Atmospheric composition, irreversible climate change, and mitigation policy

Susan Solomon
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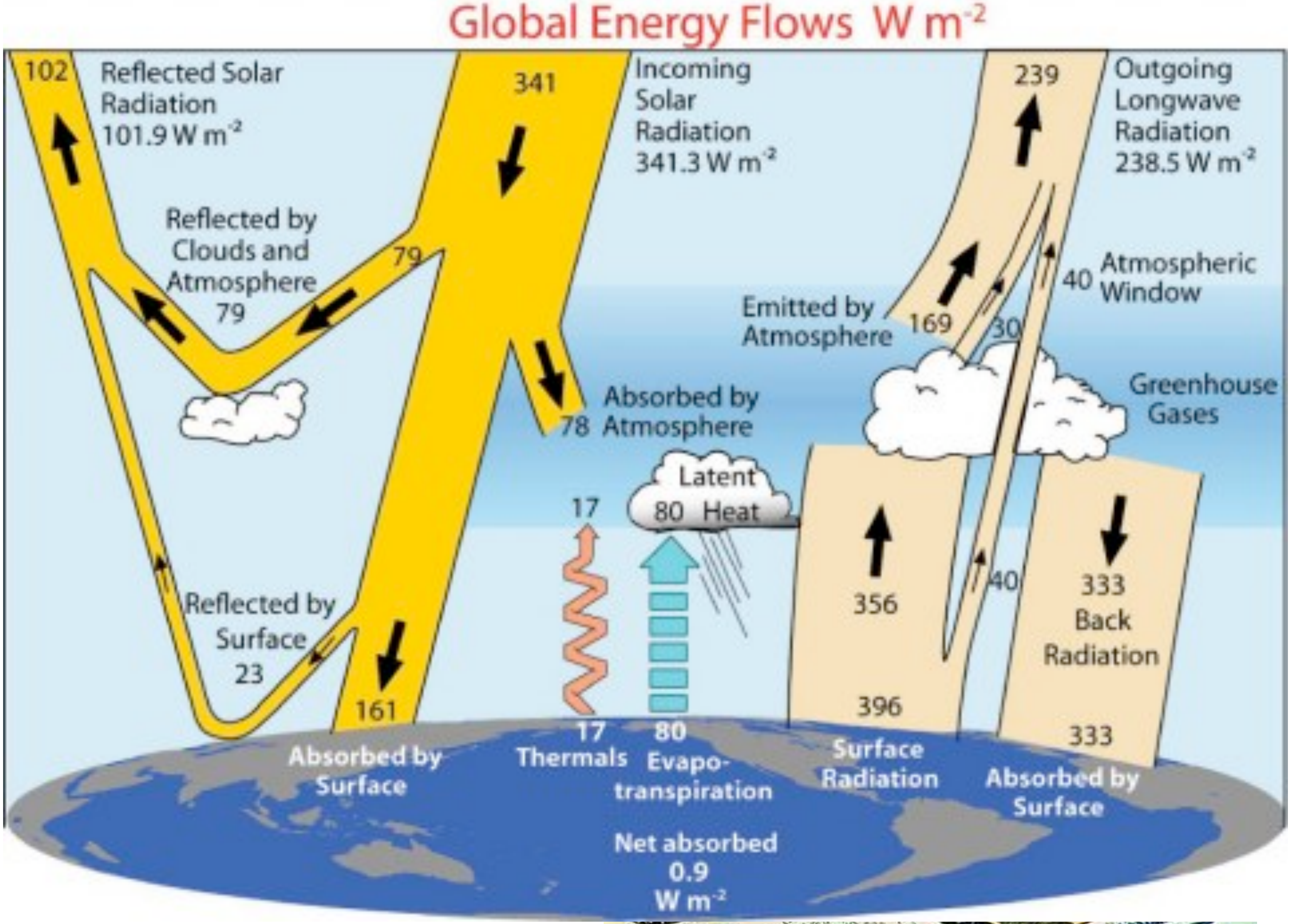
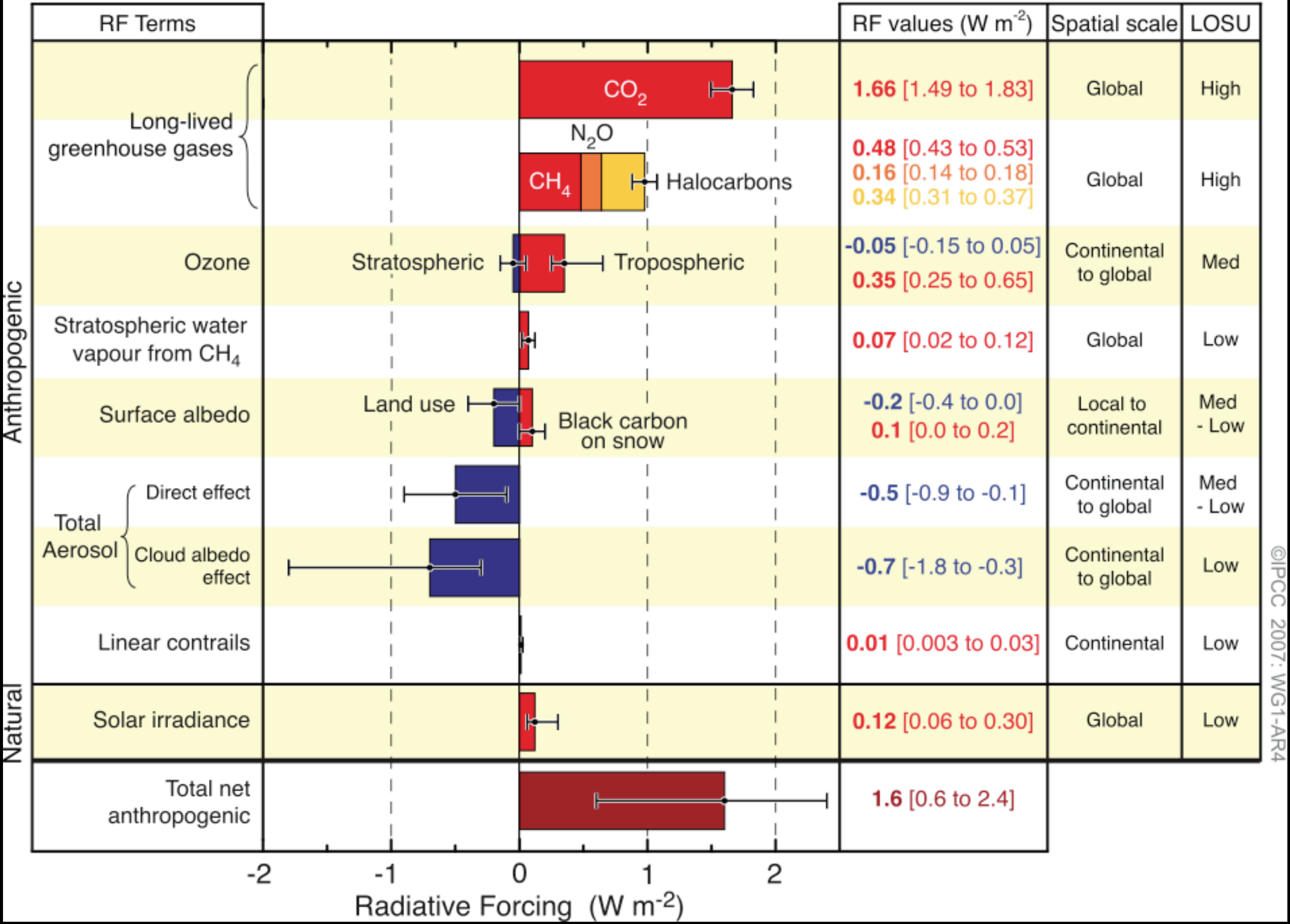

Global Energy Flows W m^{-2}
102
Reflected Solar Radiation 101.9 W m^{-2}
341
Incoming Solar Radiation 341.3 W m^{-2}
239
Outgoing Longwave Radiation 238.5 W m^{-2}
Reflected by Clouds and Atmosphere 79
79
40 Atmospheric Window
Emitted by Atmosphere
169
30
Greenhouse Gases
Absorbed by Atmosphere
78
Latent Heat
80
17
Reflected by Surface 23
356
40
333 Back Radiation
161
396
333
17 Thermals
80 Evapo-transpiration
Surface Radiation
Absorbed by Surface
Absorbed by Surface
Net absorbed 0.9 W m^{-2}

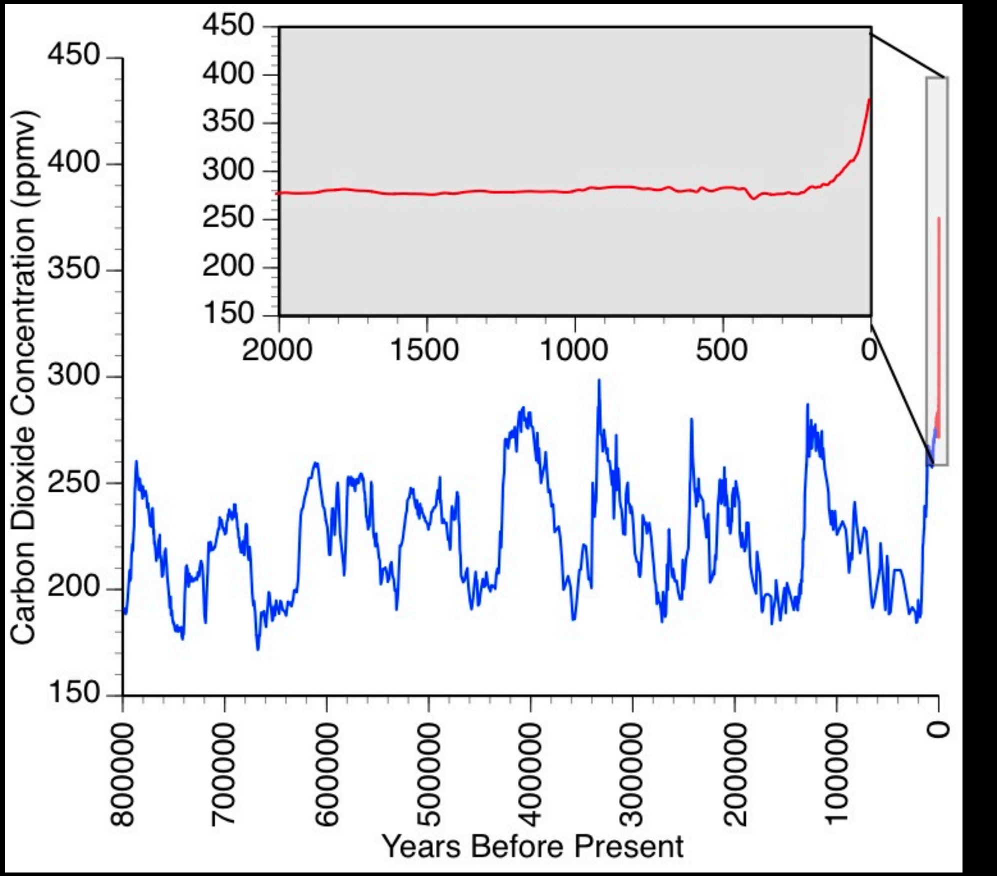


Radiative forcings in 2005; from Ramaswamy et al.

Human Drivers of Climate Change: Unprecedented Increases

CARBON DIOXIDE

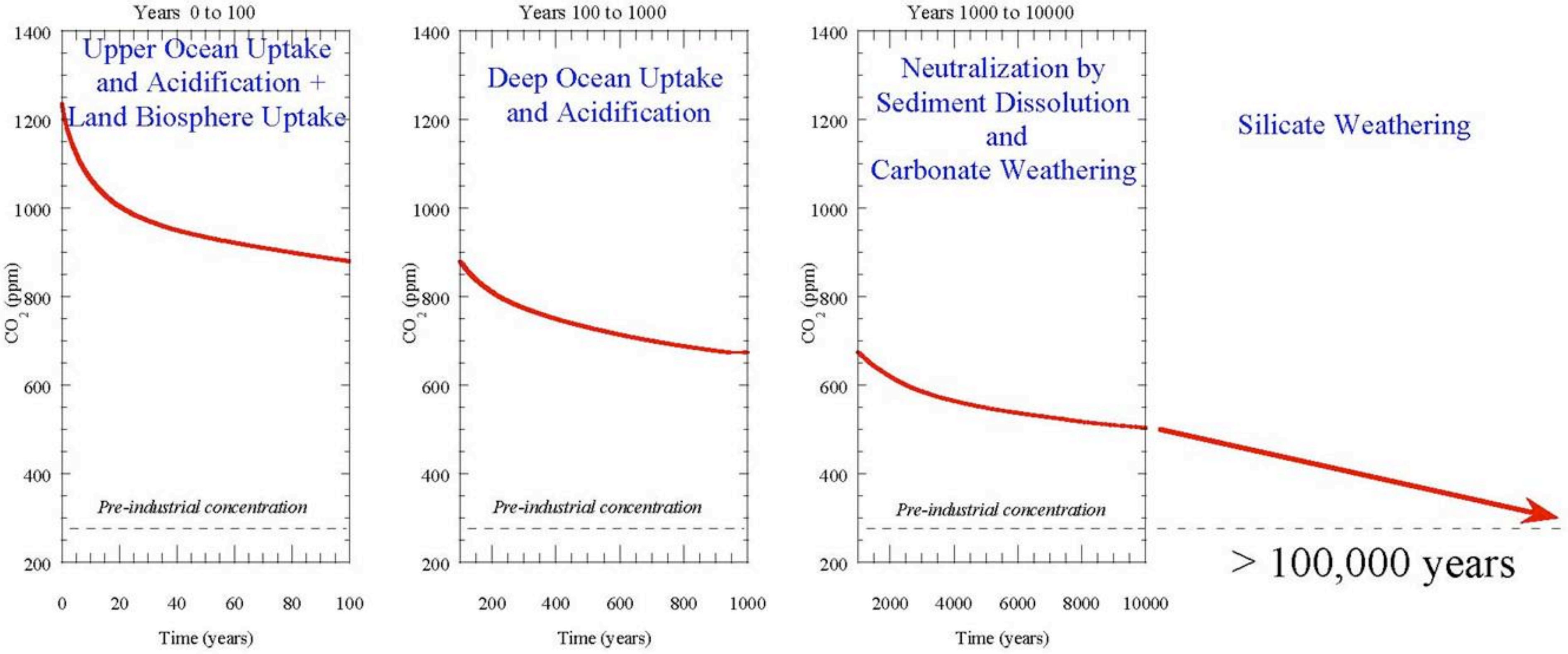
- A critical 'greenhouse gas' that absorbs energy
- Dramatic increase in industrial era, 'forcing' climate change and acidifying the oceans
- Higher concentration than for more than 800,000 years



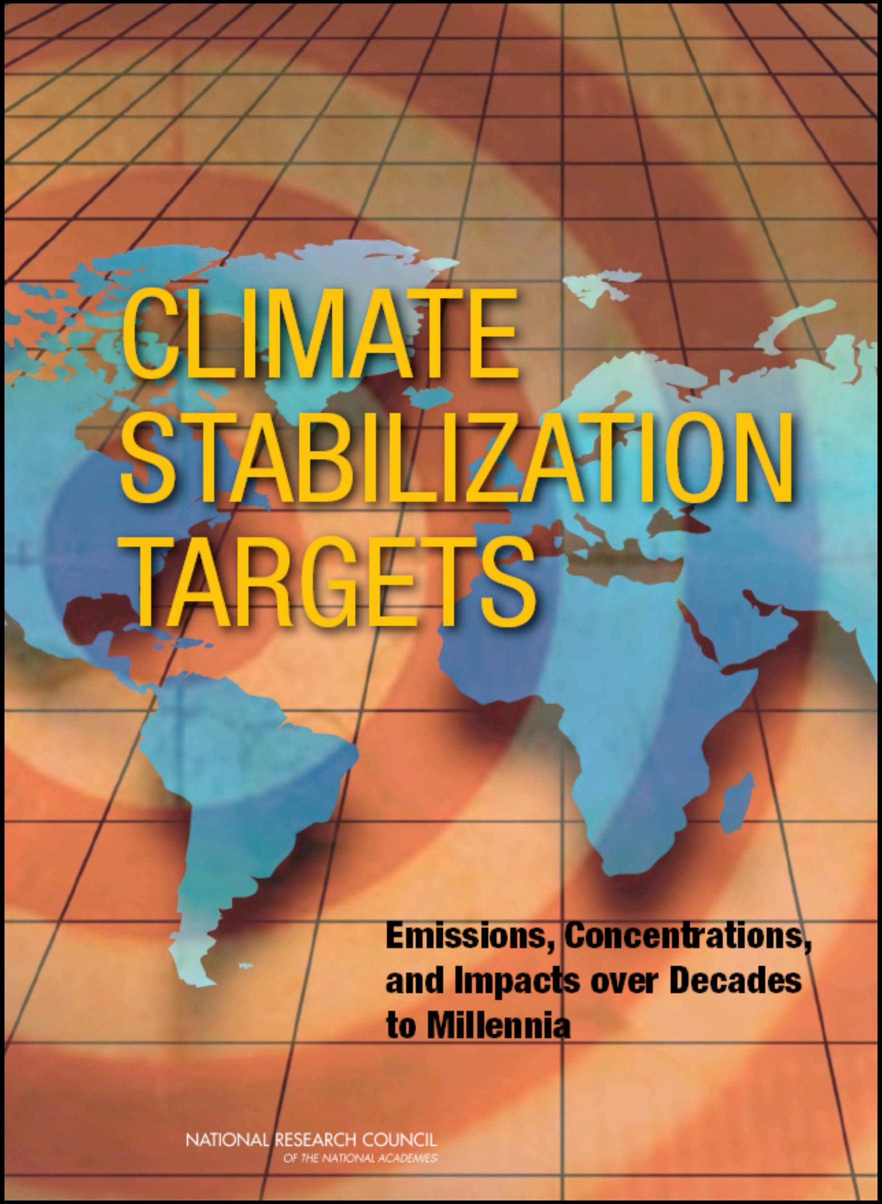
Pre-industrial: 270 ppmv Today: almost 390 ppmv

Position paper for this conference, Solomon et al.

What controls CO2 removals over time?



There is no single carbon dioxide lifetime or removal time scale. There is a sequence of sinks and a lot left for a long time. *Stabilization Targets, NRC, 2010*



Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia

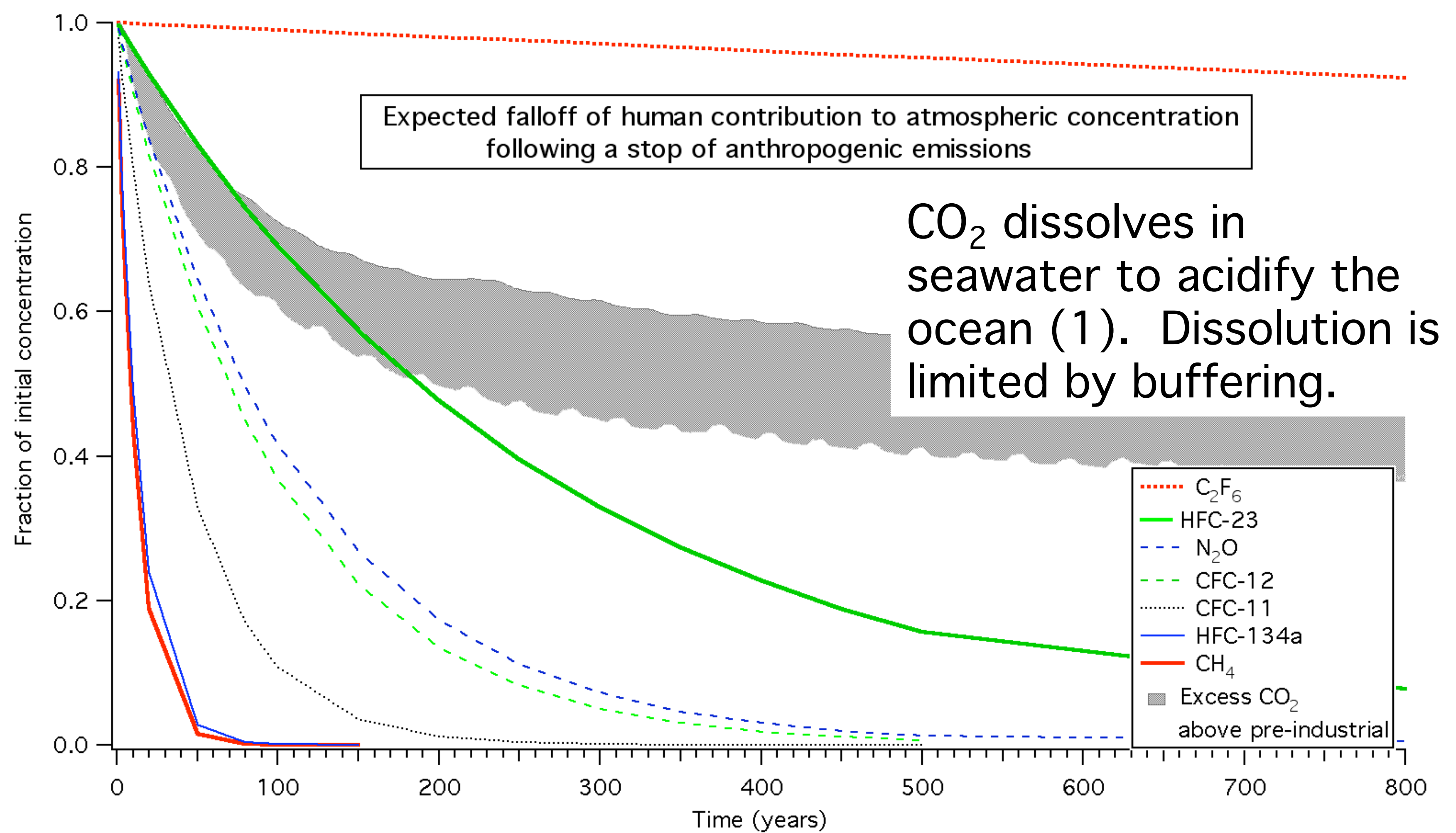
Report from The National Academies

Board on Atmospheric Sciences and Climate

Solomon et al., 2010

Choices? 350? 450? 700? 1000 ppmv

Carbon Dioxide Is A Unique Gas



Expected falloff of human contribution to atmospheric concentration following a stop of anthropogenic emissions

CO_2 dissolves in seawater to acidify the ocean (1). Dissolution is limited by buffering.

(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

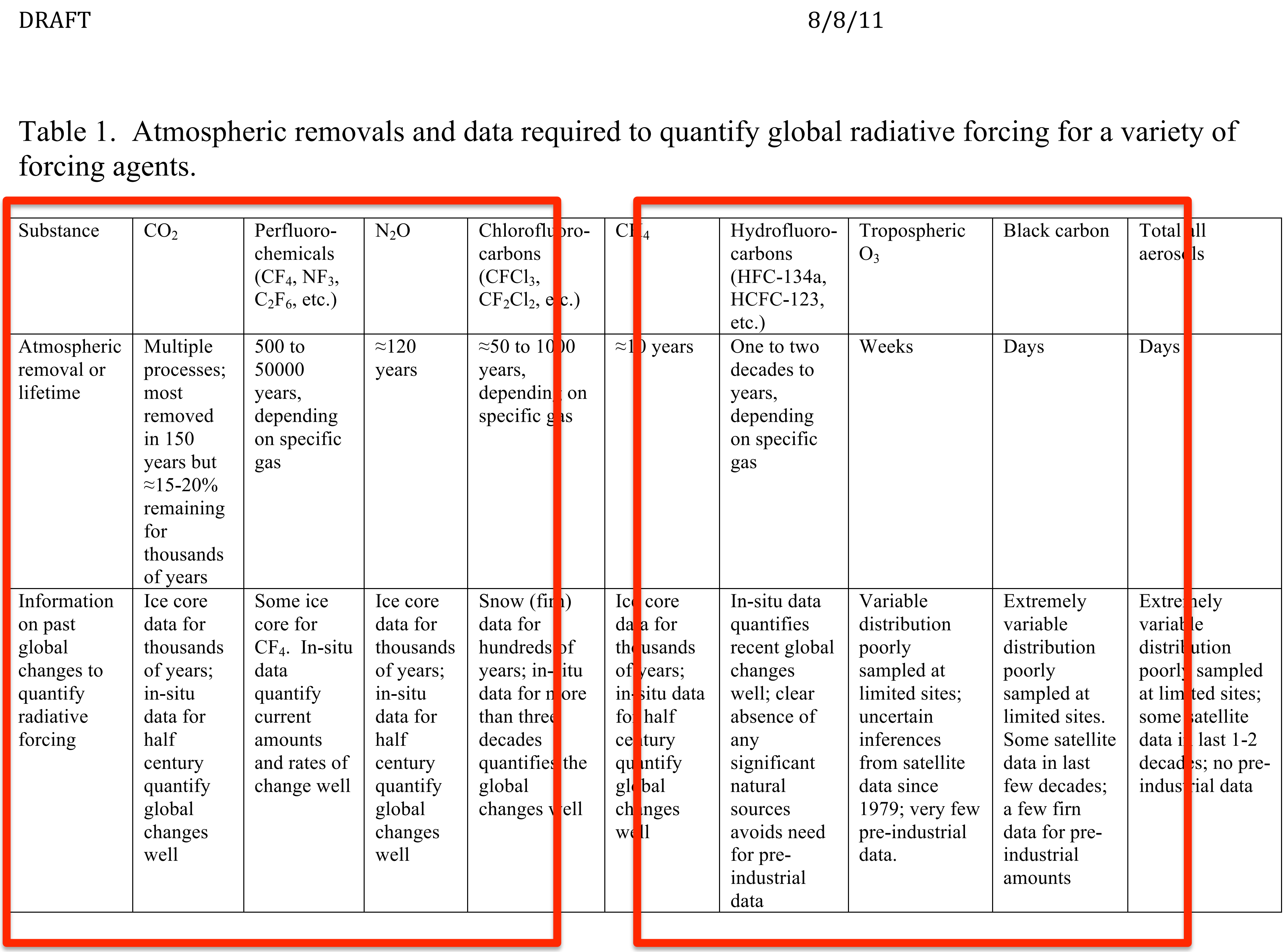


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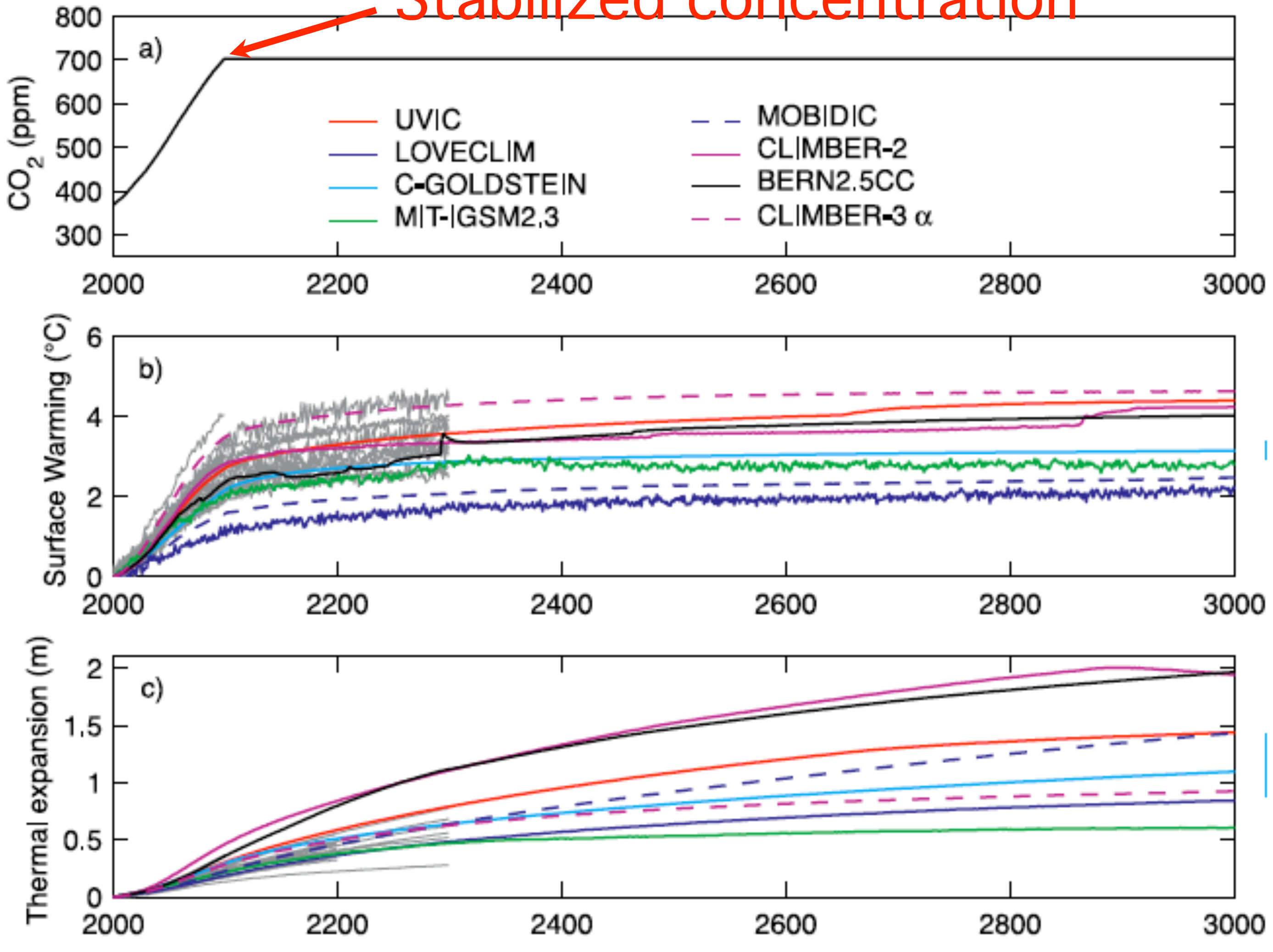
Table 1. Atmospheric removals and data required to quantify global radiative forcing for a variety of forcing agents.

Substance	CO_2	Perfluoro-chemicals (CF_4, NF_3, C_2F_6, etc.)	N_2O	Chlorofluoro-carbons ($CFCl_3$, CF_2Cl_2, etc.)	CH_4	Hydrofluoro-carbons (HFC-134a, HCFC-123, etc.)	Tropospheric O_3	Black carbon	Total all aerosols
Atmospheric removal or lifetime	Multiple processes; most removed in 150 years but ≈15-20% remaining for thousands of years	500 to 50000 years, depending on specific gas	≈120 years	≈50 to 1000 years, depending on specific gas	≈10 years	One to two decades to years, depending on specific gas	Weeks	Days	Days
Information on past global changes to quantify radiative forcing	Ice core data for thousands of years; in-situ data for half century quantify global changes well	Some ice core for CF_4. In-situ data quantify current amounts and rates of change well	Ice core data for thousands of years; in-situ data for half century quantify global changes well	Snow (firn) data for hundreds of years; in-situ data for more than three decades quantifies the global changes well	Ice core data for thousands of years; in-situ data for half century quantify global changes well	In-situ data quantifies recent global changes well; clear absence of any significant natural sources avoids need for pre-industrial data	Variable distribution poorly sampled at limited sites; uncertain inferences from satellite data since 1979; very few pre-industrial data.	Extremely variable distribution poorly sampled at limited sites. Some satellite data in last few decades; a few firn data for pre-industrial amounts	Extremely variable distribution poorly sampled at limited sites; some satellite data in last 1-2 decades; no pre-industrial data

Position paper, Solomon et al.

Beyond the 21st Century: “stabilization”?



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”

IPCC, WG1 (2007), chapter 10

Stabilized *concentration*

Some definitions.....

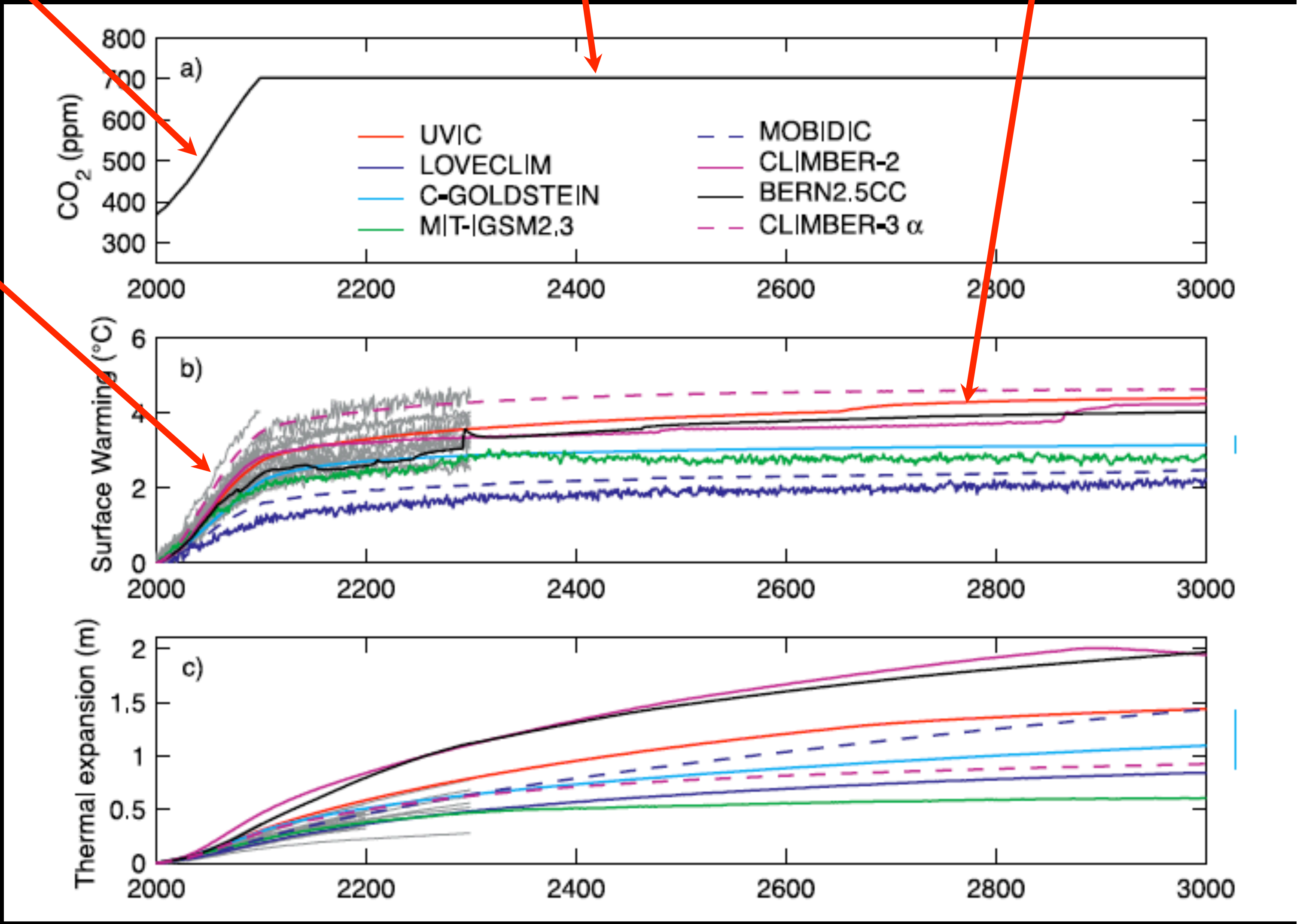
Radiative forcing increasing

Transient climate response occurring

For double pre-industrial CO2, TCR≈1.5; λ≈3

Radiative forcing stabilized

Quasi equilibrium climate response



Carbon Sink, Heat Transport, Climate Change, and Thermal Expansion of the Ocean.....

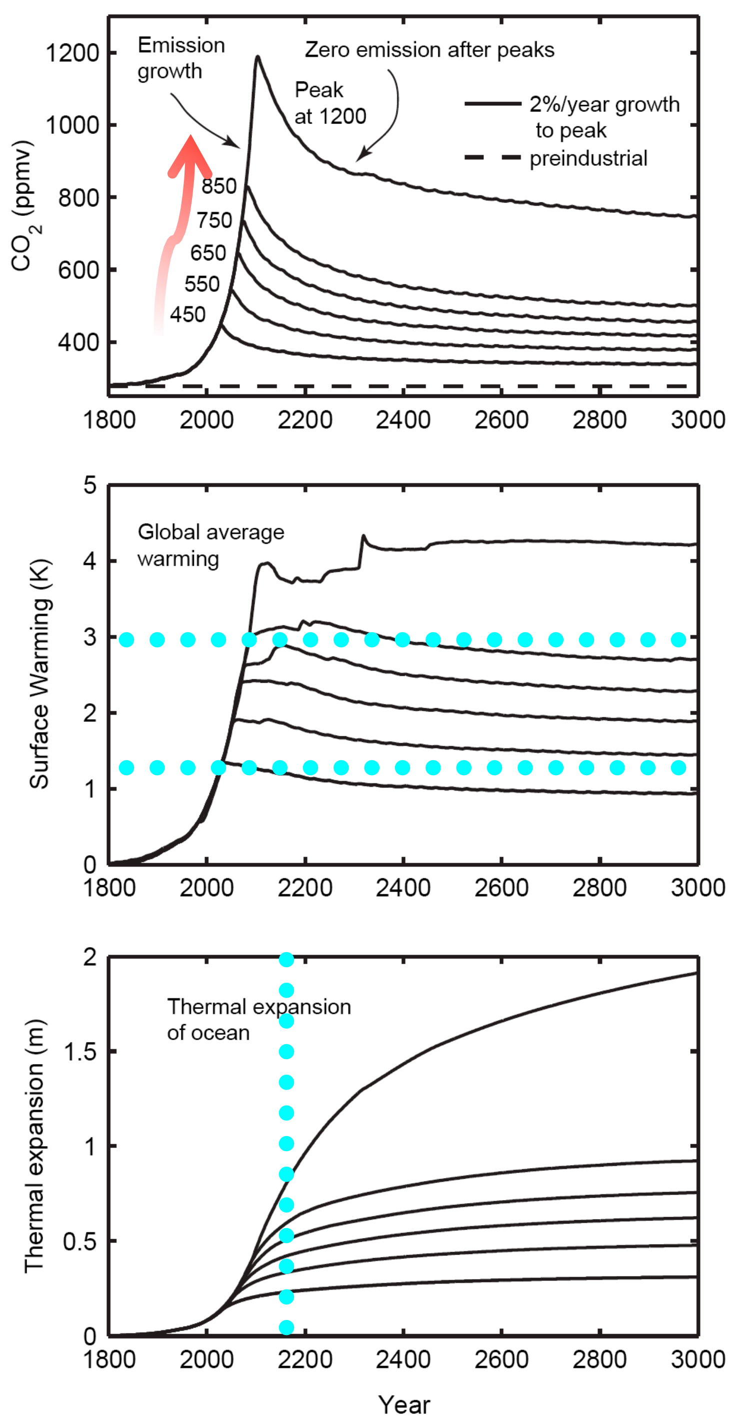
Broad range of test cases:

- *Every year of climate change that occurs (warming, precip, snow cover, sea ice retreat, ocean acidification, etc...) due to carbon dioxide increases is nearly irreversible for at least 1000 years (human time scales).*

- *Run out of fossil fuel? Warming persists.*

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

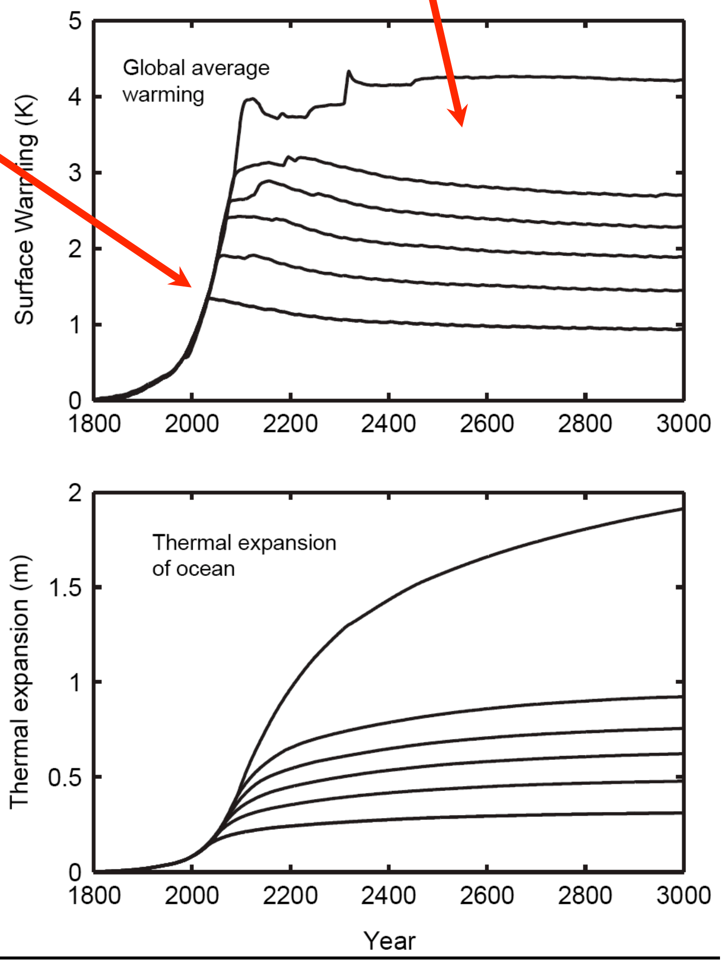
Solomon et al., PNAS, 2009; see Matthews&Caldeira, 2008; Allen et al., 2009; Lowe et al., 2009



Carbon Sink, Heat Transport, Climate Change, and Sea Level Rise Due to Thermal Expansion

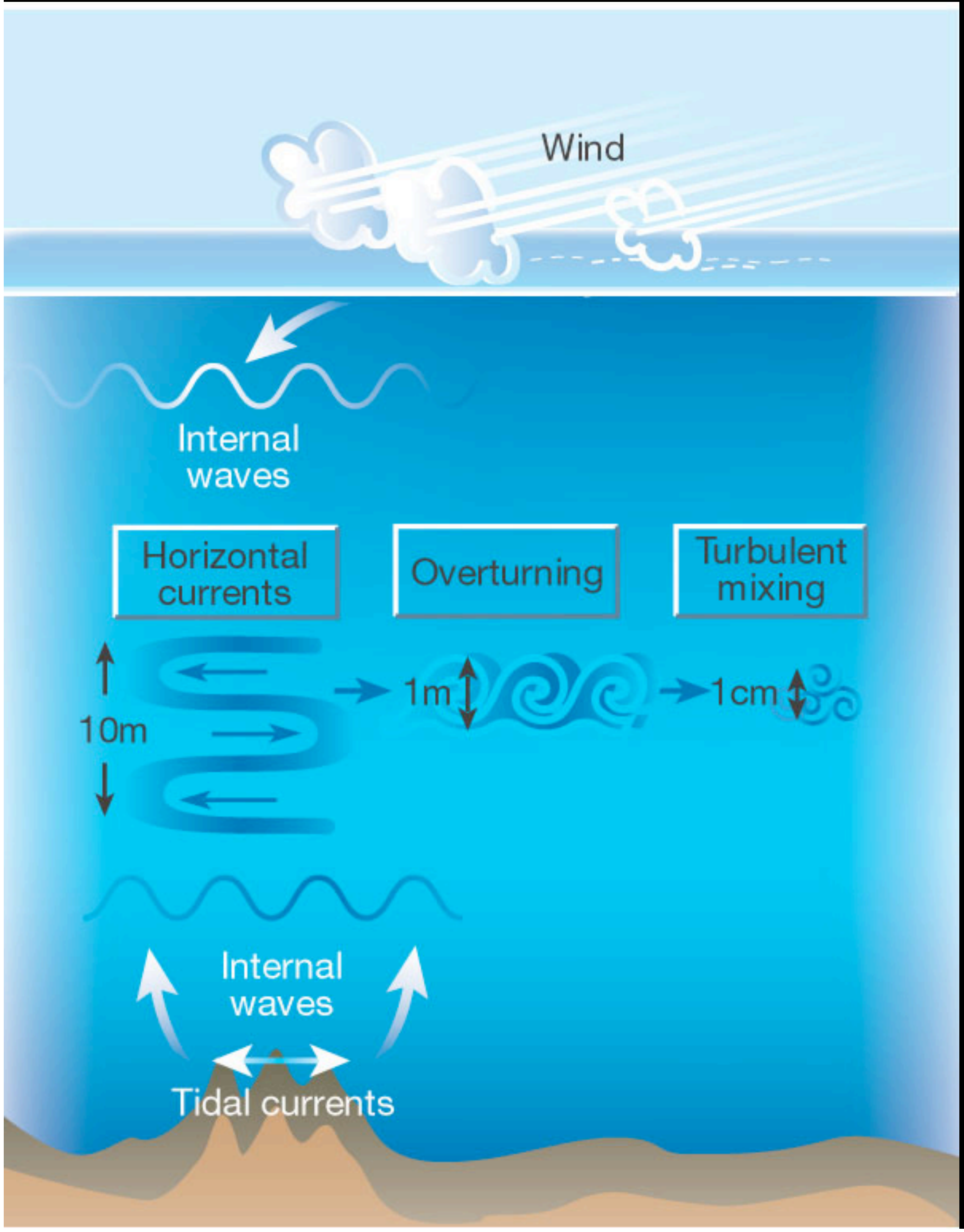
Near equilibrium....

Transient climate response occurring



Solomon et al., PNAS, 2009

Carbon Sink and Heat Transport: Links to Deep Ocean



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

Warming is realized over time, and carbon is taken up over time, and both involve deep ocean time scales.

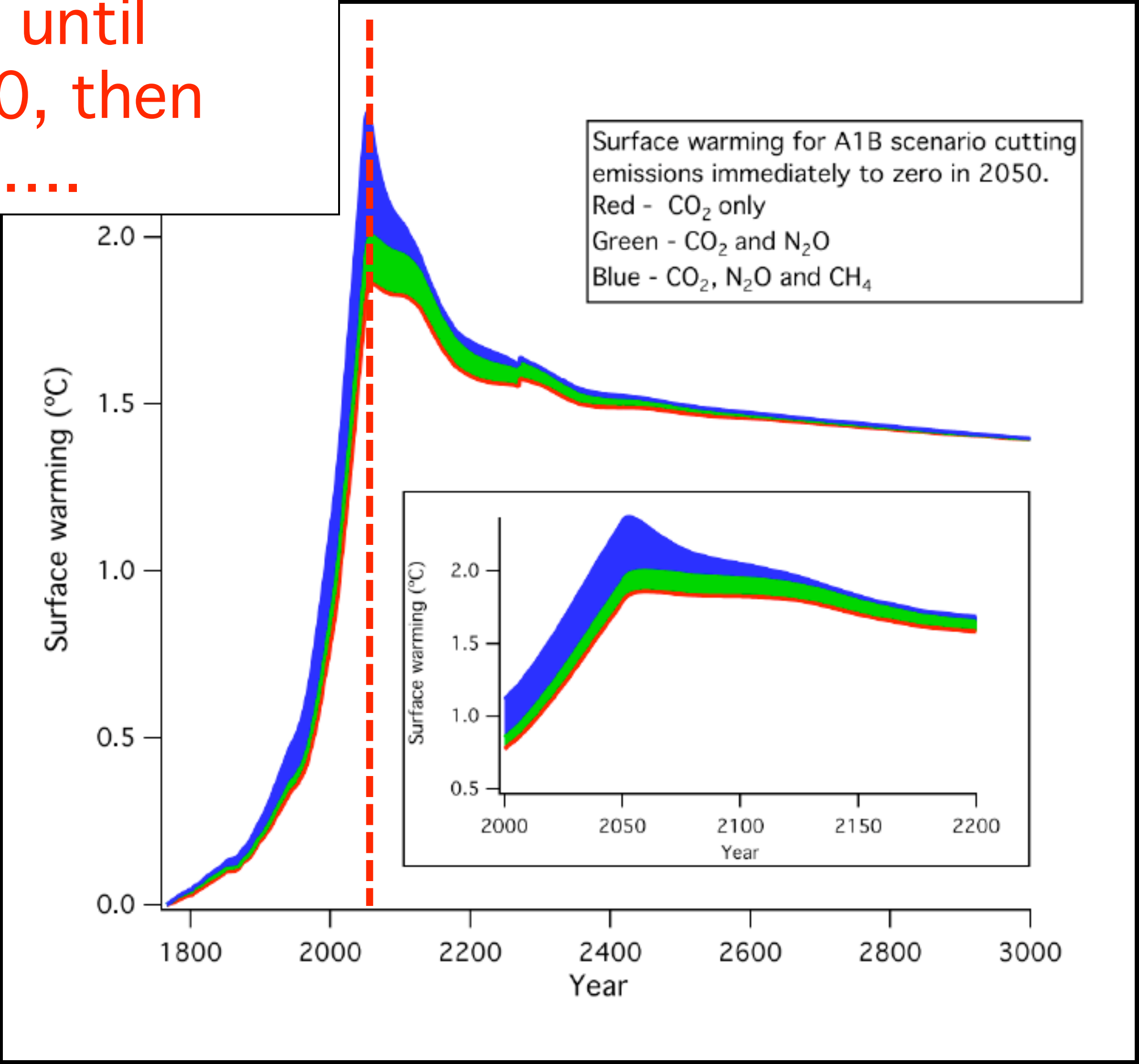
What about gases other than CO2?

Beyond CO_2 to other manmade greenhouse gases?

Lifetime of $N_2O \approx$ 110 years

Lifetime of $CH_4 \approx$ 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.

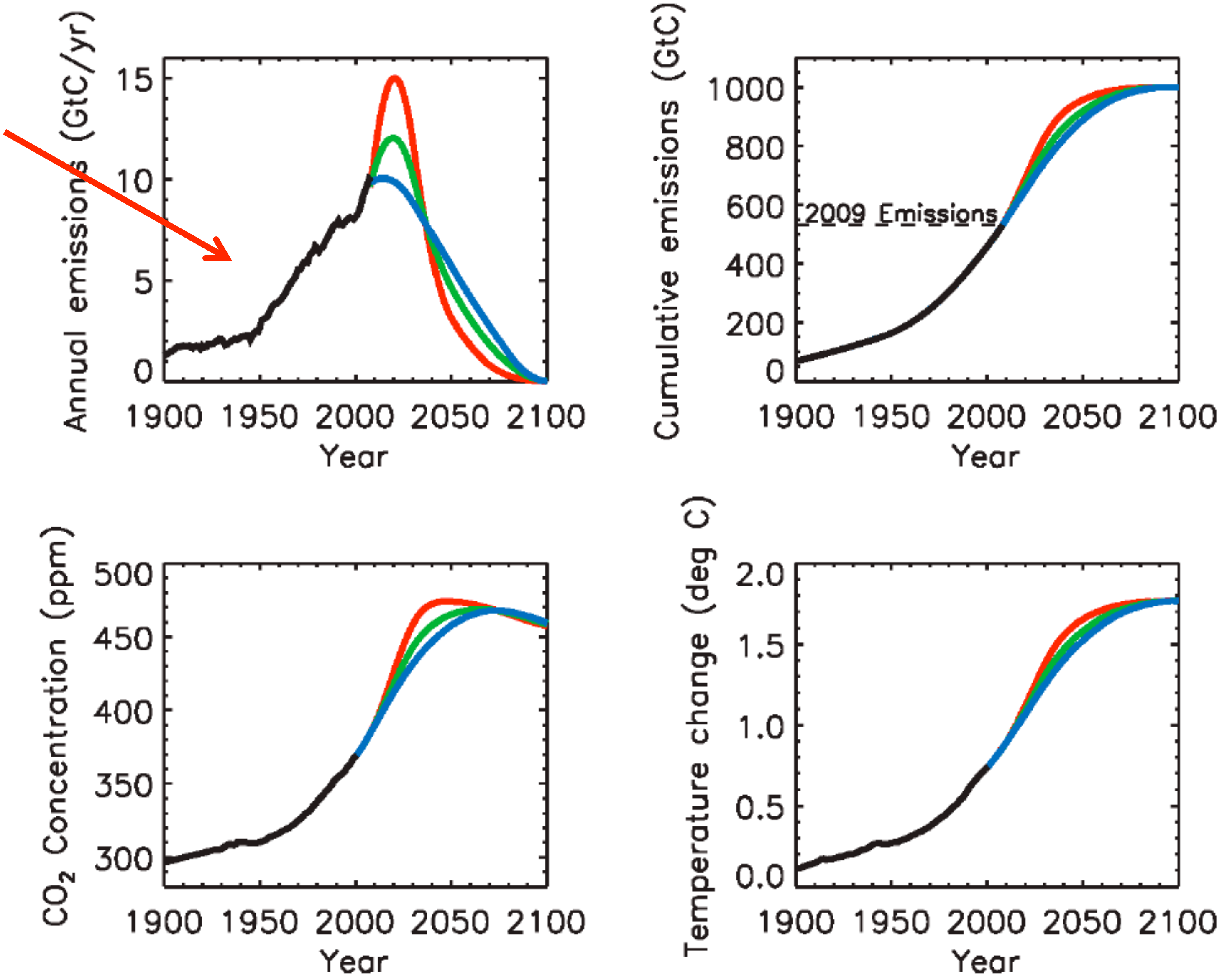


Emit until 2050, then stop....

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

Cumulative carbon and stabilization

Different trajectories for emission, same warming. Cumulative carbon determines the warming.



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

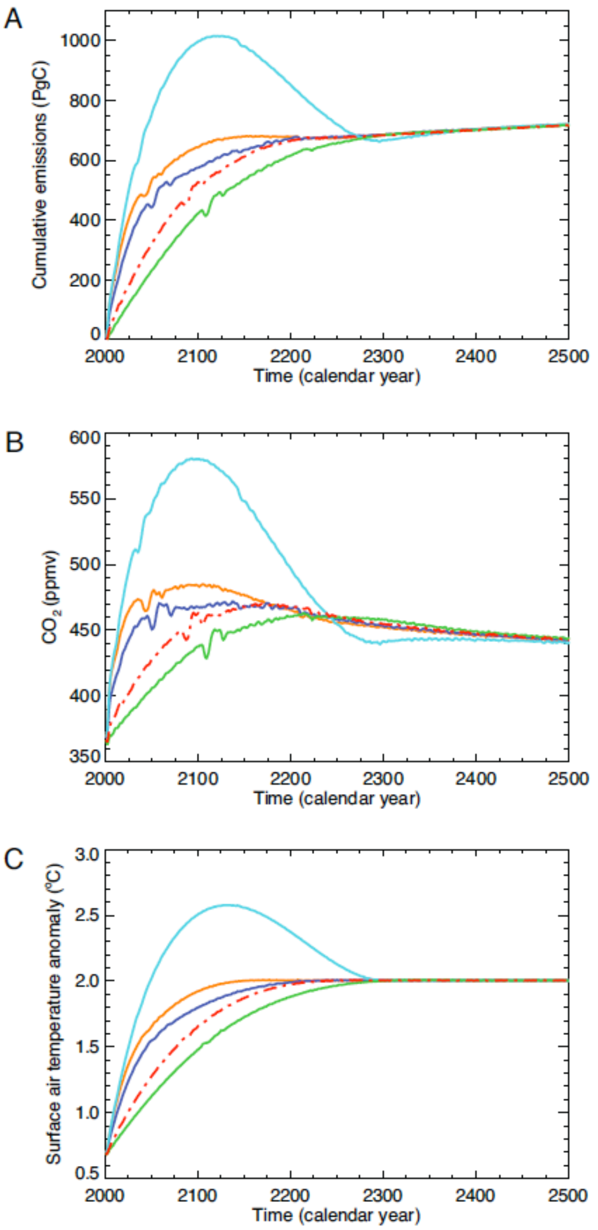
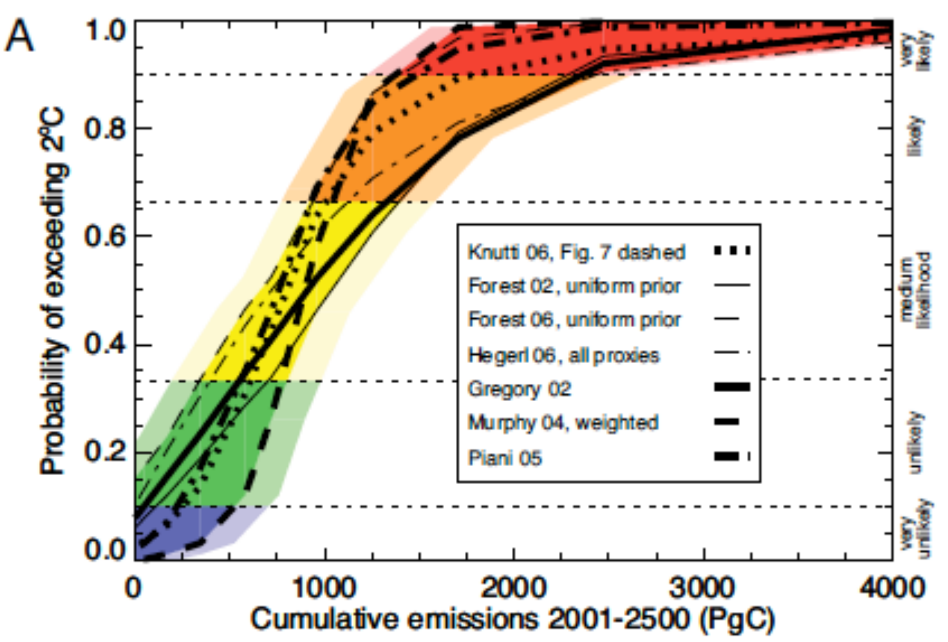


Fig. 1. Path independency of cumulative CO$_2$ emissions. (*A*) Cumulative CO$_2$ emissions and (*B*) CO$_2$ concentrations compatible with a global mean temperature increase of 2 °C relative to preindustrial times. The different curves refer to experiments with different prescribed temperature change trajectories (*C*). The red-dashed trajectory is the standard trajectory used throughout the analysis. Cumulative emissions are computed from the year 2001 onwards.

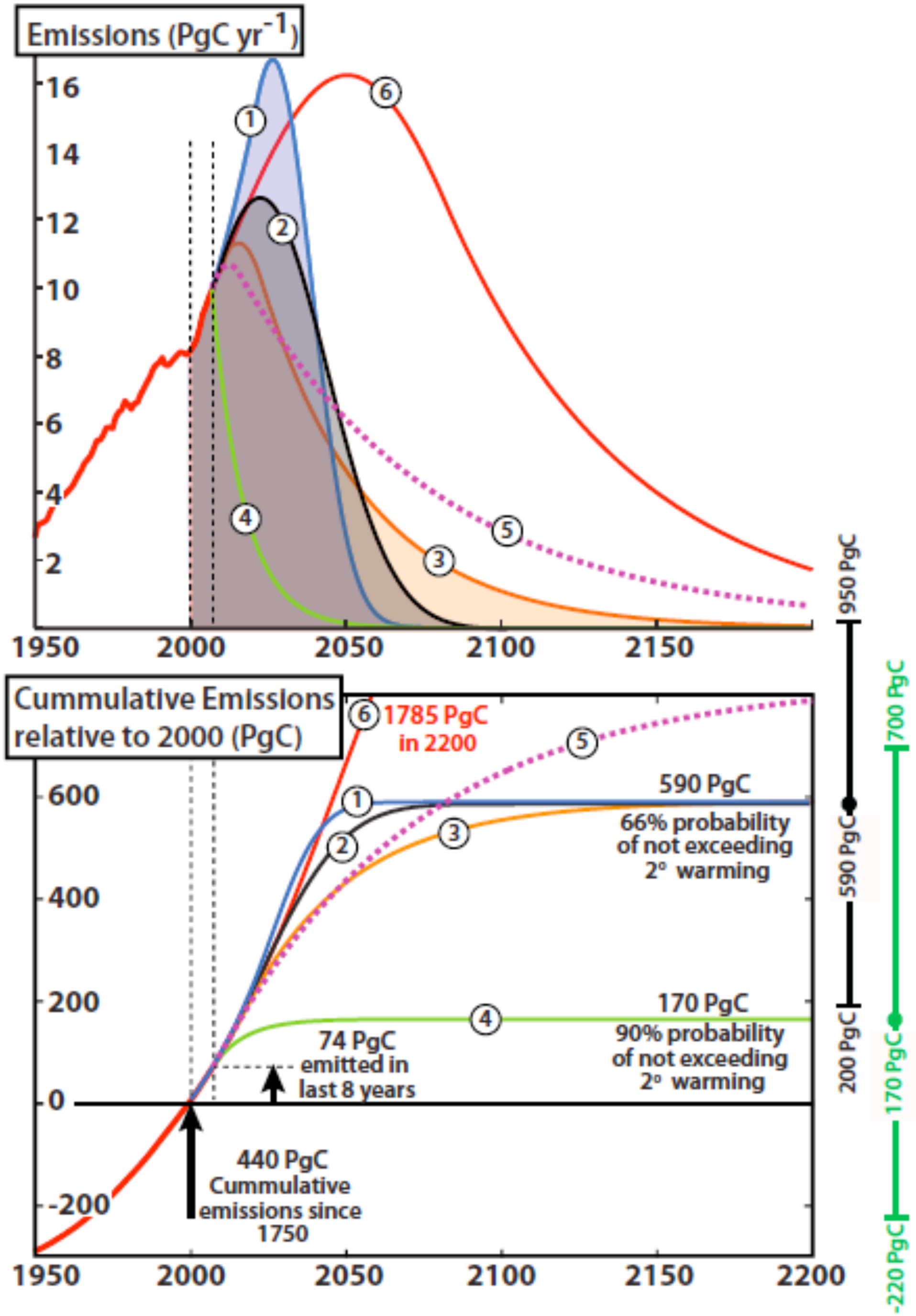
Setting cumulative emissions targets to reduce the risk of dangerous climate change

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



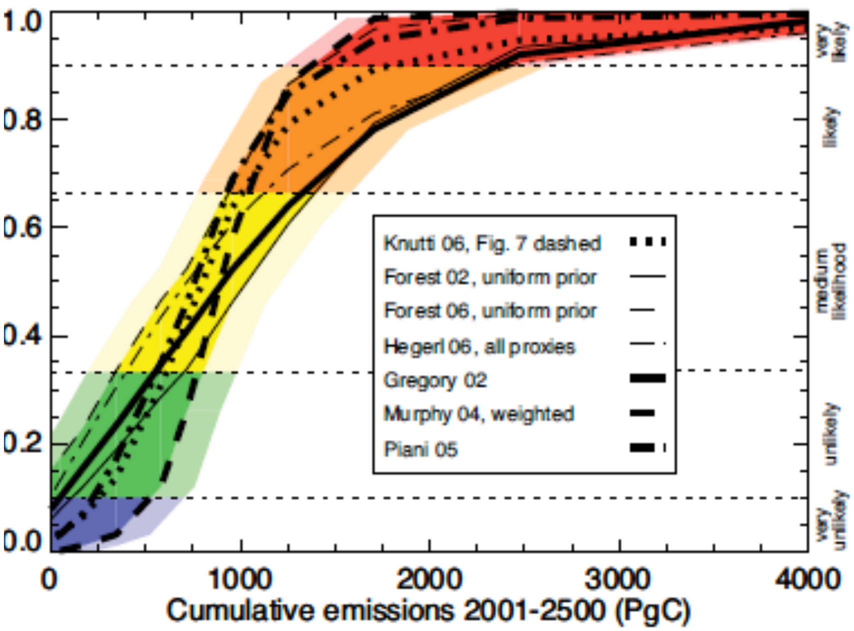
Cumulative carbon, climate sensitivity uncertainty, carbon feedback uncertainties, and stabilization targets

Zickfeld et al., PNAS, 2009



ting cumulative emissions targets to reduce the
of dangerous climate change

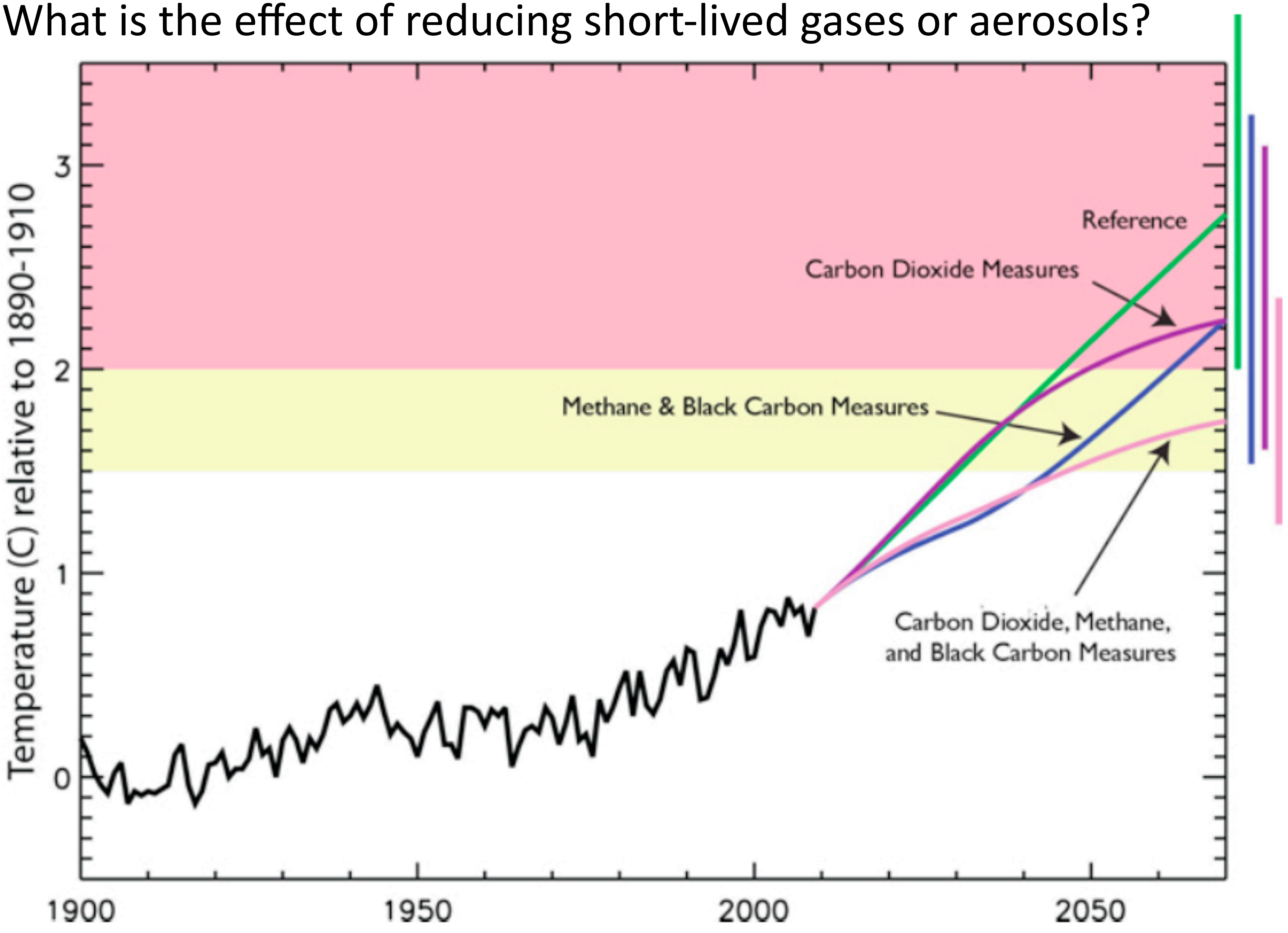
Zickfeld[a,1,2], Michael Eby[a], H. Damon Matthews[b], and Andrew J. Weaver[a]



Cumulative carbon, climate sensitivity uncertainty, and stabilization targets

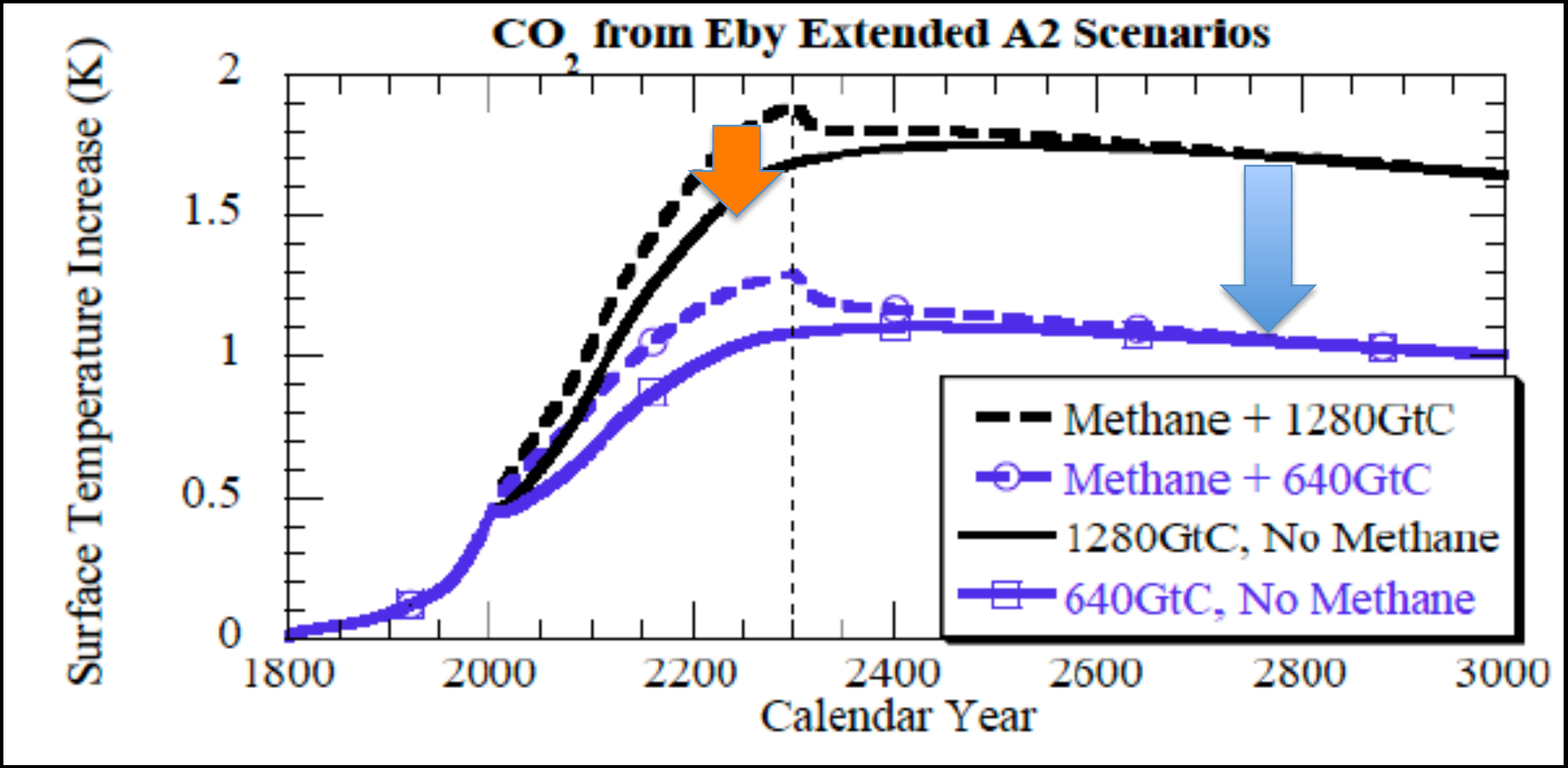
Zickfeld et al., PNAS, 2009; England et al., 2009

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



UNEP, 2011

Two distinct challenges, two baskets?

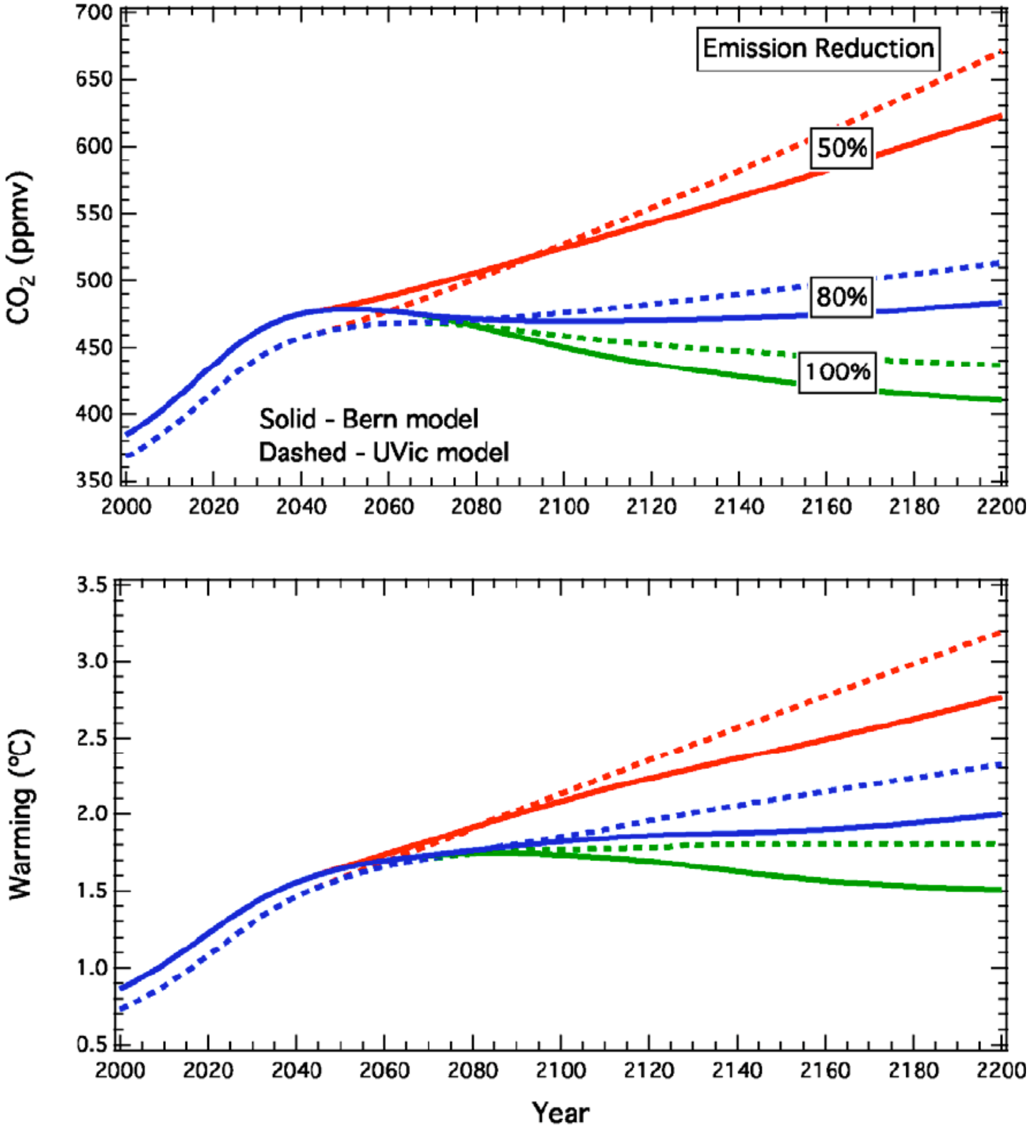


1) Curb the peak->
reduce short-lived species such as methane, trop ozone, soot, etc. This does not "buy time" for CO_2

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

Position paper, Solomon et al.

Warming and Stabilization Targets



Stabilization Targets, 2010

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

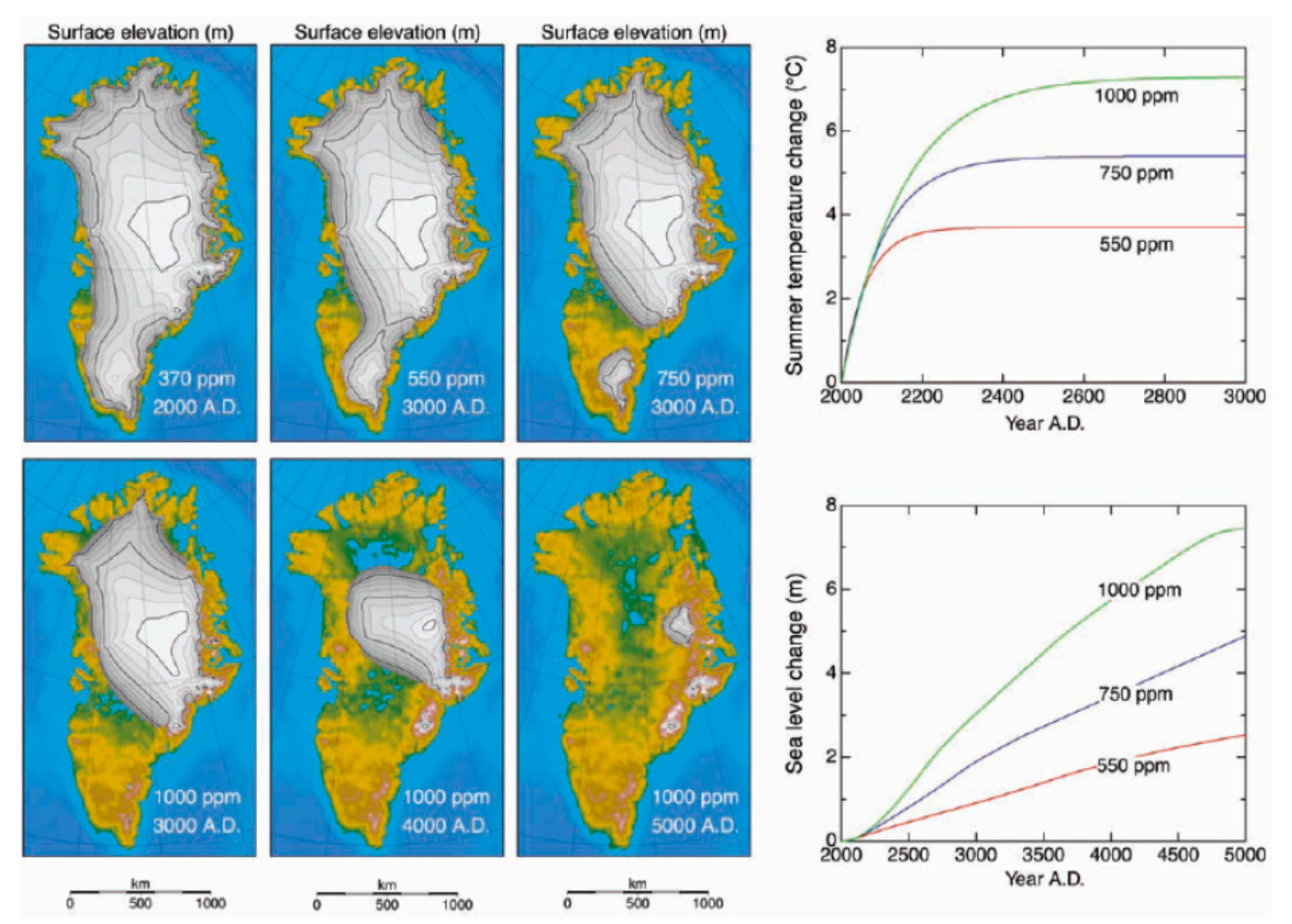
AND

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?

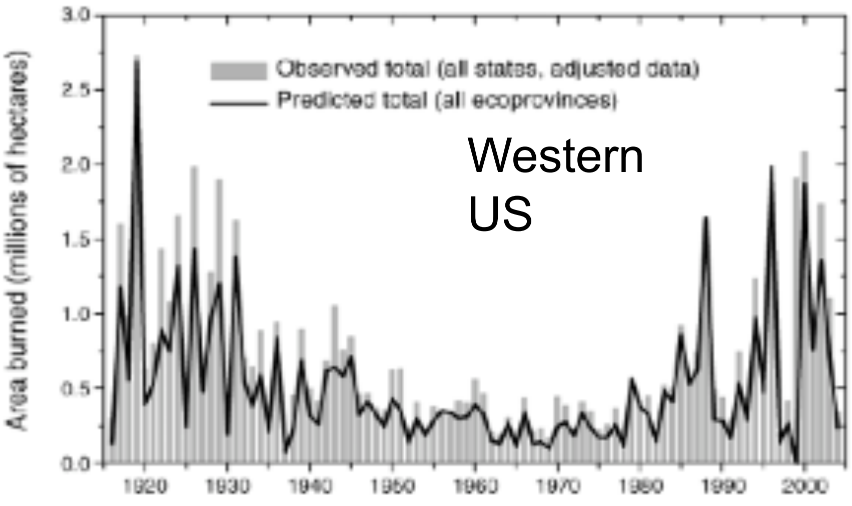
Long-term (carbon-controlled) and short-term (carbon and methane and aerosols…..)?

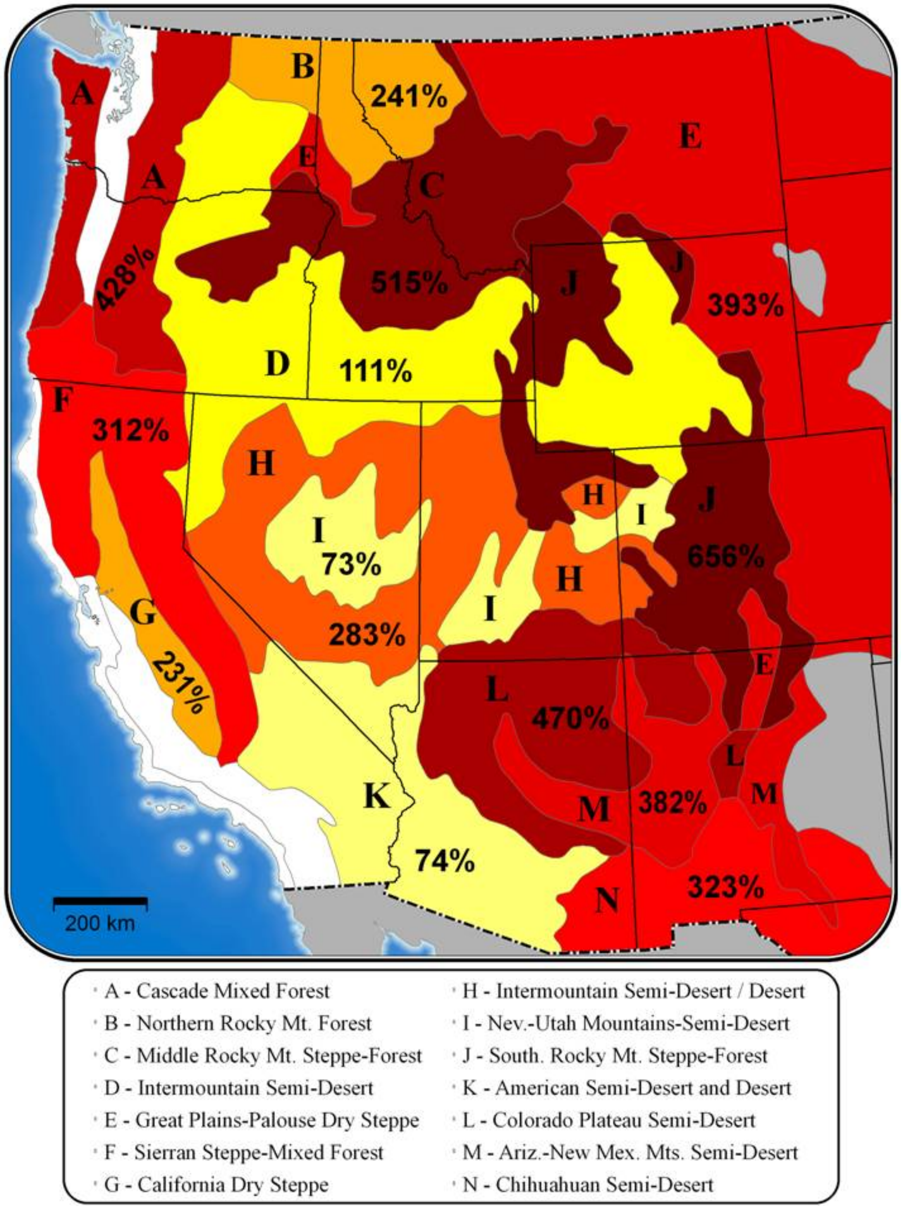
Example need for a long term plan: long-term warming and Greenland



Alley et al.; see Stabilization Targets, 2010

Example need for a short-term plan: short-term wildfire (1-2°C warming)





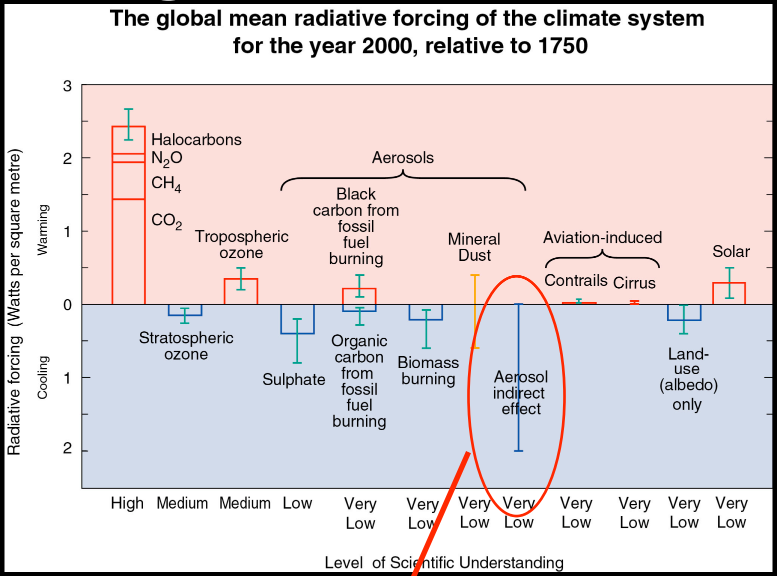
Stabilization Targets, 2010

Key Conclusions

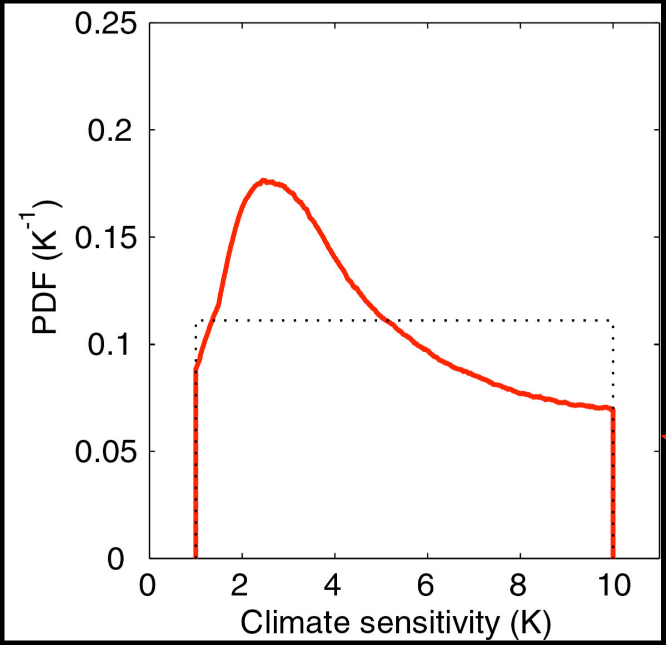
- Warming due to human emissions of carbon dioxide is essentially irreversible for > 1000 yrs
- Warming due to other gases or aerosols also has persistence beyond its lifetime.
- The memory in the ocean is key to persistence and irreversibility, along with gas (or aerosol) lifetime.
- Cumulative carbon is an instructive framework for understanding long-term human-induced change.
- Reductions in non-CO2 forcing agents can help to manage short-term warming, i.e., curb the peak.
- Science-based policy: Trade in two baskets (long/short), plus an overall global carbon limit?

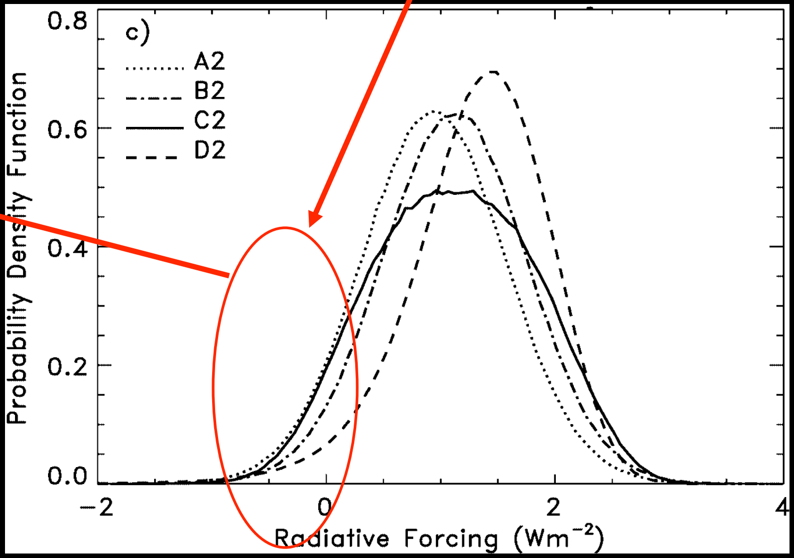
[redacted]

Radiative Forcing, Climate Sensitivity and Why Every Little Chemical Forcing Term Matters



Why don't 20th century trends tell us exactly what climate sensitivity is? Uncertainty in forcing.....ie., chemistry!





After Knutti et al., Nature, 2002

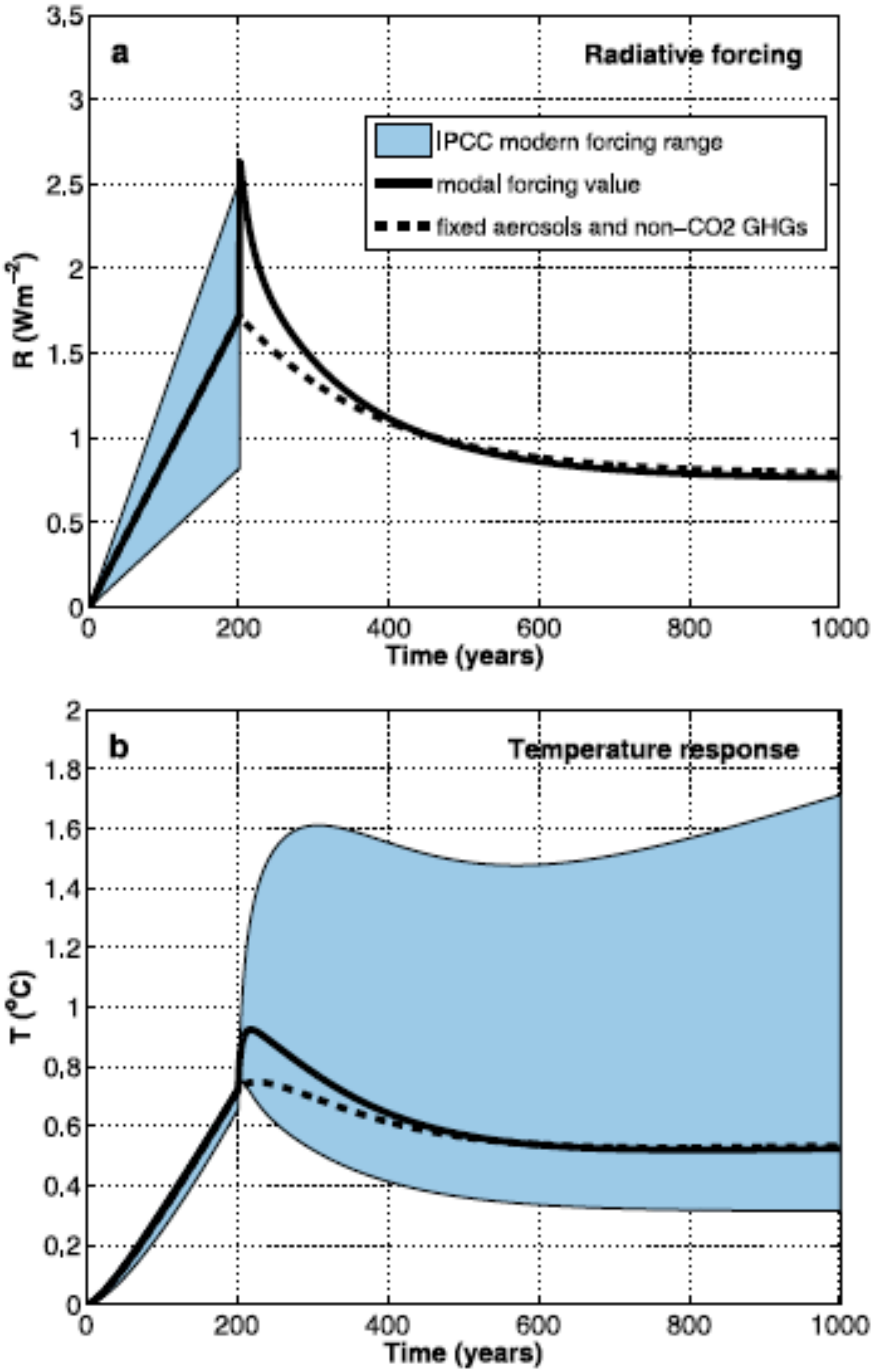
Short and long-term:

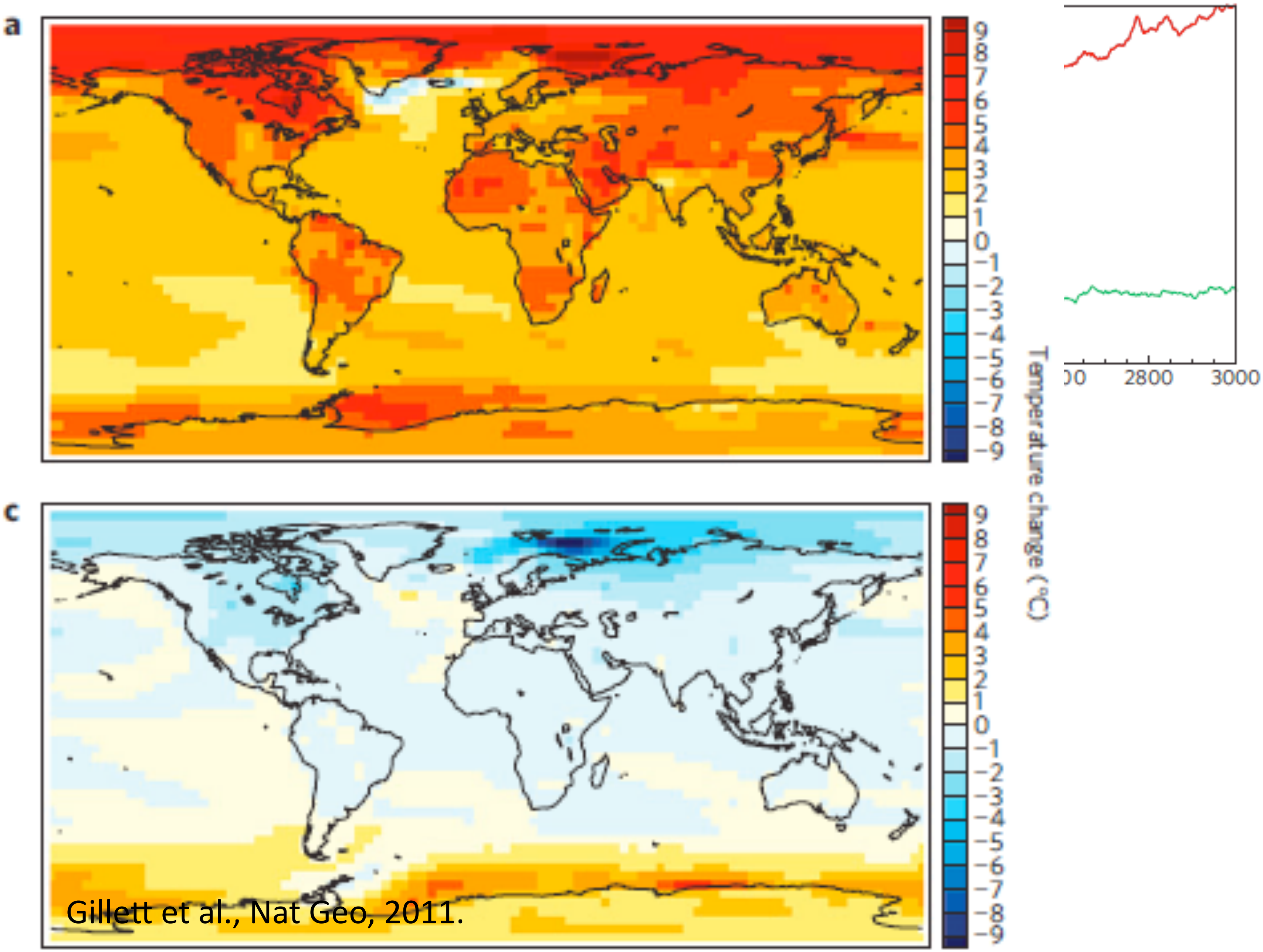
- Faustian bargains…..less CO2 emission will likely impact aerosols and contribute to short-term warming

- Uncertainties in climate sensitivity and aerosol negative forcing….risk of a big warming spike in the short term?

- CO2/sulfur dual roles in long-term/short-term….consider along with energy system, economics, choices…..

Armour and Roe, GRL, 2011





Gillett et al., Nat Geo, 2011.

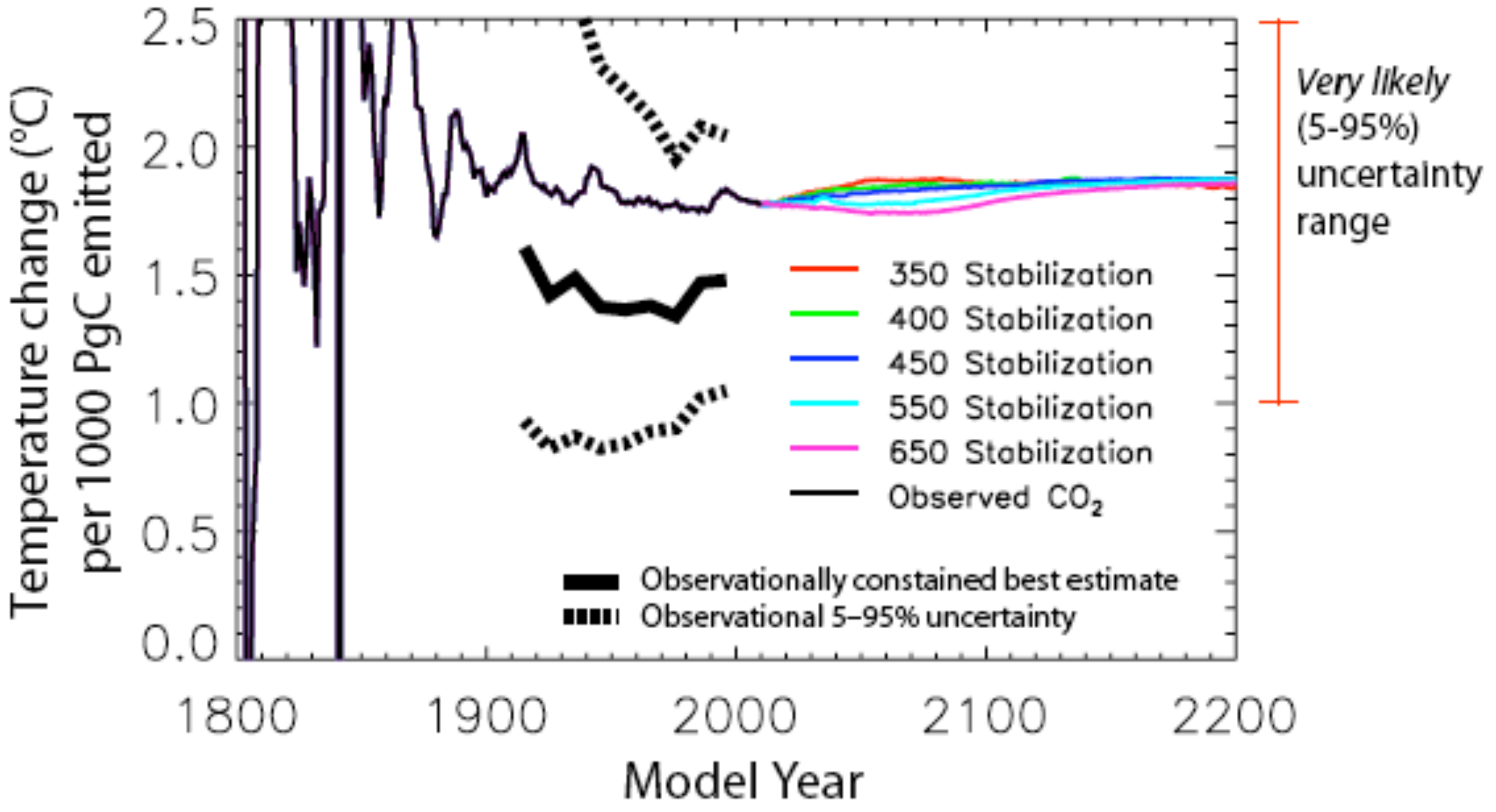


Figure 2: Simulated temperature change per 1000 PgC cumulative carbon emitted. Observational constraints for the twentieth century are given by the thick solid and dashed lines, as in *Matthews et al.* (2009). The *very likely* (5-95%) uncertainty range is indicated by the red error bar, based on a combination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

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

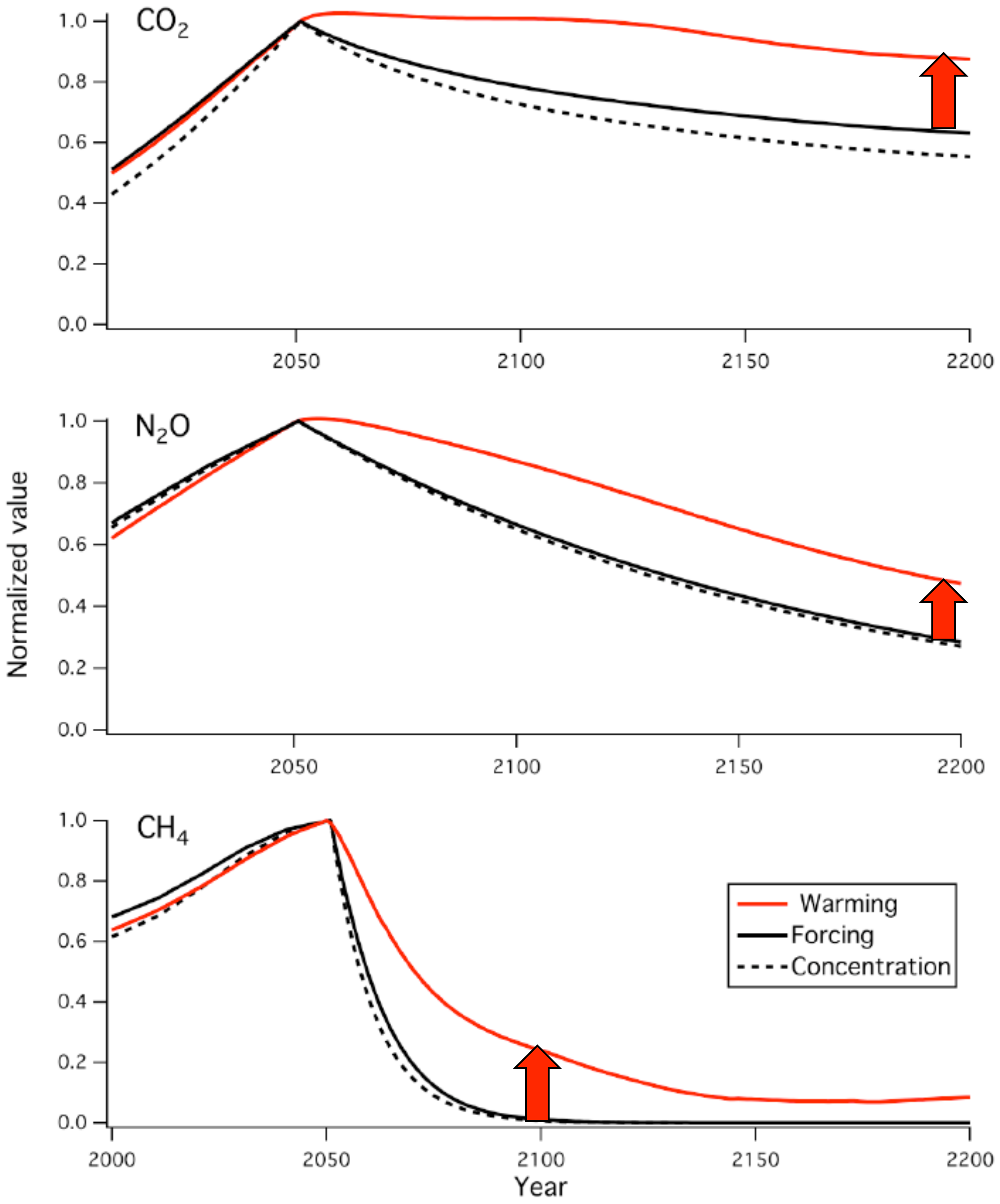
Warming lasts longer than the gases do!

Why?

-Climate system lags (ocean heat uptake)

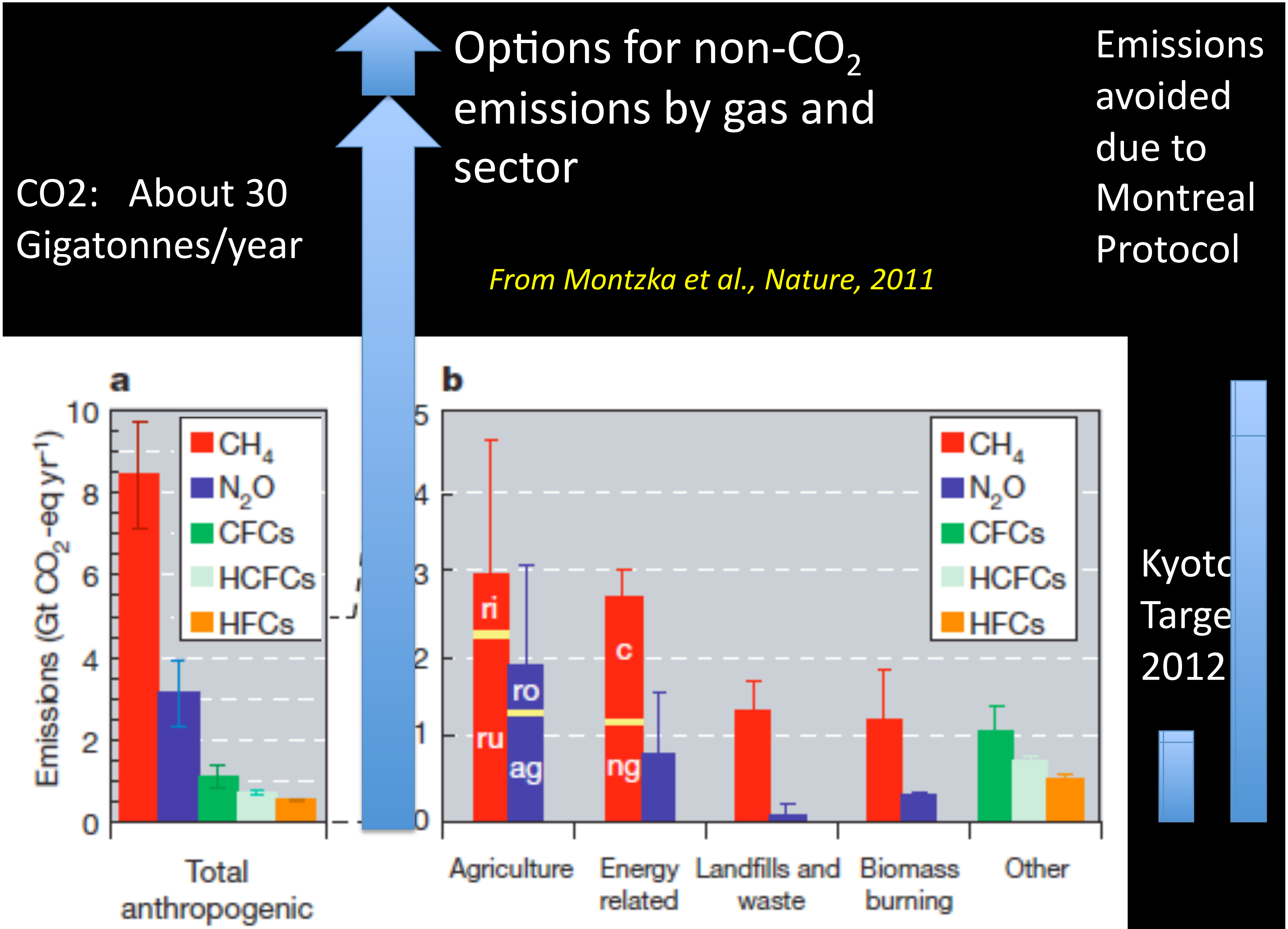
-Nonlinear spectroscopy for some (CO_2, CH_4).

->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.

Options for non-CO$_2$ emissions by gas and sector



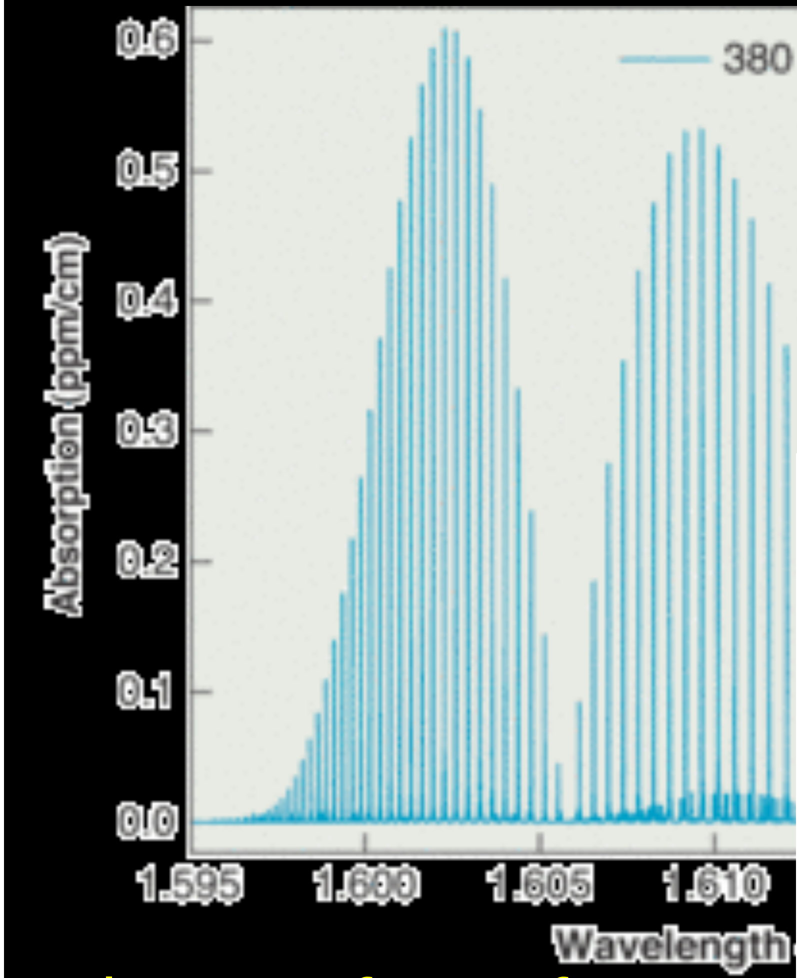
CO2: About 30 Gigatonnes/year

From Montzka et al., Nature, 2011

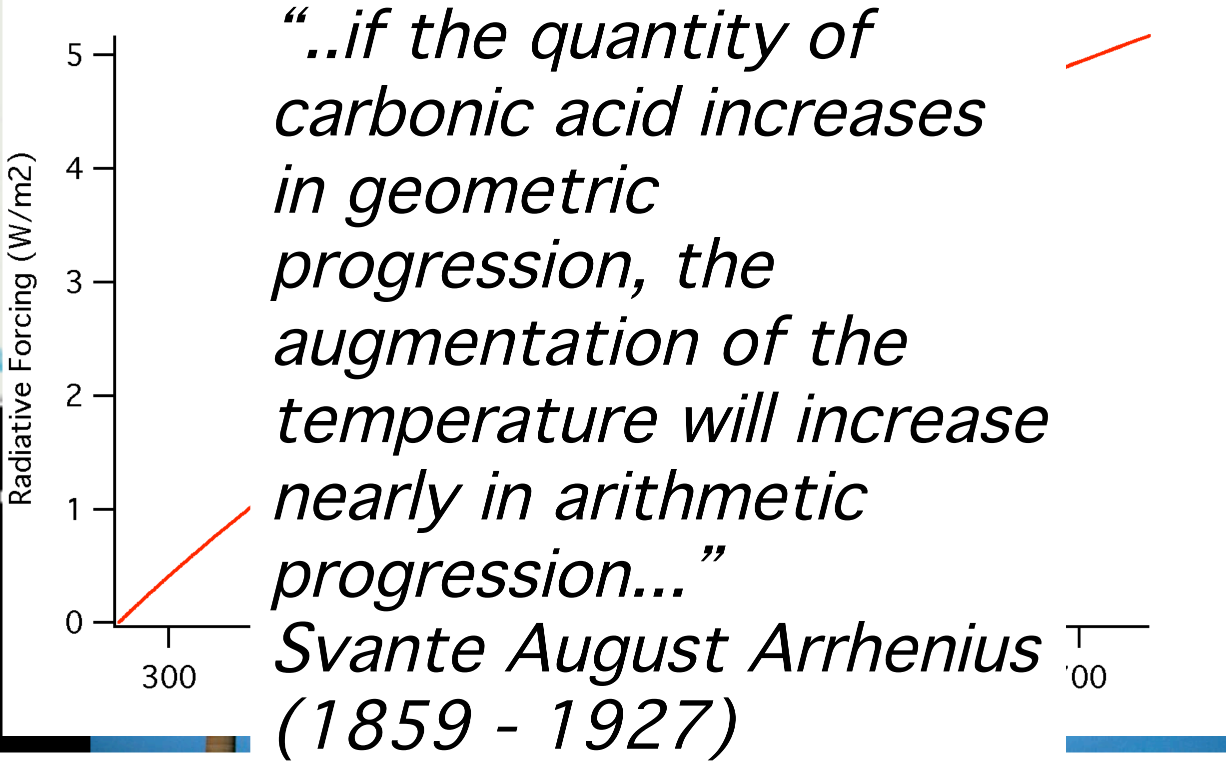
Emissions avoided due to Montreal Protocol

Kyoto
Targe
2012

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)

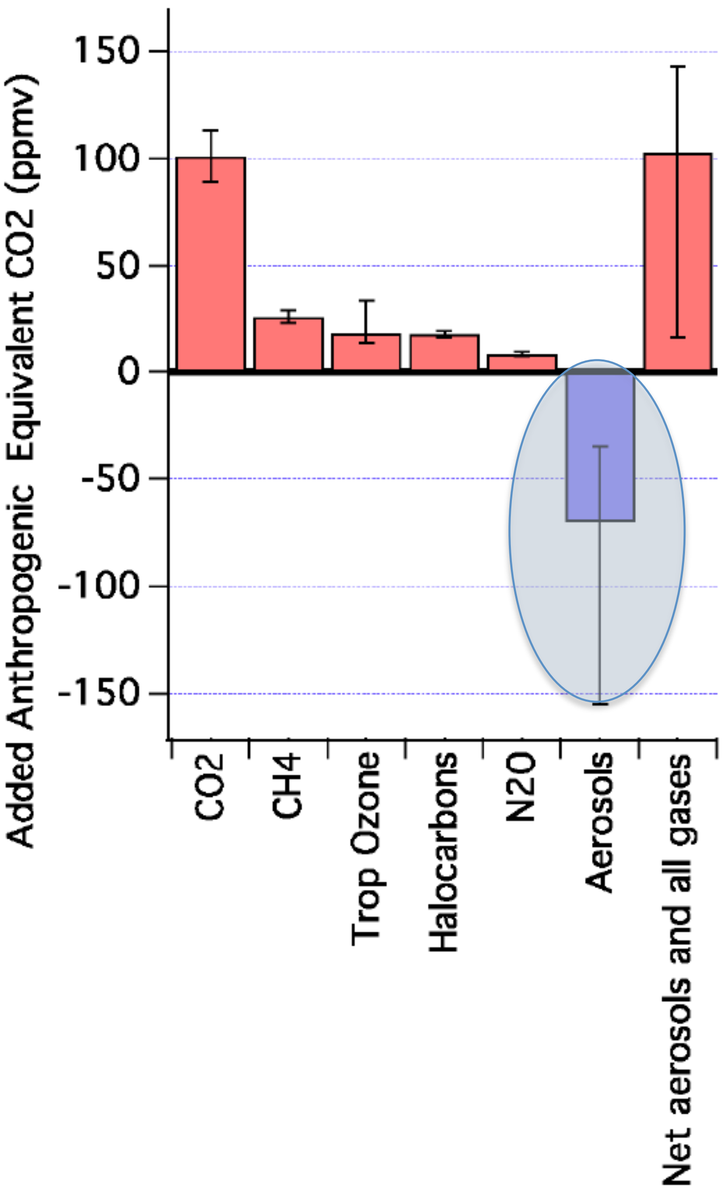
Also significant for
CH4 but not other
GHGs

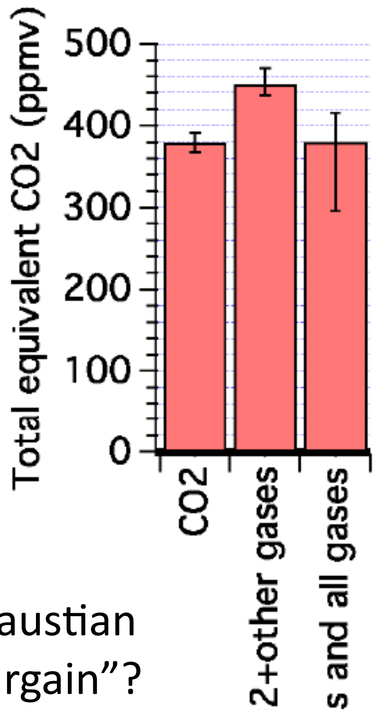
What equivalent carbon dioxide concentration would be represented by the various forcings?

The fraction due to manmade carbon dioxide is more than half now, and is expected to grow to >80% by 2100.

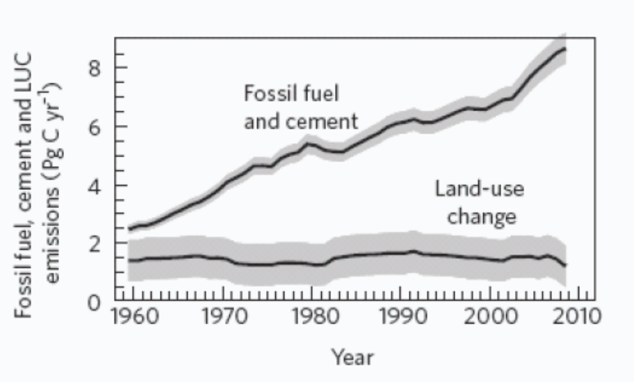
Best estimates of both CO2 and total CO2 equivalent concentrations happen to be ≈390 ppmv.

Organic aerosols? Huge current uncertainty....





“Faustian Bargain”?

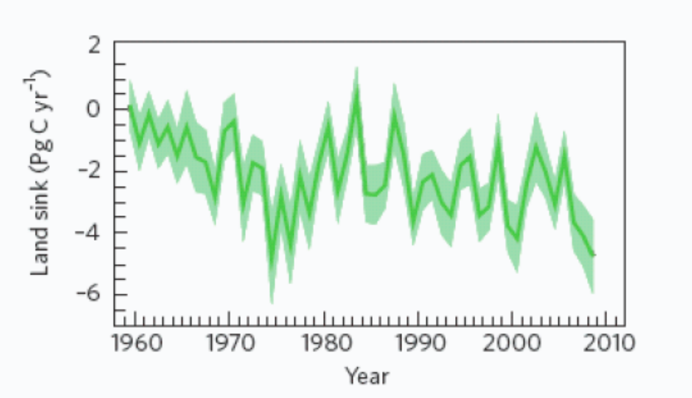


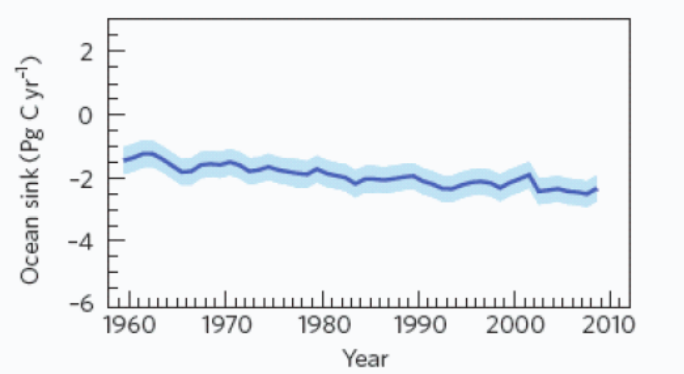
Emissions

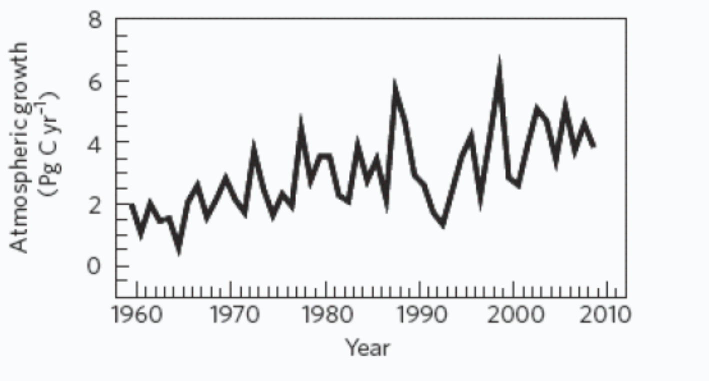
–

Land sink

Ocean sink







Atmospheric carbon dioxide growth rate

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What about ‘geoengineering’ the climate?

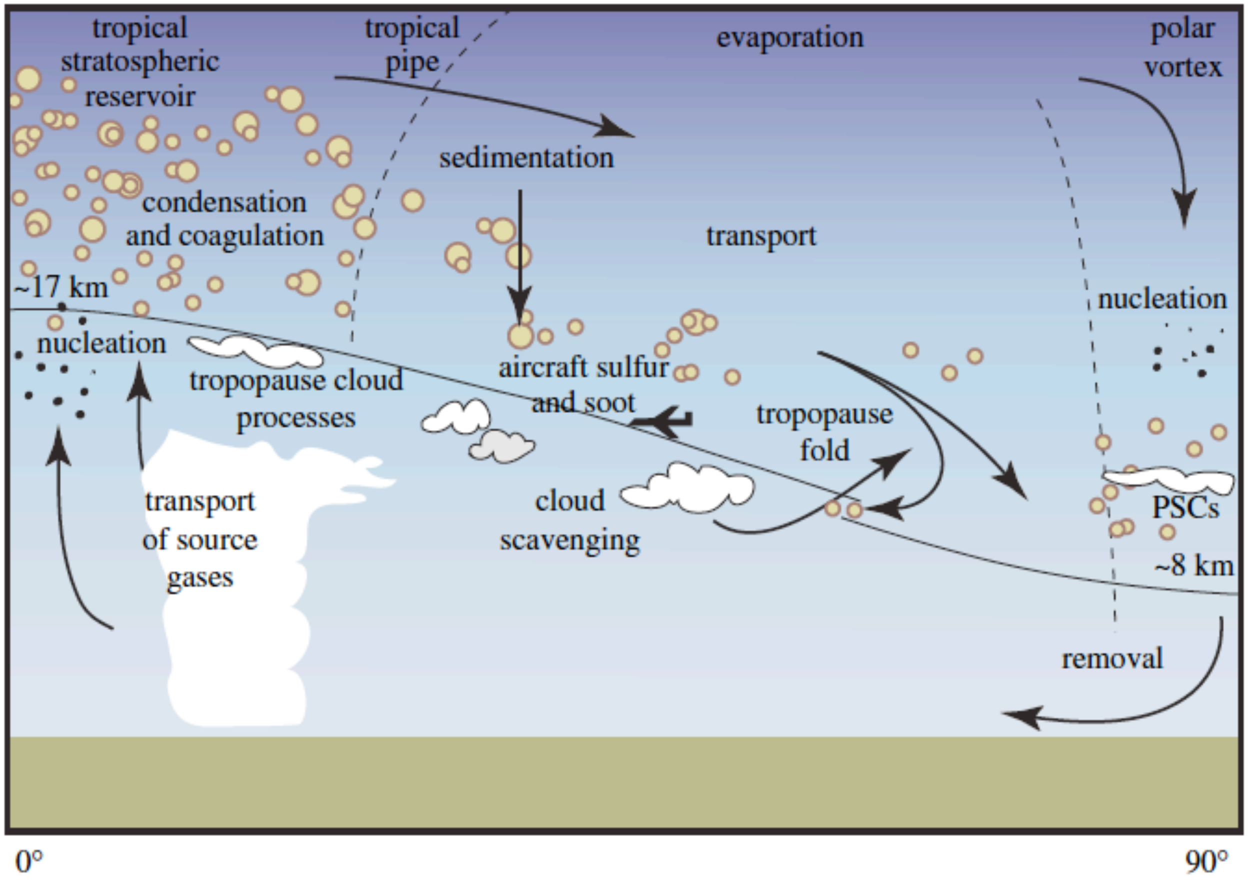


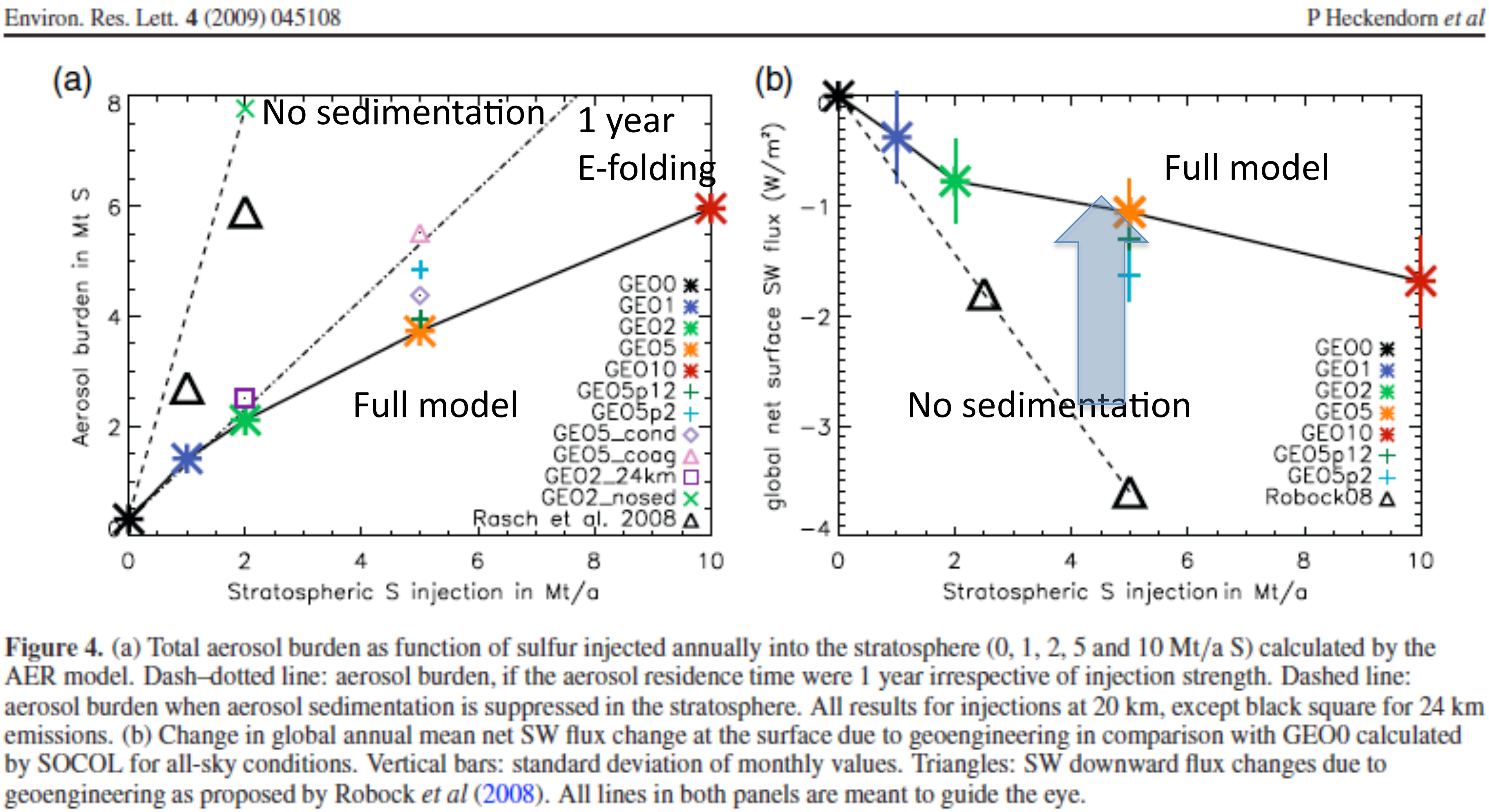
Image from Rasch et al., Phil Trans Roy. Soc., 2008; adapted from SPARC, 2006

One option: Inject SO_2 to increase the stratospheric sulfate aerosol backscatter, just like some volcanoes can?

How much sulfur?

Unintended consequences? Ozone loss?

Detailed calculations: nucleation, coagulation, sedimentation…



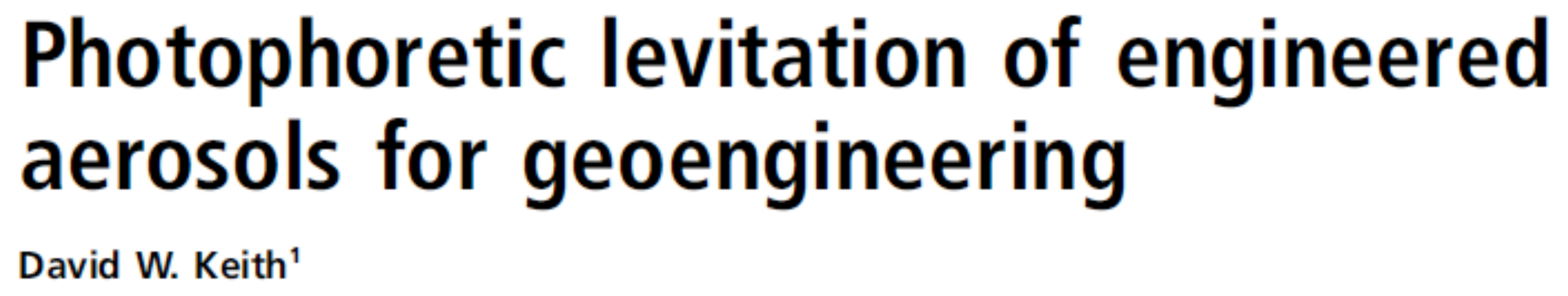
Environ. Res. Lett. **4** (2009) 045108 P Heckendorn *et al*

Figure 4. (a) Total aerosol burden as function of sulfur injected annually into the stratosphere (0, 1, 2, 5 and 10 Mt/a S) calculated by the AER model. Dash–dotted line: aerosol burden, if the aerosol residence time were 1 year irrespective of injection strength. Dashed line: aerosol burden when aerosol sedimentation is suppressed in the stratosphere. All results for injections at 20 km, except black square for 24 km emissions. (b) Change in global annual mean net SW flux change at the surface due to geoengineering in comparison with GEO0 calculated by SOCOL for all-sky conditions. Vertical bars: standard deviation of monthly values. Triangles: SW downward flux changes due to geoengineering as proposed by Robock *et al* (2008). All lines in both panels are meant to guide the eye.

Heckendorn et al., Env. Res. Lett., 2009;
Pierce et al., Goephys Res Lett, 2010

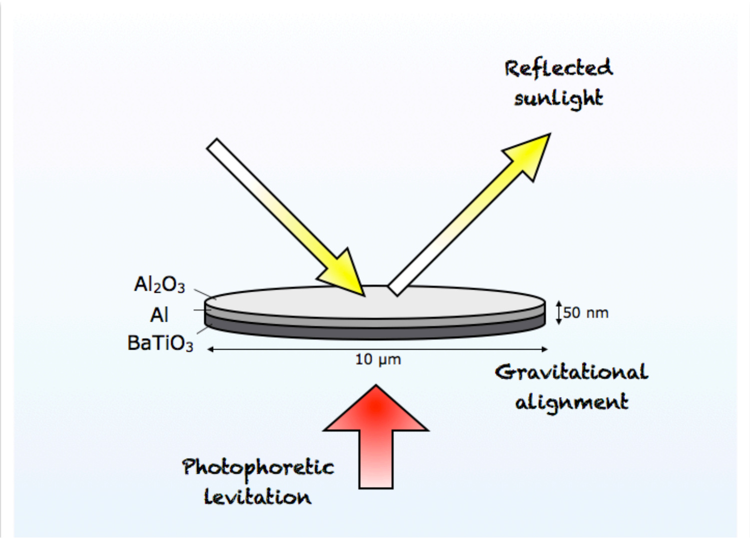
Hard to make SO_2 work….aerosols grow and fall out! Tiny H_2SO_4 drops instead?

New ideas in materials chemistry and geoengineering



Photophoretic levitation of engineered aerosols for geoengineering

David W. Keith[1]



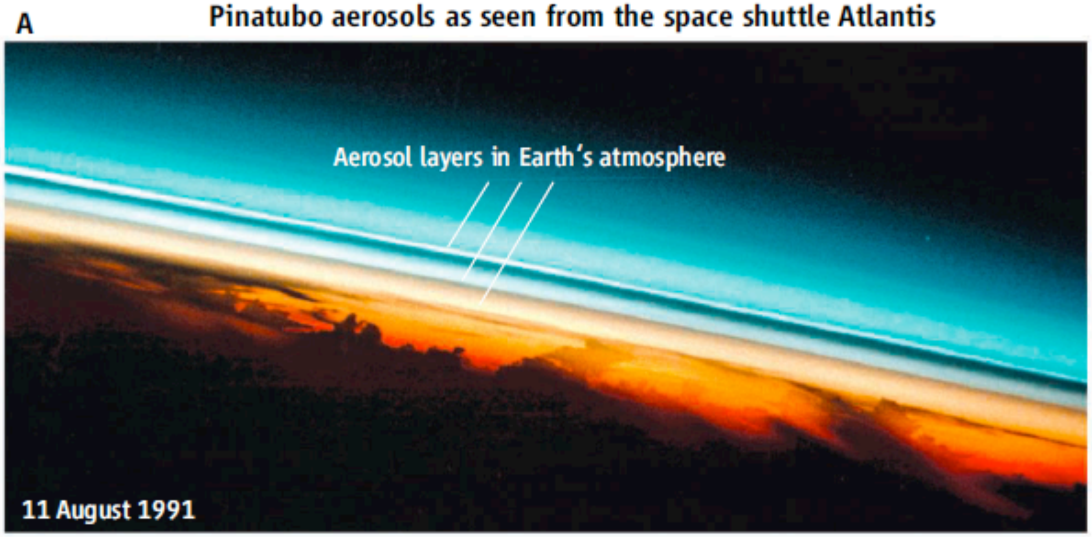
http://2020science.org/2010/09/13/could-precisely-engineered-nanoparticles-provide-a-novel-geoengineering-tool/

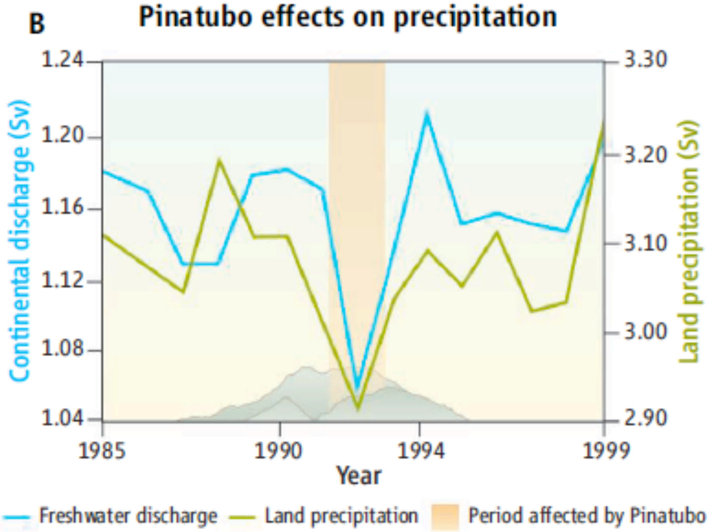
Thermal gradients, gravity to keep particles suspended in the atmosphere? Custom made nanoparticles?

Particle is illuminated by the sun, heating it, but different composition on upper and lower sides could drive an upward force if engineered so that air molecules absorb and desorb at just the right velocities from the two sides. How long could the particles stay in the stratosphere? What about the circulation (not just sedimentation)? How expensive would they be?

Keith, 16428–16431 | PNAS | September 21, 2010 | vol. 107 | no. 38

Unintended Consequences?

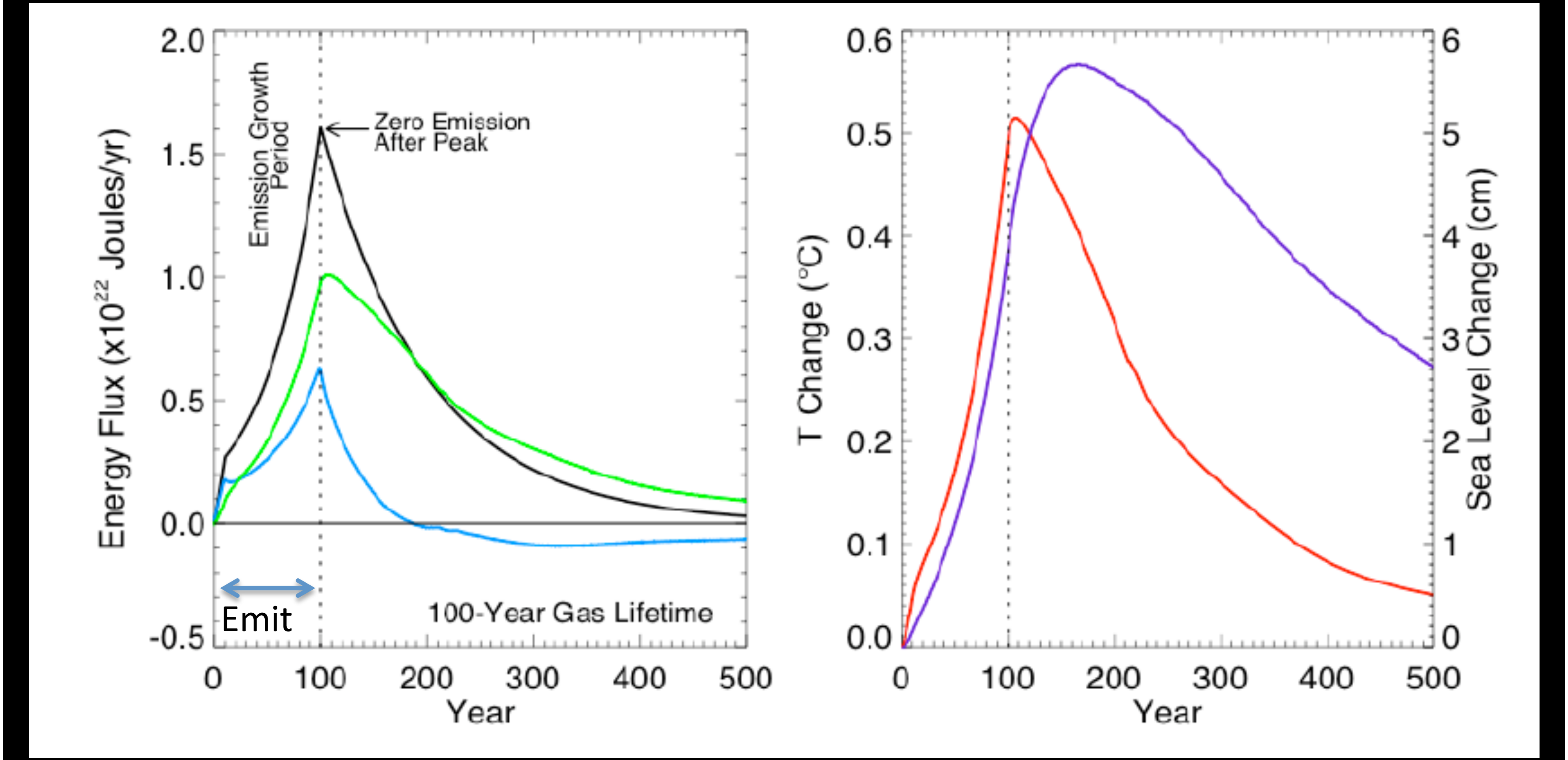




Greenhouse gases affect outgoing infrared light from the planet.
Scheme of 'solar radiation modification' by particles could cool the planet…..but by reflecting incoming solar visible light.
This would also affect precipitation…..cooler but drier? Who wins? Who loses? And ocean acidification would mount up.
Other options? Need for an 'escape' for Faust (ie. CO_2 removal)?

Trenberth and Dai, GRL, 2007; see also Hegerl and Solomon, Science, 2009.

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…

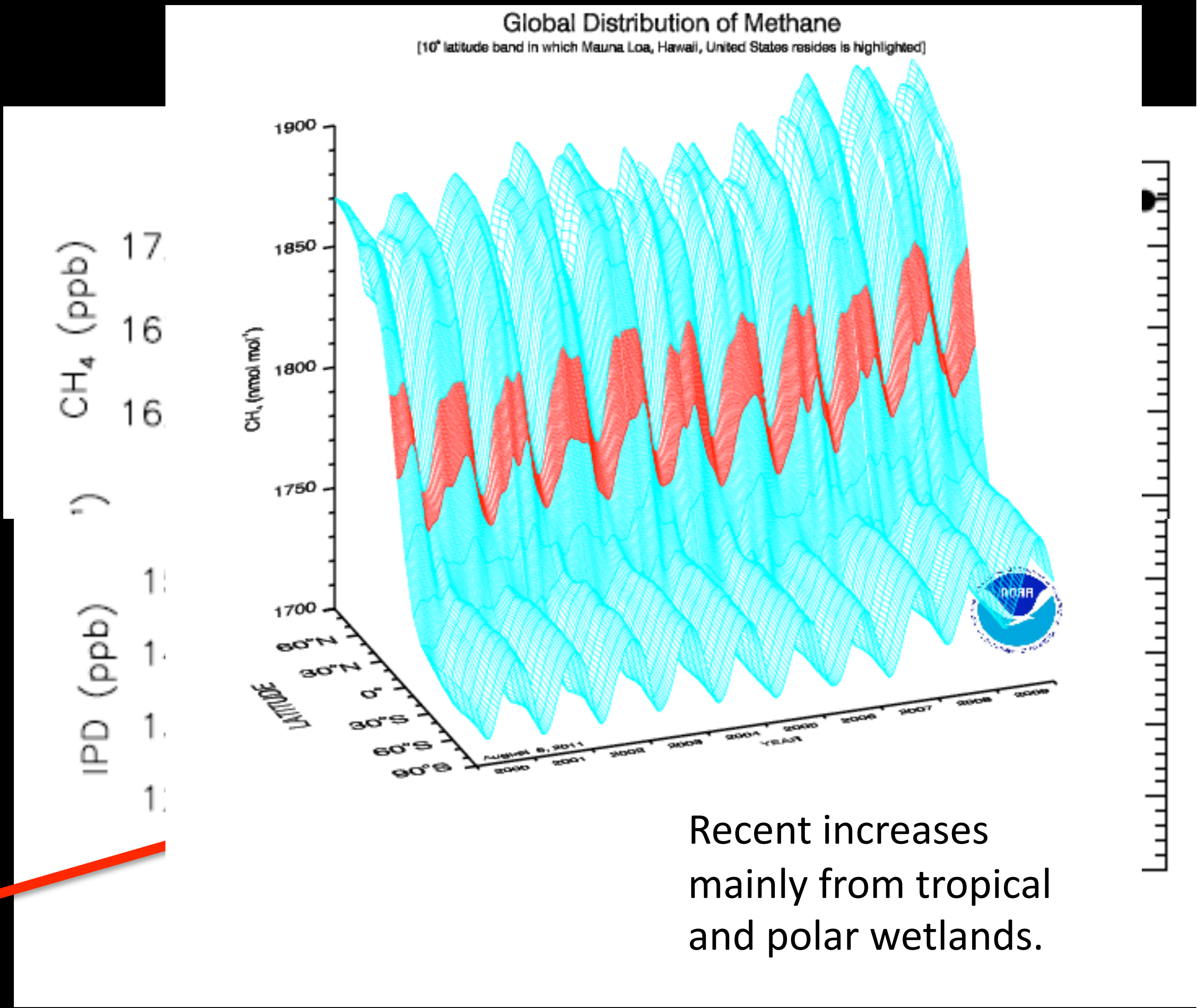


Bern 2.5CC EMIC runs - Solomon et al., PNAS, 2010.

Much More Recent Changes in Methane

But….Nature in Aug 2011…..
One study uses ethane (purely fossil) to back up the view that FF efficiency contributed, while another uses ΔC13 to argue that biogenic source changes linked to fertilizers were dominant…..

Note changes in trends since the collapse of the Soviet Union (less release from mining)



Recent increases mainly from tropical and polar wetlands.

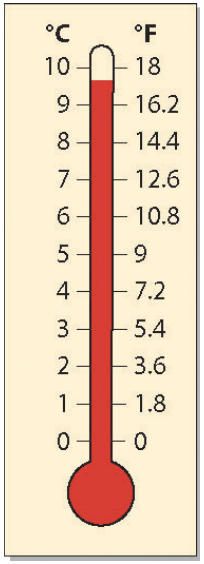
Dlugocencky et al., GRL, 2003; 2009.

Transient and quasi-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

Climate sensitivity is the temperature response for CO_2 double the pre-industrial value of 550 ppmv. Estimated "likely" range is 2.1-4.3°C, with a best estimate of about 3°C.

Note: transient response at the time of doubling is about half of the long-term response for doubling, due mainly to the ocean's slow warming, i.e. λ/TCR ≈2



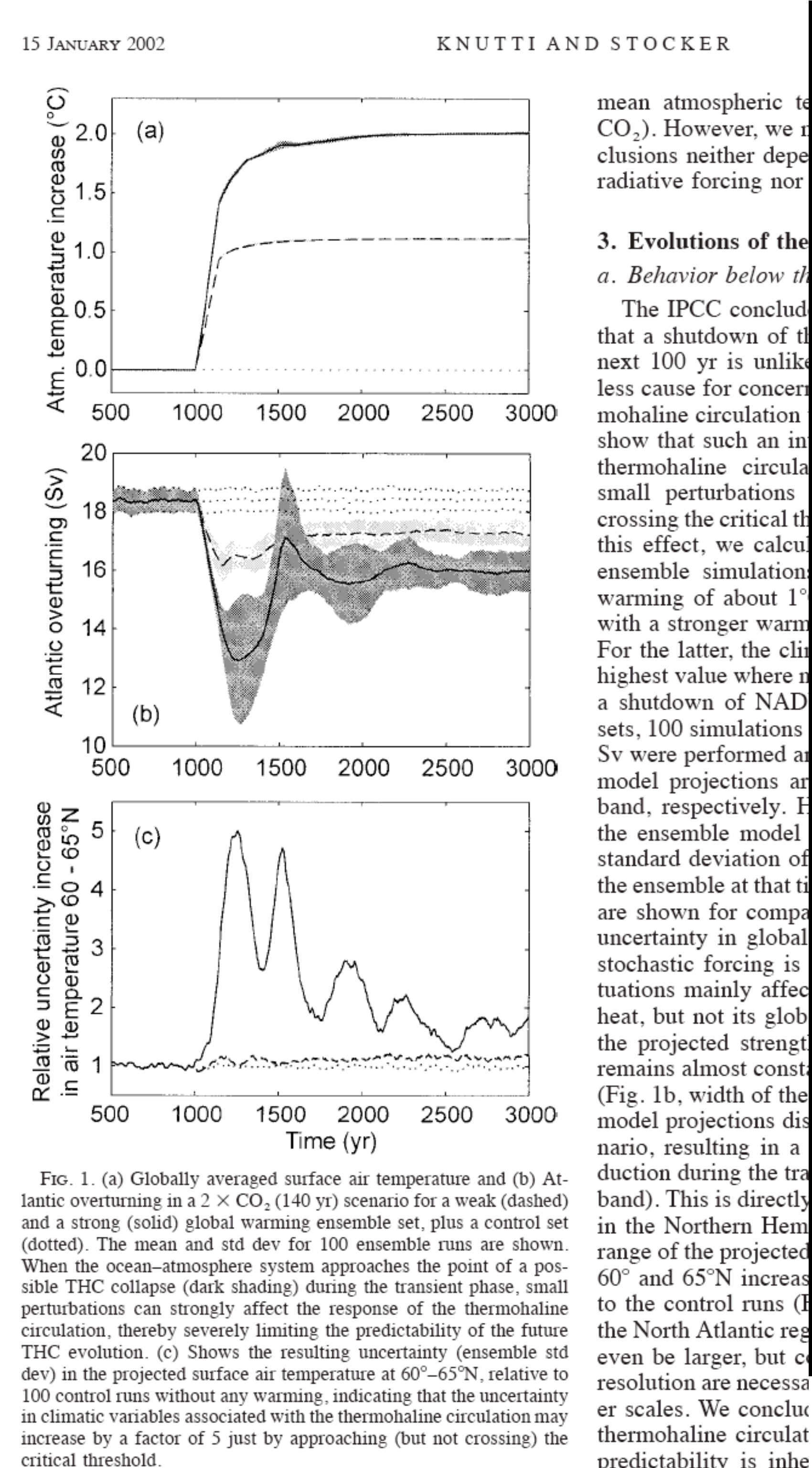


FIG. 1. (a) Globally averaged surface air temperature and (b) Atlantic overturning in a 2 × CO$_2$ (140 yr) scenario for a weak (dashed) and a strong (solid) global warming ensemble set, plus a control set (dotted). The mean and std dev for 100 ensemble runs are shown. When the ocean–atmosphere system approaches the point of a possible THC collapse (dark shading) during the transient phase, small perturbations can strongly affect the response of the thermohaline circulation, thereby severely limiting the predictability of the future THC evolution. (c) Shows the resulting uncertainty (ensemble std dev) in the projected surface air temperature at 60°–65°N, relative to 100 control runs without any warming, indicating that the uncertainty in climatic variables associated with the thermohaline circulation may increase by a factor of 5 just by approaching (but not crossing) the critical threshold.

mean atmospheric te
CO$_2$). However, we r
clusions neither depe
radiative forcing nor

3. Evolutions of the

a. Behavior below th

The IPCC conclud
that a shutdown of th
next 100 yr is unlike
less cause for concern
mohaline circulation
show that such an in
thermohaline circula
small perturbations
crossing the critical th
this effect, we calcul
ensemble simulations
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For the latter, the cli
highest value where n
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sets, 100 simulations
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model projections ar
band, respectively. H
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in the Northern Hem
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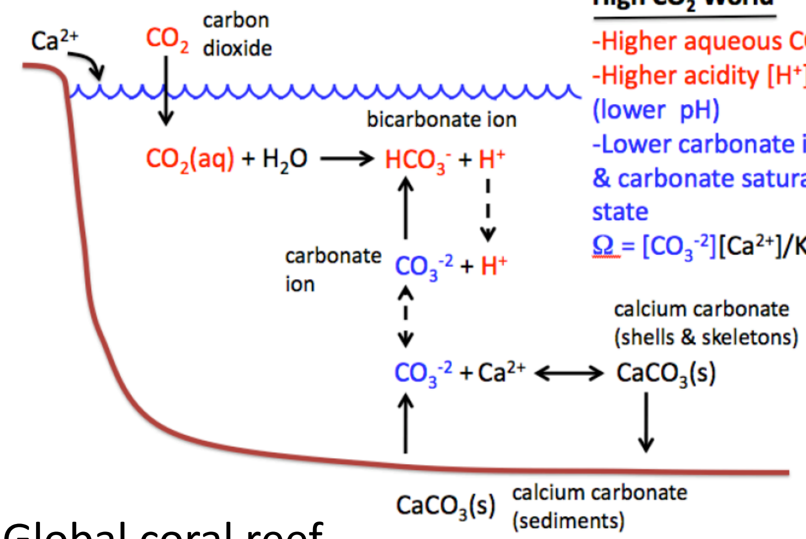
resolution are necessa
er scales. We conclu
thermohaline circulat
predictability is inhe

Bern model Atlantic overturning circulation (MOC, or THC). MOC exhibits instabilities and changes in strength of ocean circulation when forcing is larger.

Effect on surface temperature evolution.

Ocean Acidification: Long and Short of It



Ca^{2+}

CO_2 carbon dioxide

bicarbonate ion

$CO_2(aq) + H_2O \longrightarrow HCO_3^- + H^+$

carbonate ion $CO_3^{-2} + H^+$

calcium carbonate (shells & skeletons)

$CO_3^{-2} + Ca^{2+} \longleftrightarrow CaCO_3(s)$

$CaCO_3(s)$ calcium carbonate (sediments)

High CO_2 World

-Higher aqueous CO_2

-Higher acidity $[H^+]$

(lower pH)

-Lower carbonate ion & carbonate saturation state

$\Omega = [CO_3^{-2}][Ca^{2+}]/K_{sp}$

Photo courtesy of Ove Hoegh-Guldberg

Global coral reef distribution and biological production of calcium carbonate skeleton (shell material) taking into account both ocean acidification and thermal bleaching

Stabilization Targets, 2010