Cumulative emissions and the long tail of carbon removal

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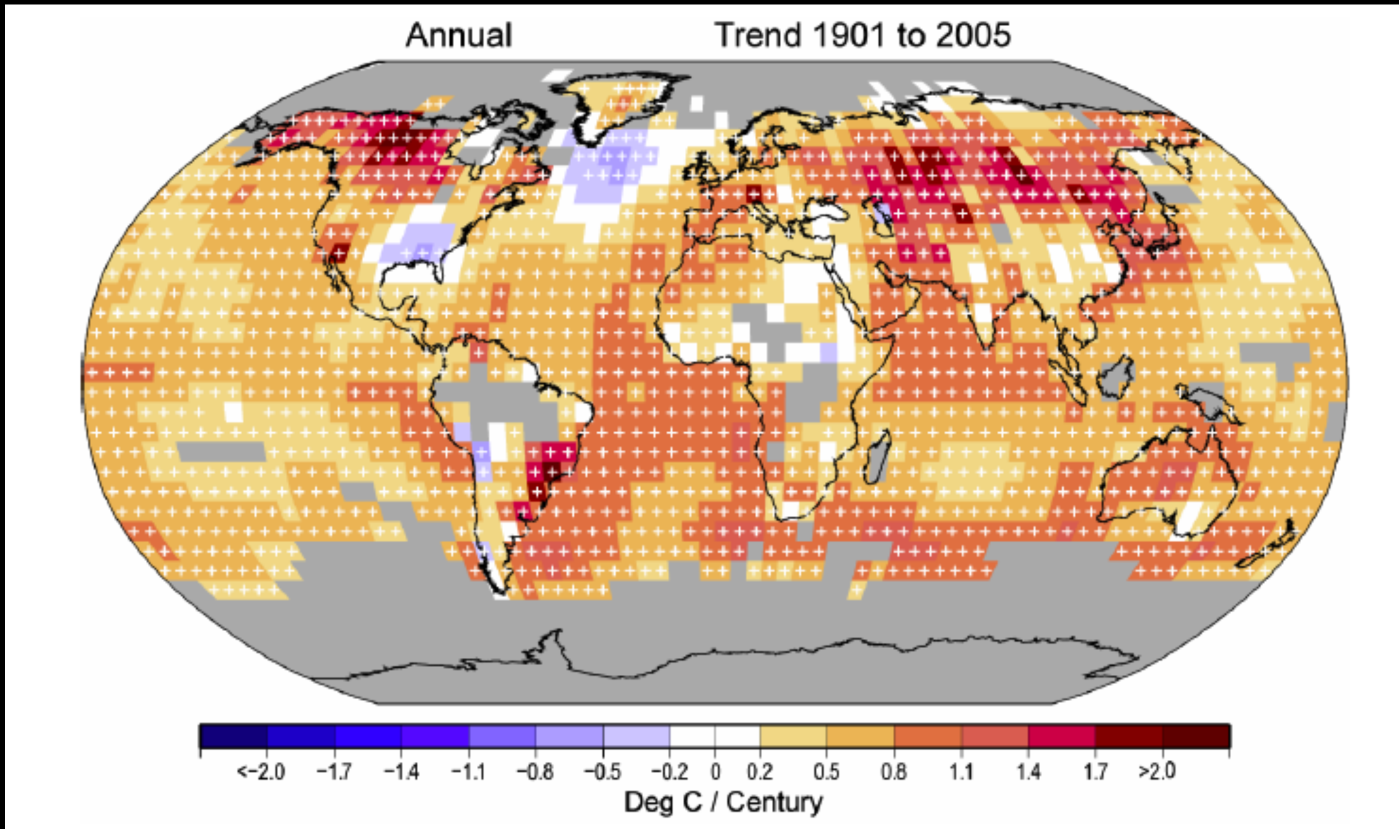
What did you find most surprising about the assigned readings?

What do you think are the things that are most confusing about carbon's long-lasting impact on climate for the public? For scientists?

EAPS
Earth, Atmospheric and Planetary Sciences

The World Has Warmed



Last ten years: warmest decade since at least the late 1800s

Widespread warming has occurred. Globally averaged, the planet is about 0.75°C warmer than it was in 1880, based upon dozens of high-quality long records using thermometers worldwide, including land and ocean.

1	2007
2	2005
3	1998
4	2002
5	2006
6	2008
7	2003
8	2009
9	2001
10	2004
11	1999
12	1995
13	1997
14	1990
15	2000
16	1988
17	1991
18	1981
19	1983
20	1994
21	1987
22	1938
23	1989
24	1944
25	1993

UNFCCC Agreements

ARTICLE 2: OBJECTIVE

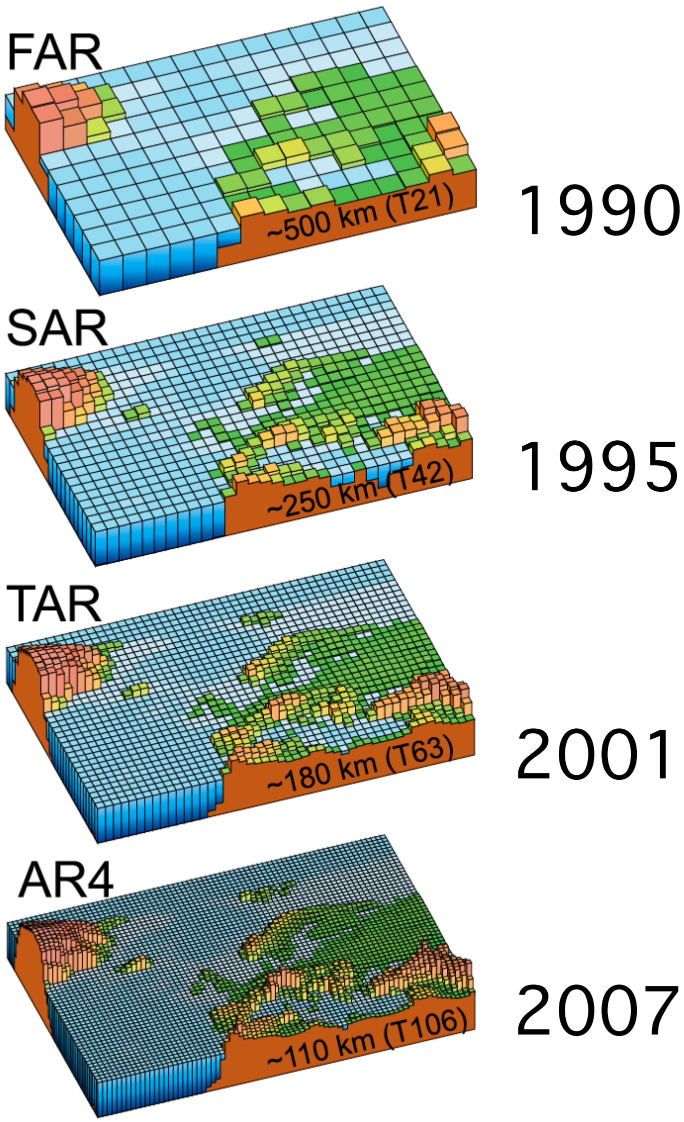
The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, *stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference* with the climate system. Such a level should be *achieved within a time-frame sufficient to allow ecosystems to adapt* naturally to climate change, to *ensure that food production is not threatened* and to *enable economic development to proceed in a sustainable manner*.

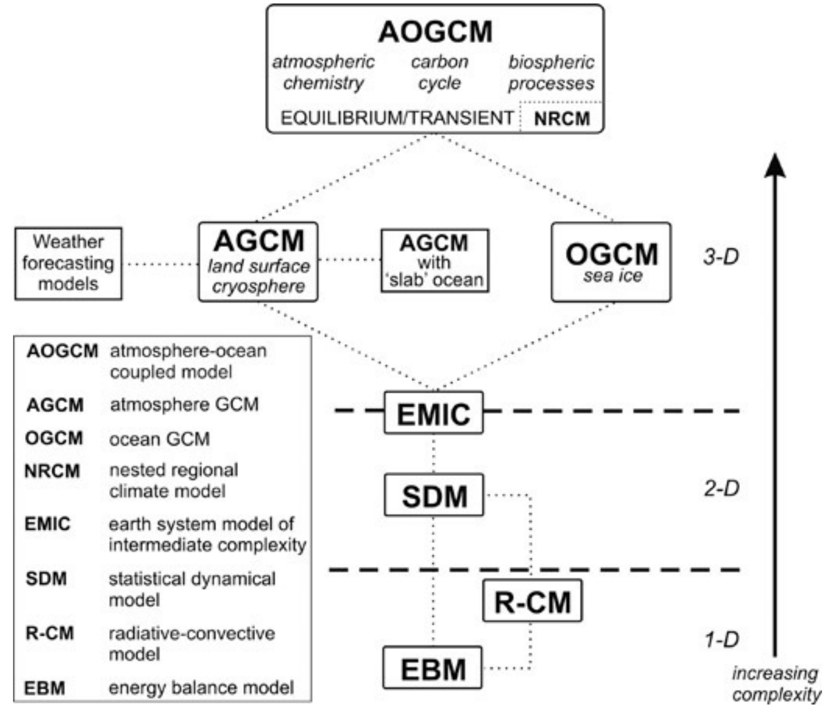
UNFCCC Agreements

ARTICLE 3: PRINCIPLES

1. The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.
2. ….
3. The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are *threats of serious or irreversible damage*, lack of full scientific certainty should not be used as a reason for postponing such measures…..

Tools used to study future change and stabilization





Bern 2.5cc EMIC: Fill the gap between box model and AOGCM.

Oceans: Equations for momentum, heat, salt and tracers…the Atlantic, Pacific, Indian and Southern Oceans are represented separately, with the Southern Ocean being the connection between the individual basins.
14 levels in the ocean, resolution 7.5-15°.

Tuned but effective

Compare temperature, salinity, $\Delta^{14}C$, dissolved inorganic carbon, alkalinity, to observations in various ocean regions.

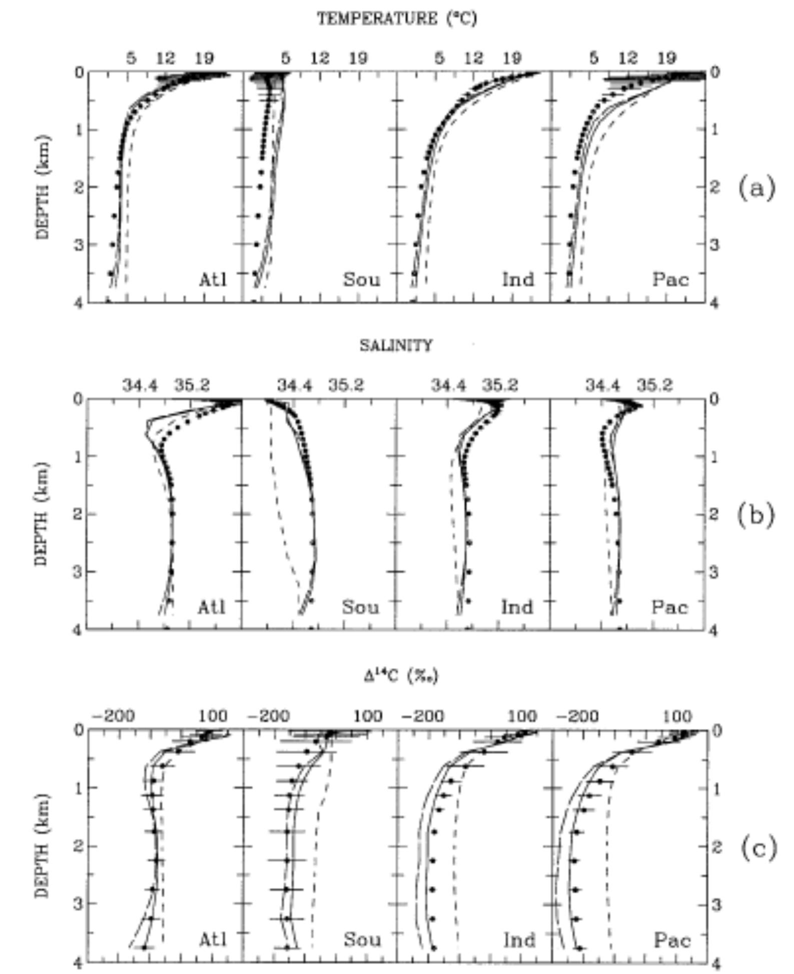


Fig. 1. Basin mean vertical profiles of (a) temperature, (b) salinity and (c) $\Delta^{14}C$ of dissolved inorganic carbon. Dots (●) are volume-weighted averages computed from the data of (a) Levitus and Boyer (1994a), (b) Levitus et al. (1994) and (c) GEOSECS (1987) interpolated onto the vertical model grid. Horizonal bars denote 1 standard deviation around these averages. The three curves are model results with $K_v = 0.1 \cdot 10^{-4}\ m^2 s^{-1}$ (— — —), $0.2 \times 10^{-4}\ m^2 s^{-1}$ (———) and $1.0 \cdot 10^{-4}\ m^2 s^{-1}$ (- - -).

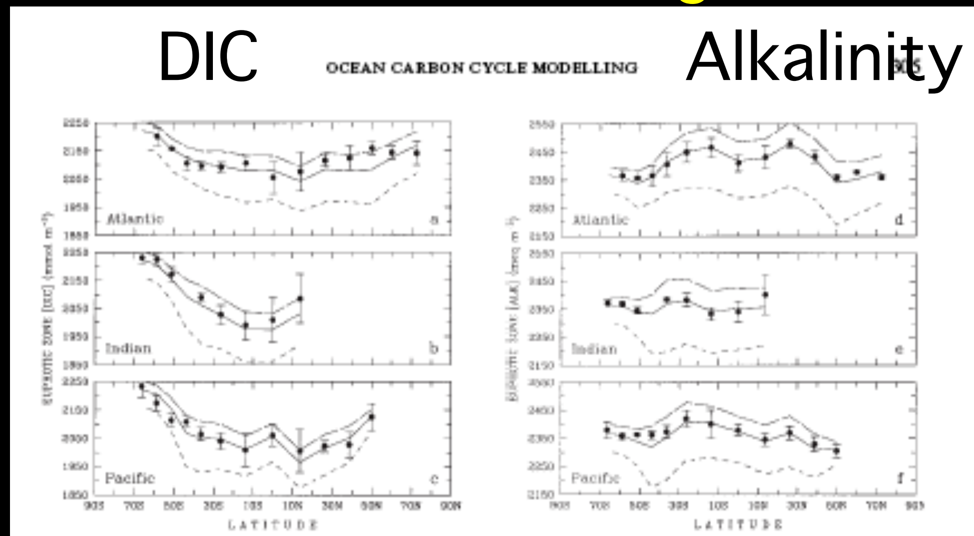
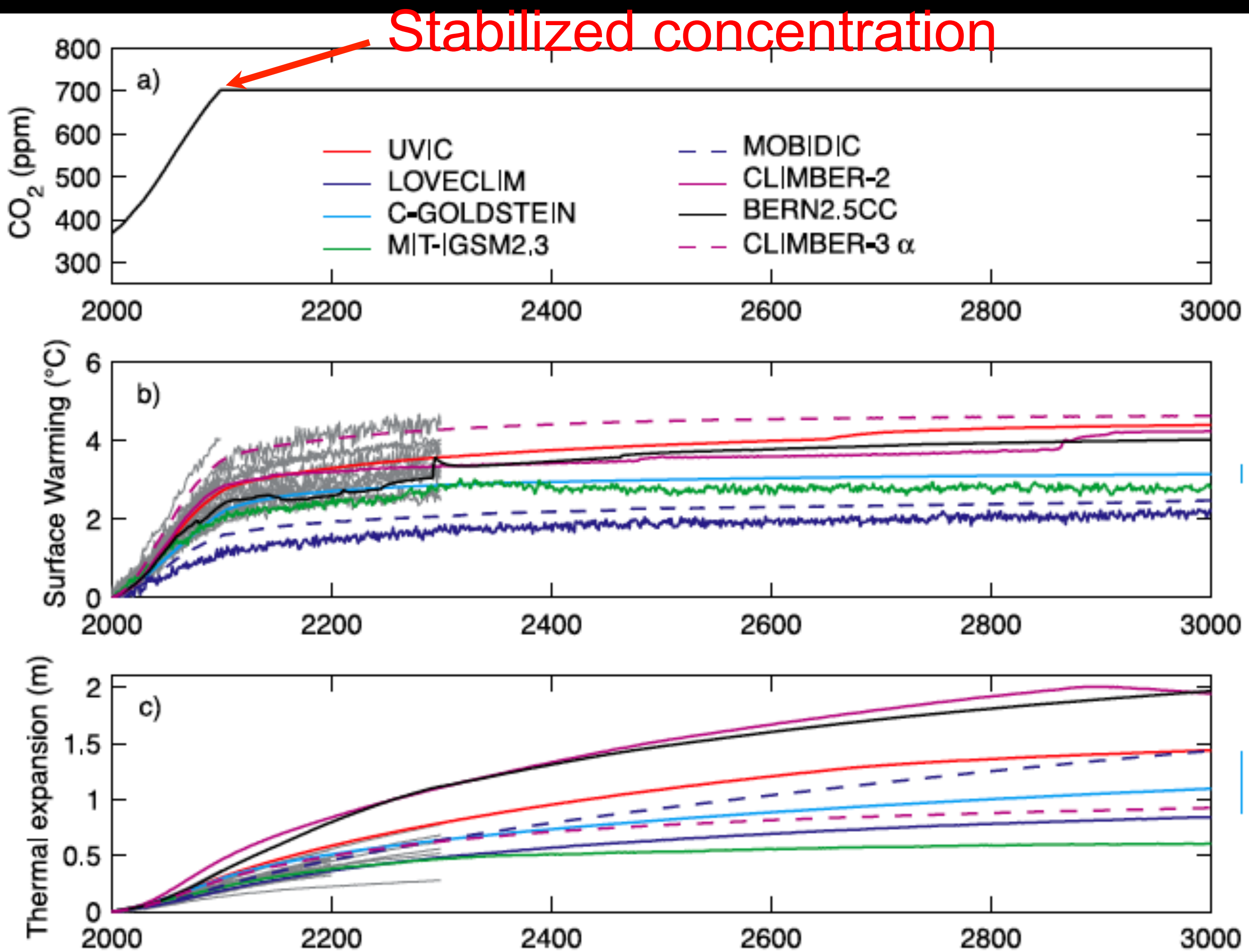


Fig. 8. Zonal mean concentration of (a–c) dissolved inorganic carbon and (d–f) alkalinity in the top 100 m in three main oceanic basins. Dots (●) are zonal averages computed from GEOSECS (1987) and TTO (1986) data (TTO stations 124, 143, 148 in the northern North Atlantic where DIC and ALK data from the GEOSECS expedition are not available). Vertical bars denote 1 standard deviation. The three curves are model results with $\overline{r_p} = 0.03$ (— — —), 0.06 (———) and 0.12 (- - -).

Marchal et al., Tellus, 1998.

Beyond the 21st Century: "stabilization"?



IPCC, WG1 (2007), chapter 10

Stabilized concentration

EMICs: New Tool to Probe the Very Long Term

UNFCCC Article 2:

Stabilization of GHG at a level that avoids 'dangerous interference'.

Article 3: emphasizes "serious or irreversible damage"

Some definitions…..

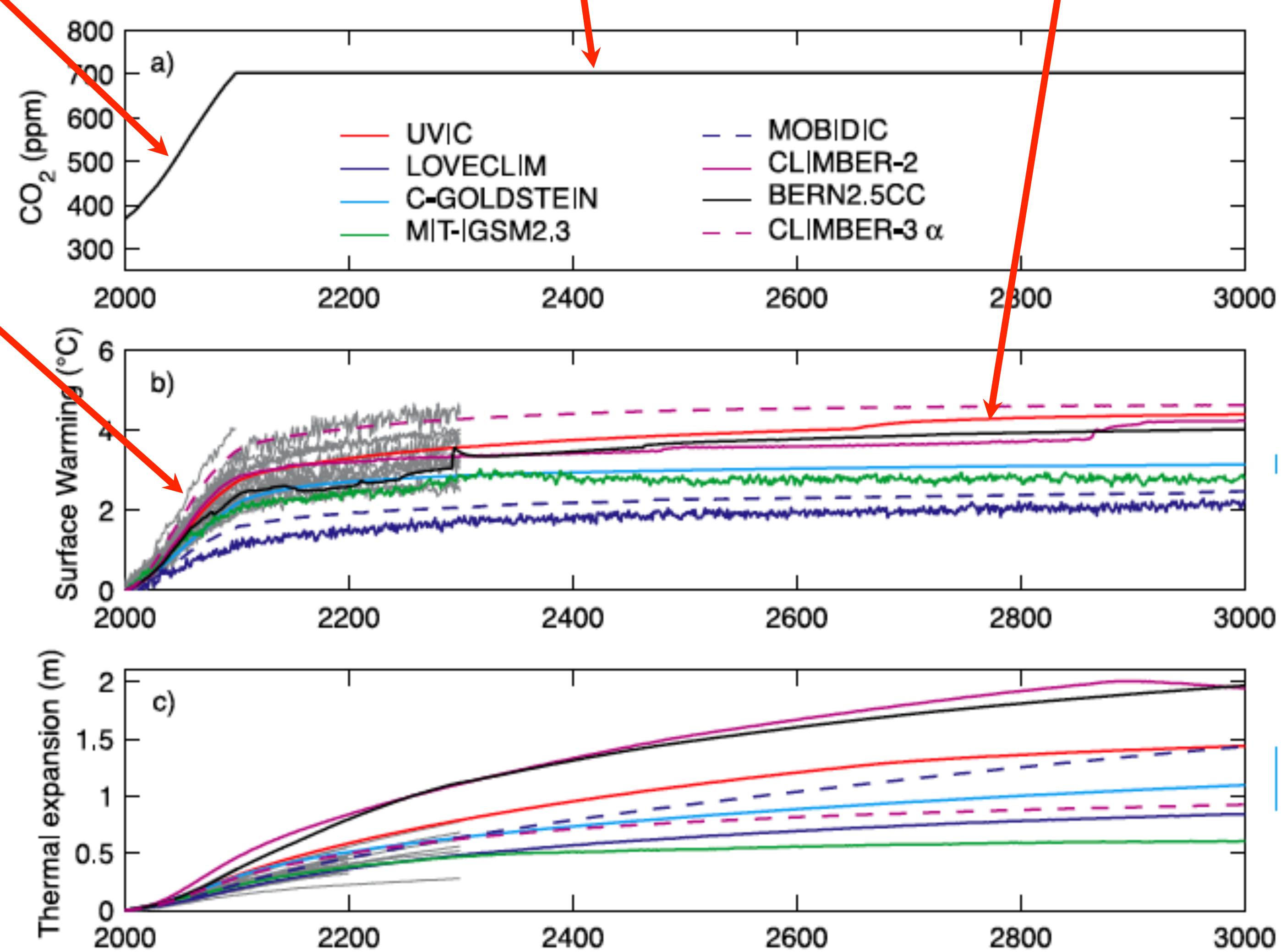
Radiative forcing increasing

Radiative forcing stabilized

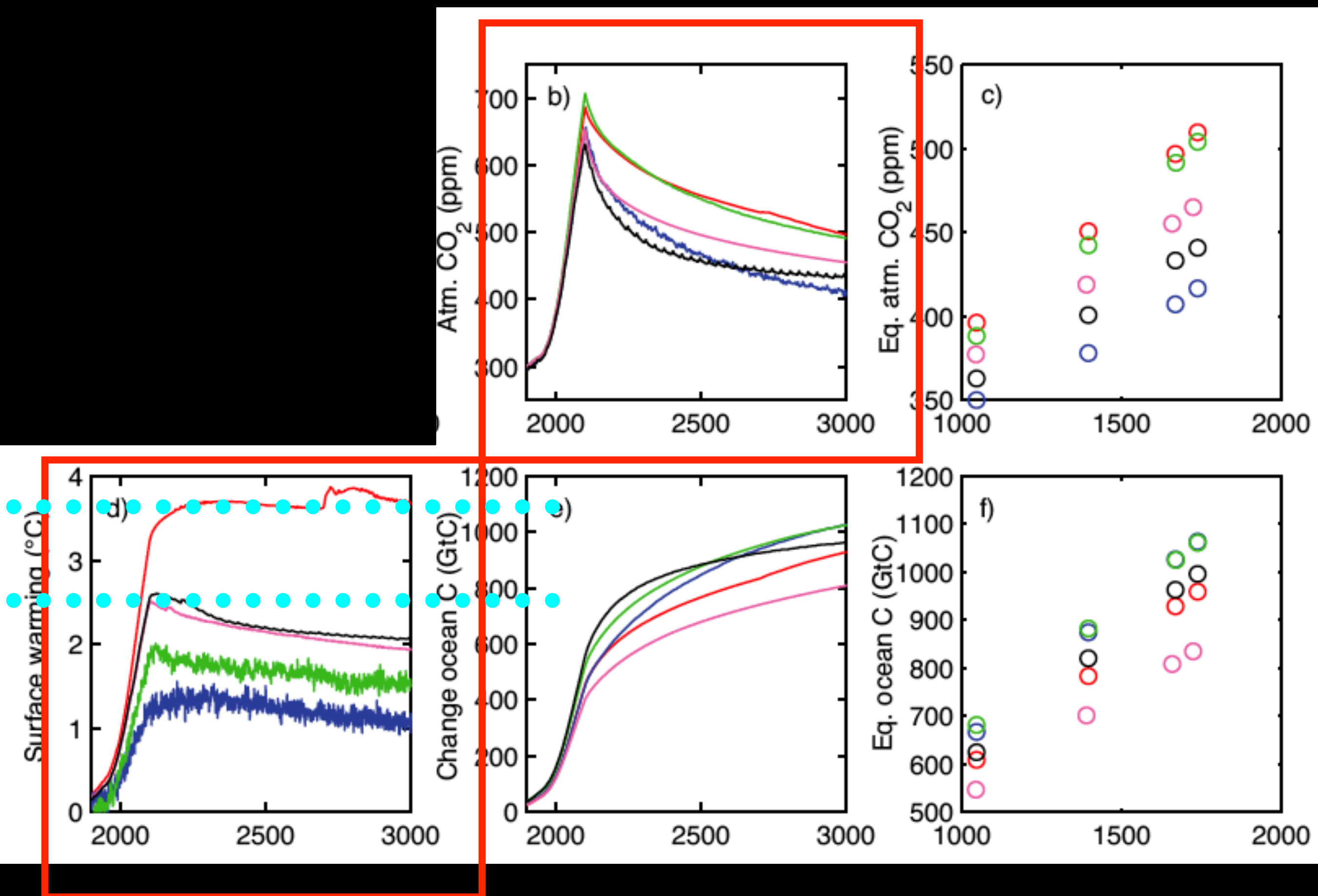
Quasi equilibrium climate response

Transient climate response occurring

For double pre-industrial CO2, TCR≈1.5°C; λ≈3°C. Stabilize→ more warming in pipeline



Stop Emissions Completely: Can The World Return to A Natural State?



One test: ramp towards 750, then stop emitting.

≈450 ppmv left in 3000. Warming remains ≈constant (±0.5°C) for more than 1000 yrs.

Note: geoengineering not considered....

IPCC, WG1 (2007), chapter 10; this general behavior is not dependent on climate sensitivity or carbon feedbacks

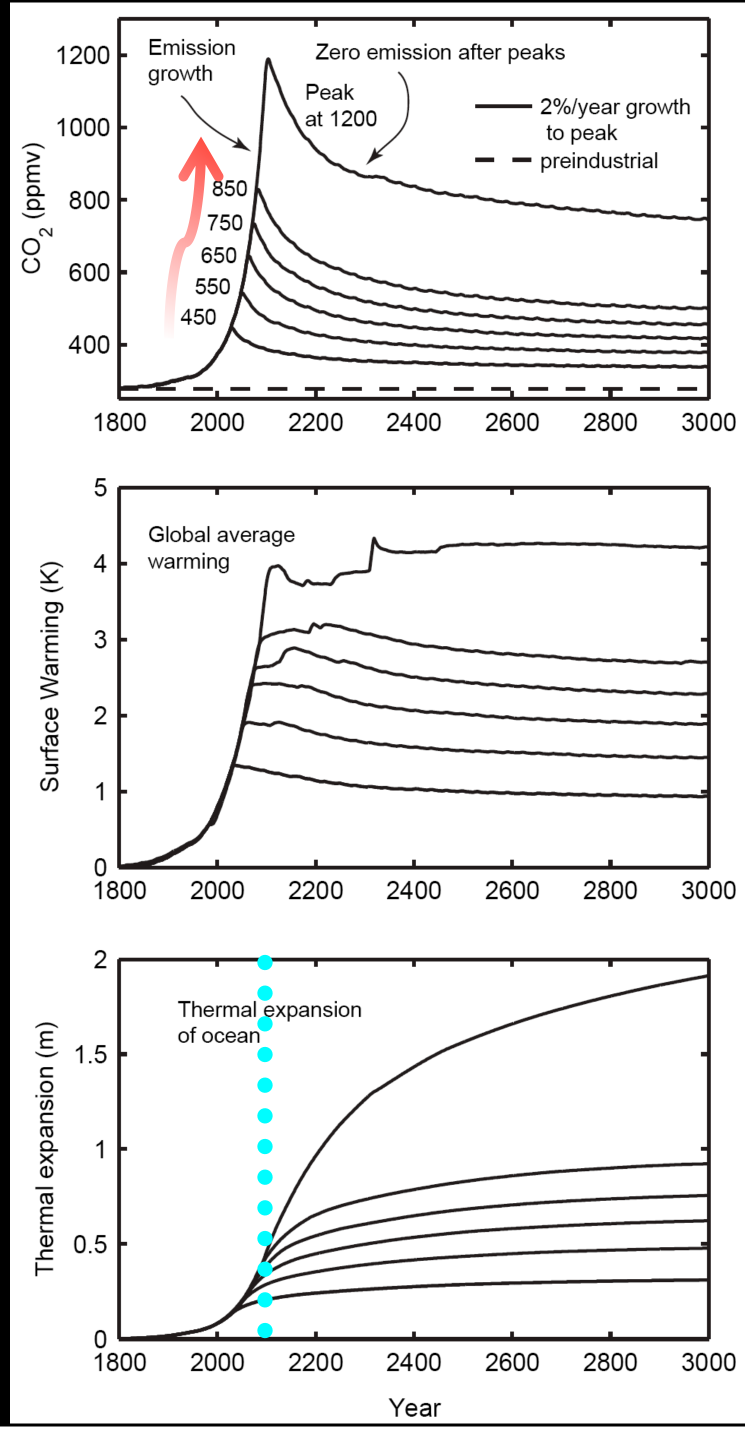
See also first EMIC paper on this by Matthews and Caldeira, 2008; AOGCM study by Lowe et al, 2009

Thermal sea level rise is slower/later, but is irreversibly linked to the peak CO2 we reach in the 21st century.

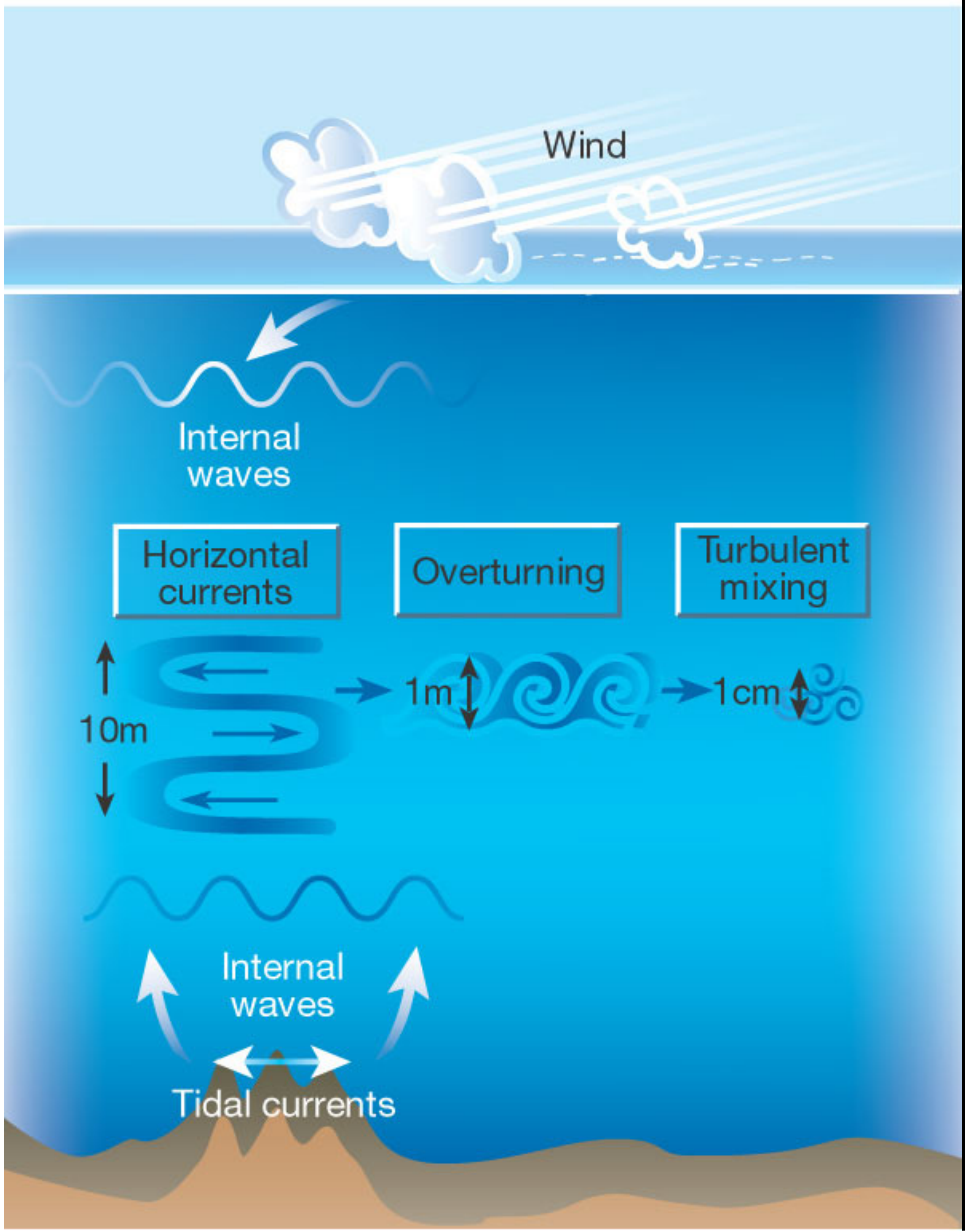
What about the ice sheets? How much will Greenland melt if temperatures stay elevated for more than a thousand years?

We humans will make decisions in this century that will change the geography of the Earth.

Solomon et al., PNAS, 2009



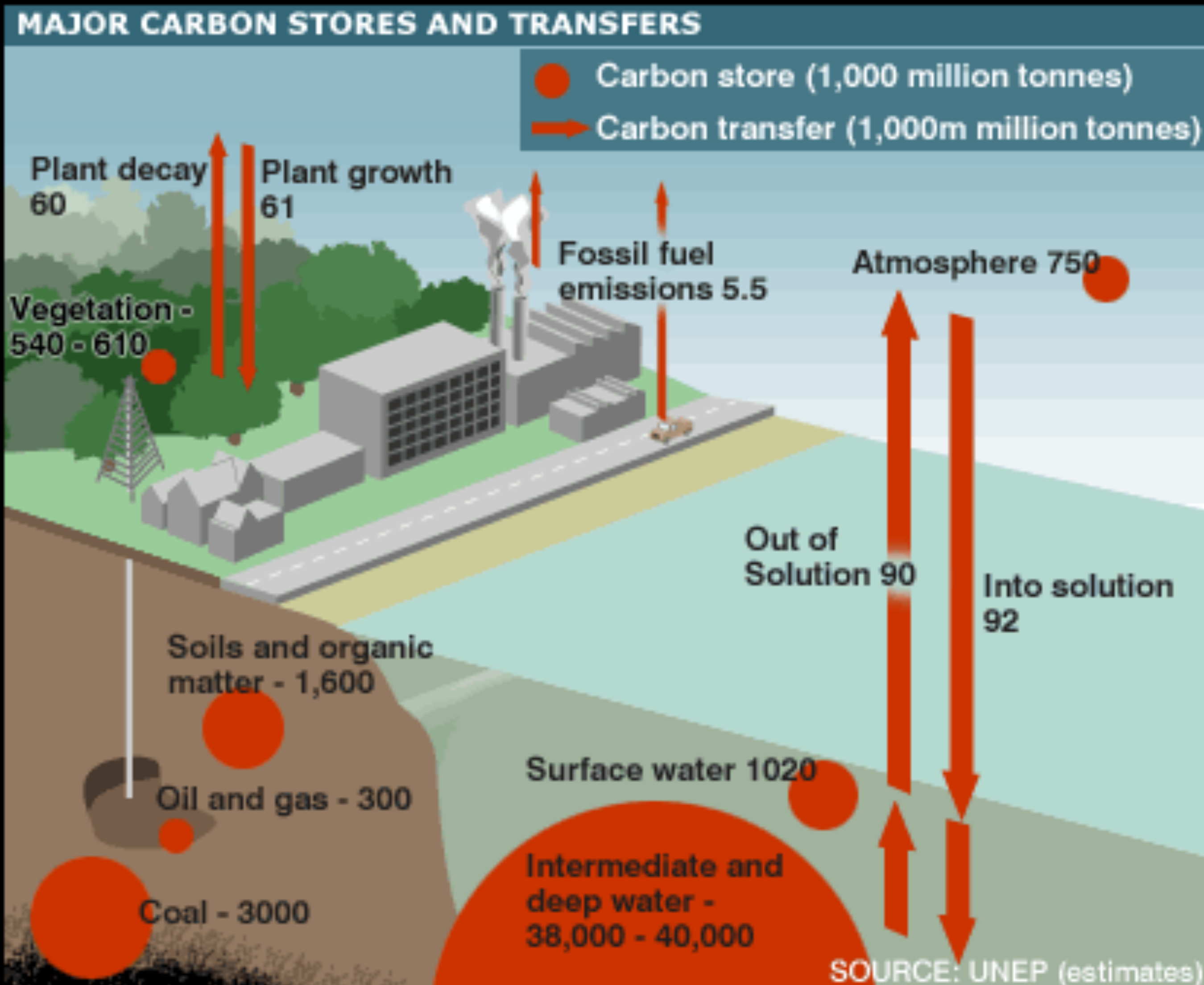
Carbon Sink and Heat Transport: Deep Ocean is Key



Linked physics and relationship to timescales for carbon and ocean-climate system inertia.

Warming and carbon both involve very slow deep ocean time scales.

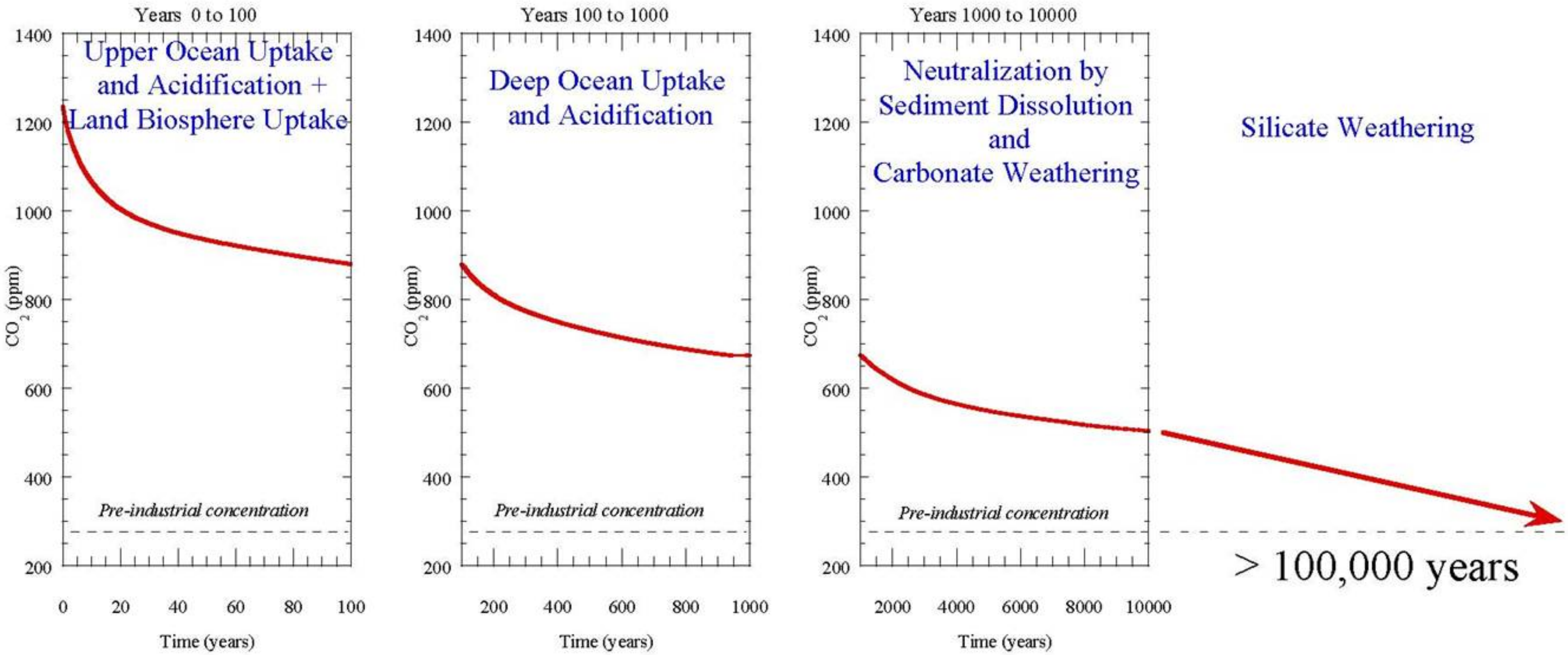
Carbon Cycle: It Really Is A Cycle



Some man-made CO2 goes (in the short-term) from the atmosphere to vegetation, surface ocean.

Long term sink is deep ocean. It's very slow.

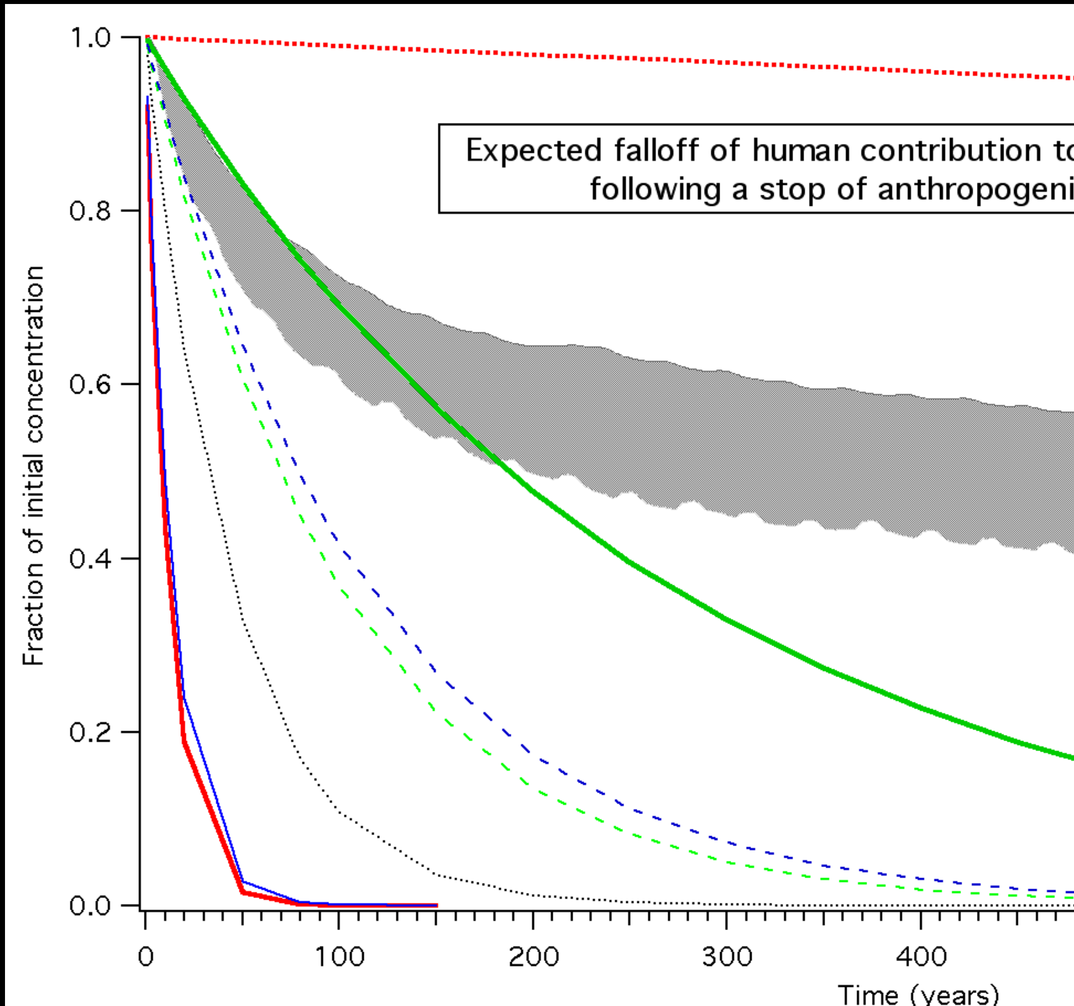
What controls CO2 removals over time?



Note: there is no single carbon dioxide lifetime or removal time scale. There is a sequence of sinks.

Stabilization Targets, NRC, 2010

Carbon Dioxide Is A Unique Gas



CO_2 dissolves in seawater to acidify the ocean (1). Dissolution is limited by buffering. Added carbonate (i.e. rock weathering) can very slowly dissolve more (2).

(1) $CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$ Initial step

(2) $CO_2 + H_2O + CO_3^{-2} \leftrightarrow 2HCO_3^-$ ~100,000 years

Archer (many papers); review in Solomon et al., PNAS, 2009; Revelle and Suess 1957

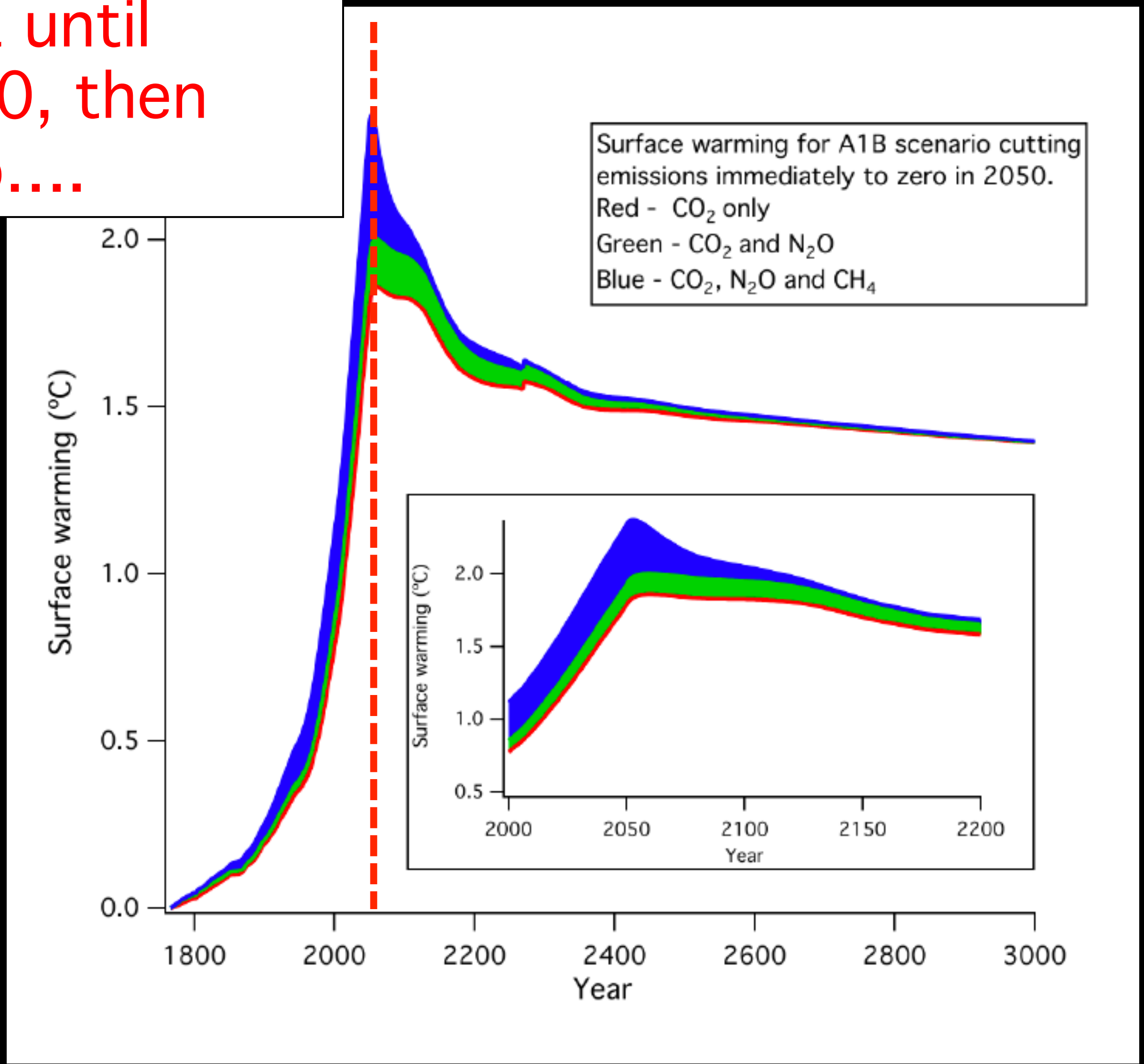
Beyond CO_2 to other manmade greenhouse gases?

Emit until 2050, then stop....

Lifetime of N_2O ≈ 110 years

Lifetime of CH_4 ≈ 10 years

Warming due to CO_2 persists in this example for >1000 yrs; for N_2O several hundred yrs; for methane many decades. The longer we emit, the worse it gets, even for shorter-lived species.



Bern 2.5CC EMIC runs - Solomon et al., PNAS, 2010.

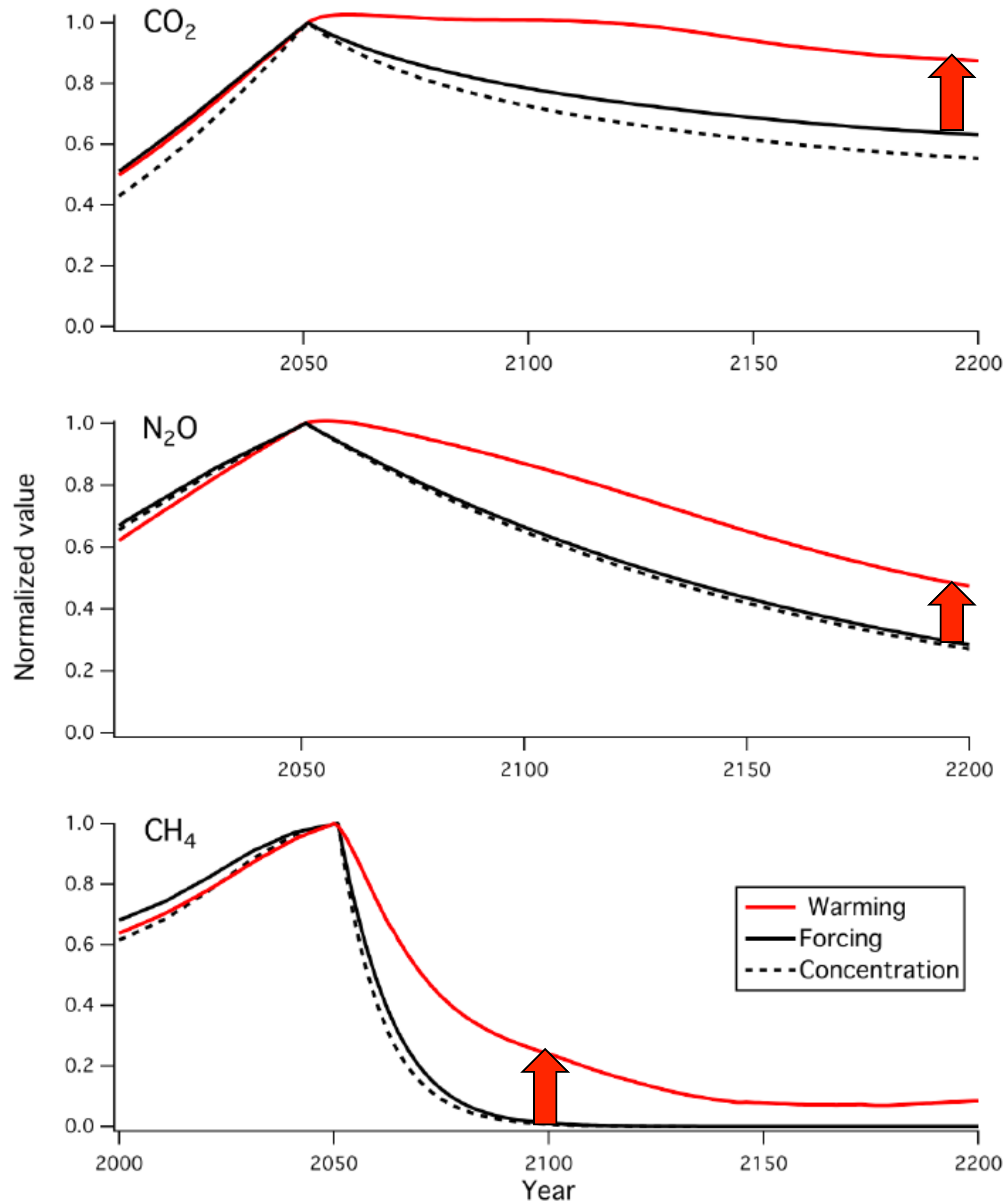
Warming lasts longer than the gases do.

Why?

-Climate system lags (ocean heat uptake)

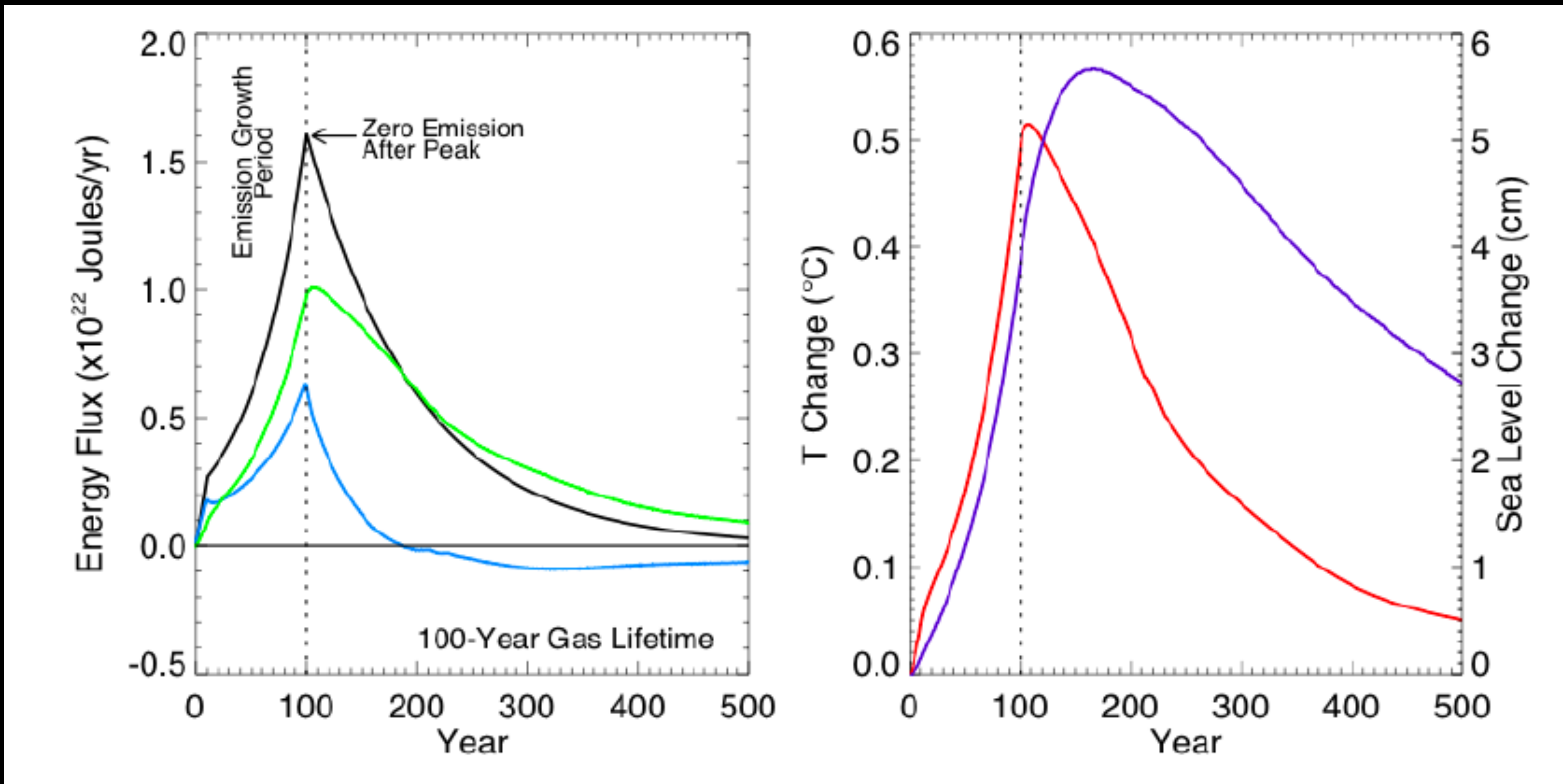
-Nonlinear spectroscopy for some (CO_2, CH_4).

->The same factors that can reduce warming 'on the way up' will slow cooling off 'on the way down'.



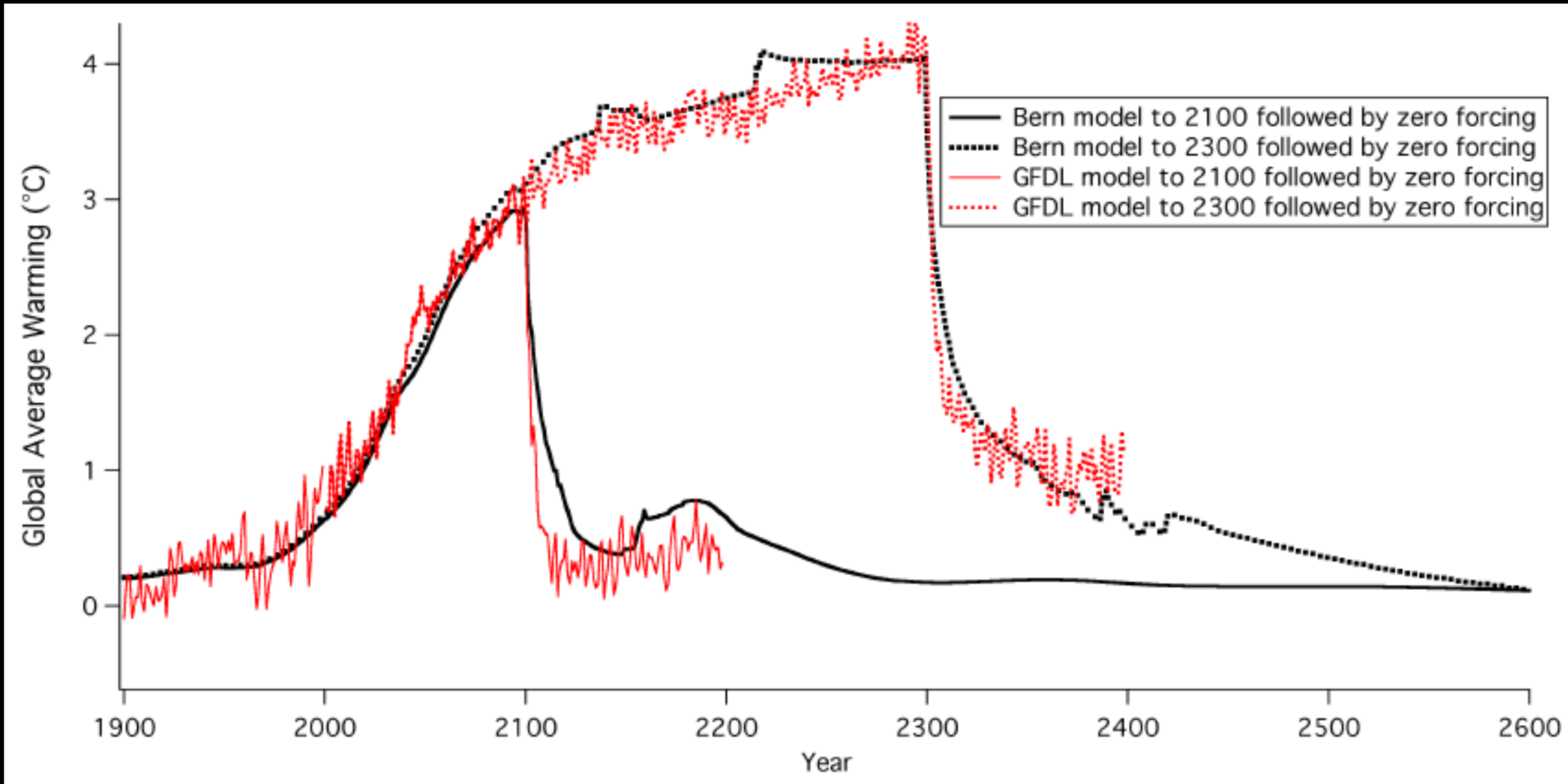
Bern 2.5CC EMIC runs - Solomon et al., PNAS, 2010.

Energy that goes into the ocean while concentrations are enhanced will come out again if emissions cease. For a short-lived gas such as methane, ocean heat uptake quickly becomes ocean heat release. For longer-lived gases, RF continues, energy keeps going into (and coming out of) the ocean for a long time...



Bern 2.5CC EMIC runs - Solomon et al., PNAS, 2010.

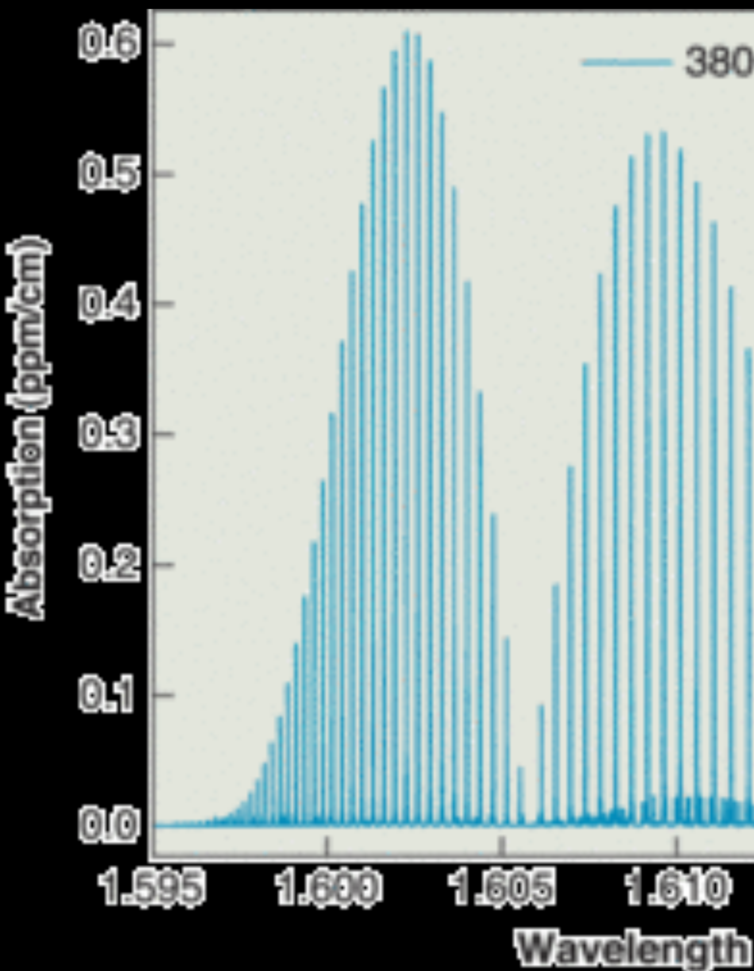
Should we believe the simple EMIC?



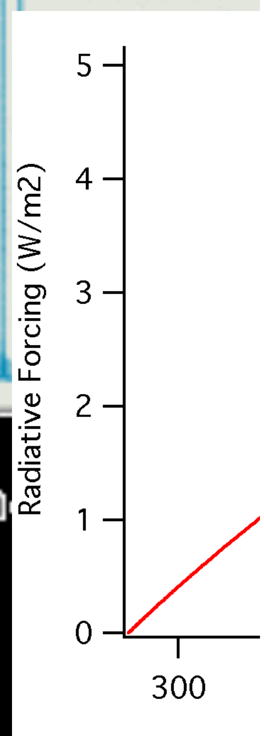
Extreme physics test for *immediate stop to all forcing* (i.e., infinitely short gas, i.e., aerosol lifetime). The longer human-induced forcing lasts, the more persistent the warming (or cooling)...

Held et al.,J. Clim. 2010; also Froelicher and Joos, Clim. Dyn., 2010

The spectroscopy of CO2:



Strong absorption in line centers
Basically Beer's law....
$I = I_o e^{-s*N}$



"..if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression..."
Svante August Arrhenius (1859 - 1927)

Also significant for CH4 but not other GHGs

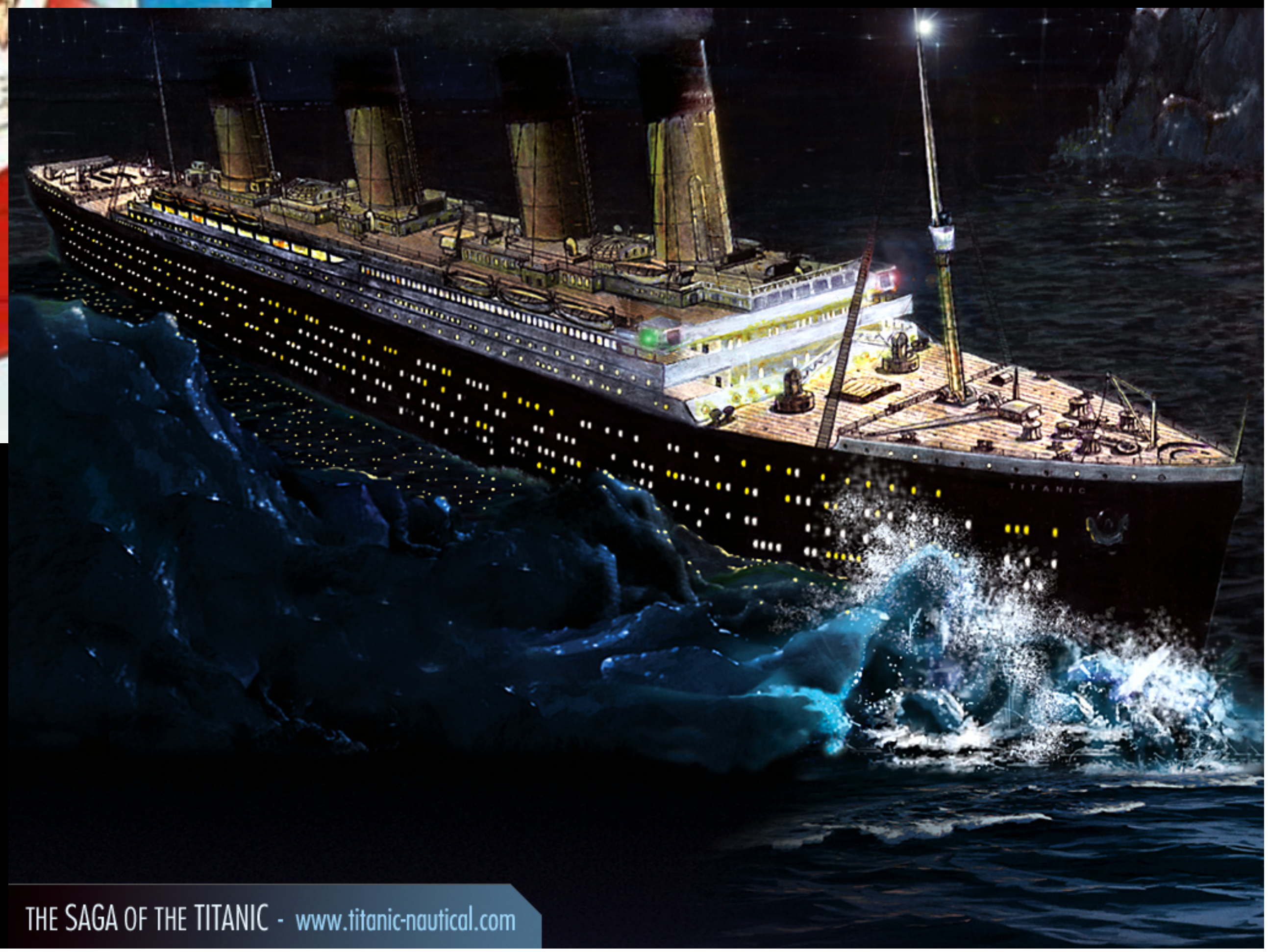
Put it all together for CO2:

-Anthropogenic contribution to CO_2 concentration decays to a value of about 40% of the peak in 1000 yrs

- Meanwhile, transient to equilibrium warming evolves; the ratio of the two is ≈1.5-2. Warming is 'realized'.

-Nonlinear spectroscopy enhances warming in decay period by about 15-30% compared to concentration decrease relative to peak (secondary but significant impact on irreversibility)

Stop on a dime



Not so fast...

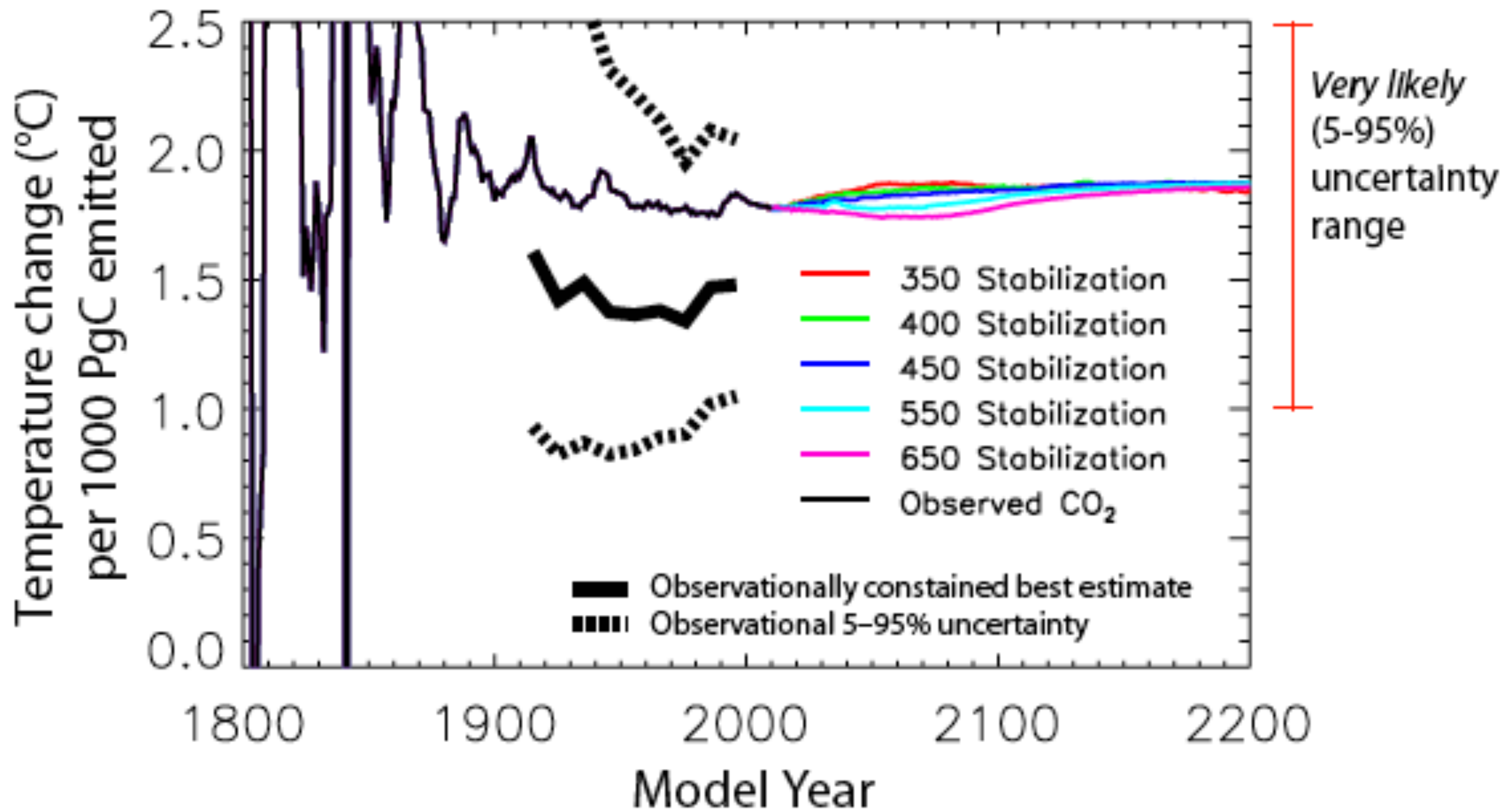
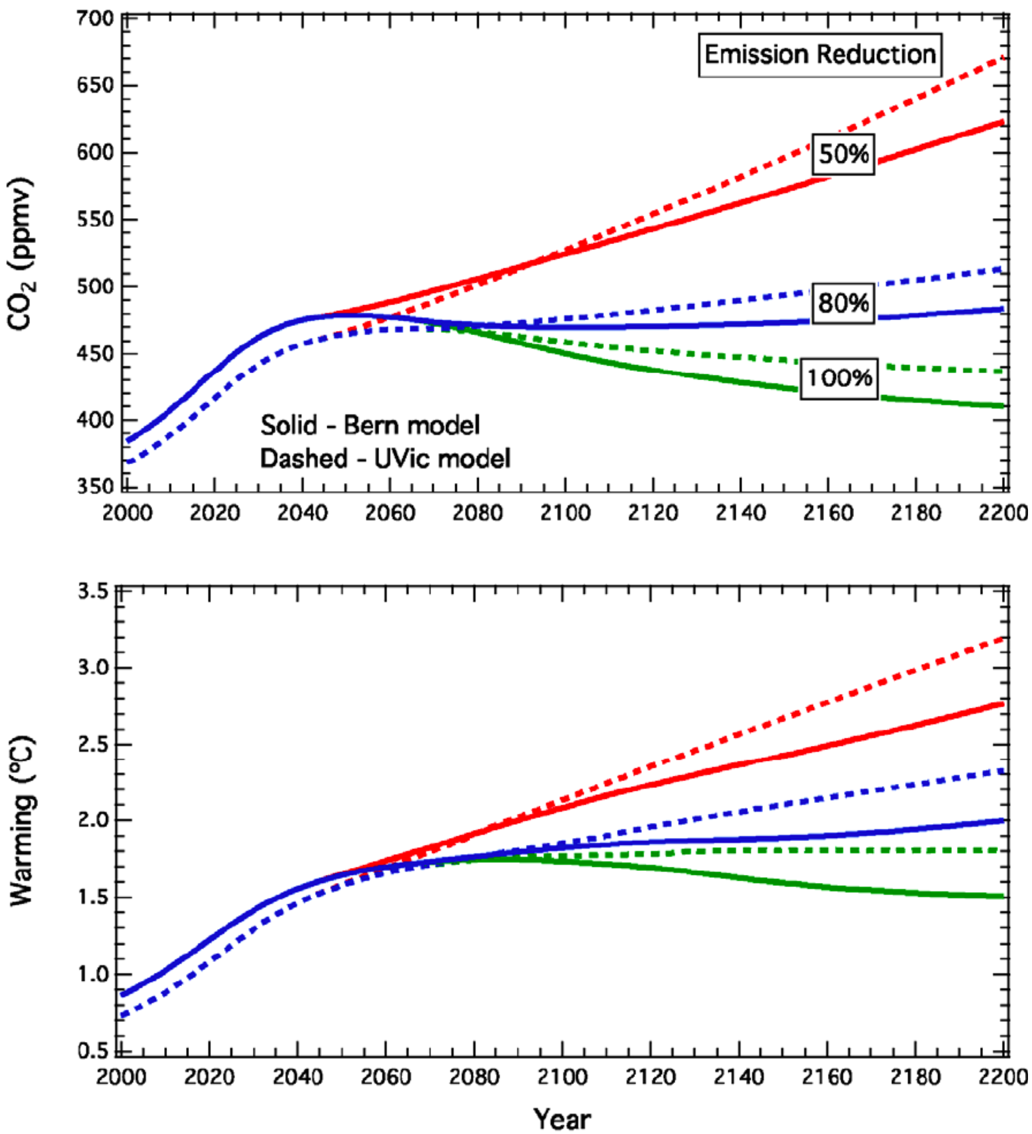


Figure 2: Simulated temperature change per 1000 PgC cumulative carbon emitted. Observational constraints for the twentieth century are given by the thick solid and dashed lines, as in *Matthews et al.* (2009). The *very likely* (5-95%) uncertainty range is indicated by the red error bar, based on a combination of estimates given by *Matthews et al.* (2009) and *Allen et al.* (2009).

From Matthews et al., 2009; see also Zickfeld et al., 2011

Warming and Stabilization Targets



Deep emissions reductions (>80%) would be required for long-term stabilization of carbon dioxide at any chosen target (450, 550, 650 ppm….).

AND

Stabilization folllowing typical trajectories imply a future with at least TWICE as much warming (and DOUBLE many of the impacts) as we observe while CO2 ramps (because λ/TCR ≈2).

Choices/drivers of the policy target?

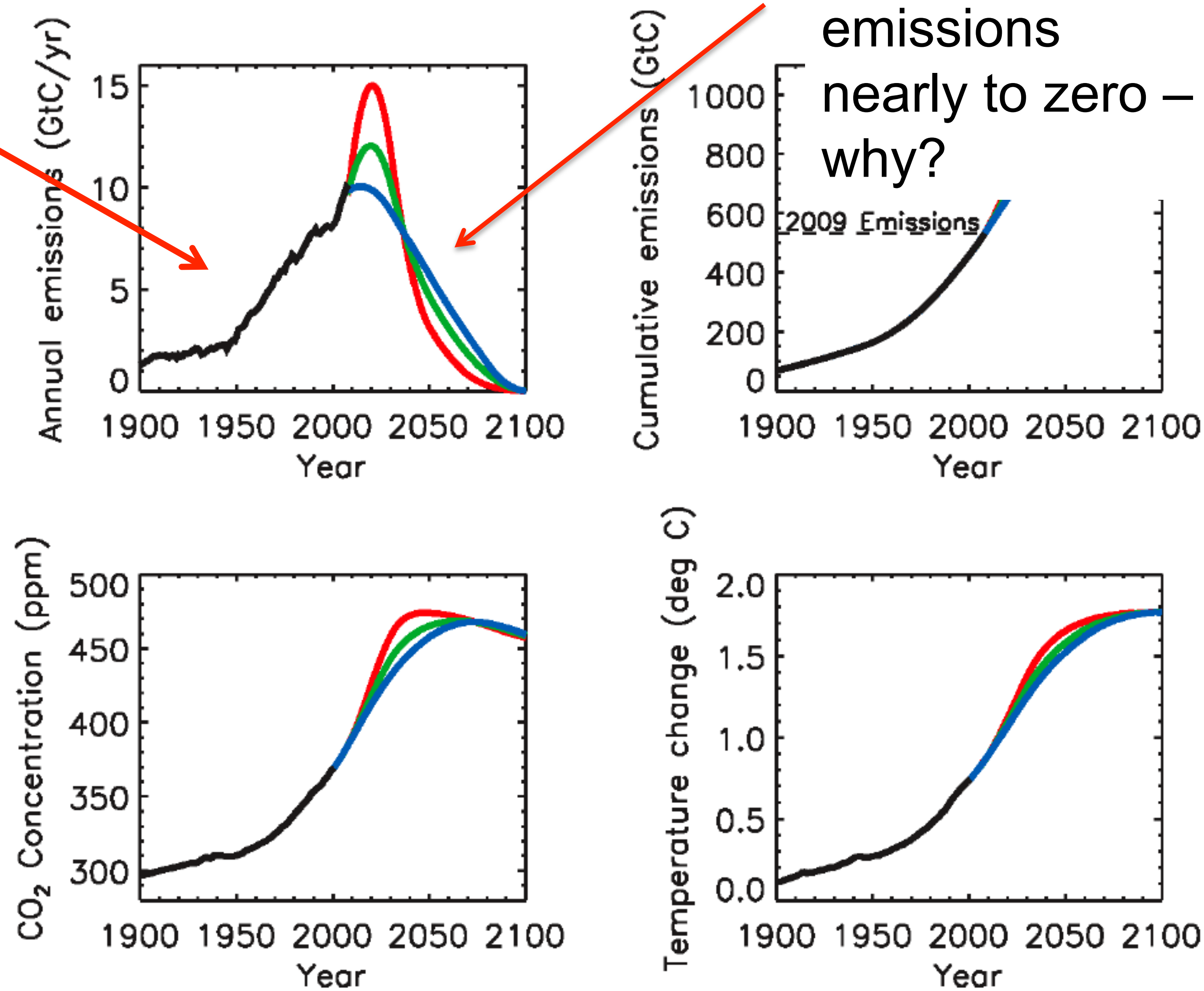
Long-term (carbon-controlled) and short-term (carbon and methane and aerosols…..)?

Stabilization Targets, National Res. Council, 2010

Cumulative carbon

Different trajectories for emission, same warming. *Cumulative* carbon determines the CO2-induced warming.

Stabilization requires driving emissions nearly to zero – why?



Matthews et al., 2009; see Stabilization Targets, National Res. Council, 2010

The robustness of future warming to cumulative carbon, and its very long timescale have been established in the past few years of research.

How much more carbon will we choose to emit as a planet?

How could this scientific result affect policy deliberations?

Stabilization Targets, National Res. Council, 2010

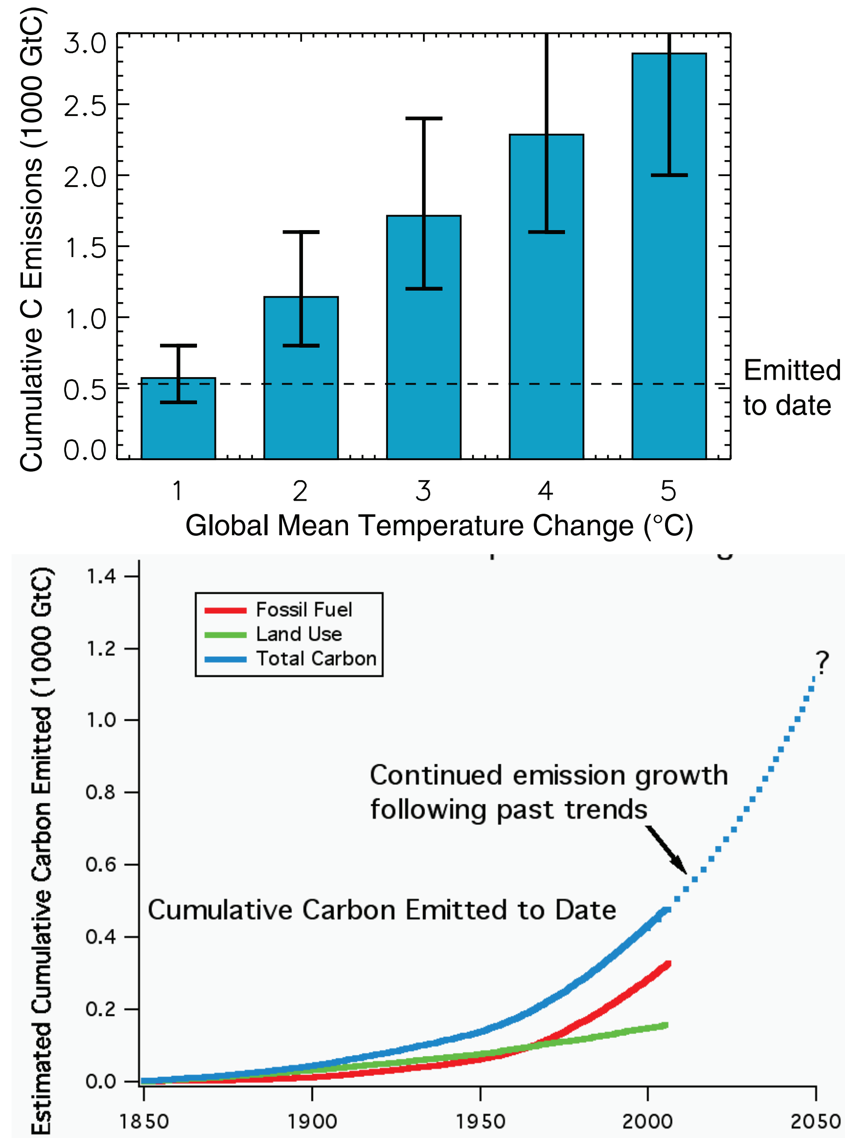


FIGURE S.2 (top) Best estimates and likely range of cumulative carbon emissions that would result in global warming of 1°C, 2°C, 3°C, 4°C, or 5°C (see Figure S.1), based on recent studies that have demonstrated a near linearity in the temperature response to cumulative emissions (see Section 3.4). Error bars reflect uncertainty in carbon cycle and climate responses to CO_2 emissions, based on both observational constraints and the range of climate-carbon cycle model results (see Section 3.4). (bottom) Estimated global cumulative carbon emissions to date from fossil fuel burning and cement production, land use, and total. The figure also shows how much cumulative carbon would be emitted by 2050 if past trends in emission growth rates were to continue in the future, based upon a best fit to the past emission growth curve. {3.4}

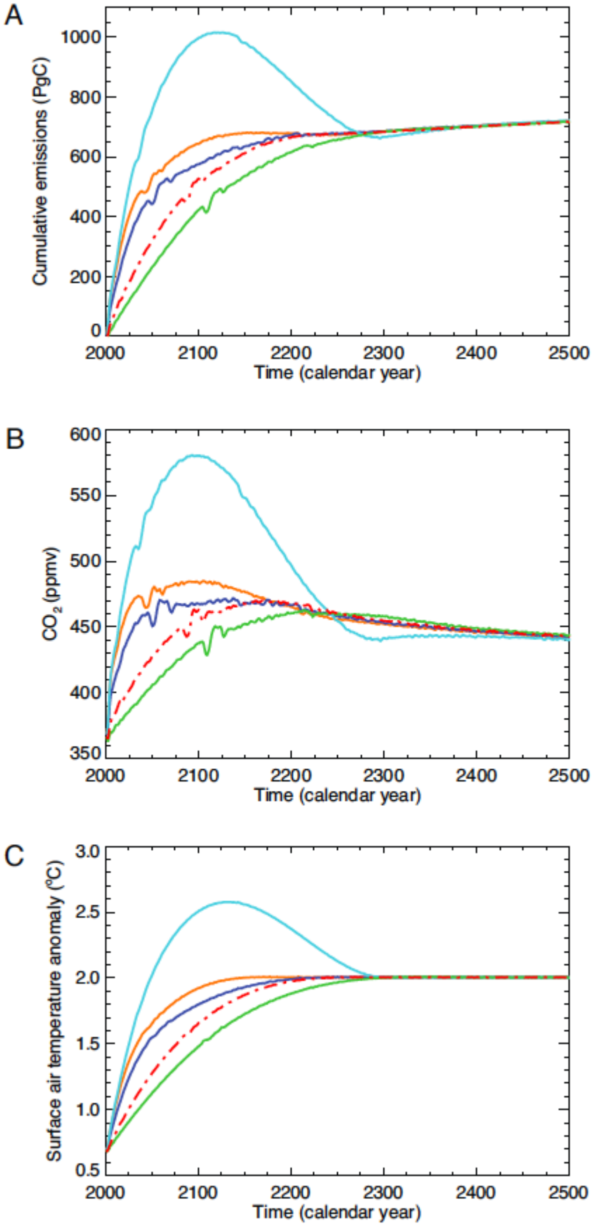
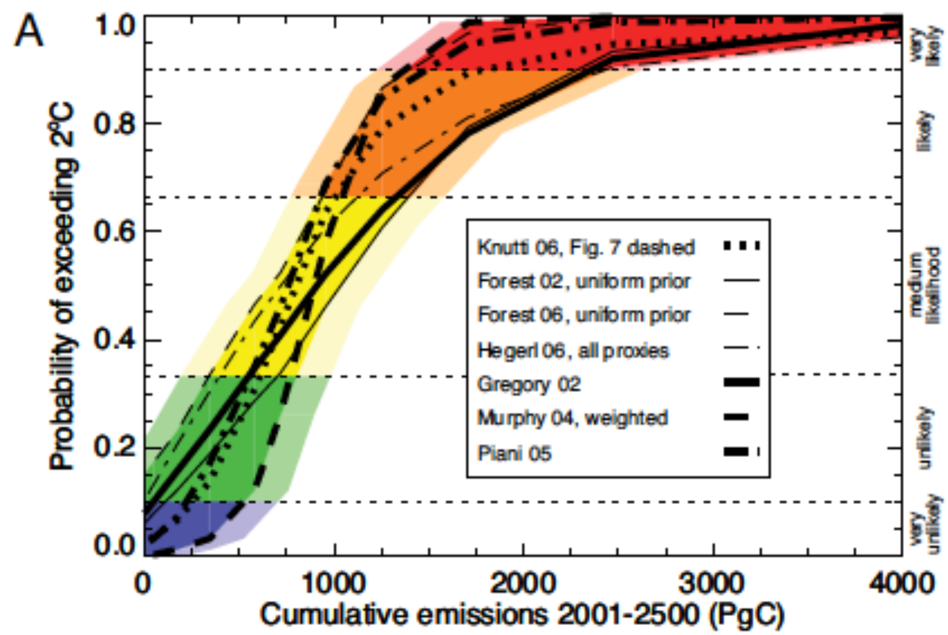


Fig. 1. Path independency of cumulative CO_2 emissions. (*A*) Cumulative CO_2 emissions and (*B*) CO_2 concentrations compatible with a global mean temperature increase of 2 °C relative to preindustrial times. The different curves refer to experiments with different prescribed temperature change trajectories (*C*). The red-dashed trajectory is the standard trajectory used throughout the analysis. Cumulative emissions are computed from the year 2001 onwards.

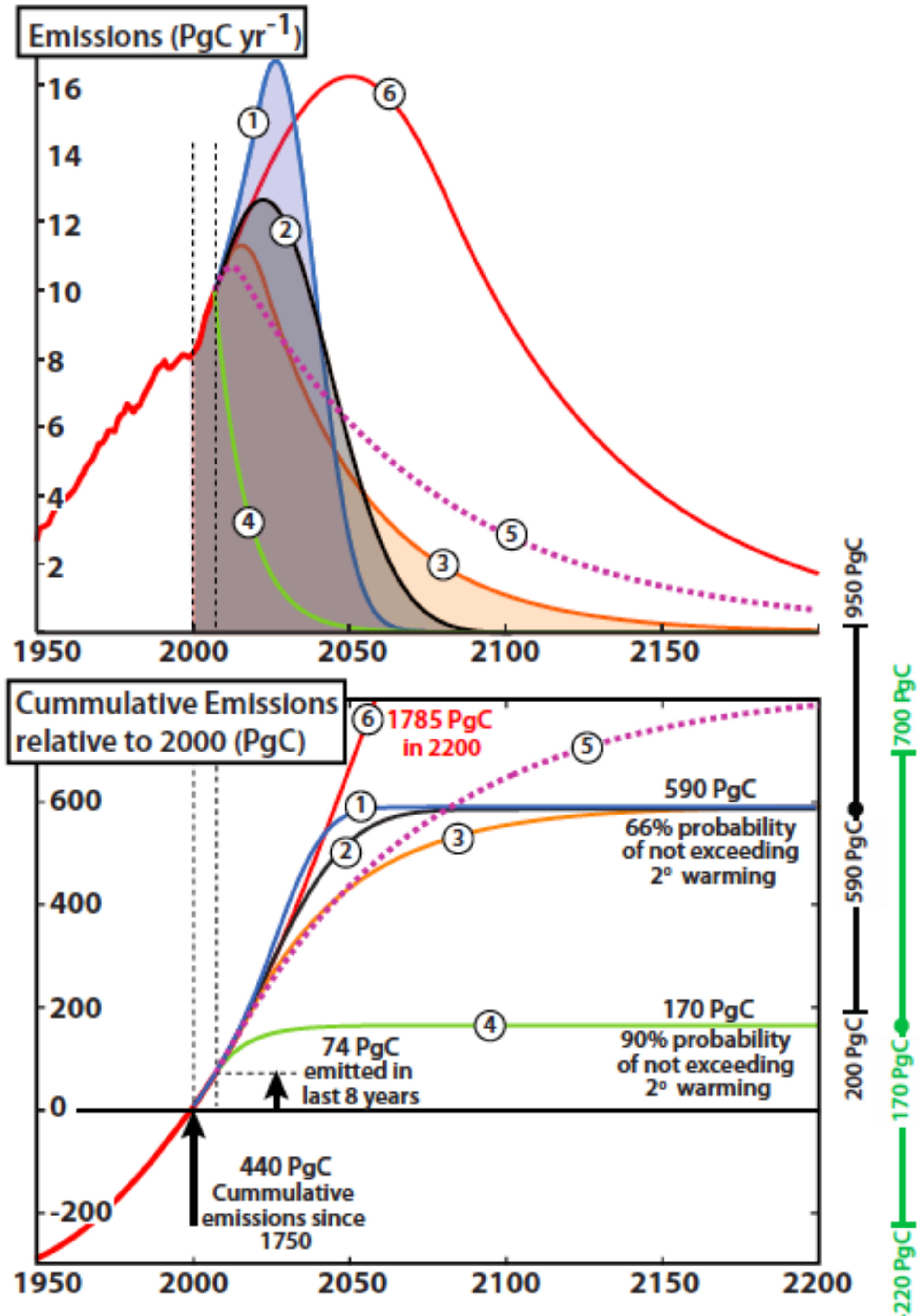
Setting cumulative emissions targets to reduce the risk of dangerous climate change

Kirsten Zickfeld[a,1,2], Michael Eby[a], H. Damon Matthews[b], and Andrew J. Weaver[a]



Cumulative carbon, climate sensitivity uncertainty, carbon feedback uncertainties, and stabilization targets

Zickfeld et al., PNAS, 2009



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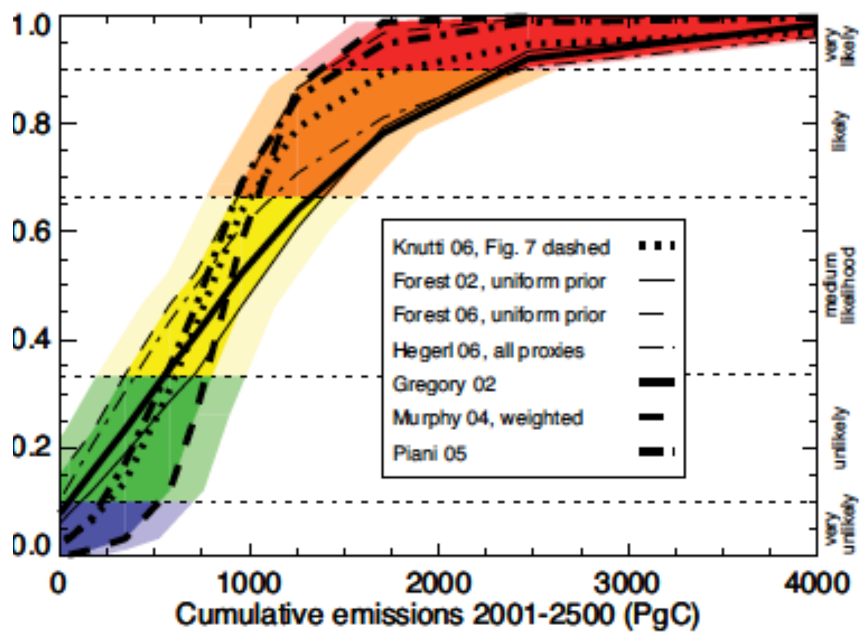
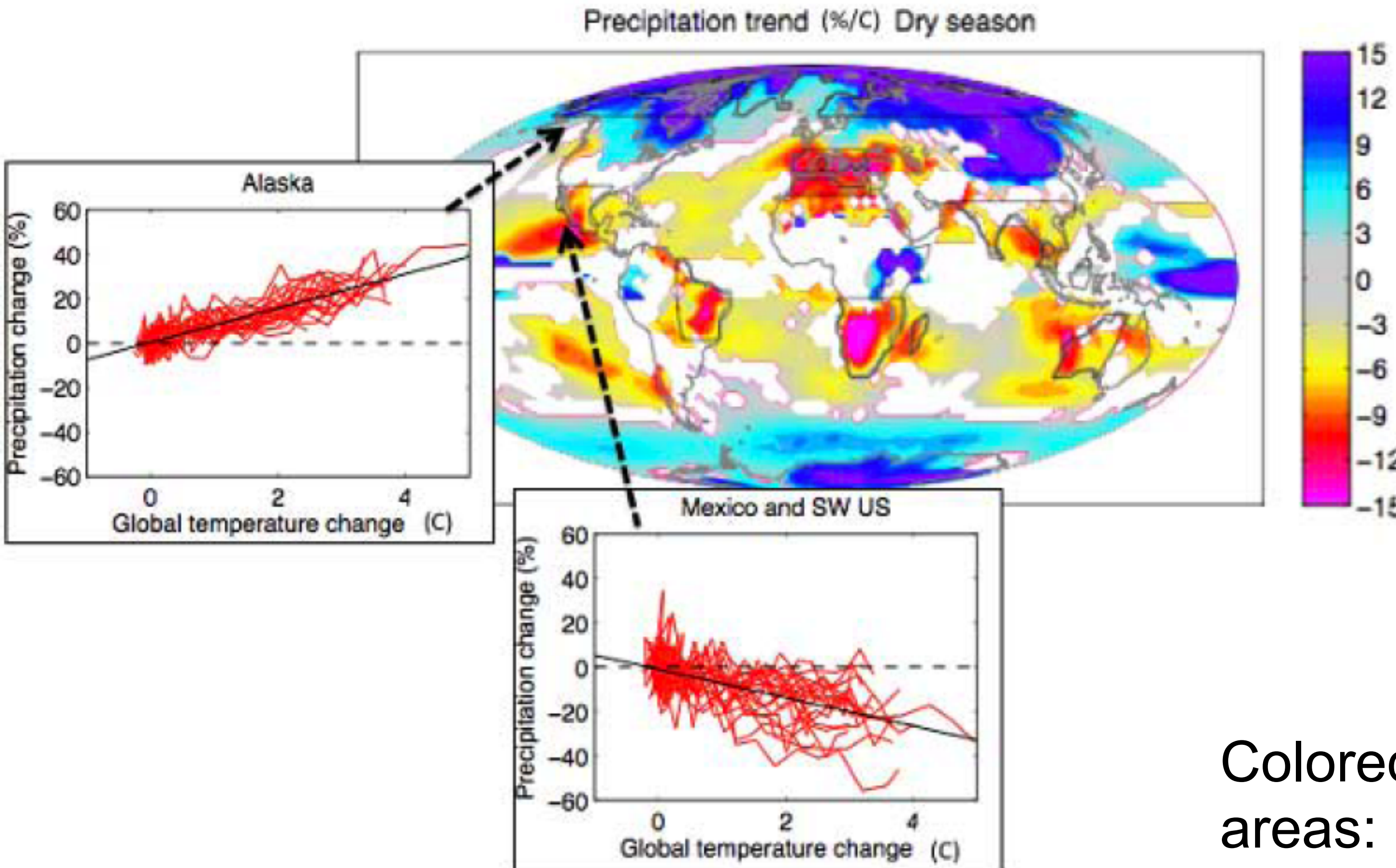


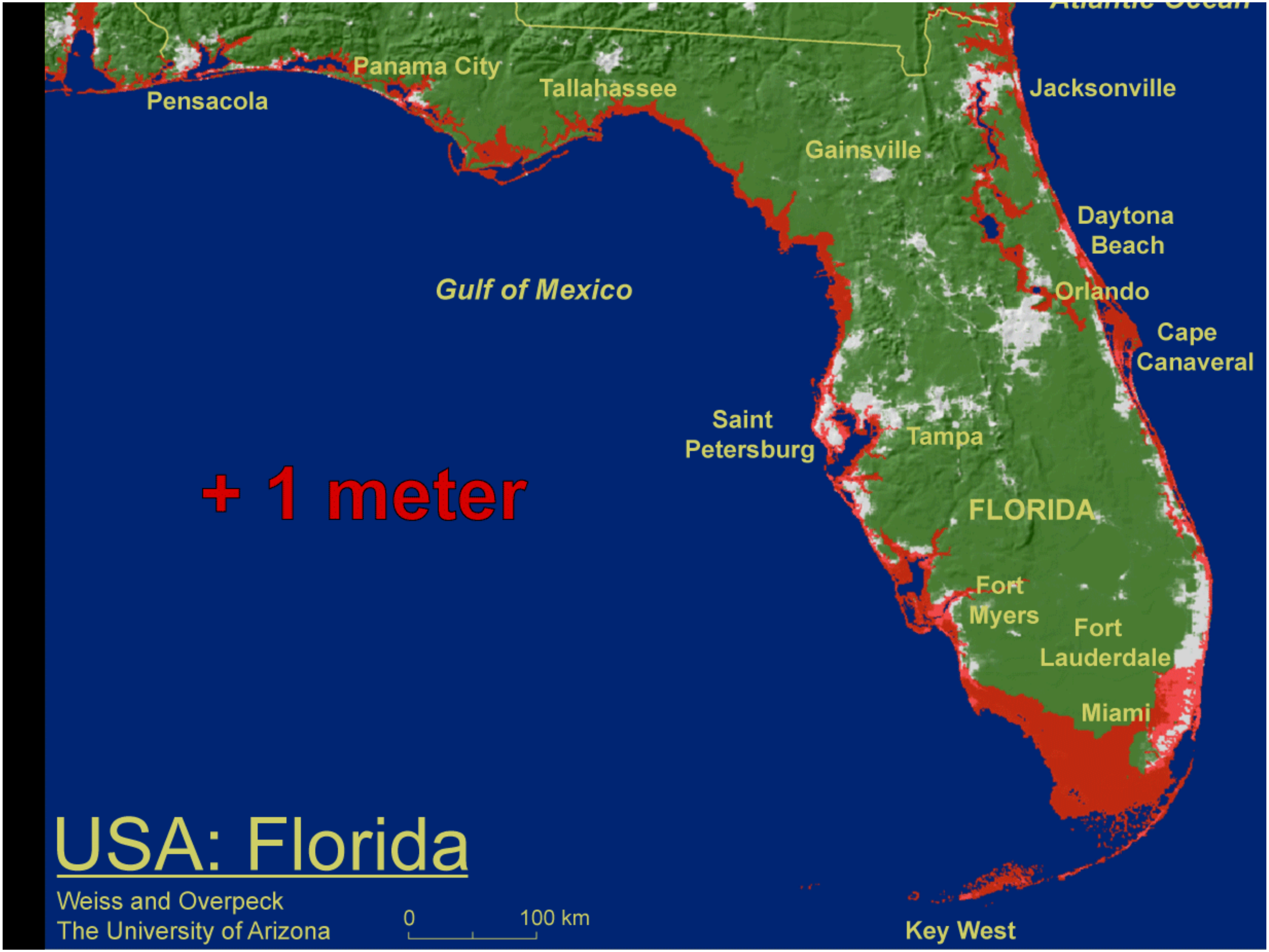
Cumulative carbon, climate sensitivity uncertainty, and stabilization targets

Zickfeld et al., PNAS, 2009; England et al., 2009

Changes in future rainfall



Colored areas: more than 2/3 of models agree

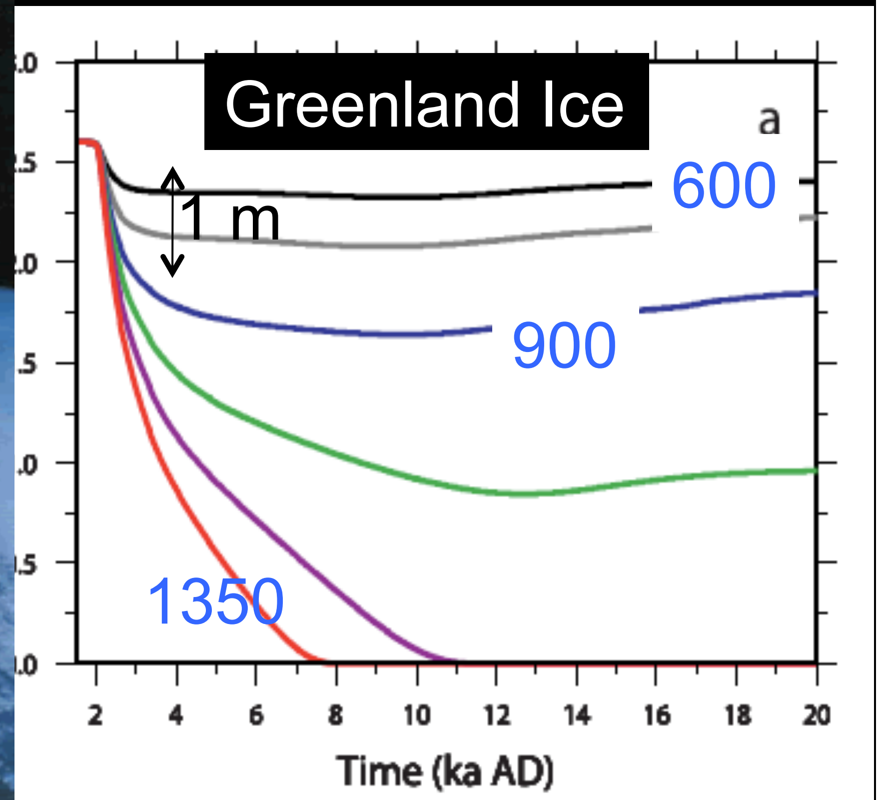

Pensacola
Panama City
Tallahassee
Jacksonville
Gainsville
Daytona Beach
Orlando
Cape Canaveral
Gulf of Mexico
Saint Petersburg
Tampa
+ 1 meter
FLORIDA
Fort Myers
Fort Lauderdale
Miami
USA: Florida
Weiss and Overpeck
The University of Arizona
0
100 km
Key West

Sea level rise of 0.5-1.0 meter would have large impacts on many people in many parts of the world.

Country	Sea-Level Rise (cm)	Potential Land Loss (km²)	Potential Land Loss (%)
Bangladesh	45	15,668	10.9
	100	29,846	20.7
India	100	5,763	0.4
Indonesia	60	34,000	1.9
Japan	50	1,412	0.4
Malaysia	100	7,000	2.1
Pakistan	20	1,700	0.2
Vietnam	100	40,000	12.1

[From IPCC WG2 (2001).]

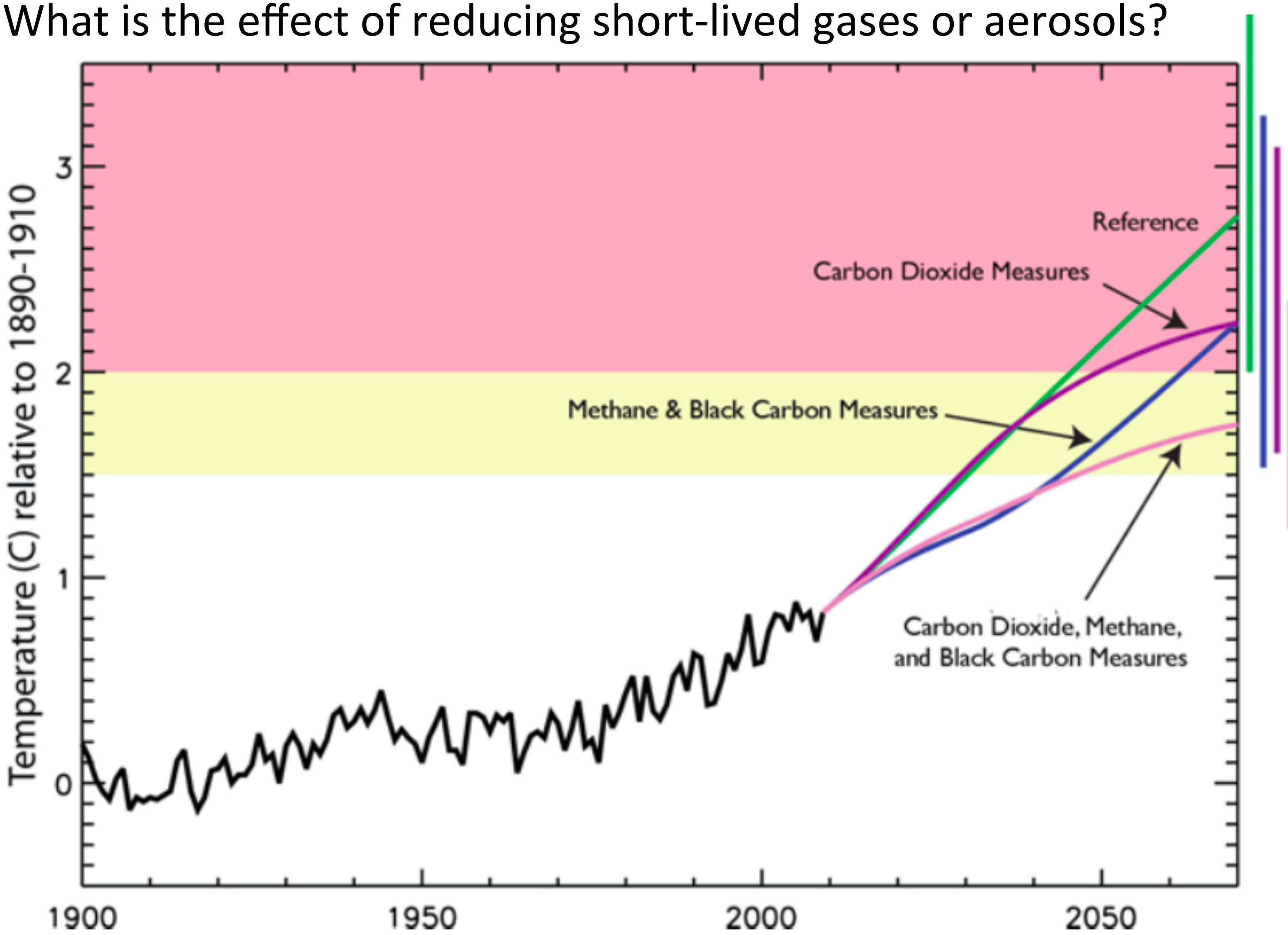
Ice Sheets: Even Longer Timescales….Many Thousands of Years



Will the ice sheets outlast the carbon? Ice sheets outlast the carbon for some levels of perturbation in this particular model (surface mass balance). Other models suggest faster losses. → a question of risk

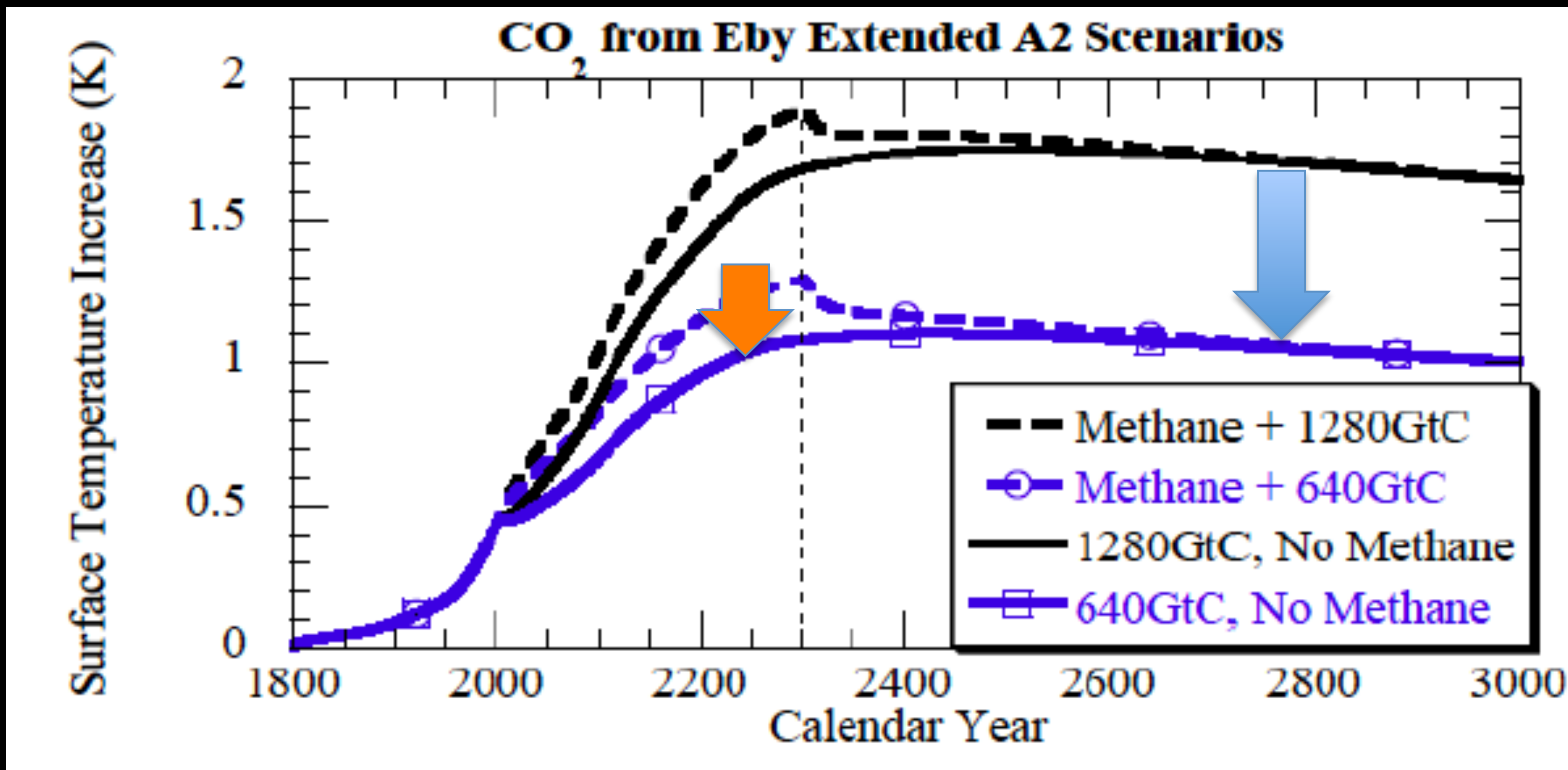
Charbit et al., GRL, 2008

What is the effect of reducing short-lived gases or aerosols?



UNEP, 2011

Two distinct challenges, two baskets?



1) Curb the peak->
reduce short-lived species such as methane, trop ozone, soot, etc. This does not "buy time" for CO_2

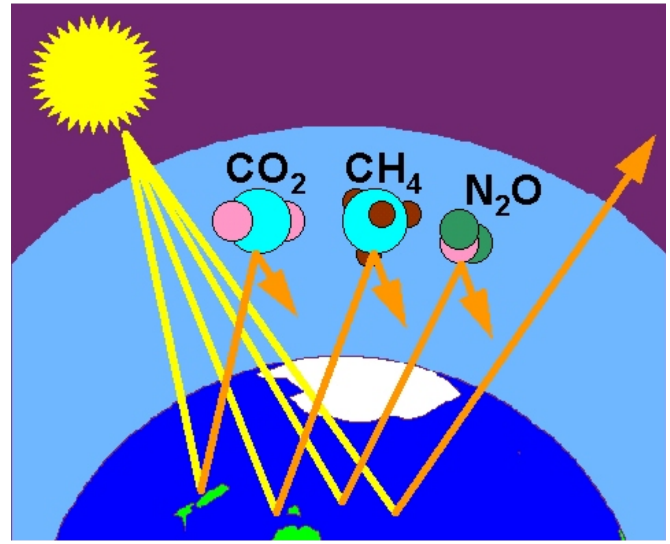
2) Reduce long-term warming ->
reduce CO_2
Set a global cumulative limit?
3) Geoengineer? Adapt?

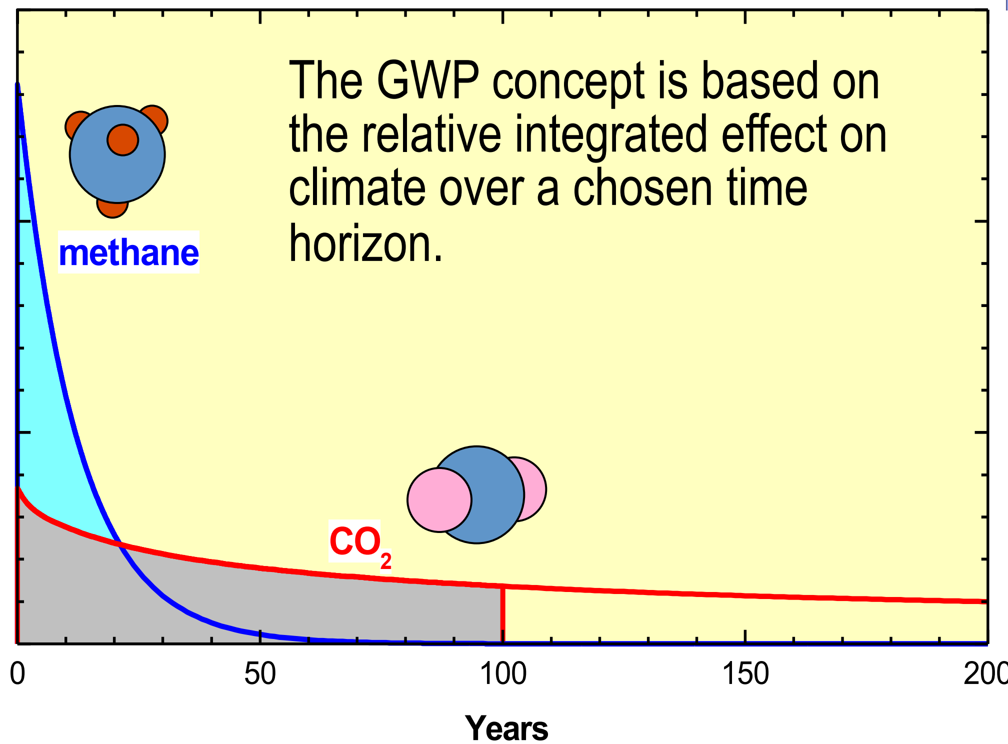
Position paper, Solomon et al.

Global Warming Potentials

Each molecule of methane has as much effect on infra-red radiation as about 60 molecules of CO_2.

But an increase in methane dies away much more quickly than one in CO_2.

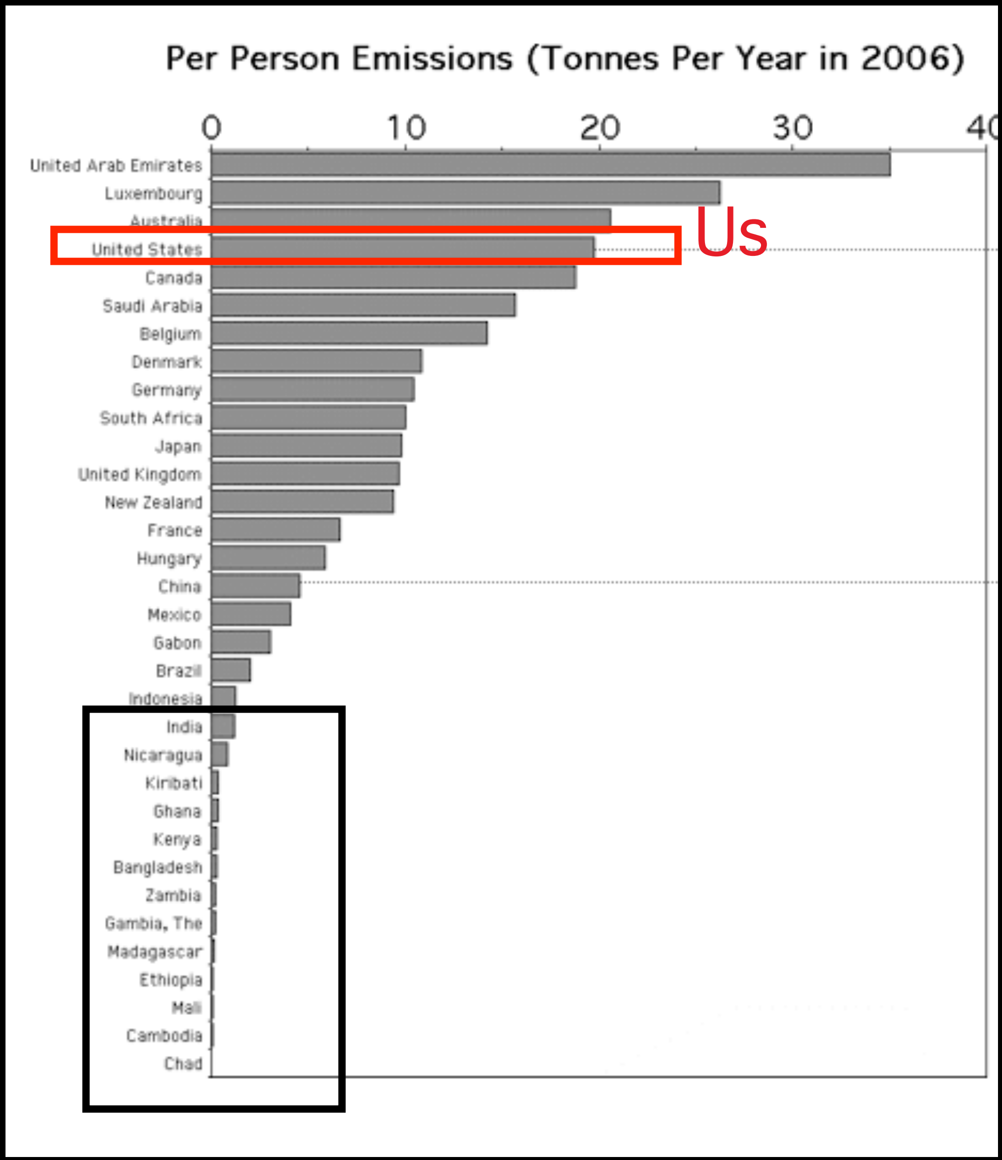




Integrated over 100 years, 1 ton of methane has the same effect as about 23 ton of CO_2. So 23 is the GWP for 100 years.

But the influence of carbon dioxide keeps going for much more than 100 years, while a pulse of methane does not.

Carbon Dioxide Emission From Fossil Fuel Burning



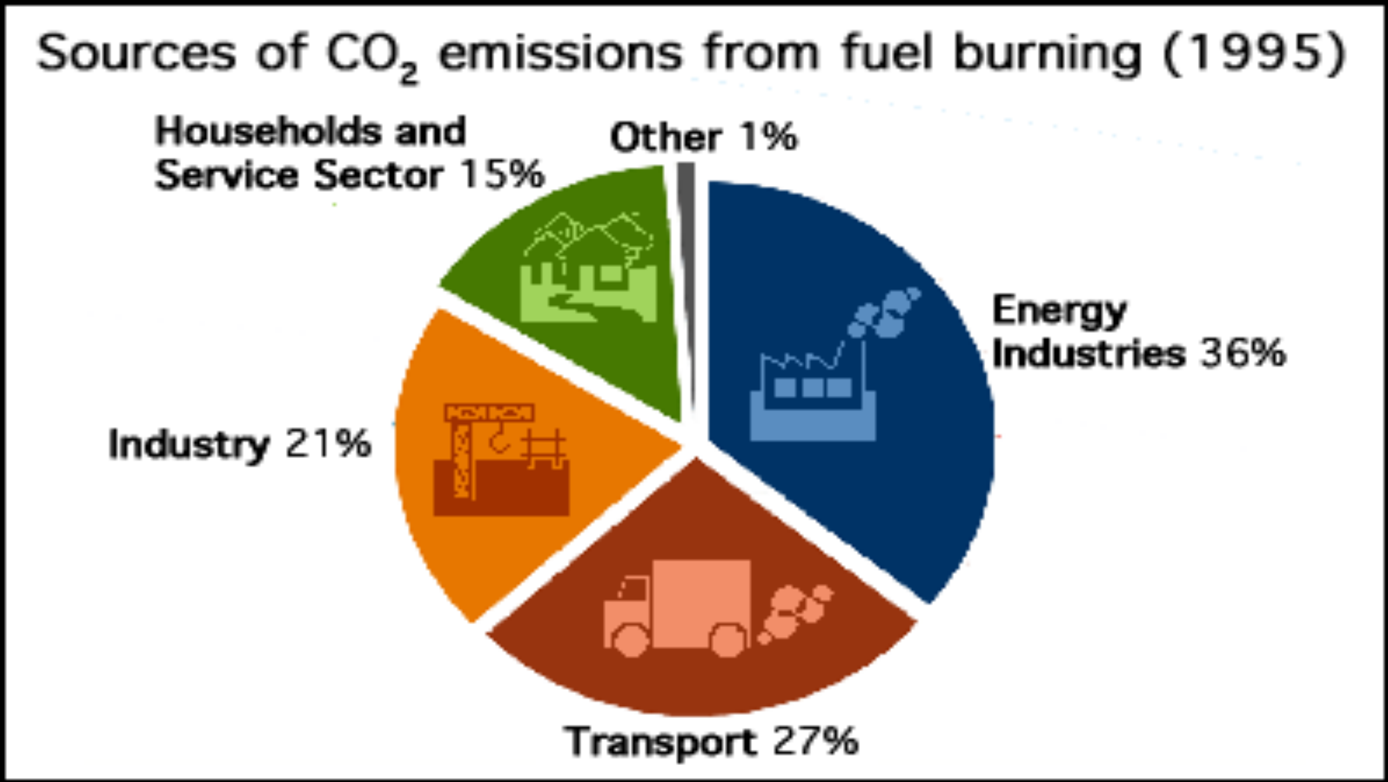
The human side of climate change.

Who?

Source: Energy Information Agency, DOE

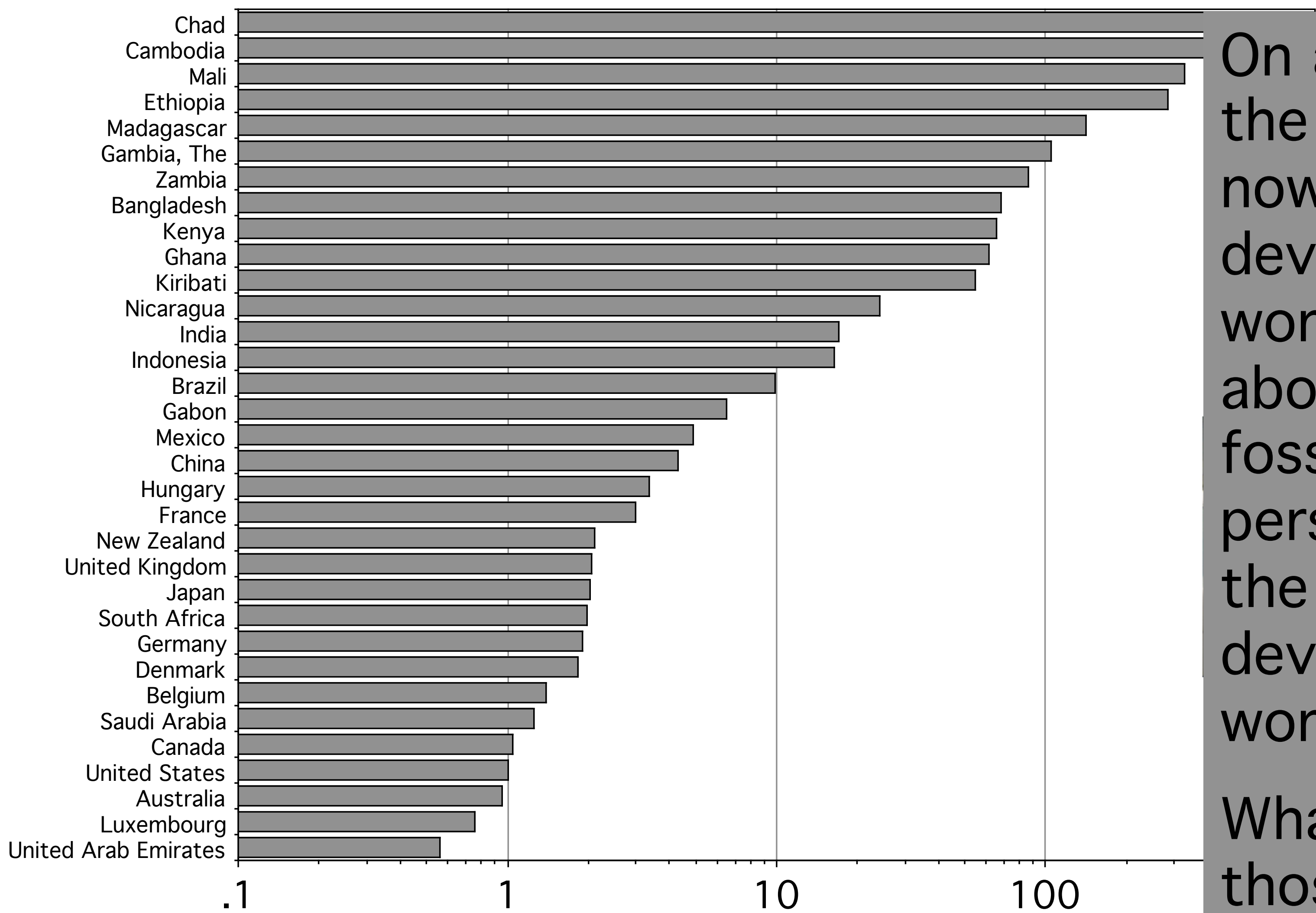
Why: Going, Doing, Making, Being Comfortable.....

In short, just about everything.



People in the Mirror: Carbon Dioxide Emission From Fossil Fuel Burning

Ratio of US per person emission/country of interest



Source: Energy Information Administr
US DOE 2006

On average, the 6 B people now in the developing world emit about 5x less fossil CO_2 per person than the 1B in the developed world.

What about those people's future?

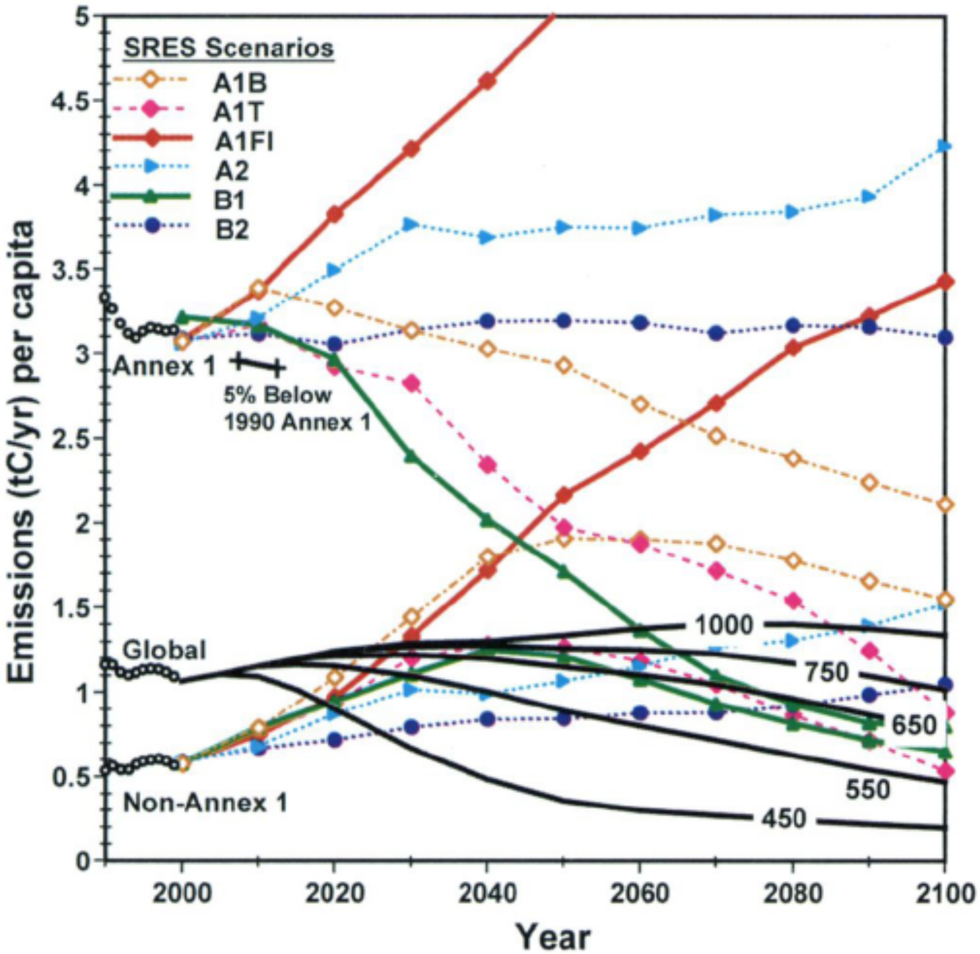


Fig. 4. Per-capita fossil emissions of CO_2. Emissions per capita from 1990 to 1999 are shown by the circles. Emissions 5% below the 1990 Annex 1 rate over the period from 2008 to 2012 are shown by a line segment. Deduced global fossil emissions leading to the specified CO_2 concentration pathways (Fig. 2) that asymptote to constant concentrations at labeled values from 450 to 1,000 ppm are shown by the solid curves. Per-capita fossil emissions for Annex 1 and non-Annex 1 regions for the six SRES scenarios are shown separately by the curves with symbols.

From Bolin and Kheshgi

Future emissions?

Consider the global total, the developed nations (annex 1) and developing nations (non-annex 1) nations – both total emissions and per capita emissions.

If the planet decides to stabilize CO2 emissions and hence climate at some level (450, 550, etc.) what does this imply for developing countries?

Stabilization at e.g., 550 would imply that the DC share would never be much more than 1tC/yr, much less than today's US value of about 5, and remaining many times lower throughout the 21st century than what it took for the developed world to develop.

Focus on decarbonizing energy sources, technology?

Some Closing Thoughts About Climate Change

-Caused mainly by different forcing agents produced by people via a well understood physical mechanism. CO_2 from fossil fuel burning is the main climate change agent.

-Climate changes from CO2 emissions should be expected to be nearly irreversible for at least 1000 years (unless we find a 'miracle cure' to remove CO2 from the atmosphere). This is linked to ocean heat uptake and (secondarily) non-linear spectroscopy.

-Climate change impacts would affect sea level rise, rainfall, wildfire, extreme seasons, etc., i.e., many people and ecosystems for a long time.

- Warmings due to other greenhouse gases also persist longer than the gas lifetimes, and depend upon how long emissions continue (mainly linked to ocean heat uptake). Implications for mitigation strategies and expected climate responses for short-lived gases or aerosols?

-The global disparities in carbon emission and cumulative carbon pose new ethical, moral, and technological challenges.


Thank you for your attention
Questions?

Transient and equilibrium warming

CO_2-equlvalent concentration (ppmv)	Best estimate transient warming (°C)	Estimated likely range of transient warming (°C)	Best estimate equilibrium warming (°C)	Estimated likely range of equilibrium warming (°C)
350	0.5	0.4-0.7	1	0.7-1.4
450	1.1	0.9 -1.5	2.2	1.4-3.0
550	1.6	1.3-2.1	3.1	2.1-4.3
650	2	1.6-2.7	3.9	2.6-5.4
1000	3	2.4-4.0	5.9	3.9-8.1
2000	4.7	3.7-6.2	9.1	6.0-12.5

Wait to observe severe impacts? A future with about twice as much warming and double the impacts…..

Stabilization Targets, National Res. Council, 2010