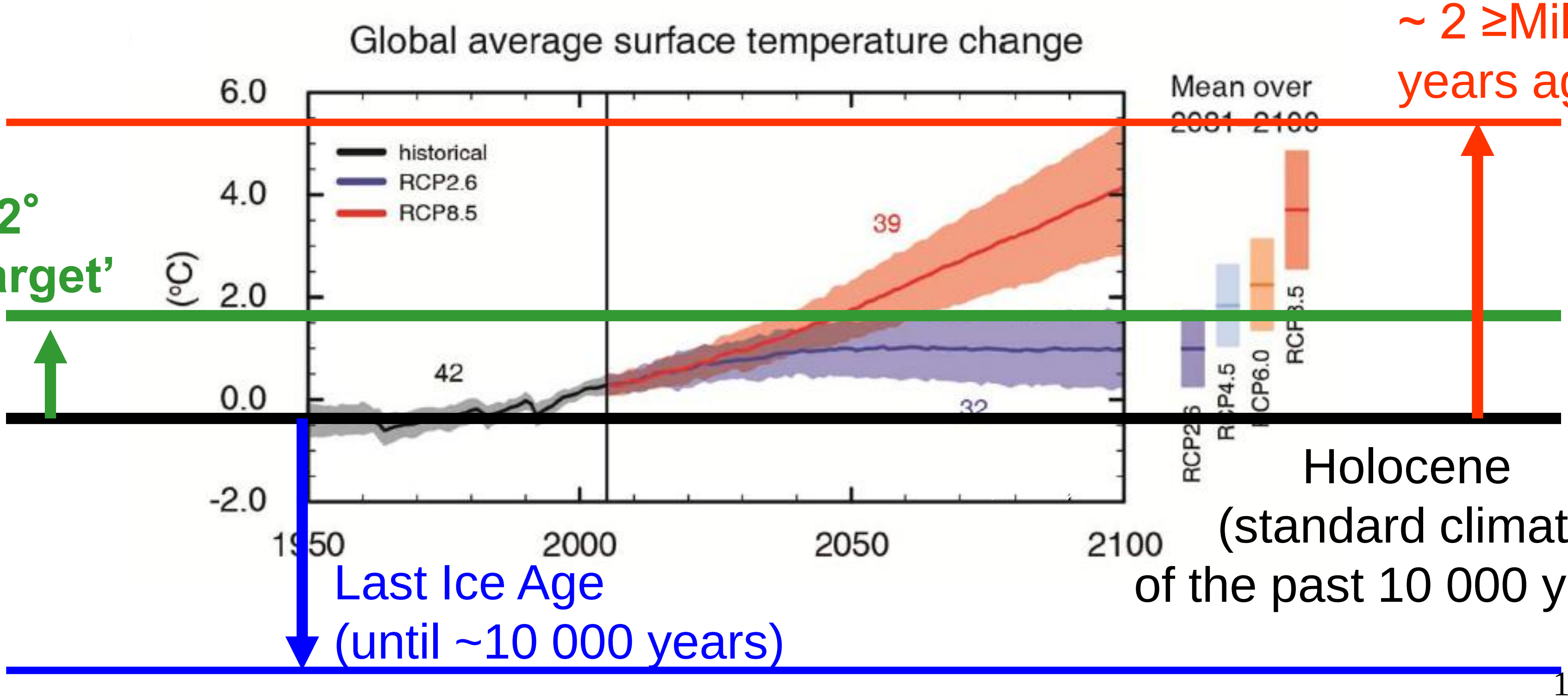
Evaluation of explicitly projected impacts of global warming

(‘facts-based approach’)

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

One Possible Interpretation of the Precautionary Principle:

Avoid Historic Dimension of Temperature Rise



('Hot House'
~ 2 ≥Million
years ago)

**'2°
-Target'**

Holocene
(standard climate
of the past 10 000 years)

Last Ice Age
(until ~10 000 years)

Two Sides of the Precautionary Argument

- Signaling the prospect of stability: What are we used to?
  - Maximum excursion to the high-end during development of humankind: 1.5° C.
  - 2° (C)-target a derivative of this by two ingredients:
    - Assumed adaptation abilities
    - The desire for a ‘simplest-possible’ number.

- Signaling the potential of threat: what are we not used to?
  - No policy scenario: would drives us into a temperature regime unknown since 2M years.

Otto et al., subm.

The 2^{o}-Target as an Amalgam of Precautionary and further Inputs

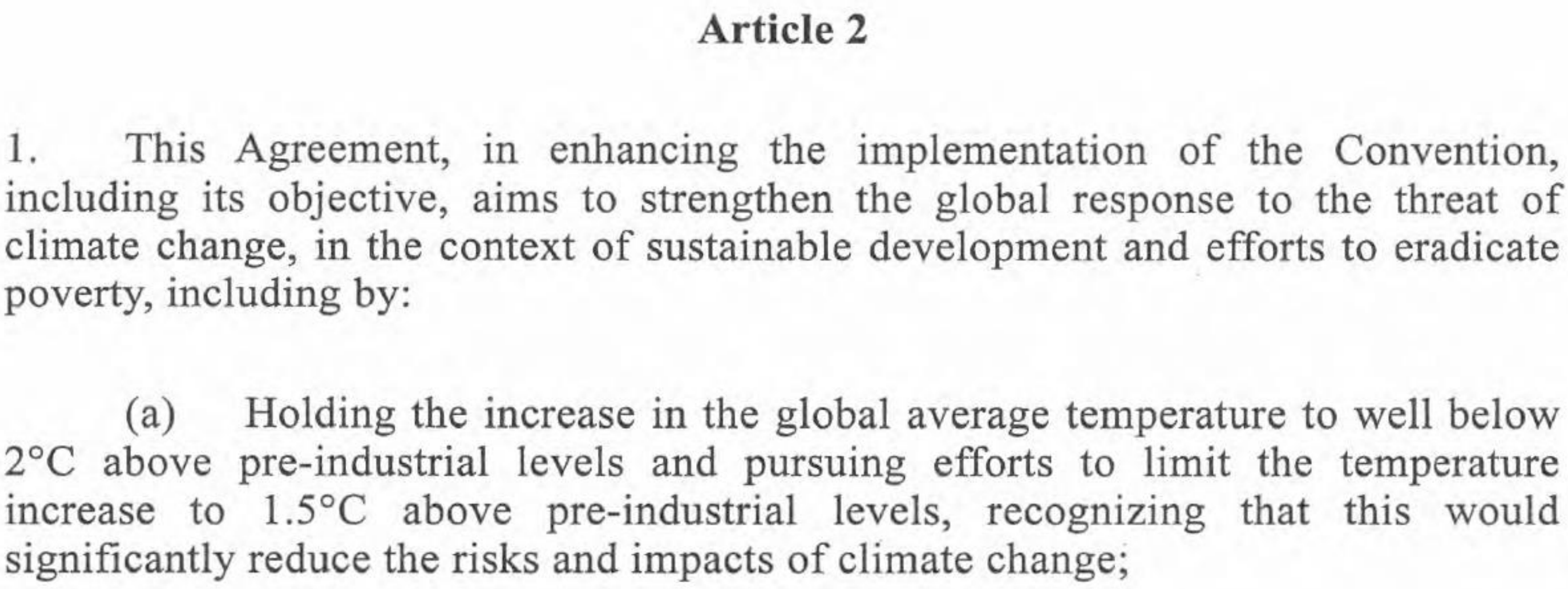
- Represents an operationalization of the precautionary principle

- Acknowledges known impacts

- *Condenses information for political discourse (‘academically informed political target’)*
  - *Analogous to a speed limit*
  - *Does* not *indicate a phase transition or bifurcation of the climate system at 2° .*

Paris Agreement 2015

https://upload.wikimedia.org/wikipedia/commons/5/54/COP21_participants_-_30_Nov_2015_%2823430273715%29.jpg

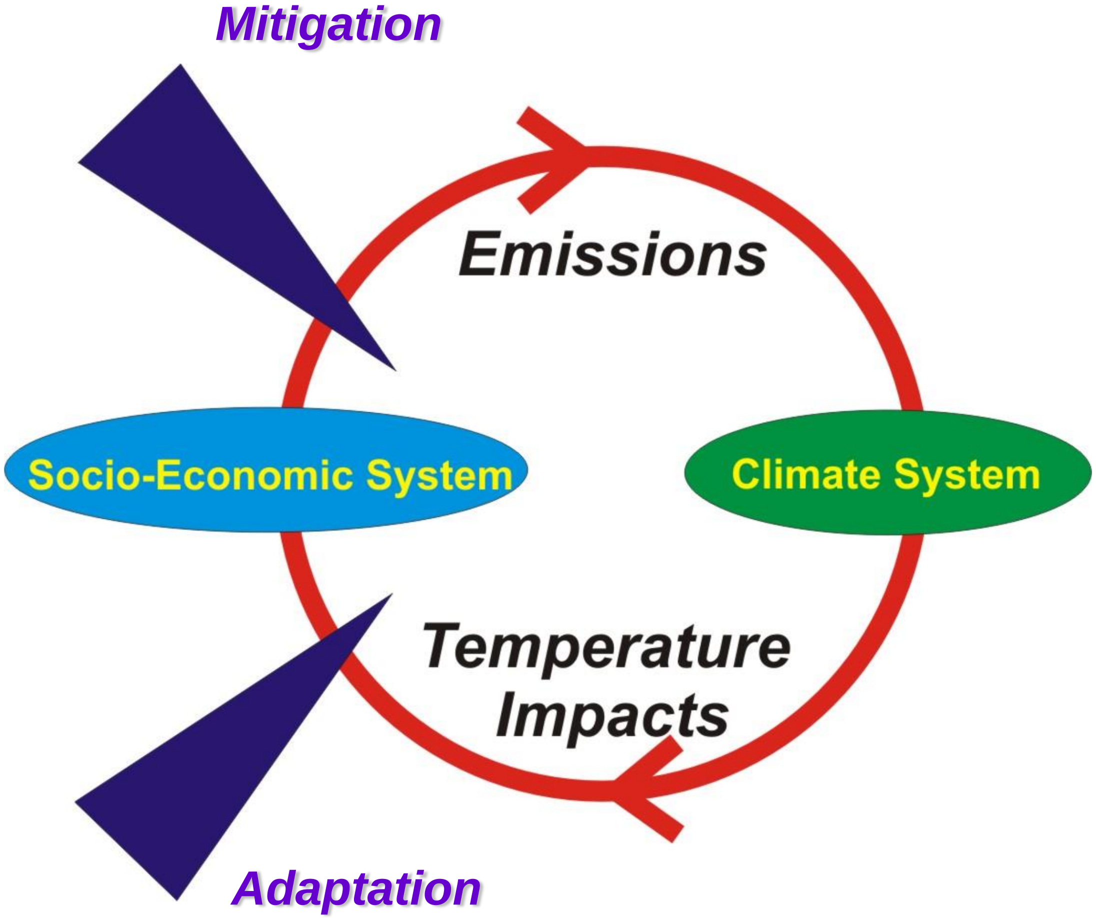


Article 2

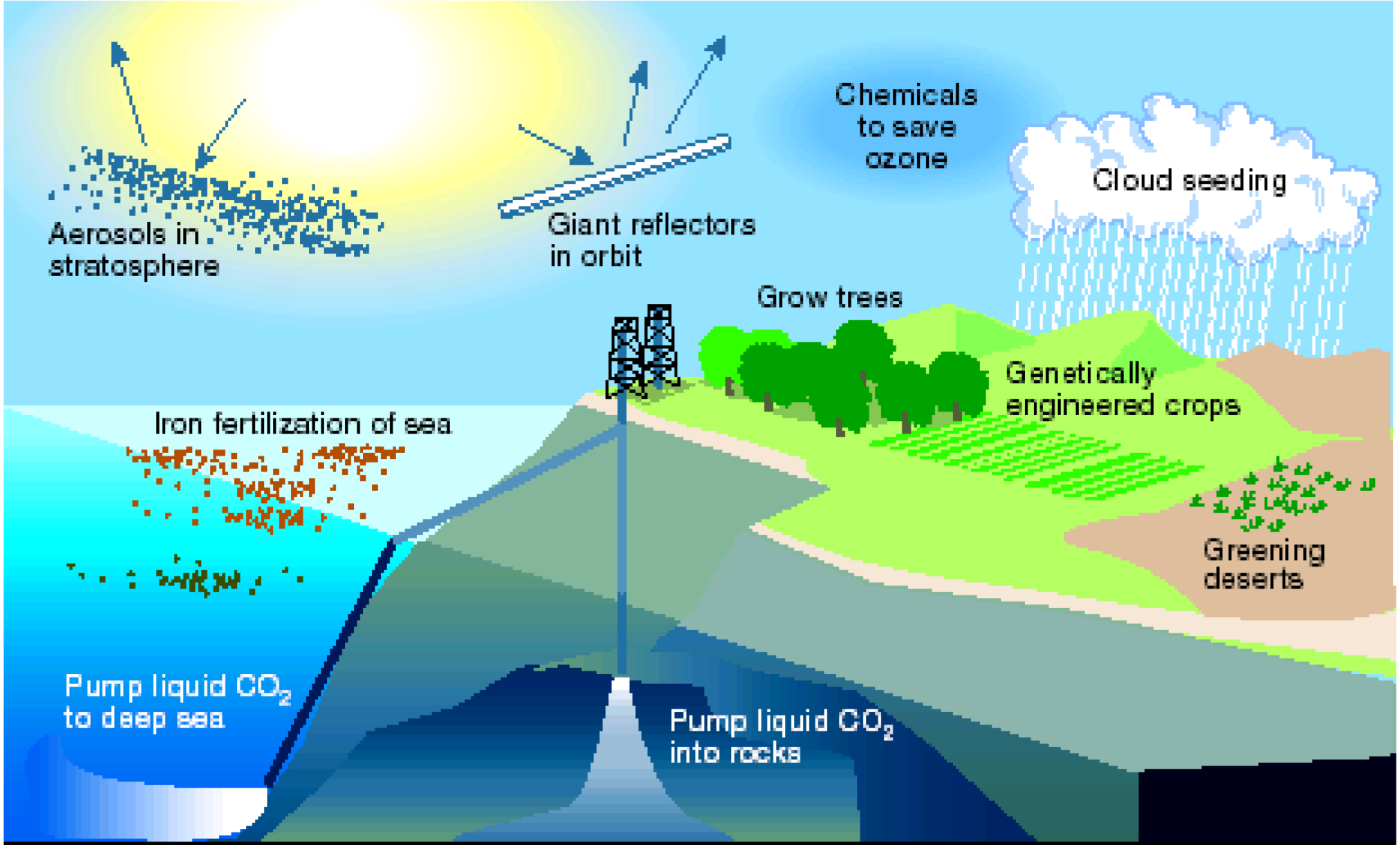
1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

(a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

Facing Global Warming: Two Possible Climate Policies



Speculative: Geo-Engineering Options (intentional large-scale operations to counteract environmental impacts, after D. Keith)



Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

Two Prominent Schools within Climate Economics

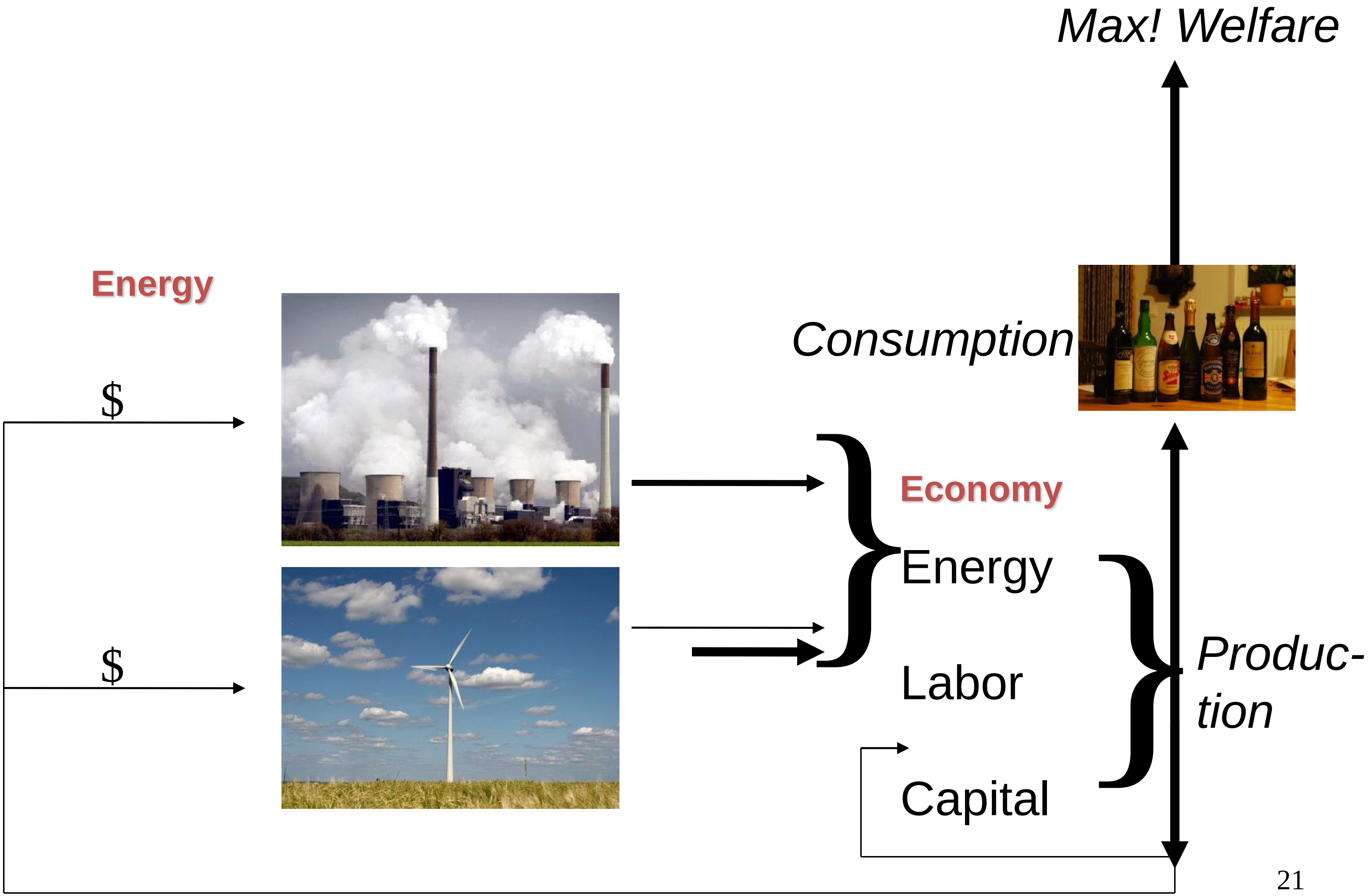
- Economic impact function → Cost benefit analysis
  - List explicitly known effects of global warming and mitigation costs
  - Determine economic optimum → optimal degree of global warming

Present-day mitigation costs

Future avoided damages

- Target-based ~ precaution-based decision making
  - Determine constrained welfare optimum for complying with a temperature
  - Target set by: ‘What has humankind survived during its development?’

An Interdisciplinary Optimisation Problem



Max! Welfare

Energy

$

$

Consumption

Economy

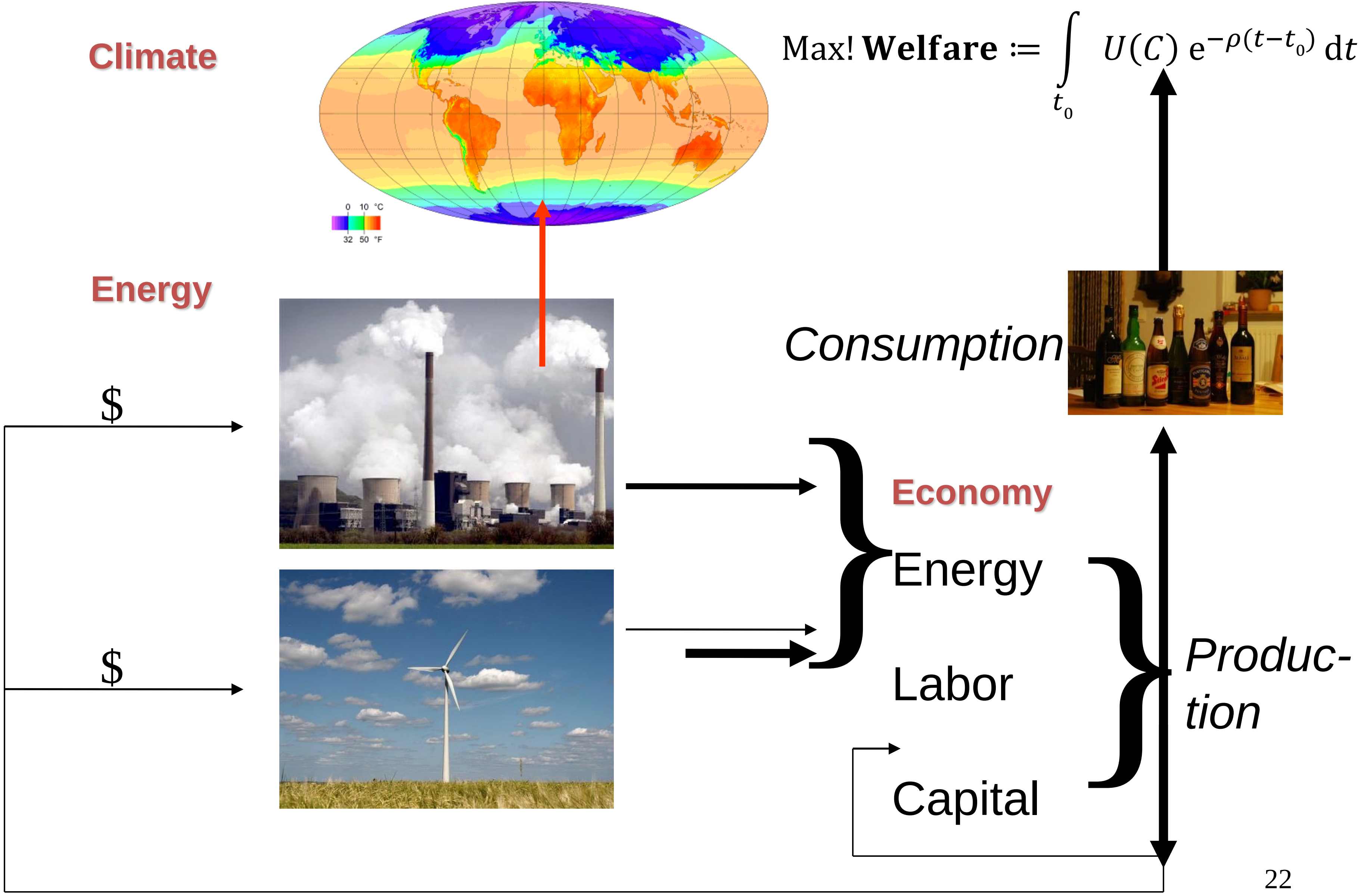
Energy

Labor

Capital

Produc-tion

An Interdisciplinary Optimisation Problem



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

Climate

Energy

$

$

Consumption

Economy

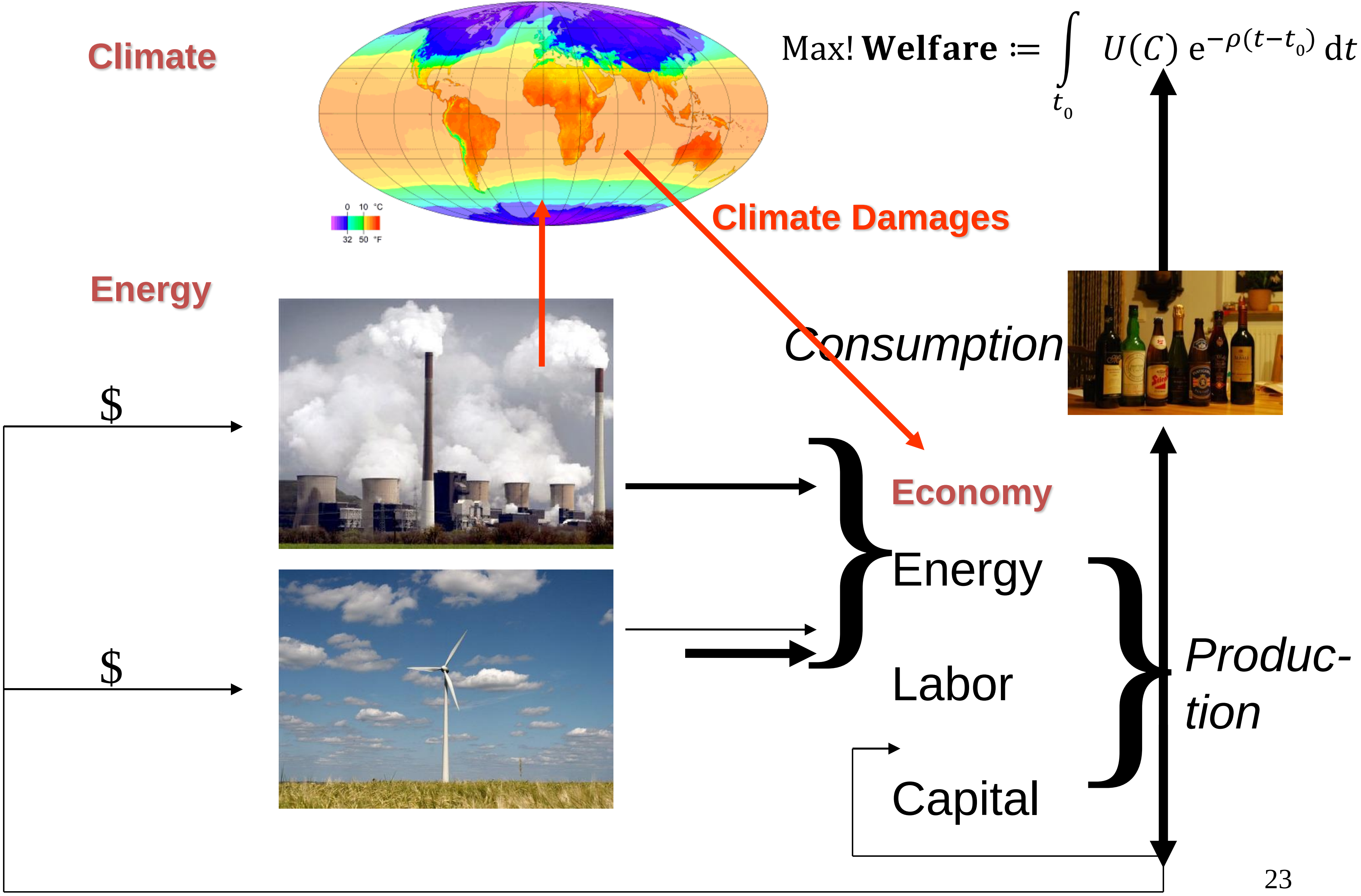
Energy

Labor

Capital

Produc-tion

An Interdisciplinary Optimisation Problem



$$\text{Max! } \mathbf{Welfare} \coloneqq \int_{t_0}^{\infty} U(C)\, \mathrm{e}^{-\rho(t-t_0)}\, \mathrm{d}t$$

Climate

Climate Damages

Energy

Consumption

$

$

Economy

Energy

Labor

Capital

Produc-tion

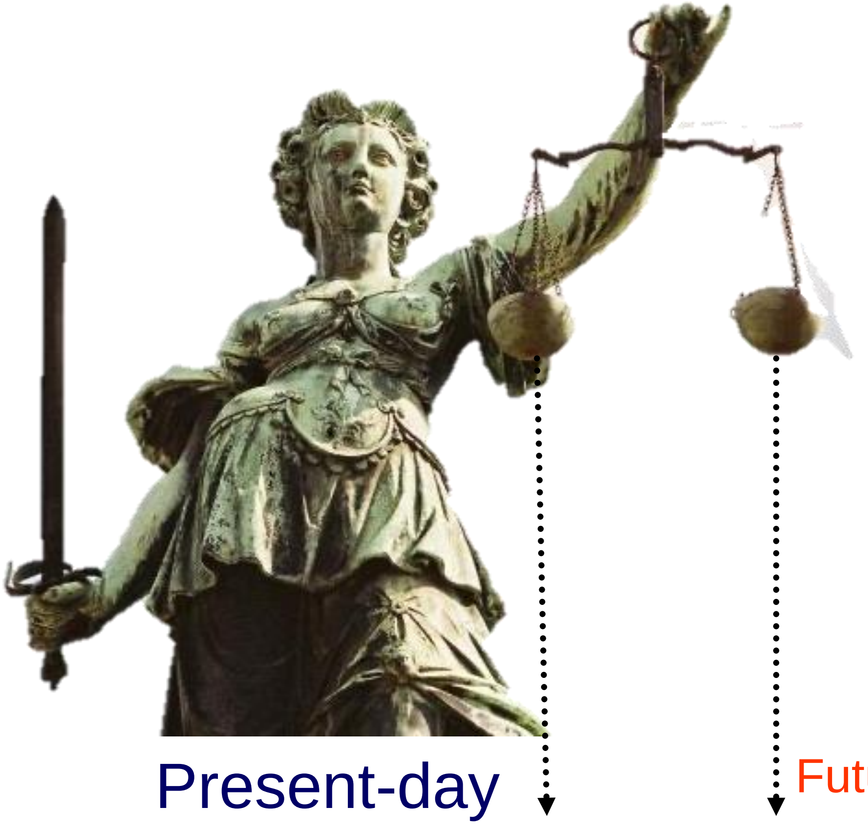
Earth System Modelling: The Fundamental Assumption of Time-Scale Separation

	Atmosphere / Ocean Dynamics	**Biosphere Dynamics**	**Economic Dynamics**
Short-Term	Weather	Ecosystem behaviour	Prices at Stock market
Long-Term (~10..100 yrs) statistical moments	Climate	Carbon Cycle	Patterns of economic growth

Economic Backing of 2° (C) target?

(How much mitigation is desirable?)

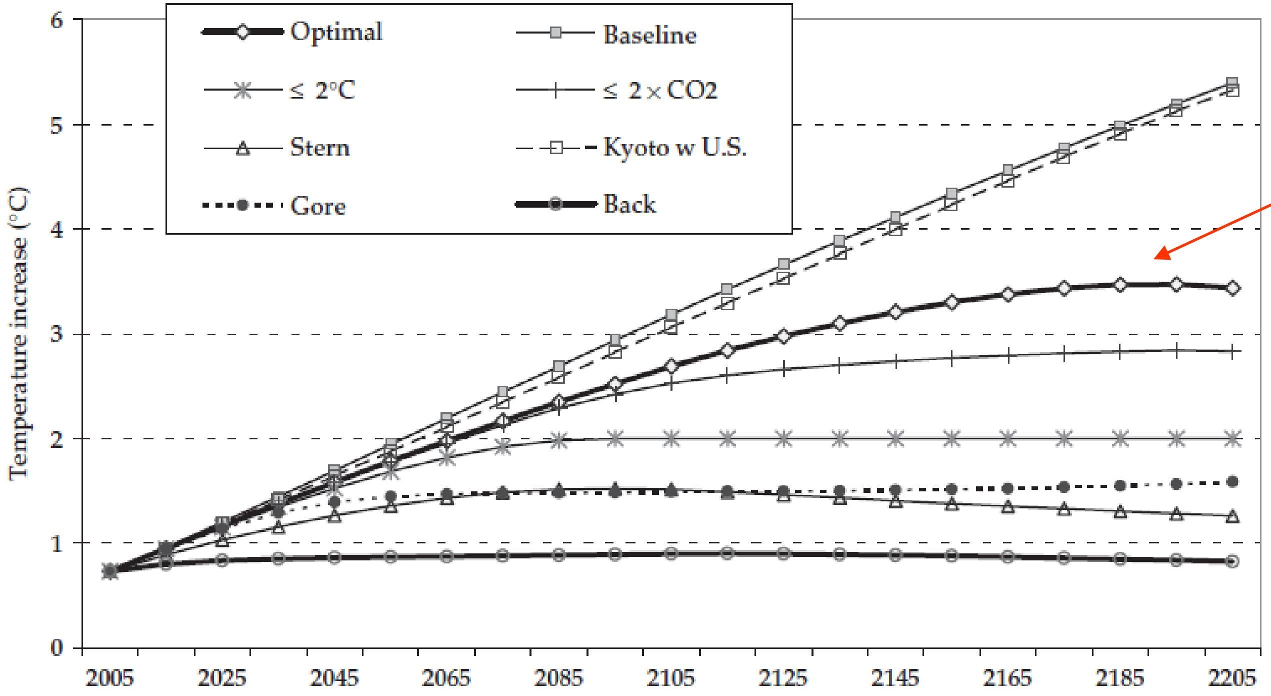
- Cost Benefit Analysis (CBA):
  The standard tool of environmental economics



Present-day
mitigation costs

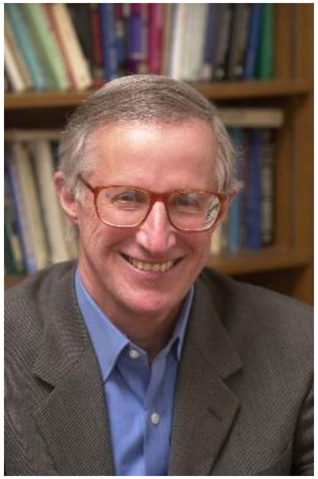
Future
avoided damages

A Generic CBA Result



‘Optimal Path’:
~ 3.5°C warming

Figure 5-8. Projected global mean temperature change under different policies. Increases are relative to the 1900 average.



W. Nordhaus: ‘A question of balance’ (2008)

(Recipient of the Nobel Prize in Economics - 2018)

Conceptual Difficulties for CBA

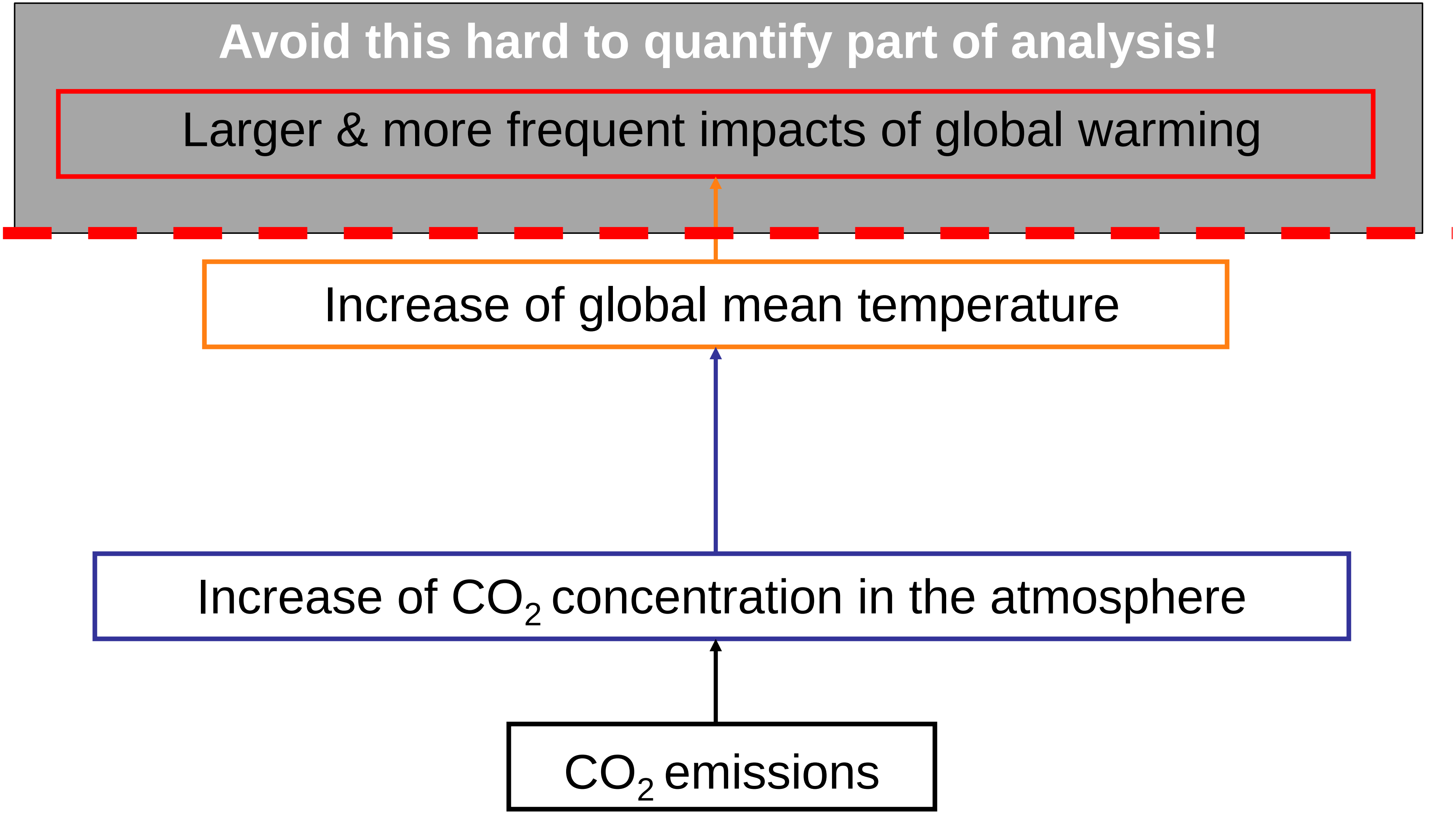
- Climate impacts are poorly known
  - – Limited natural science/engineering knowledge (at least today)
  - – Need for valuation of goods

- Need to weigh
  - – Present mitigation costs … against …
  - – Future avoided damages

Results in vastly diverging policy recommendations:

For e.g. Emissions control rate
- ~ 25% in 2050 (3-3.5° C warming; *Nordhaus, 2008*)
- 100% immediately (*Weitzman, 2009*)

Carbon Dioxide Impact Cascade: Avoid the Damage Part



Avoid this hard to quantify part of analysis!

Larger & more frequent impacts of global warming

Increase of global mean temperature

Increase of CO_2 concentration in the atmosphere

CO_2 emissions

Cost Effectiveness Analysis (CEA)

An easier & better-posed decision-theoretical framework?

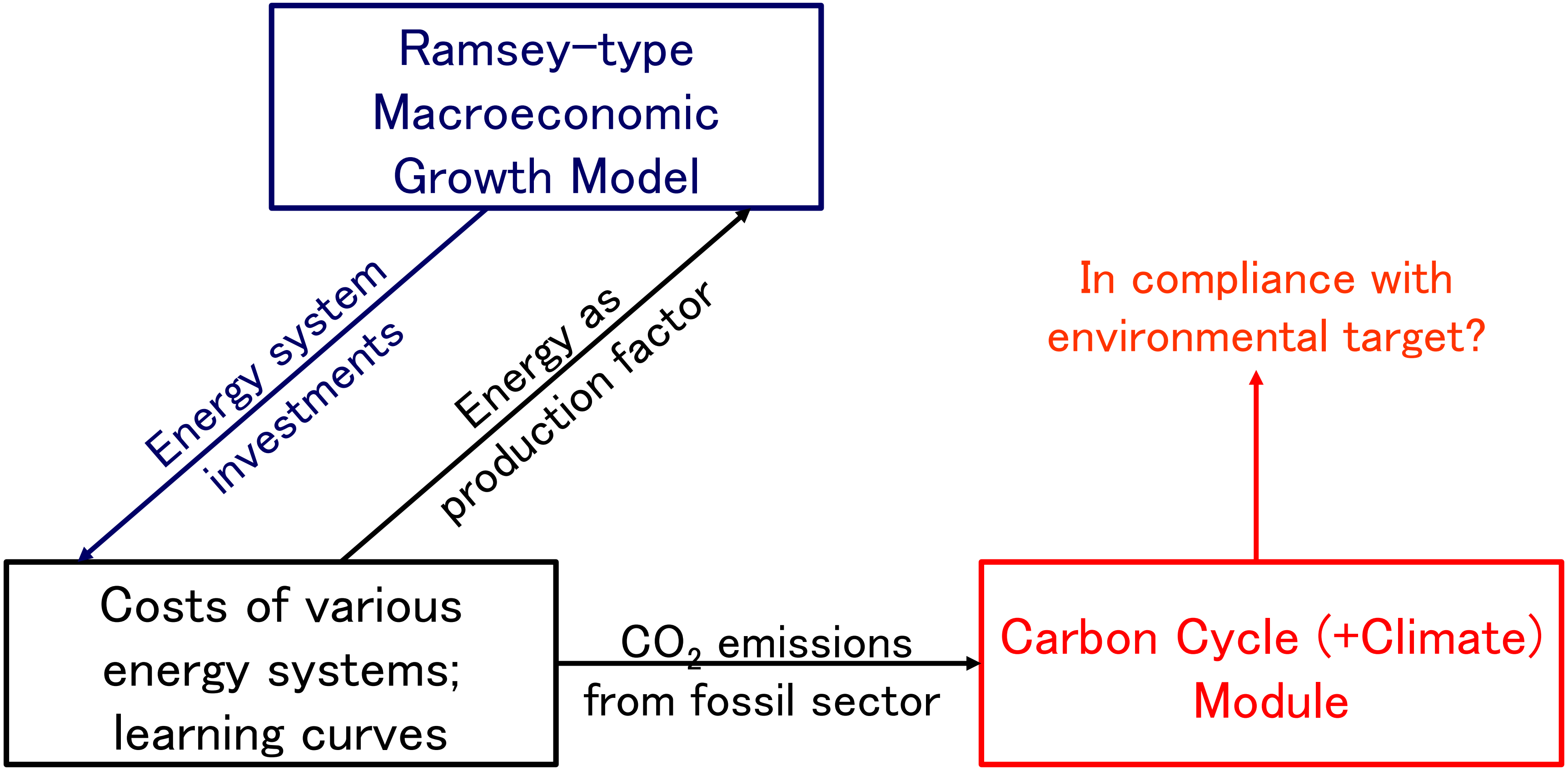
- Avoids talking about the hard to quantify damages

- Instead:
  - Assumes an environmental target (e.g. 2° (C) target)
  - Strives for a **cost-minimal mix** of energy investments to **achieve this target**.

- ‘Lexicographic preference order’

Costs of Climate Targets

The standard model setup



Ramsey–type Macroeconomic Growth Model

Energy system investments

Energy as production factor

Costs of various energy systems; learning curves

CO_2 emissions from fossil sector

Carbon Cycle (+Climate) Module

In compliance with environmental target?

Based on MIND by Edenhofer et al. (2005)

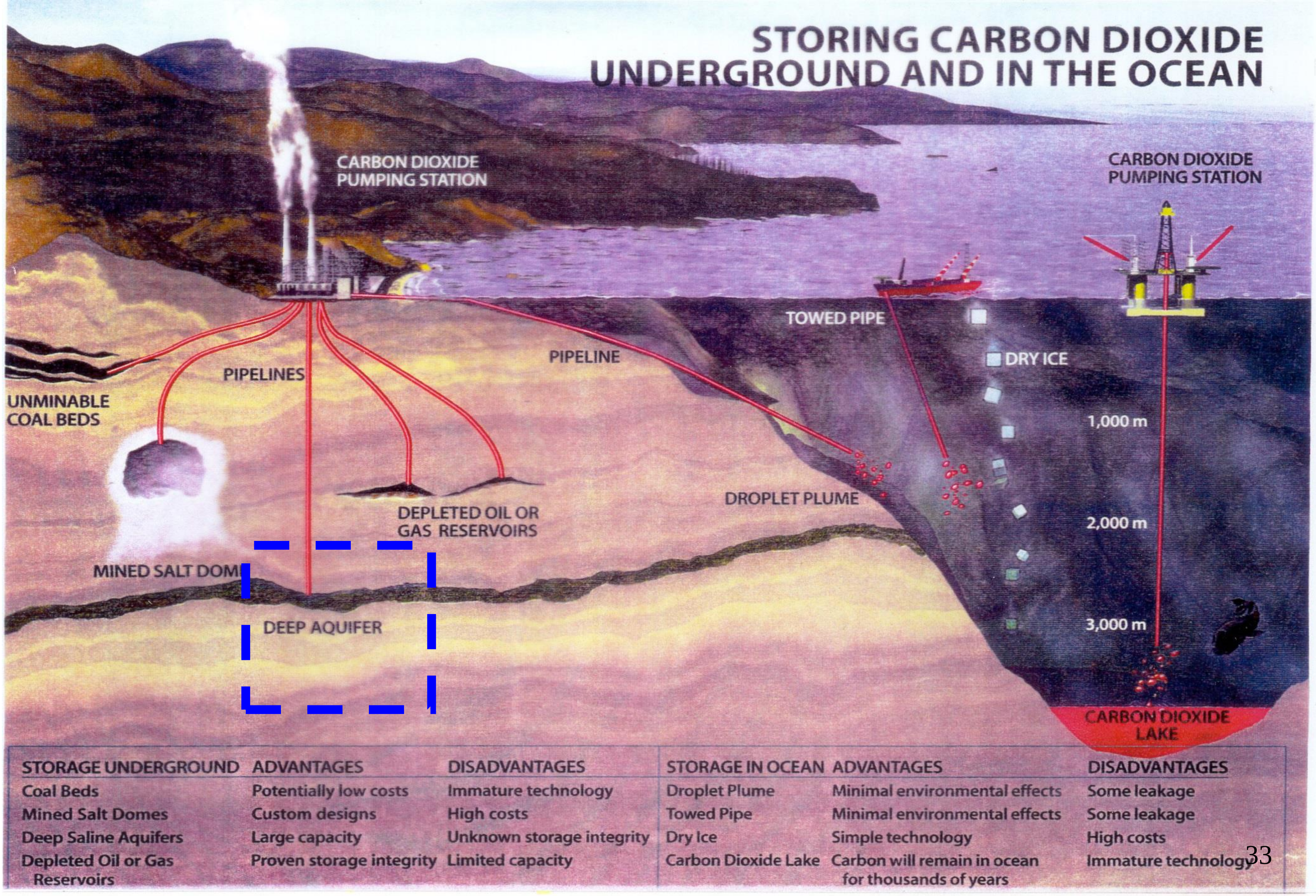
Box: A List of Assumptions

Mitigation Options Considered in Cost Effectiveness Analyses

- Enhancing Energy Efficiency
- Renewable Sources
- Carbon Capture & ‘Storage’
- Nuclear Energy (Fission)

Several dozens of energy technologies resolved in state-of-the-art models.

Carbon Capture & Storage



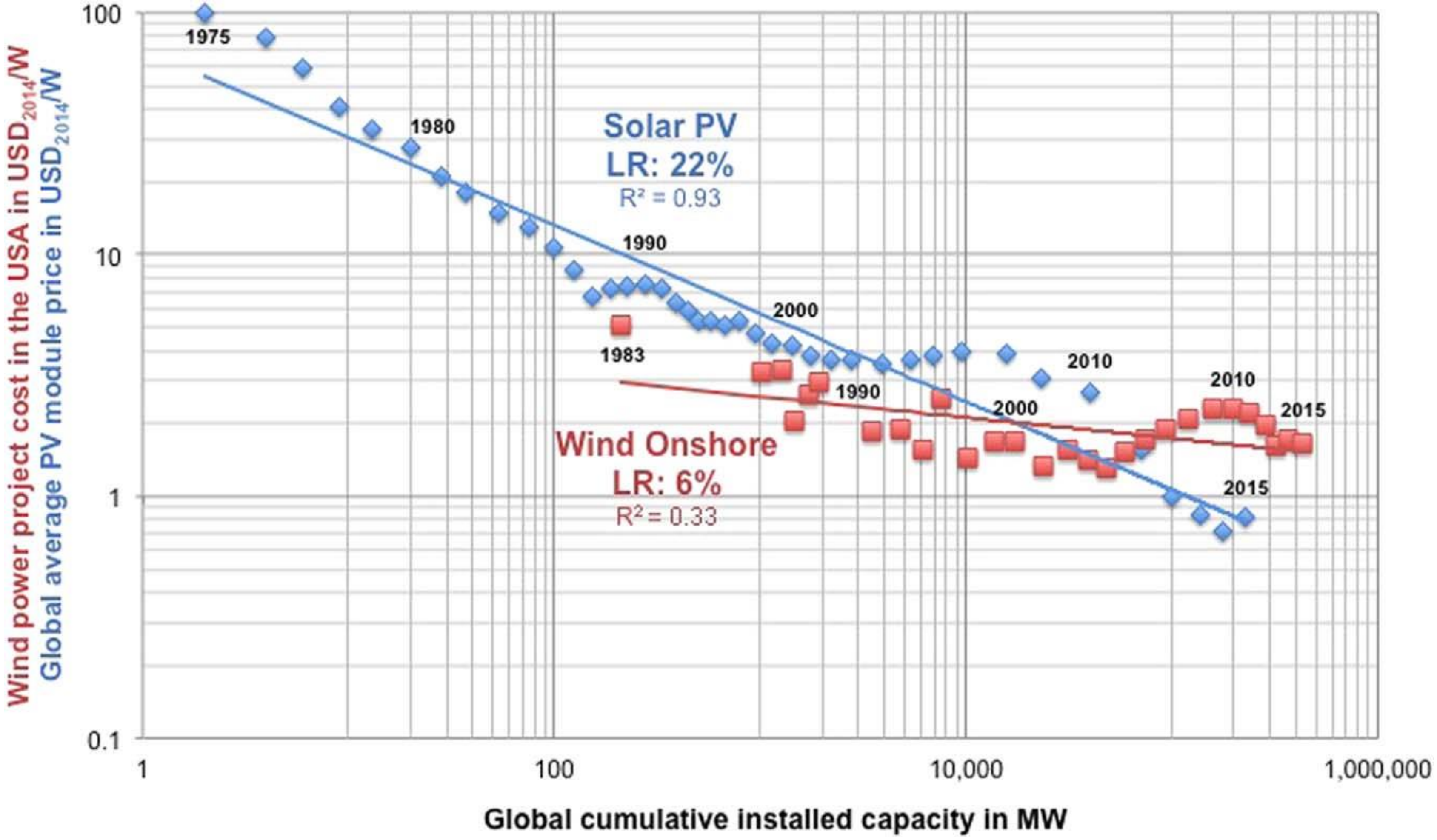
STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES	STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology	Droplet Plume	Minimal environmental effects	Some leakage
Mined Salt Domes	Custom designs	High costs	Towed Pipe	Minimal environmental effects	Some leakage
Deep Saline Aquifers	Large capacity	Unknown storage integrity	Dry Ice	Simple technology	High costs
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity	Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

Nuclear

- In most analyses fission only …

- …as economic numbers on fusion still too uncertain

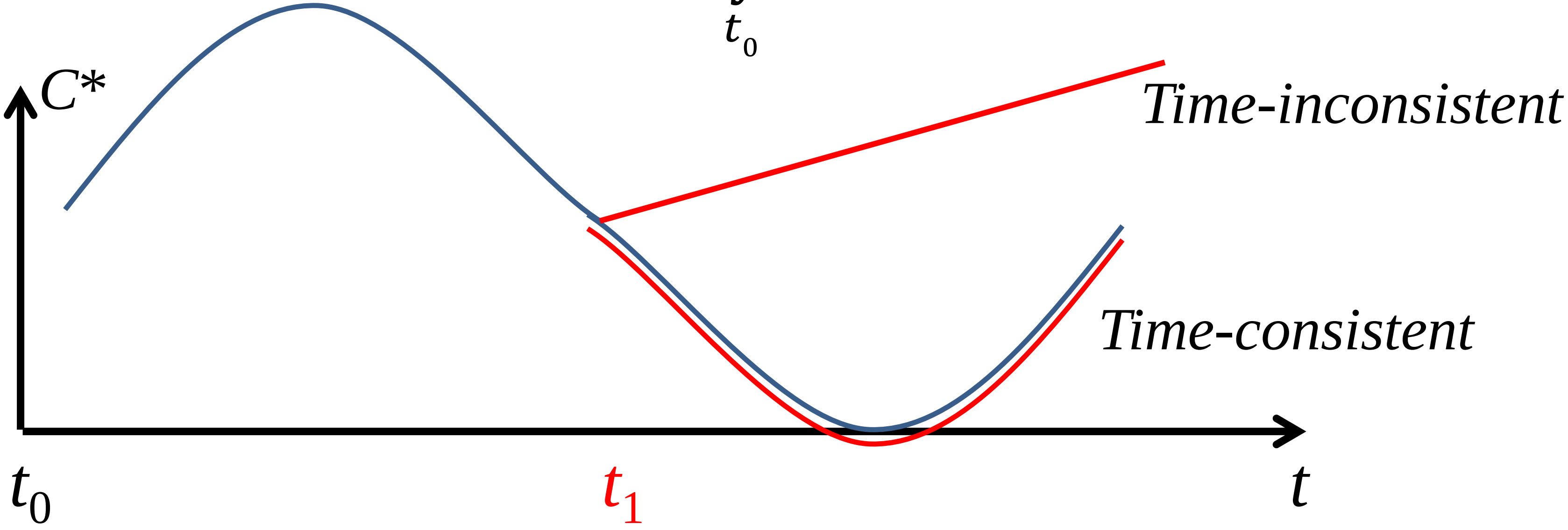
Learning Curves Included



Samadi, 2017

A Desirable Property of the Welfare Functional

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



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

- Exponential discounting is both necessary and sufficient for time-consistent decision-making (if assuming time-additive welfare; Strotz, 1955).
- Time consistency conserves the optimal path under time-shift of decision moment.

End of Box on the List of Assumptions

1200 Scenarios classified by IPCC AR5 WGIII

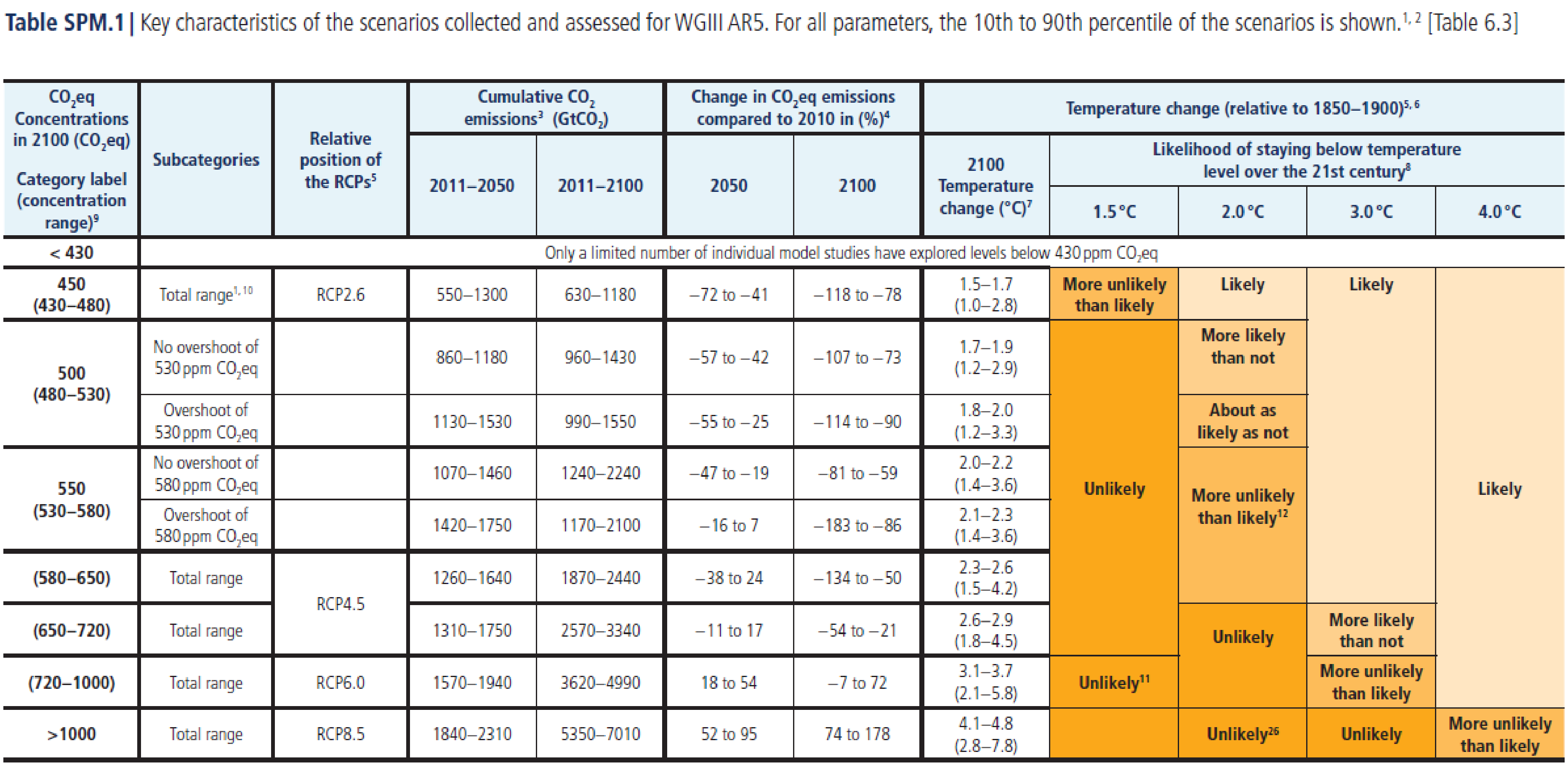
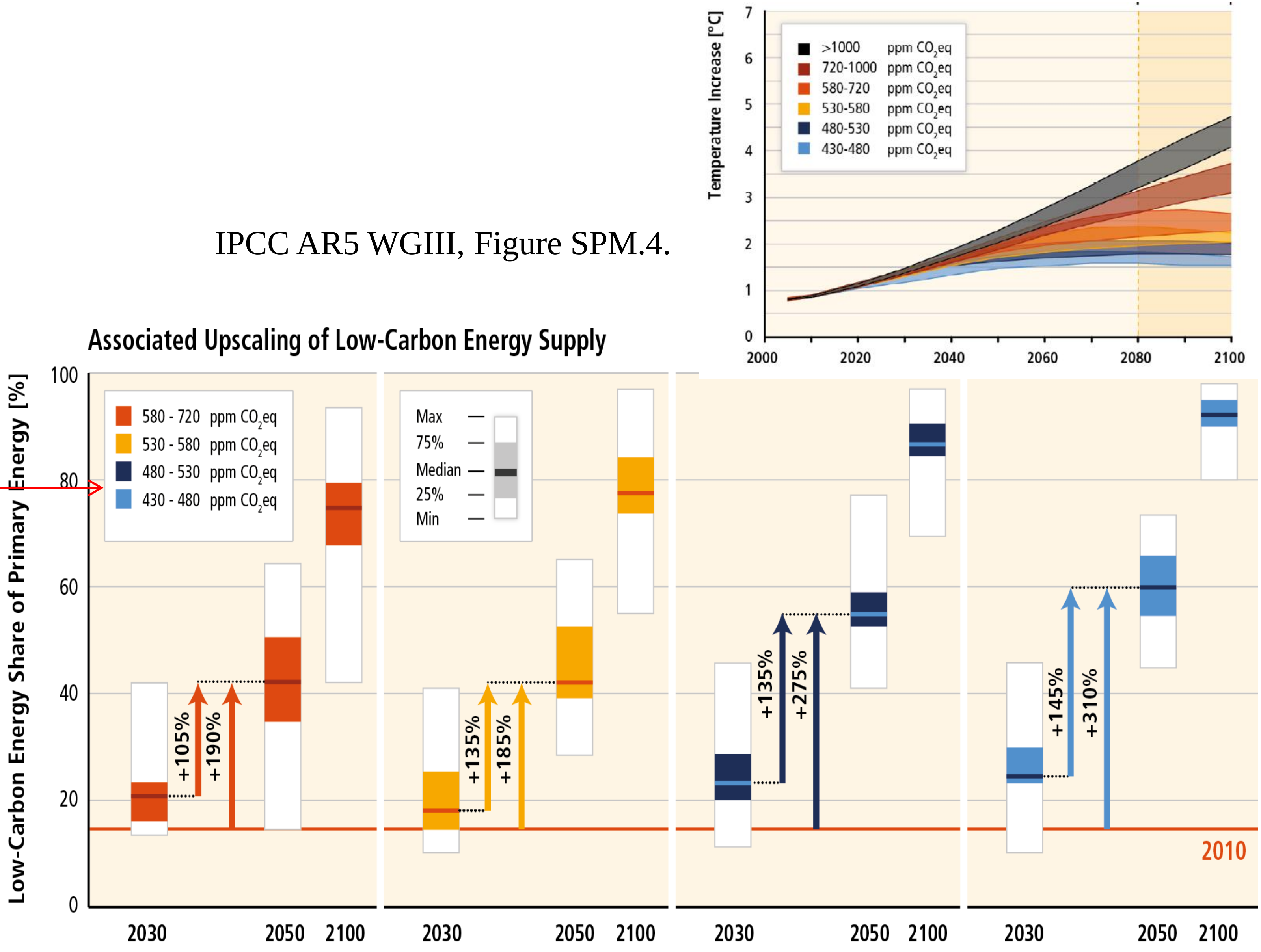


Table SPM.1 | Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters, the 10th to 90th percentile of the scenarios is shown.[1, 2] [Table 6.3]

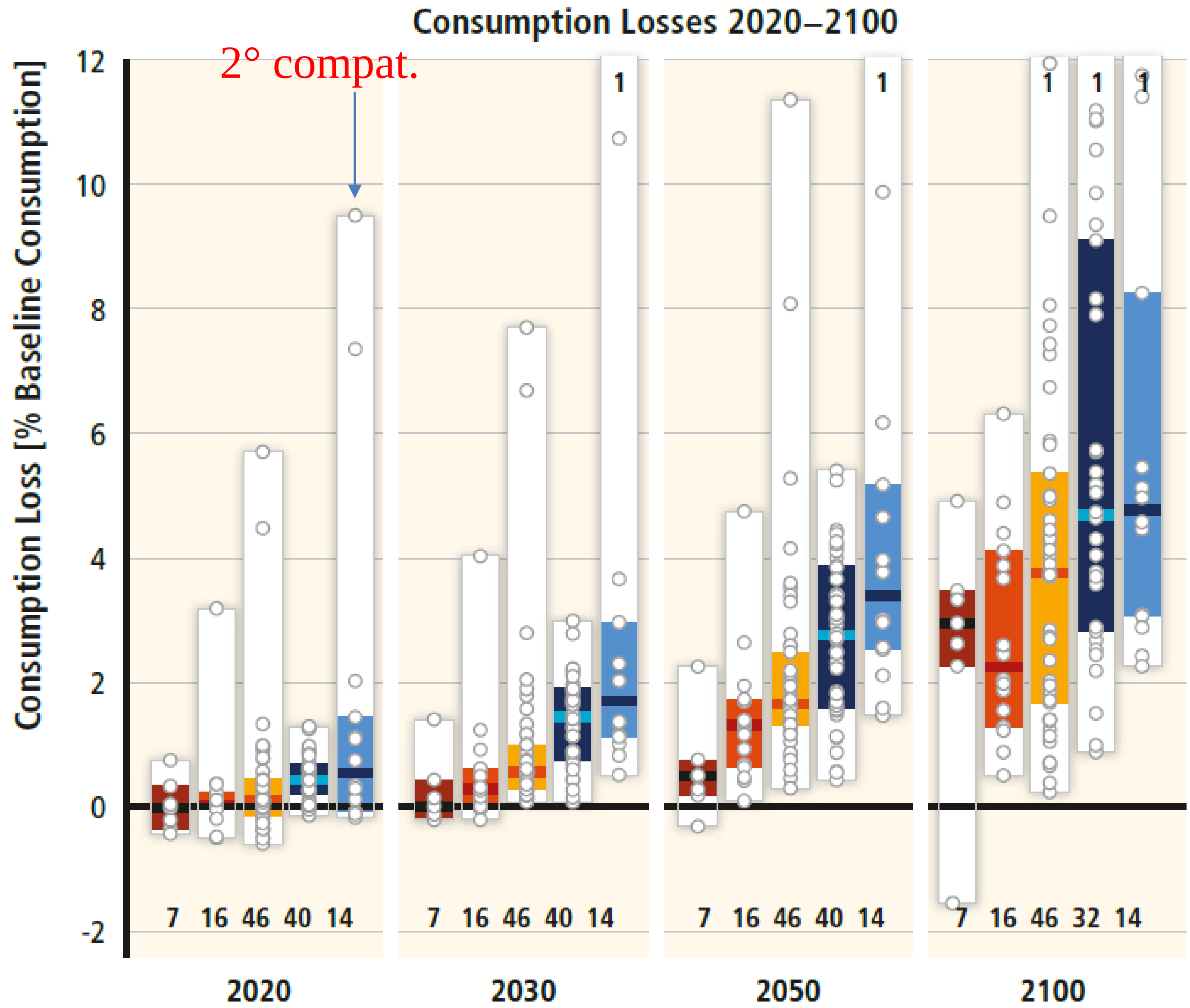
CO_2eq Concentrations in 2100 (CO_2eq) Category label (concentration range)[9]	Subcategories	Relative position of the RCPs[5]	Cumulative CO_2 emissions[3] ($GtCO_2$)		Change in CO_2eq emissions compared to 2010 in (%)[4]		Temperature change (relative to 1850–1900)[5, 6]				
			2011–2050	2011–2100	2050	2100	2100 Temperature change (°C)[7]	Likelihood of staying below temperature level over the 21st century[8]			
								1.5 °C	2.0 °C	3.0 °C	4.0 °C
< 430	Only a limited number of individual model studies have explored levels below 430 ppm CO_2eq										
450 (430–480)	Total range[1, 10]	RCP2.6	550–1300	630–1180	−72 to −41	−118 to −78	1.5–1.7 (1.0–2.8)	**More unlikely than likely**	**Likely**	**Likely**	**Likely**
500 (480–530)	No overshoot of 530 ppm CO_2eq		860–1180	960–1430	−57 to −42	−107 to −73	1.7–1.9 (1.2–2.9)	**Unlikely**	**More likely than not**		
	Overshoot of 530 ppm CO_2eq		1130–1530	990–1550	−55 to −25	−114 to −90	1.8–2.0 (1.2–3.3)		**About as likely as not**		
550 (530–580)	No overshoot of 580 ppm CO_2eq		1070–1460	1240–2240	−47 to −19	−81 to −59	2.0–2.2 (1.4–3.6)		**More unlikely than likely**[12]		
	Overshoot of 580 ppm CO_2eq		1420–1750	1170–2100	−16 to 7	−183 to −86	2.1–2.3 (1.4–3.6)				
(580–650)	Total range	RCP4.5	1260–1640	1870–2440	−38 to 24	−134 to −50	2.3–2.6 (1.5–4.2)				
(650–720)	Total range		1310–1750	2570–3340	−11 to 17	−54 to −21	2.6–2.9 (1.8–4.5)		**Unlikely**	**More likely than not**	
(720–1000)	Total range	RCP6.0	1570–1940	3620–4990	18 to 54	−7 to 72	3.1–3.7 (2.1–5.8)	**Unlikely**[11]		**More unlikely than likely**	
>1000	Total range	RCP8.5	1840–2310	5350–7010	52 to 95	74 to 178	4.1–4.8 (2.8–7.8)		**Unlikely**[26]	**Unlikely**	**More unlikely than likely**

Mitigation requires major technological changes including the upscaling of low- and zero carbon energy.



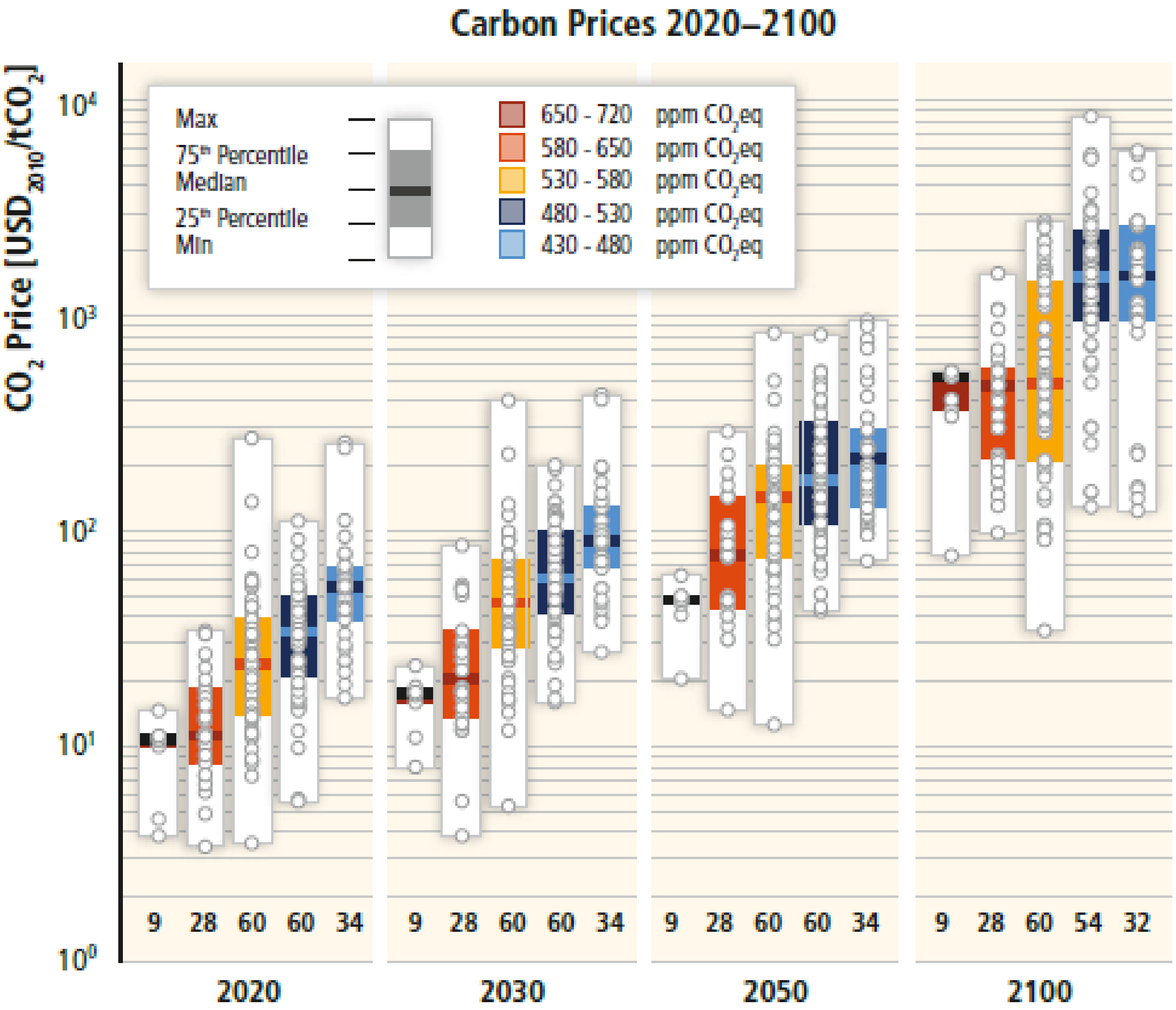
IPCC AR5 WGIII, Figure SPM.4.

2° compat.



2° compat.

Figure TS.12 | Global carbon prices (left panel) and consumption losses (right panel) over time in cost-effective, idealized implementation scenarios. Consumption losses are expressed as the percentage reduction from consumption in the baseline. The number of scenarios included in the boxplots is indicated at the bottom of the panels. The 2030 numbers also apply to 2020 and 2050. The number of scenarios outside the figure range is noted at the top. Note: The figure shows only scenarios that reported consumption losses (a subset of models with full coverage of the economy) or carbon prices, respectively, to 2050 or 2100. Multiple scenarios from the same model with similar characteristics are only represented by a single scenario in the sample. [Figure 6.21]



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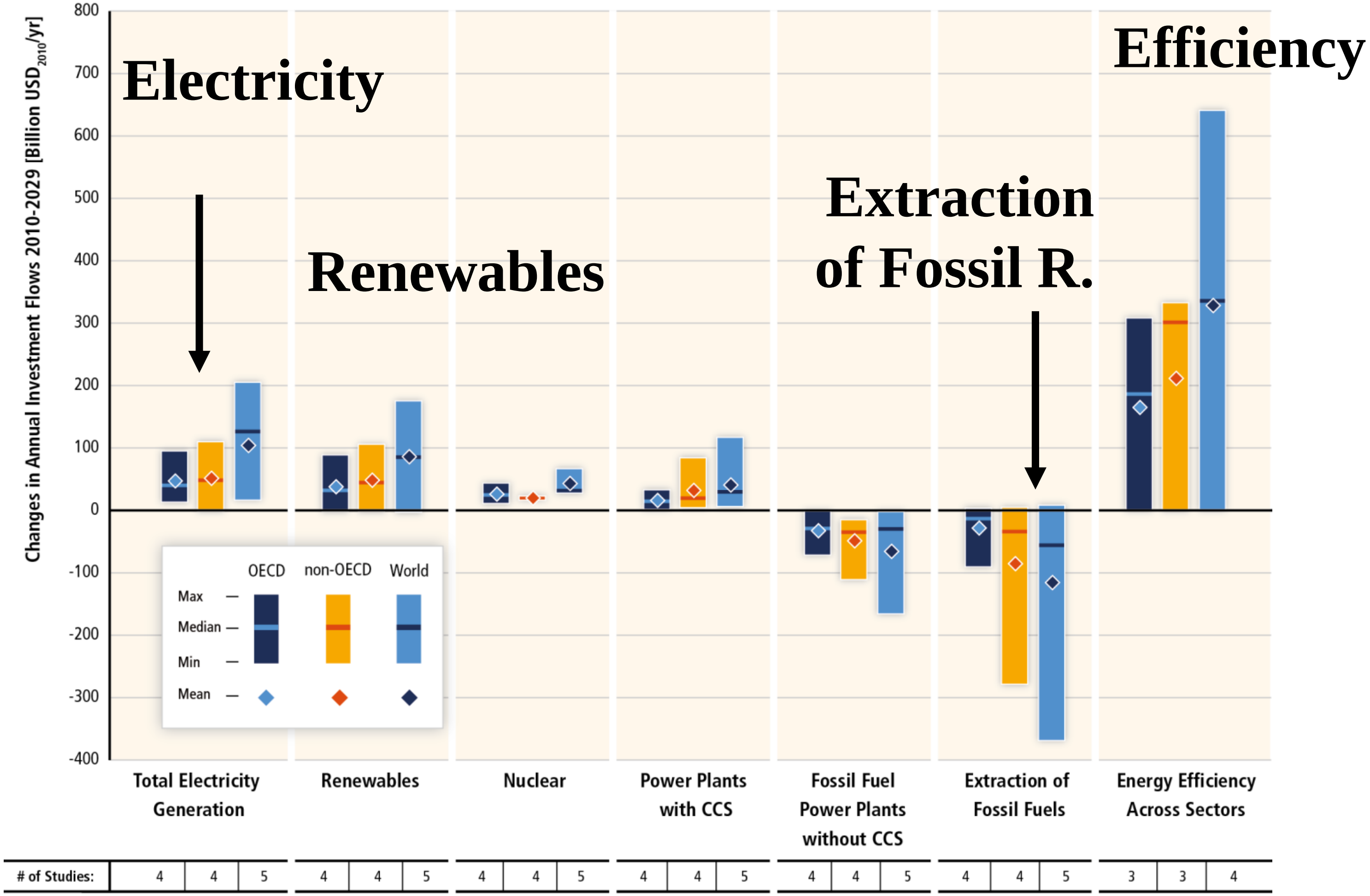
2°-Compatible Emissions-Reductions Require Shifts in Investments 2010-2029



stabilize concentrations within the range of
approximately 430–530 ppm CO2eq by 2100

IPCC AR5 WGIII, Figure SPM.9.

Economic Welfare Effects of 450ppmeq (~2° C) Target?

- Economic reference case:

  Scenario without climate damages and without climate policy
- This is characterized by global economic growth of 1.6 - 3 % / year.

- 2°-oriented scenarios compatible with continued global economic growth.
- Annual growth rate reduced by 0.06 %- points .

- Hereby avoided warming-induced net damages not yet included.

- *(After IPCC AR5 WGIII SPM)*

- 2° target '~insurance premium against unpredictable warming damages'

How Do the Numbers Change for the 1.5° Target?

Temperature, Impacts, Mitigation Costs

Target	Additional Damages (Selection)	Consumption Loss in 2030
1.5°C	+3° of hottest days	3.8%*
2°C	8% → 16% Plant species loss; corals; run-away greenhouse effect?* Ice sheets at risk +>100 millionen poor affected. (2050)	1.7%
3°C	10% GDP-loss**	0.3%
4°C	Sure loss of the Greenland ice sheet -> +7m sea level	

IPCC AR5 WGII SPM & 1,5° (2018)
**Steffen et al., 2018*
***Dietz et al., 2018*

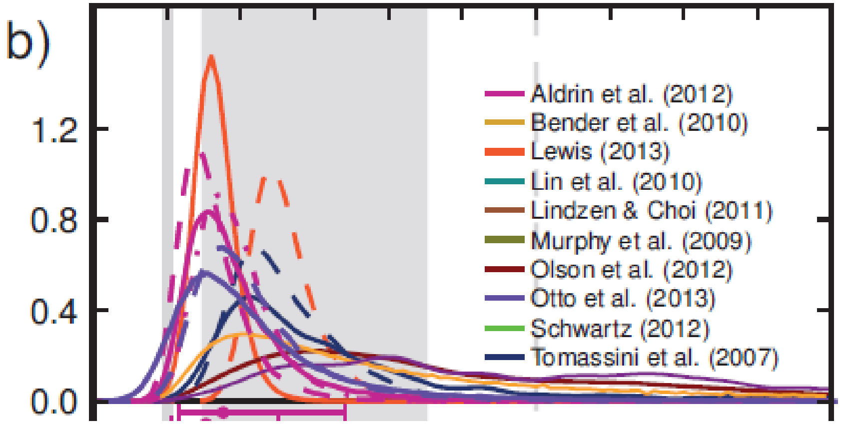
IPCC AR5 WGIII SPM
**Extrapolated from Rogelj et al., 2015*

Inclusion of Uncertainty:
Only a Book-Keeping Exercise?

- So far, uncertainty has silently been encapsulated in the request that temperature targets are complied with, prescribing a probability of 66%.

- However, from economics we know that in a dynamic setting, target-based decision-making is at odds with anticipated future learning.

Distributions on Climate Sensitivity



IPCC AR5 WGI (2013)

- An upper bound for allowed carbon budget scales with $(2^{T^* / CS} - 1)$ (Kriegler & Bruckner, 2004)
- Hence, as there is no upper bound on CS, no temperature target can be complied with under $P^*=100\%$!
- Therefore we can only formulate temperature targets in conjunction with a compliance prob. target $P^* < 100\%$!
  - Weaker, probabilistic target $P\,(T<T^*) >!\, P^*$

Chance Constraint Programming Presently Leading Paradigm

- Cost effectiveness analysis (CEA) under *probabilistic* target:

‘**Chance Constraint Programming**’

(Charnes & Cooper, 1959)

- ~1000 deterministic CEAs as assembled in IPCC AR5 have potential to be seen as good approximations of chance constraint programming solutions
  - On the mechanism: see Held et al., 2009.

Conceptual Flaws of Cost Effectiveness Analysis even for Probabilistic Targets

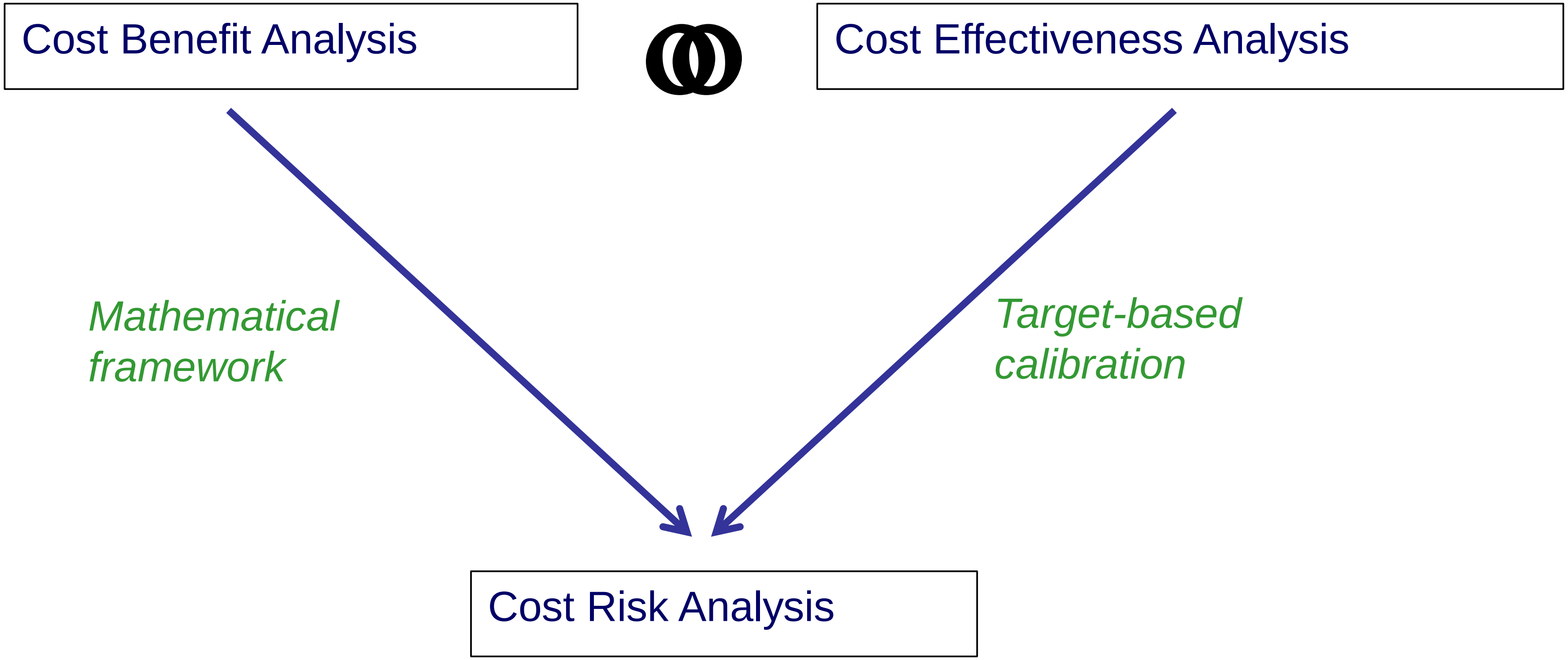
Probabilistic target might become *infeasible* (due to stock-pollutant dynamics) if…

- …in the future we learn with certainty that climate sensitivity is ‘too large’, or…
- …an implementation of a global mitigation strategy is delayed too much (‘delayed participation’).

Furthermore, the expected value of information on climate sensitivity can be negative (Schmidt et al., 2011).

  - An effect known in principle since Blau, 1974.

Hence we suggest a hybrid approach



Cost Benefit Analysis

Cost Effectiveness Analysis

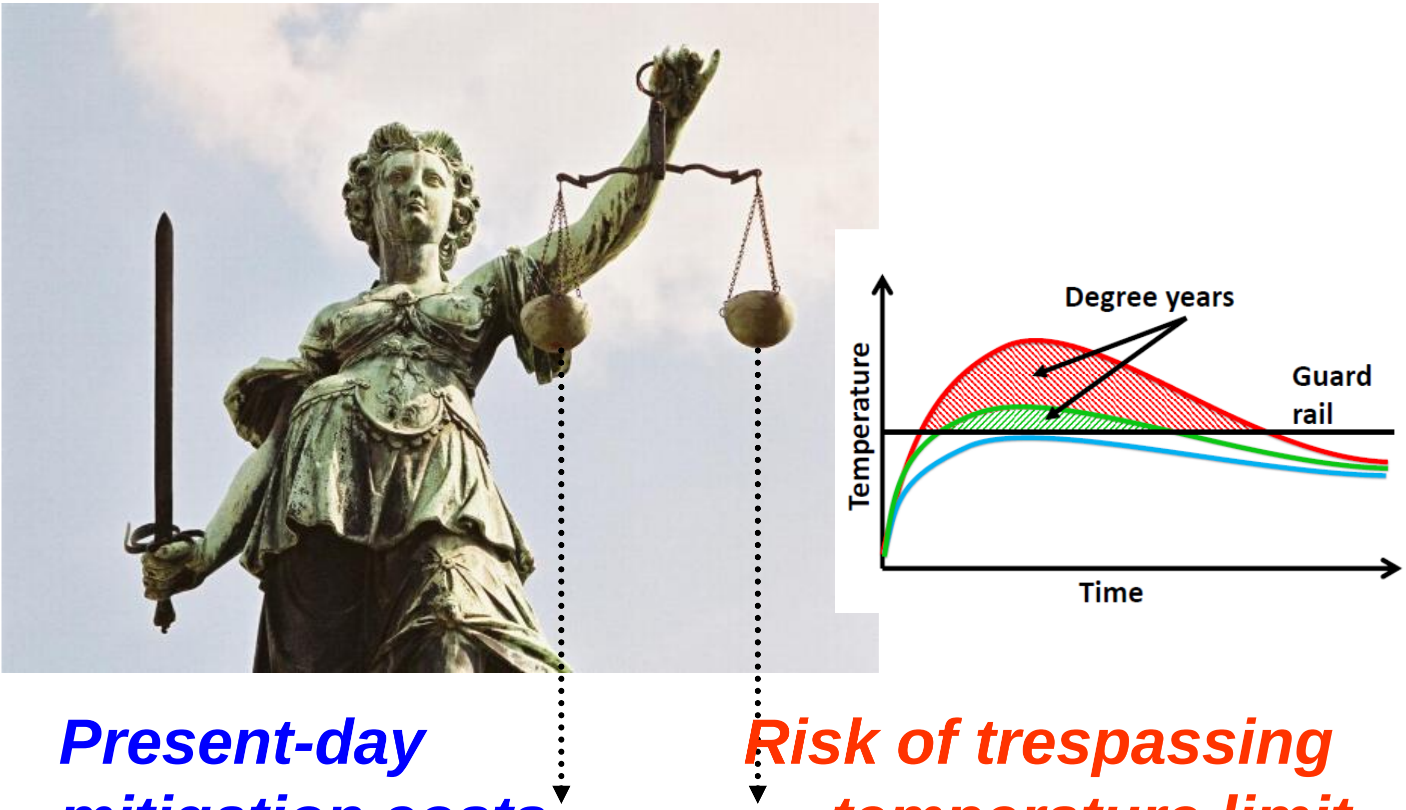
Mathematical framework

Target-based calibration

Cost Risk Analysis

Schmidt et al., 2011

“Cost Risk Analysis” (CRA):
A hybrid decision analytic tool



Present-day mitigation costs

Risk of trespassing temperature limit

"Cost Risk Analysis"

Welfare Equation

δ: time preference
s: state of the world
t: time
x: control

Maximize!

$$\text{Welfare} \quad W = \sum_{t} \sum_{s=1}^{S} p_s \Big[\underbrace{U\big(C(t,s,x)\big)}_{\text{Utility from consumption}} - \beta \overbrace{R\big(T(t,s,x)\big)}^{\text{Risk from Trespassing}} \Big] e^{-\delta t}$$

β: Trade-off parameter (needs to be calibrated)

- Discount factor being *outside* of the bracket ensures time consistency.

“Cost Risk Analysis”

Welfare Equation

δ: time preference
s: state of the world
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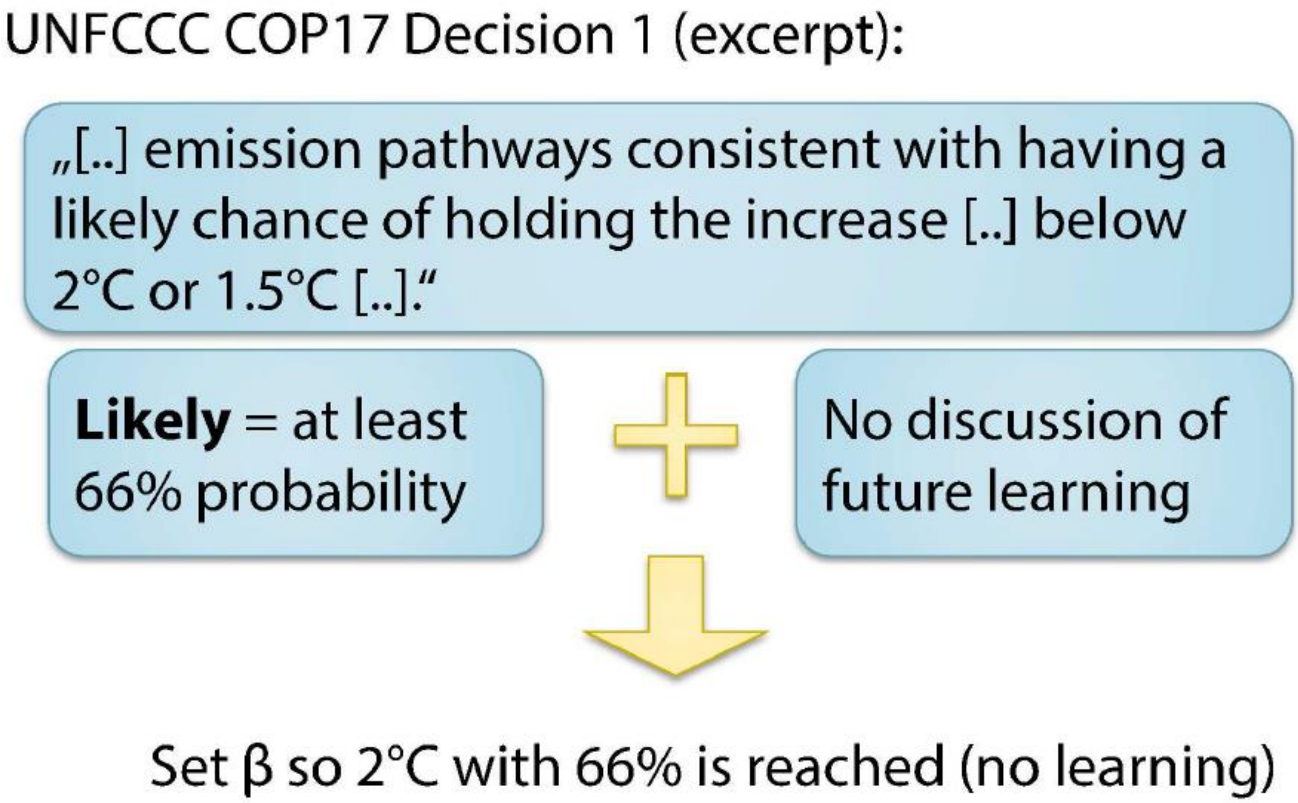
Maximize!

$$\text{Welfare} \quad W = \sum_{t} \sum_{s=1}^{S} p_s \Big[\underbrace{U\big(C(t,s,x)\big)}_{\substack{\text{Utility from} \\ \text{consumption}}} - \underset{\substack{\nwarrow \\ \text{Trade-off parameter} \\ \text{(needs to be calibrated)}}}{\beta} \overbrace{R\big(T(t,s,x)\big)}^{\substack{\text{Risk from} \\ \text{Trespassing}}} \Big] e^{-\delta t}$$

Problems:

- How to choose $R(T)$? (risk metric)
- How to choose β? (trade-off parameter)

Calibration



UNFCCC COP17 Decision 1 (excerpt):

„[..] emission pathways consistent with having a likely chance of holding the increase [..] below 2°C or 1.5°C [..].“

Likely = at least 66% probability

+

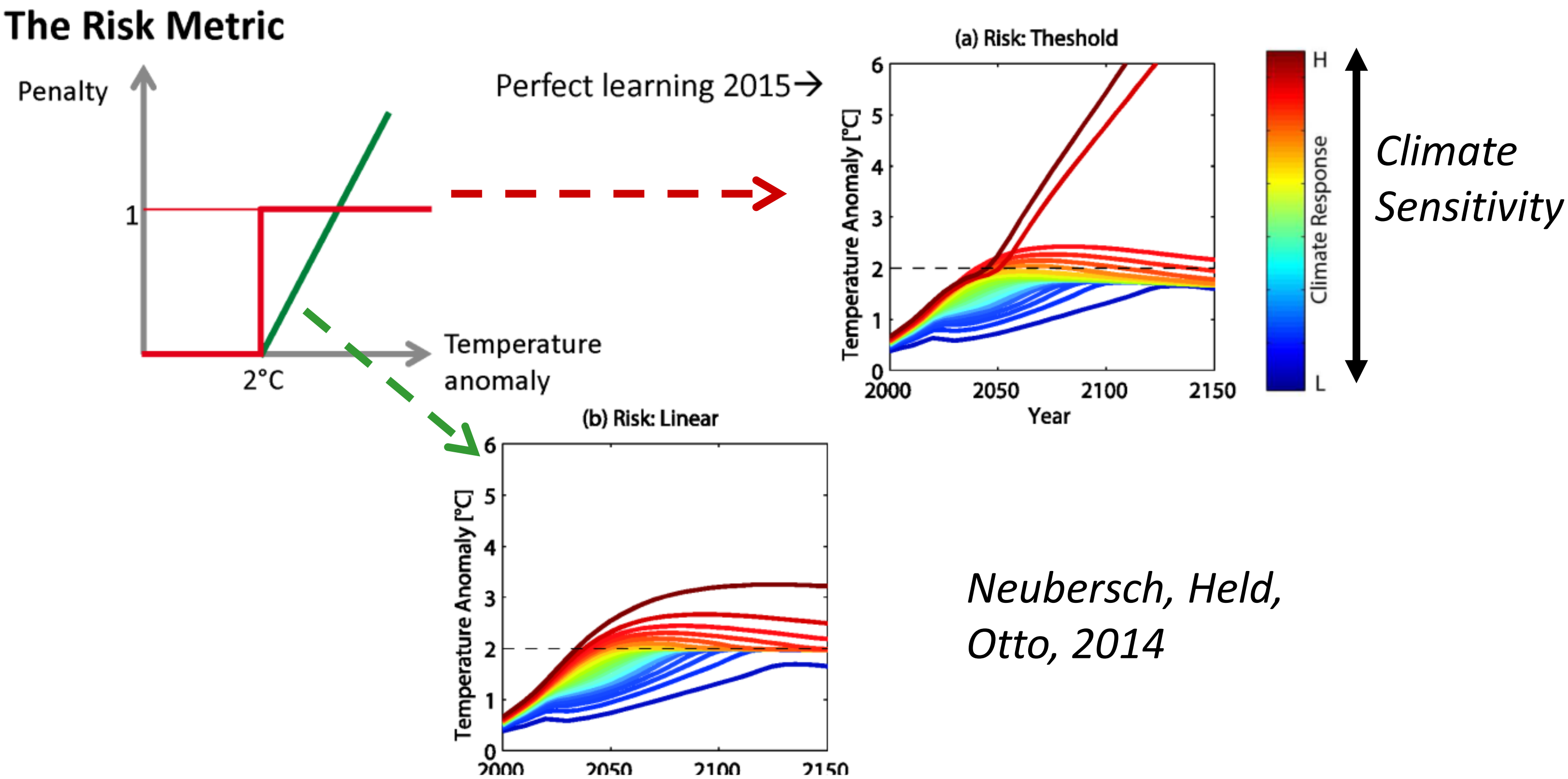
No discussion of future learning

Set β so 2°C with 66% is reached (no learning)

“Extract the value system of the COP / 2° community.”

Neubersch, Held, Otto, 2014

Axiomatic Basis of a Linear Risk Function: Most Conservative Function that Avoids “Holocene Sacrifice”



Neubersch, Held, Otto, 2014

- **Axiom of “Holocene sacrifice inhibition”.**

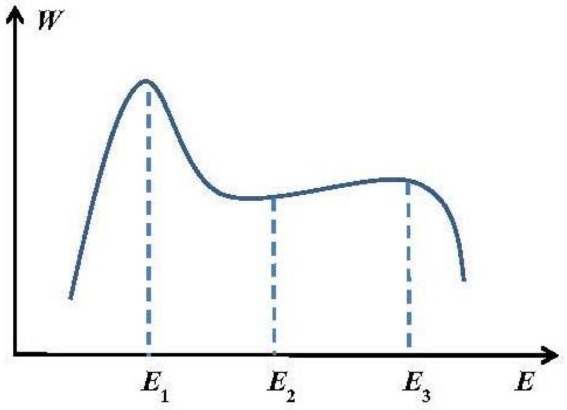
⇒ Multiple optima of welfare must be avoided for *any* mitigation cost function.

⇒ The risk function must be *at least linearly* convex…

…to preserve convexity of welfare for *any* convex mitigation cost structure.

- **i.e. ‘veil of ignorance-approach regarding mitigation costs to infer risk function’**

- Learning that climate sensitivity is larger than expected is equivalent to emitting more than optimal.



Axiom of Sacrifice Inhibition

Imagine society, in a static setting, regards a budget of emissions E* for the world as welfare optimal. If, for some reason, new information arrives that this budget cannot be met because an amount of dE emissions has or will be emitted too much, then the optimal budget goal should be

$$E^{**}=E^{*}+dE$$

and not any larger value.

This is prevented if welfare equation is convex, then there cannot be any jumps in optimal solution.

Neubersch, Held, Otto, 2014

Findings from Cost Risk Analysis for Immediate Action

- ~1000 mitigation scenarios assembled in IPCC AR5 mainly based on CEA.
  - However MIND-based results indicate fair chances CEA control paths can be re-interpreted as good approximations of CRA-based results.

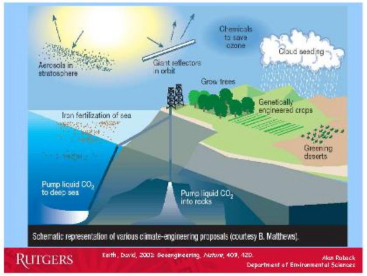
- Then they represent upper limits of mitigation costs due to lack of learning.

- Infeasibilities of lexicographic preferences avoided.

- The expected value of perfect climate information could be on the order of hundreds of billions € / year under a 2° target
  - (on average 1/3 of mitigation costs saved).

(Neubersch, Held, Otto, Climatic Change, 2014)

Joint Mitigation & Solar Radiation Management (SRM) Assessment



Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

Keith, David, 2001: Geoengineering. *Nature*, 409, 420.

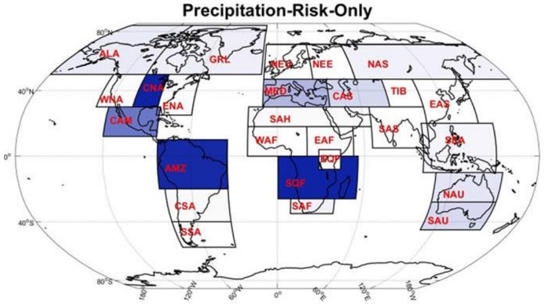
Alan Robock
Department of Environmental Sciences

Assuming compliance with the 2° target:

How would the optimal portfolio of mitigation options change

if we added sulphur aerosol injection to the portfolio ?

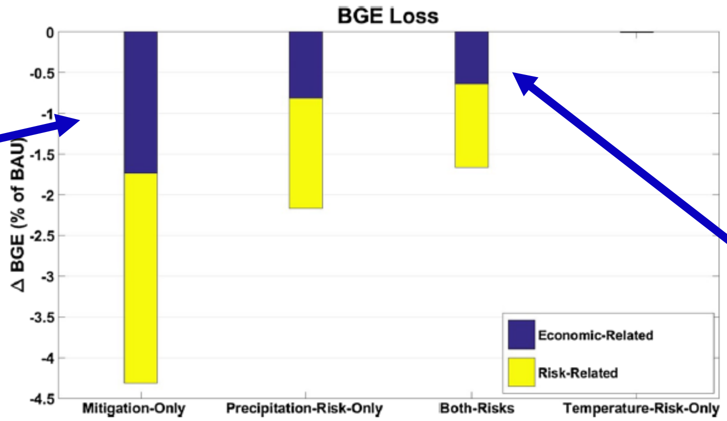
- Include regional climate mismatch in the analysis
- SRM destroys global mean temperature as a good indicator for regional climate
- → Model regional climate explicitly
- Regional targets induced by 2° target:



  - ‘What regional climate would a 2°-proponent have accepted before the advent of SRM?’ (Stankoweit et al., 2015)

Inclusion of SRM: CEA vs CRA

	CEA	**CRA**
Costs only	Mitigation crowded out	Mitigation crowded out
Regional targets activated (all other SRM-risks ignored)	SRM approximately prohibited	SRM significant



Costs: Mitigation only

Costs: SRM +Mitigation

Roshan et al., 2019

Summary on Cost Risk Analysis

- Currently, both cost benefit and cost effectiveness analysis are structurally unstable against climate(impact)-uncertainty.

- Cost risk analysis, as a hybrid of both, approximately and tentatively reconfirms CEA-based results for {immediate action and w/o climate engineering}.

- CRA allows for specifying an expected value of information for reducing climate response uncertainty.
  - ~ 1/3 of expected mitigation costs could be saved.

- CRA would recommend qualitatively
  - less mitigation under delayed action and
  - more solar radiation management (regional climate risk only)

  than CEA would do.

A Persistent Discrepancy Between the 2° Target and Emission Reduction Action

- The Paris agreement formulated the 2° target as a legally binding target.
- However, current policies point towards 3° C warming (Climate Action Tracker, 2020).
- A list of hypotheses why this is the case…:

Frictions & Instruments

Friction	Potential solution
Free rider problem	Coalition formation & border tax adjustments
Lobbying of owners of fossil resources	Resolution of information asymmetries
Impacts on diverse income groups	Targeted distributional policies
Side effects of mitigation options	Metrics of sustainability also for technology options
Uncertainty about outcomes of policy interventions	Decision-making under uncertainty-based approaches

Frictions & Instruments

Friction	Potential solution
Resignation in civil society	Communicate climate problem in combination with solution options
Academic scepticism about climate targets as a valid concept	Generate a precaution-based theoretical approach for decision-making
Abstractness of temperature targets	Communicate pros & cons of various temperature levels

Expectation: CLICCS Will Shed Light on the Underlying Mechanisms

Photo: J.Marotzke/M.Böttinger

- Cluster of Excellence Climate, Climatic Change, and Society (CLICCS)
- Balanced contribution from natural science and social science

Summary

- The 2°-target was derived from considerations of precaution, oriented at natural variability.
- In case of complete ignorance of avoided damages, the 2° target would induce a reduction of the centennial growth rate [in 1/yr] of 0.06% points.
- The underlying decision-analytic framework could be generalized to a dynamically consistent interpretation which retroactively confirms above numbers for the limiting case of immediate implementation of a mitigation policy.
- The integration of natural and social climate science will be key in order to explain the persistent discrepancy of climate targets and action.