Woodrow Wilson School 585b
cross-listed: MAE 580

Living in a Greenhouse: Technology and Policy

Professor: Robert Socolow
AI: Phil Hannam

Week 2: Impacts and Adaptation
September 18, 2013

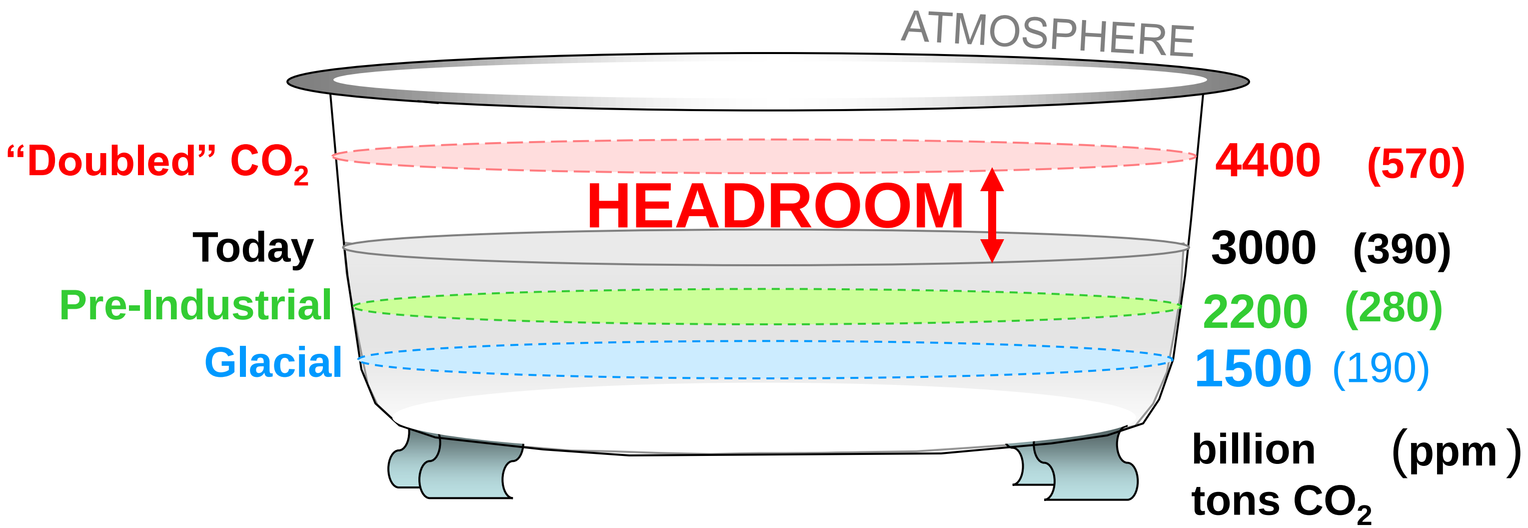
Outline for Lecture 2

A short preamble on greenhouse gas quantities.

What are the impacts of climate change?

How are goals being formulated that would constrain emissions?

Past, present, and potential future levels of CO_2 in the atmosphere



Rosetta Stone: To raise the concentration of CO_2 in the atmosphere by **one part per million:**

add **7.8 billion tons of CO_2,**

in which are **2.1 billon tons of carbon.**

The Deutsche Bank Carbon Counter

Penn Station, New York City
June 18, 2009, about 9:15 a.m.
Real time: www.dbcca.com

The number shown is the mass of CO_2 that would provide as much warming ("forcing") as is provided by *all* the current long-lived gases (Kyoto and Montreal gases).

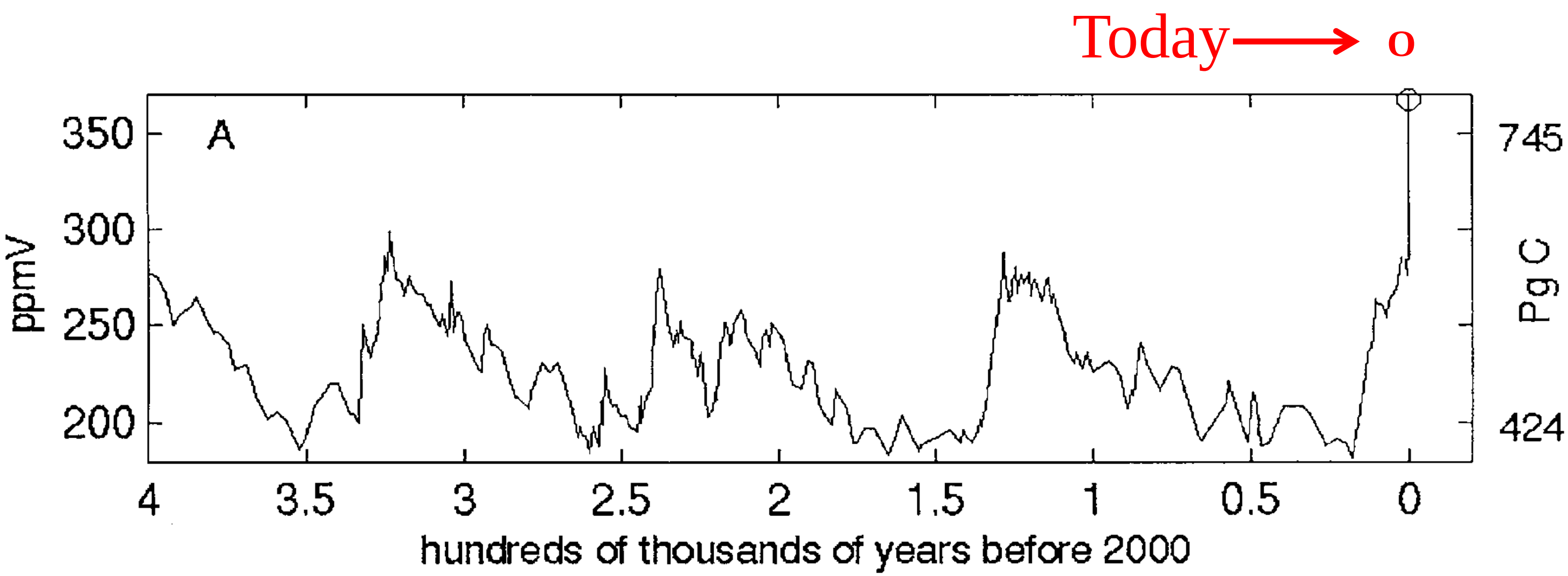
The mass of CO_2 in the atmosphere is about 3.0 trillion tons.

September 16, 2013, 8:00 pm: 3.74 trillion tons. 100 billion tons in 4.25 years, or 135 million seconds, so the number has been climbing 750 ton/second, or two-thirds of one percent per year.

Antarctic Ice Core

Source: Gabrielle Walker, "Frozen time," *Nature;* Jun 10, 2004; 429, 6992; Research Library Core, pg. 596

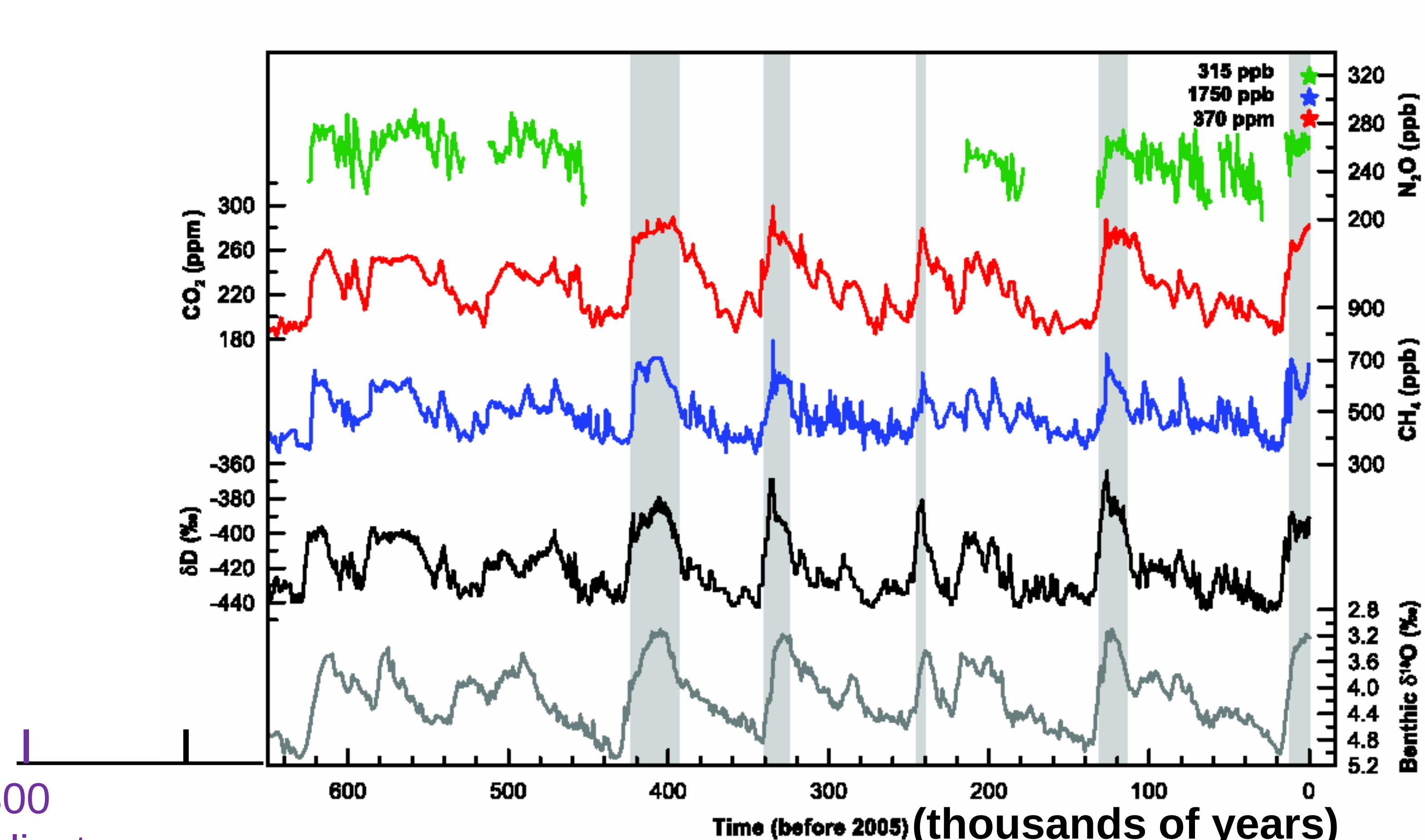
400,000 Years of CO_2 Data: Four Ice Ages



Variations of atmospheric CO_2 over glacial/interglacial times (Petit et al. 1999, Keeling and Whorf 1999). ^Red Circle at upper right shows current concentration.

Paleoclimate studies are at the center of the unease among climate scientists about rising CO_2 . The phenomena are large, and the causes are poorly known.

The ice-core record



800
Earliest
ice in
icecores

Temperature, CO_2, and methane track each other.
But a new paper from Japan during the 2013 summer:
ice ages can be explained without CO_2!

Source: Michael McElroy, website

The first measurements above 400 ppm

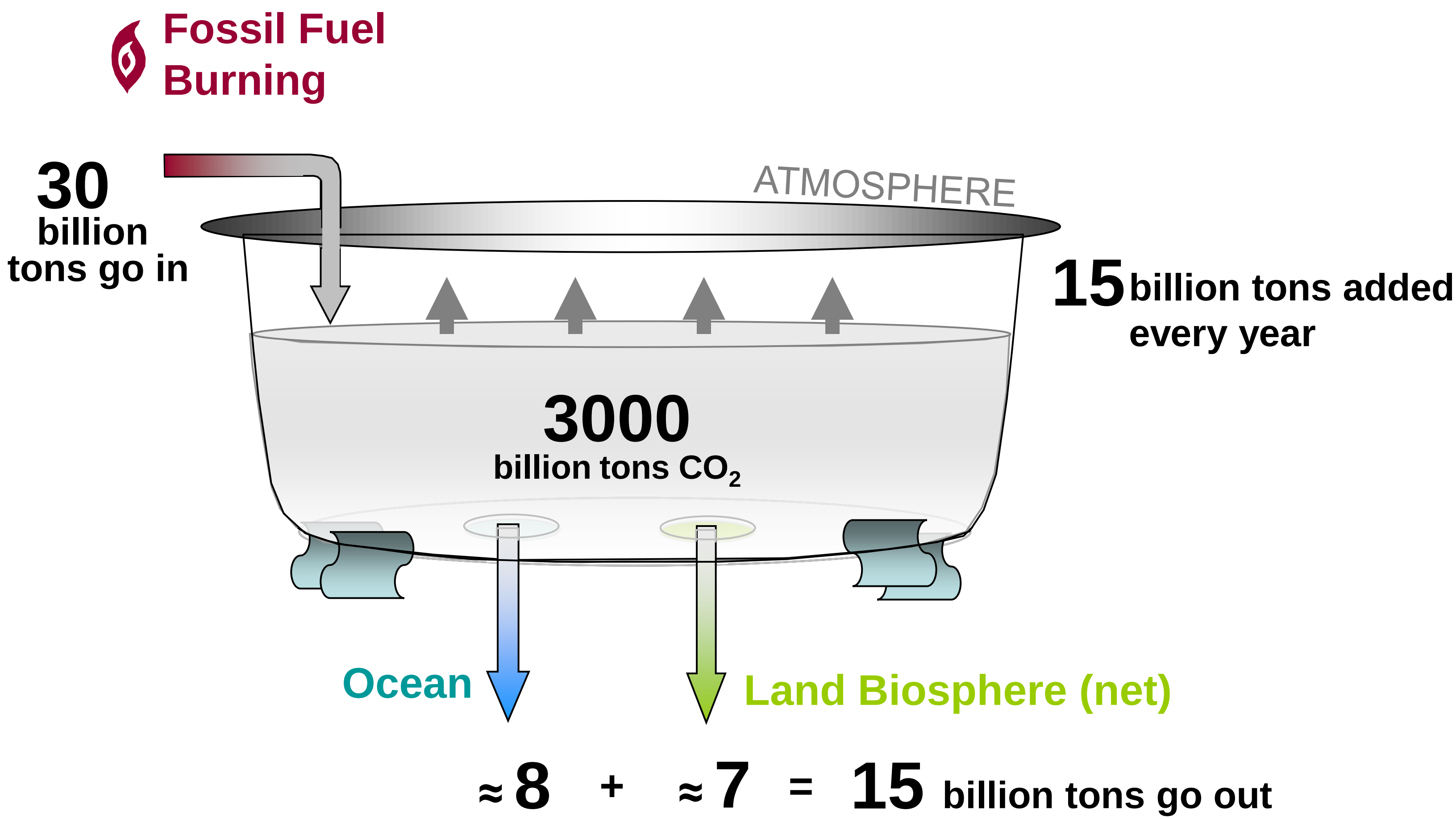
The *monthly* average CO_2 concentrations in April 2012 at the arctic stations of the global CO_2 network exceeded 400 ppm – the first such measurements anywhere.

The annual-average CO_2 concentration in the arctic is less than in temperate latitudes, but the amplitude of the annual swing from May peak to November valley is much larger, with the result that the April and May arctic concentrations are larger. (I am trying to understand why.)

On May 9, 2013, NOAA announced that the *daily* average concentration at Mauna Loa exceeded 400 ppm, and there was a lot of media attention.

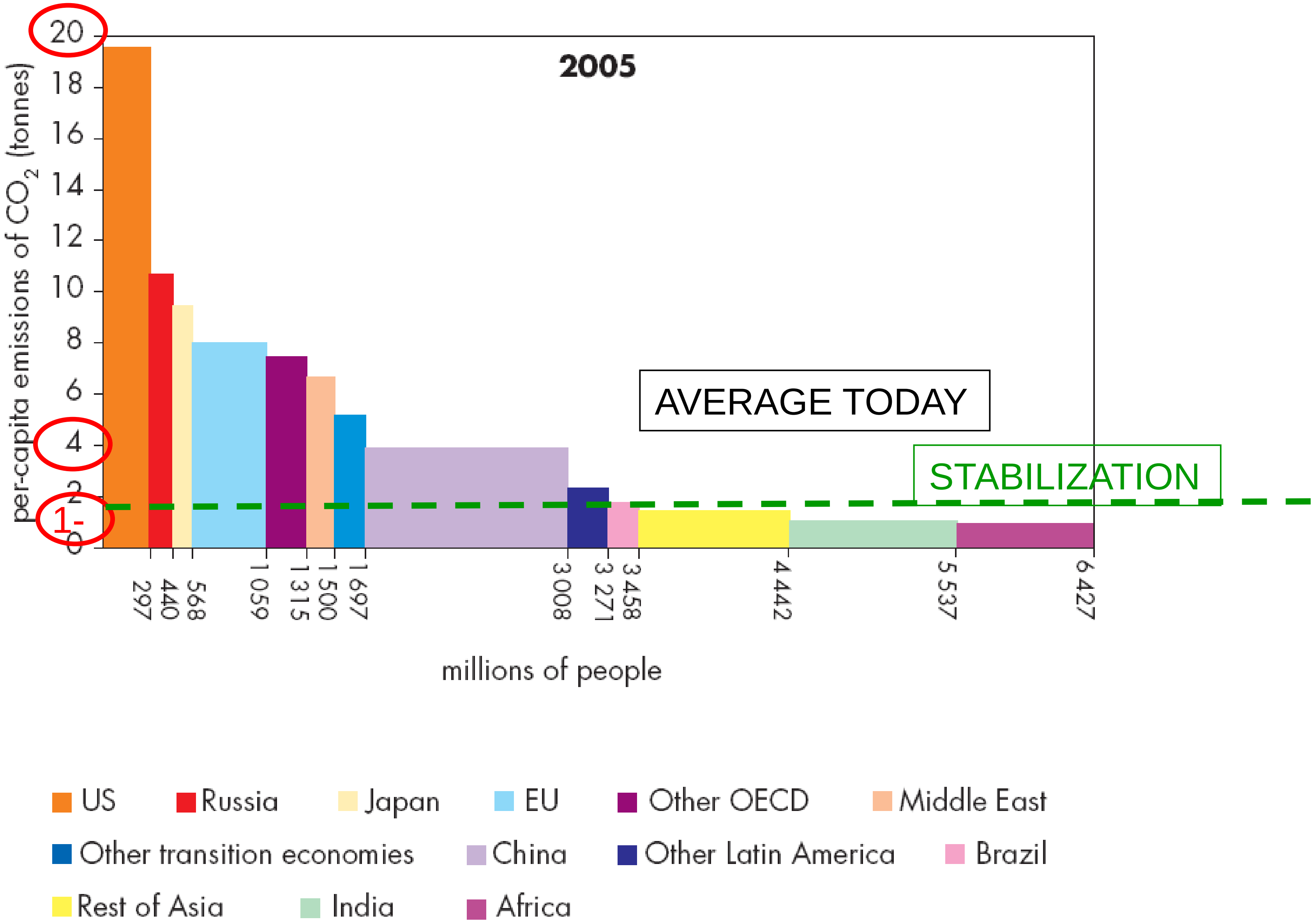
Four days later, NOAA revised it to 399.89 ppm!

About half of the CO_2 we burn stays in the atmosphere for centuries



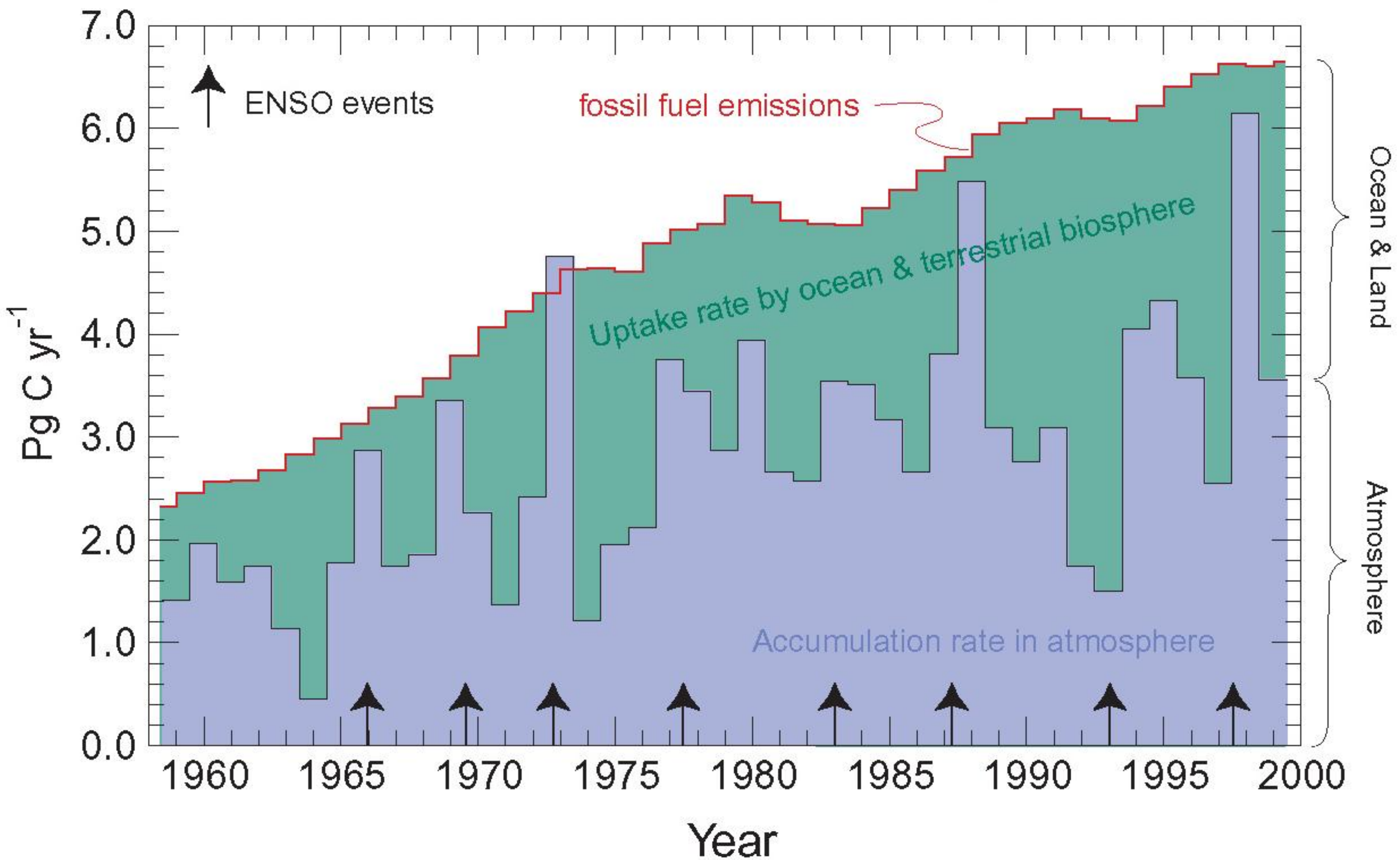
Today, global per-capita emissions are ≈ 4 tCO_2/yr.

Per-capita fossil-fuel CO_2 emissions, 2005



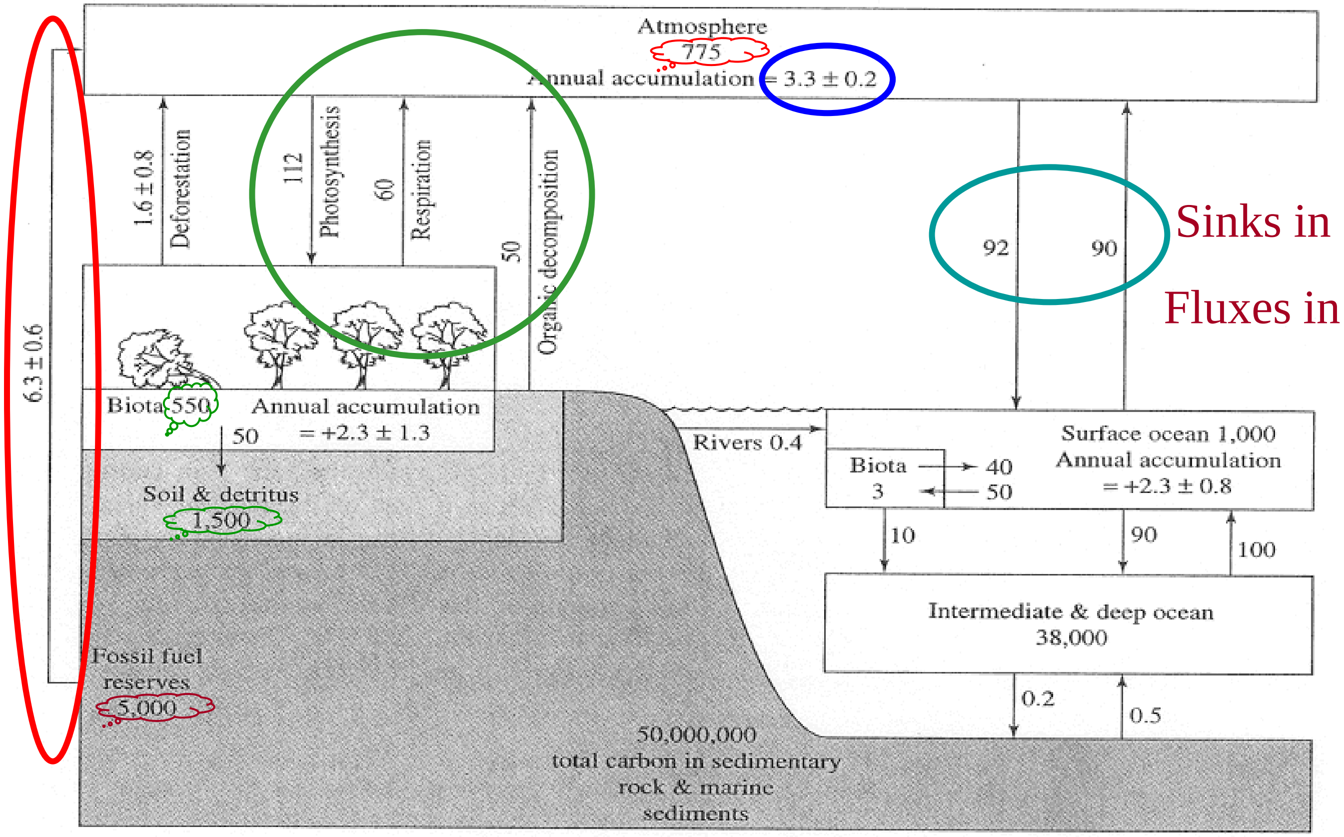
Source: IEA WEO 2007

Growth rate of carbon reservoirs



The year-to-year variability in CO_2 uptake is mostly due to the land, not the ocean.

Fossil carbon, biocarbon, and CO_2



Sinks in GtC

Fluxes in GtC/yr

Figure 6.18 The carbon cycle (in Gt C for pools; Gt C/yr for fluxes). Net annual accumulation in biota is the difference between enhanced biomass accumulation (2.3 ± 1.3 Gt C/yr) and deforestation (1.6 ± 0.8 Gt C/yr), which equals about +0.7 Gt C/yr. *Sources:* Adapted from the Carbon Dioxide Information Analysis Center (2000). *Global Carbon Cycle (1992–1997)* (Oak Ridge National Laboratory, U.S. Department of Energy) (http://cdiac.esd.ornl.gov); Intergovernmental Panel on Climate Change (IPCC) (2000). *Summary for Policymakers, Land Use, Land-Use Change, and Forestry* (Geneva, Switzerland: World Meteorological Organization/United Nations Environment Programme).

Spiro & Stigliani, p. 171

"Other" greenhouse gases

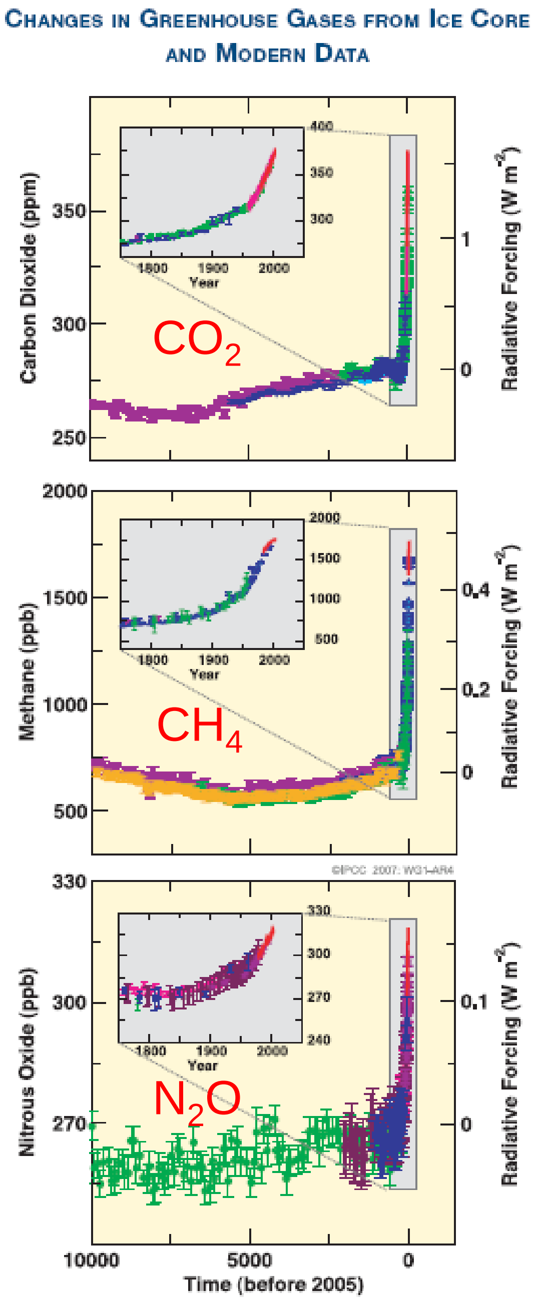


Figure SPM.1. *Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. {Figure 6.4}*

The quantity of CO_2 only that has the same effect as a combination of several greenhouse gases is called its "CO_2 equivalent (CO_{2e})." But beware. There are two unrelated "CO_{2e}" out there, one for emissions, and one for concentrations:

CO_{2e} for concentrations [ppm]: same instantaneous "forcing" (same downward infrared radiation from the top of the atmosphere).

CO_{2e} for emissions [t/y]: same cumulative forcing over a specified number of years (20 yr,, 100 yr.).

Source: 2007 IPCC *Summary for Policy Makers*

Outline for Lecture 2

A short preamble on greenhouse gas quantities.

What are the impacts of climate change?

How are goals being formulated that would constrain emissions?

Effects of Global Warming

LET’S MAKE A LIST.

Effects of Global Warming

1. Gradual climate change (temperature, rainfall)
2. Extreme events (record-hot days, hurricanes, droughts)
3. Surface ocean change (warmer, fresher, more acidic)
4. Sea-level rise
5. Effects on animals and plants; changes to ecosystems
6. Diseases spreading to new places

Affected: health, agriculture, civilization, other species

Which effect is most salient

to you?

to the general public?

VOTE (twice)!

The earth as transformed by human action*

*An excellent book by BL Turner *et al*., published in 1990, has this title. It focuses on all changes produced by human beings, not just those that are mediated by the atmosphere.

Its list of changes is much longer than the one we just made.

The book is mostly about land-use change.

The earth as transformed by human action

Degradation of natural ecosystems
- forest clearing
- fire setting and fire prevention
- animals in pastures
- hunting and fishing
- introduction of invasive species

Hydrocycle disturbance
- dams inhibiting sediment flow, smoothing out flow variability
- irrigation and salination of land
- depletion of ground water, land subsidence
- sea-water intrusion into coastal fresh-water supplies

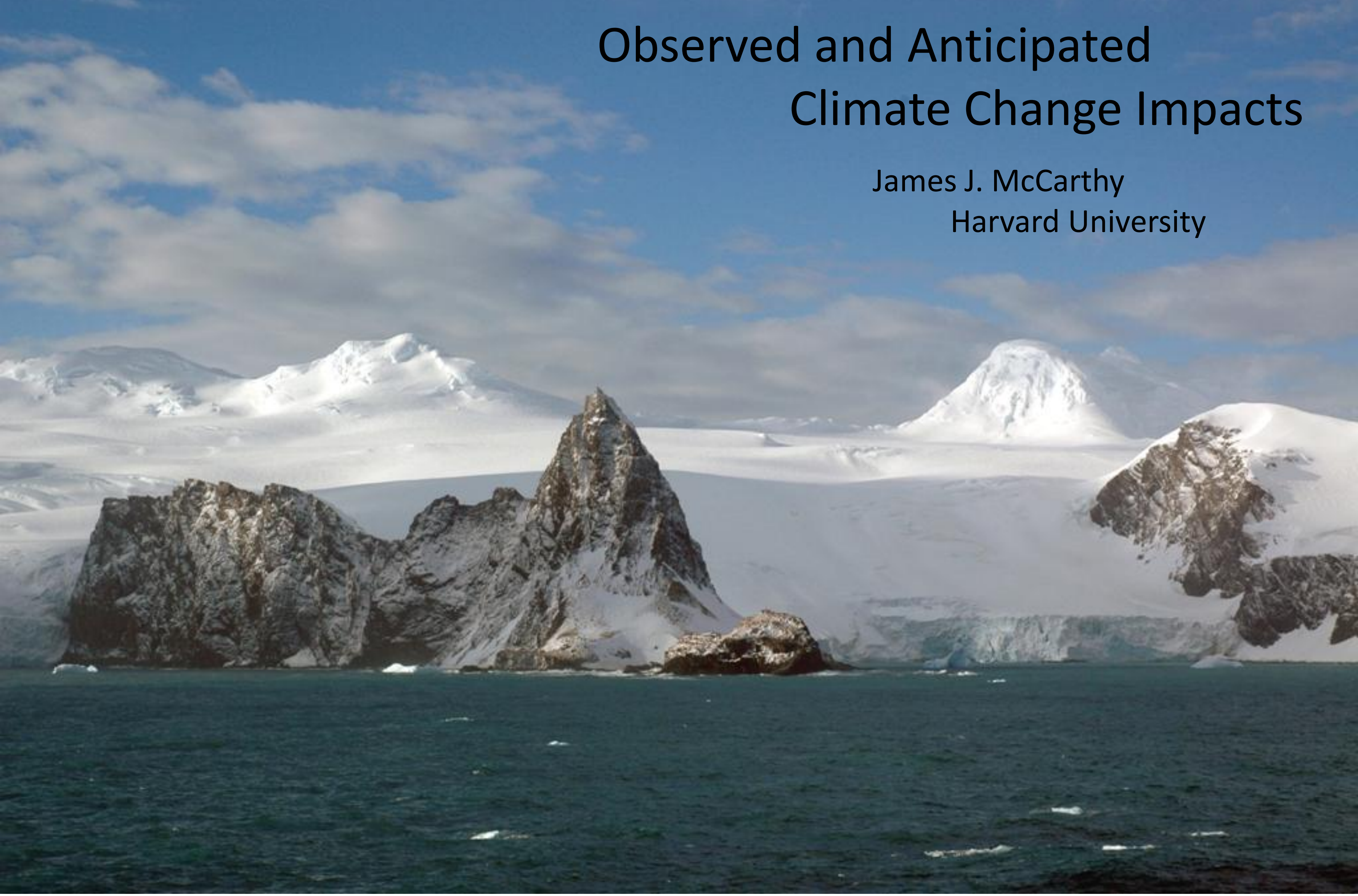
Biogeochemical cycles
- increase in “fixed” N via fertilizers

Diminishment of mineral and fuel endowment via entropy increase
- Dispersal of minerals and fuels initially found in high concentration

Land transformation via urbanization
- road building
- settlement

Observed and Anticipated Climate Change Impacts

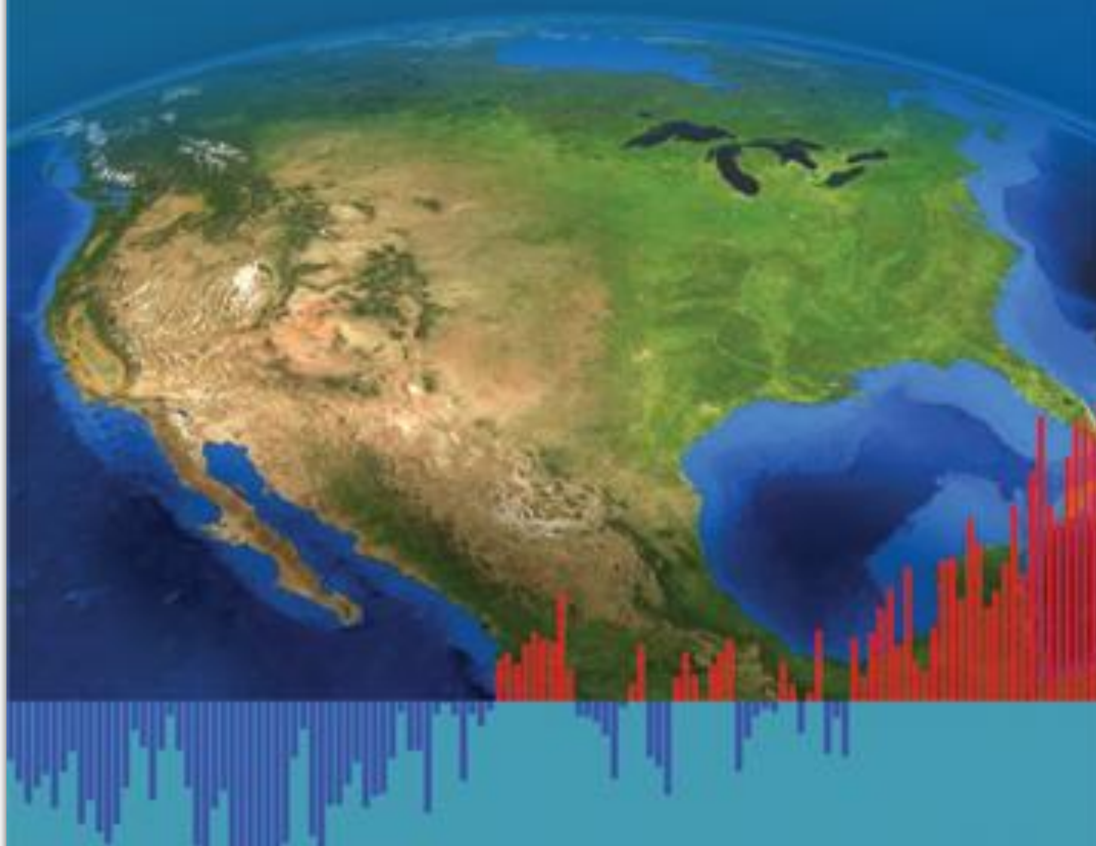
James J. McCarthy
Harvard University



Talk in Boston, MA. Meeting of the American Chemical Society, August 23, 2010

Global Climate Change Impacts in the United States

U.S. GLOBAL CHANGE RESEARCH PROGRAM



Hotter

“Warming is unequivocal”

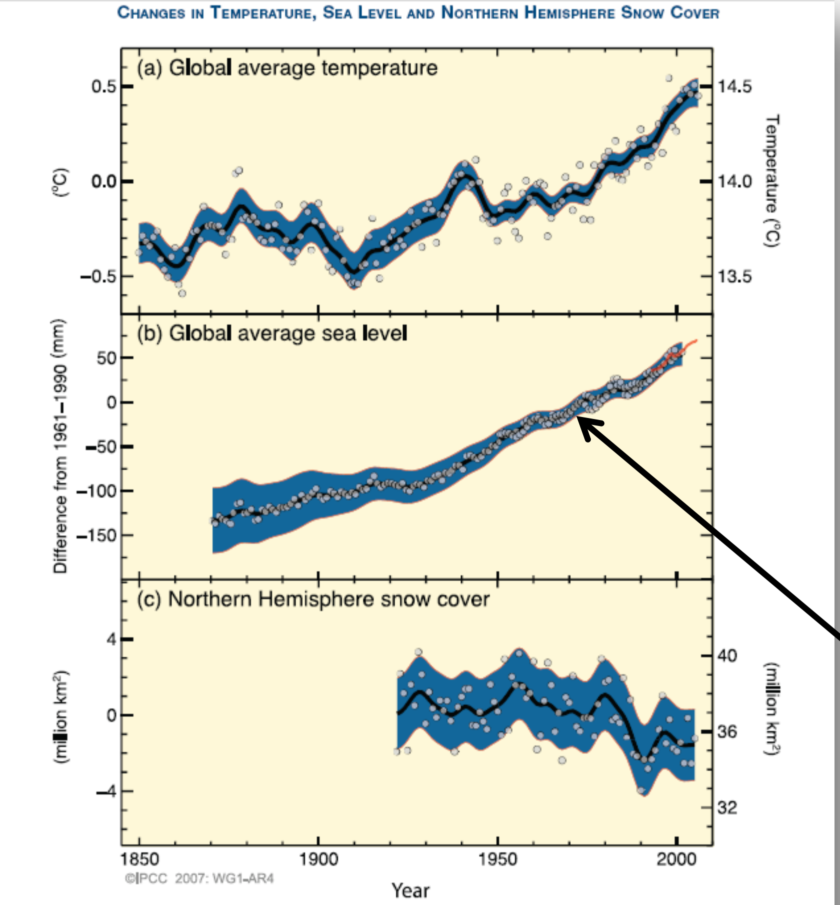


Figure SPM.3. *Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal average values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). {FAQ 3.1, Figure 1, Figure 4.2, Figure 5.13}*

These are some of the trends in past data that led IPCC AR4 to conclude that “warming of the climate system is unequivocal.” The hypothesis of no warming is not defensible, statistically.

The analysis is driven by measurements, more than models.

Sea level slope ≈ 20 cm/century

Source: IPCC 2007, *Synthesis Report*, AR4, Summary for Policymakers

Attribution via models

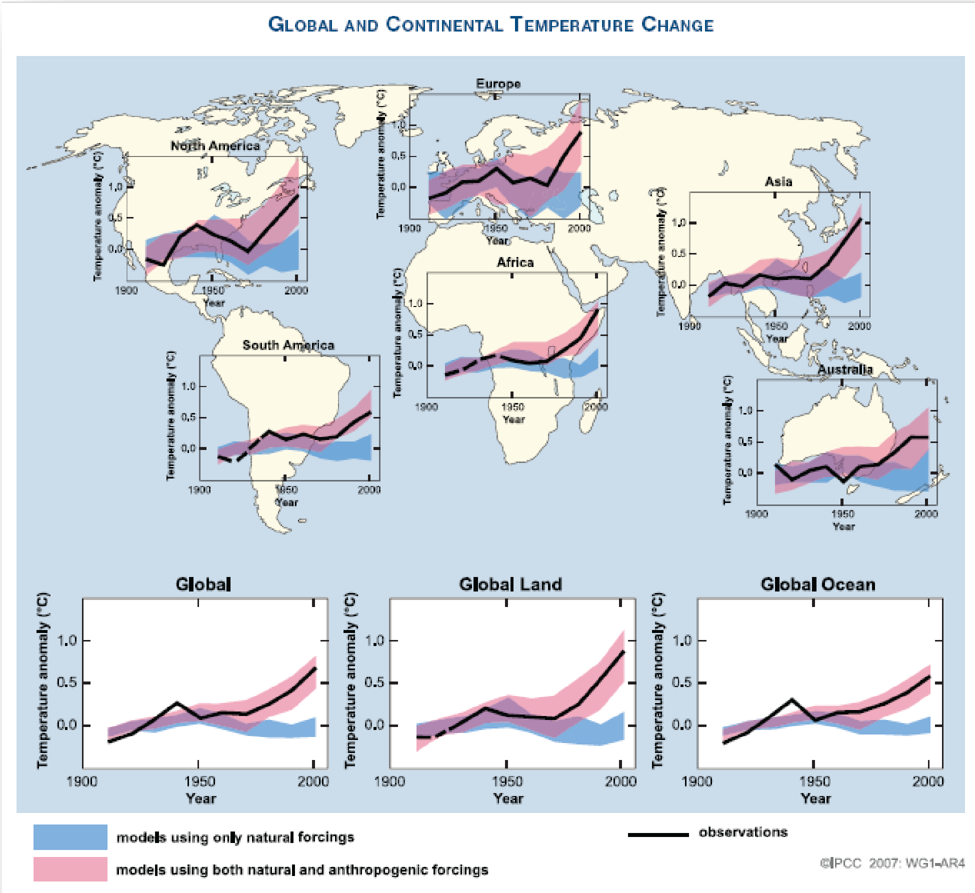


Figure SPM.4. *Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. {FAQ 9.2, Figure 1}*

Evidence of *human responsibility* for warming is not “unequivocal.” Rather, “Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations.” The alternative is natural fluctuations.

“Very likely” means p > .90.

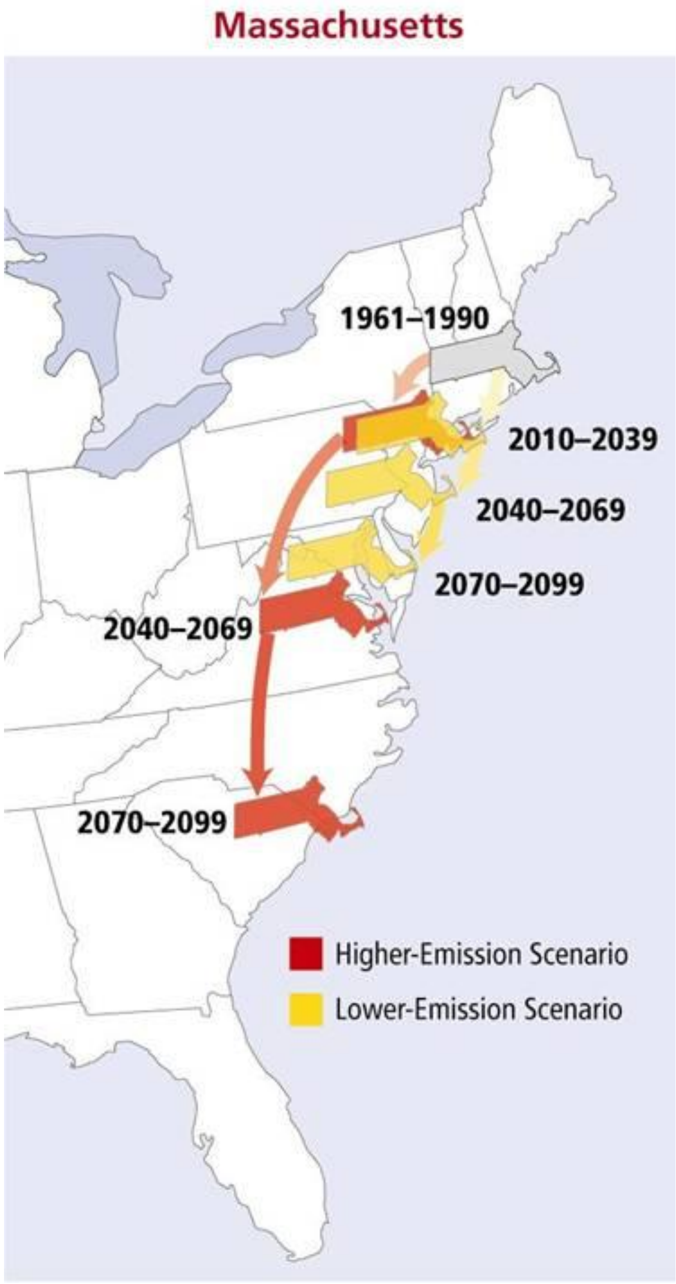
Source: IPCC, 2007, *Synthesis Report*, AR4, Summary for Policymakers

How much hotter summers?

Note: The uncertainty here is due to alternative emissions paths, not alternative climate models.

This graph probably shows how winters could feel too (to be verified).

Figure from James McCarthy, Harvard



NECIA, 2007 (see: www.climatechoices.org/ne/)

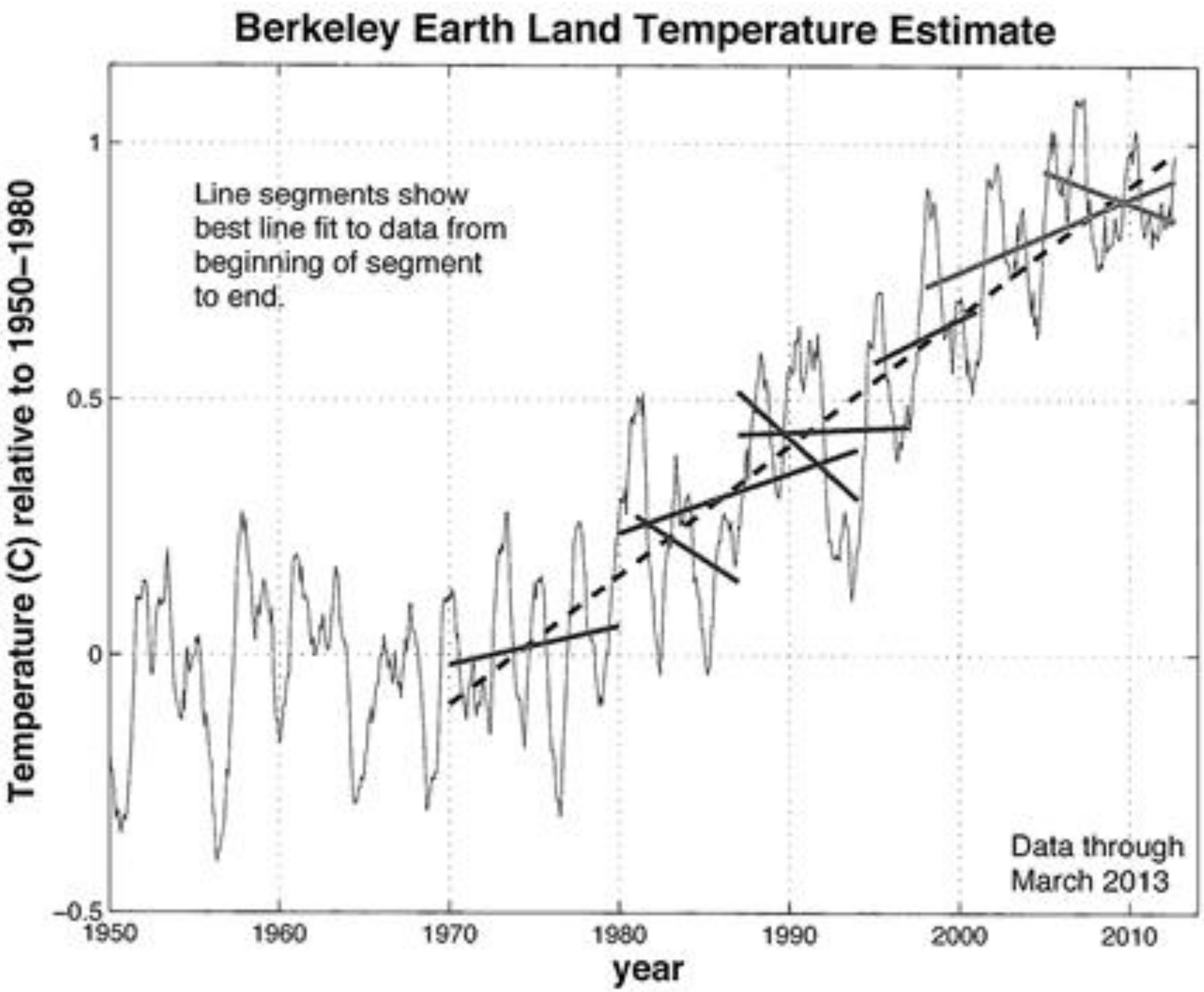
Adaptation to “hotter”

Farmers grow heat-resistant crops.
Air conditioning investment and use increase.
Ski resorts move up-mountain and (in N Hem) northward.
People migrate from hottest regions.
Cities implement emergency response (e.g., for elderly)

Net positive benefit to the U.S.? U.S. internal migration is toward warmth.

For the developing world: how is adaptation different from development?

Whoops! “Flat temperature”?

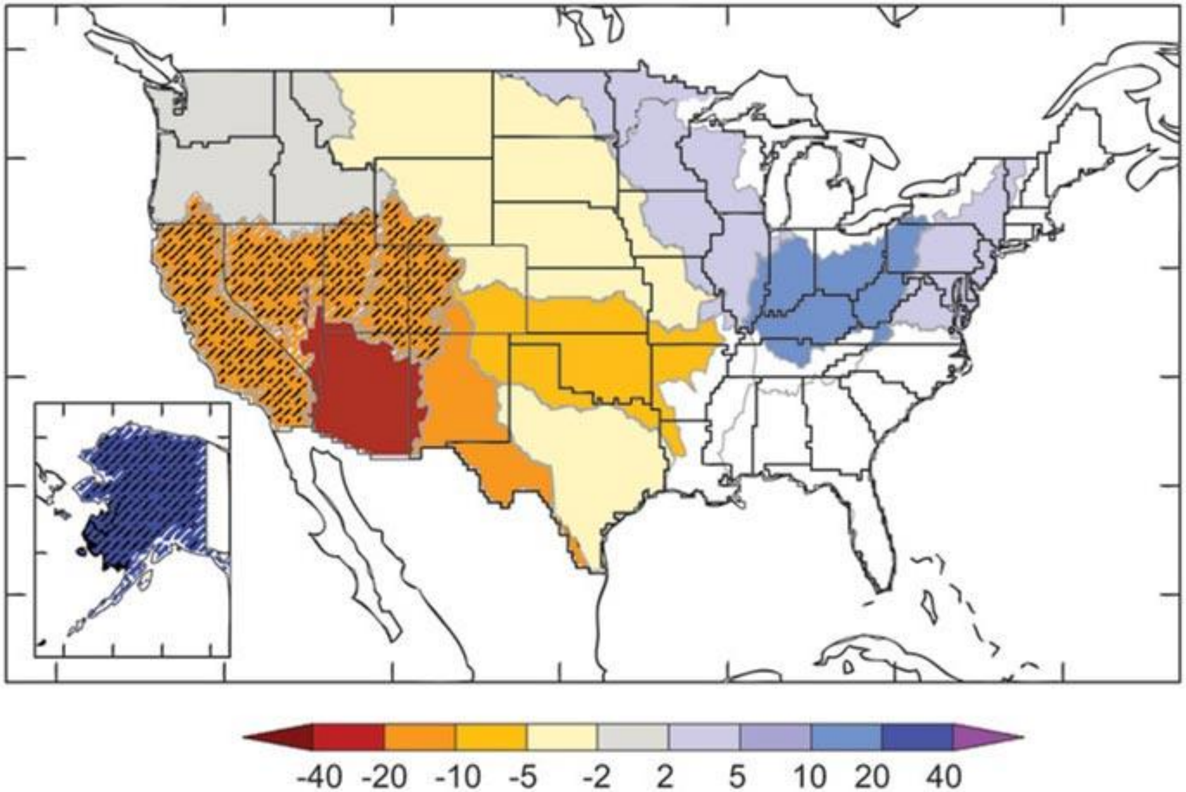


Source: Richard Muller, private communication, 2013

A confidential source: The flat temperature has preoccupied AR5 WG1. Watch for how it is dealt with.

Wetter, drier

How much wetter? How much drier?



Projected Changes in Annual Runoff, 2041-60 vs. 1901-70

Hatched areas indicate greater confidence due to strong agreement among model projections. White areas indicate divergence among model projections. Emissions rate used is in-between the lower and higher emissions scenarios.

Source: globalchange.gov/usimpacts

Adaptation to “wetter, drier”

Water infrastructure (dams, aqueducts, redirected rivers)
– a bonanza for civil engineering
Flood-plain zoning (checkered history, so far)
Rainmaking (hasn’t worked, so far)

Changed Ecosystems

Projected shifts in forest ecosystem composition

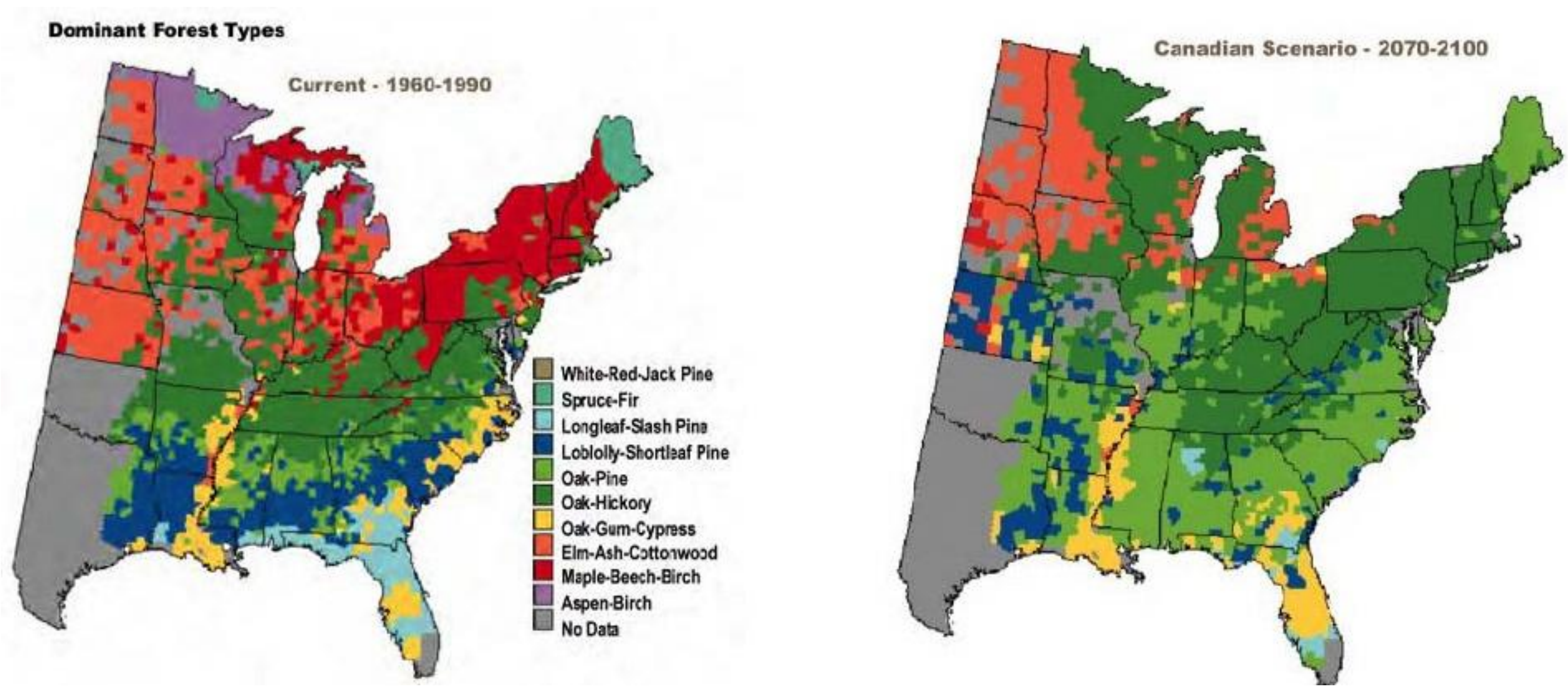


FIGURE 2.7 Potential changes in the geographic ranges of the dominant forest types in the eastern United States under projections of future climate change. Many forest types shift their ranges northward or shrink in areas, while some expand their areas.

Confession: I don't know what the "Canadian Scenario" is.

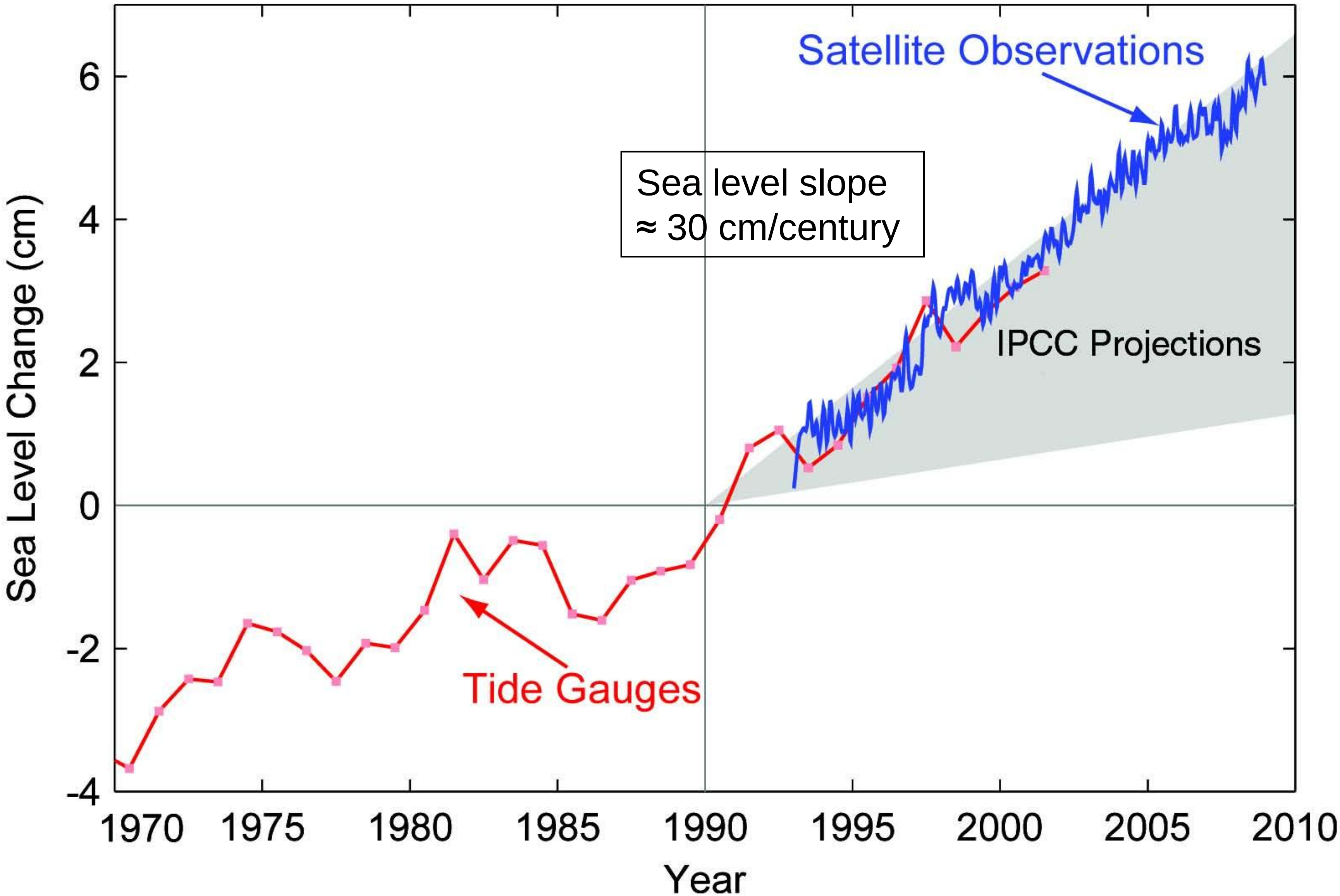
NAS 2010

Adaptation to changed ecosystems

Managed ecosystems: new species and revised management strategies.

Natural ecosystems: wildlife corridors (limited adaptation opportunities)

Higher sea level



Watch for this in *AR5* too.

See Gillis, *New York Times*, published and distributed last week.

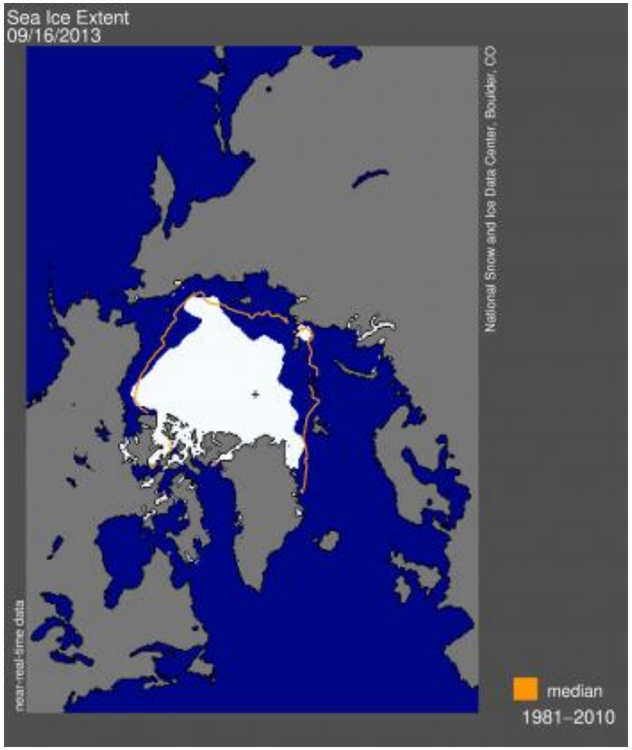
Projected globally-averaged sea level rise by the end of the 21st century

Note!

Case	Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations [b]	NA
B1 scenario	0.18 – 0.38
A1T scenario	0.20 – 0.45
B2 scenario	0.20 – 0.43
A1B scenario	0.21 – 0.48
A2 scenario	0.23 – 0.51
A1FI scenario	0.26 – 0.59 meters

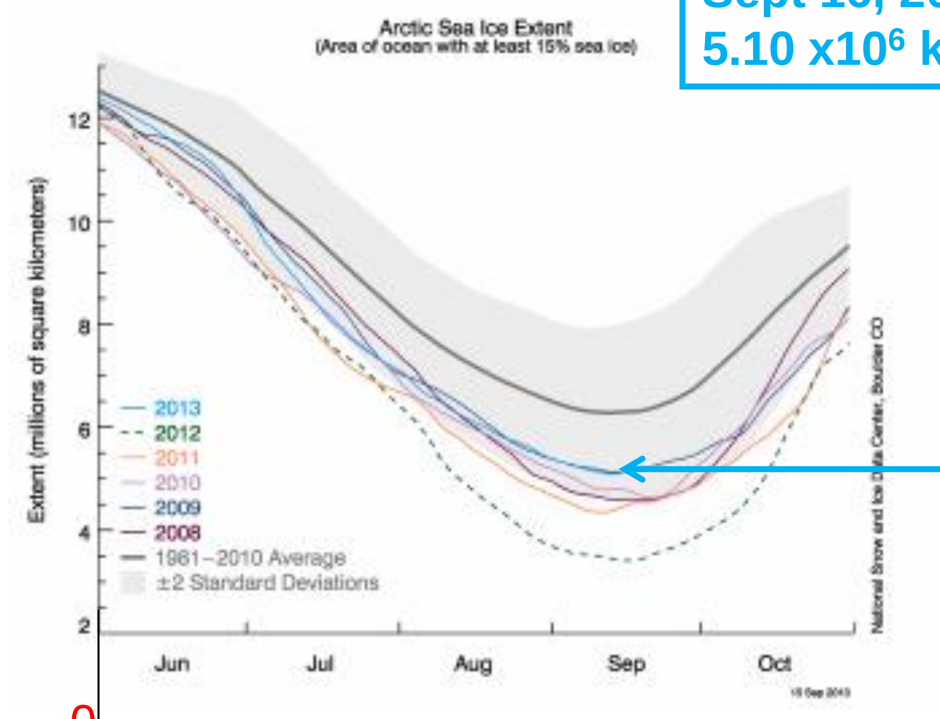
Source: IPCC *Summary for Policy Makers*, February 2007

Arctic ice cap



Sea Ice Extent, Sept 16, 2013

The colored line shows the 1981-2010 median extent for September.



Sept 16, 2013
5.10 x10^6 km^2

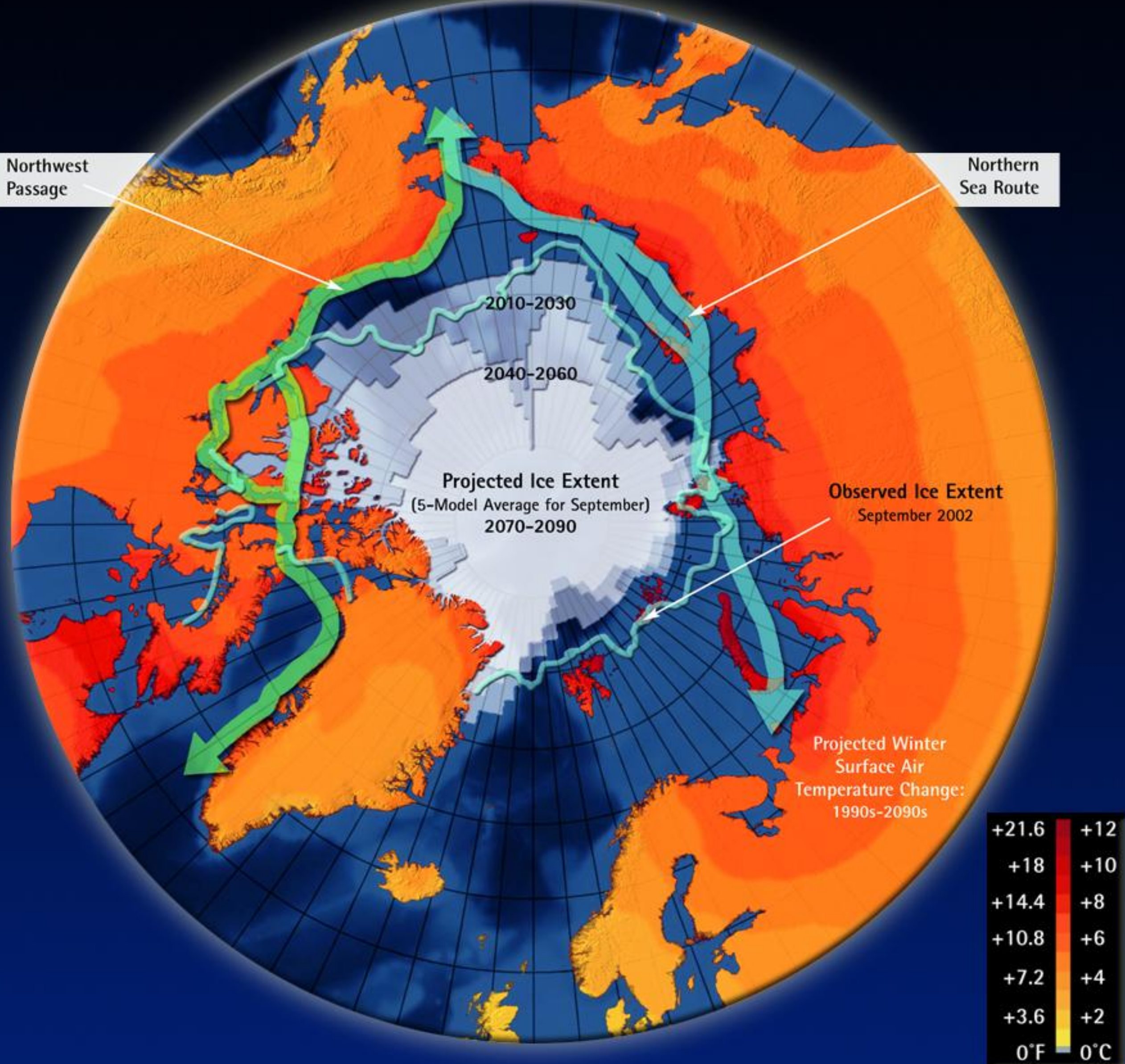
2012 was the worst year yet.

The melting of arctic ice is a classic example of positive feedback: the albedo of the ice is about 0.5 and the albedo of the sea is close to zero. As the ice melts, the immediate region gets warmer and more ice melts.

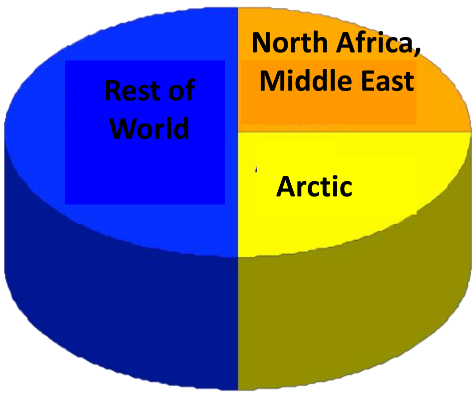
Source: http://nsidc.org/arcticseaicenews/. Accessed 9/17/13.

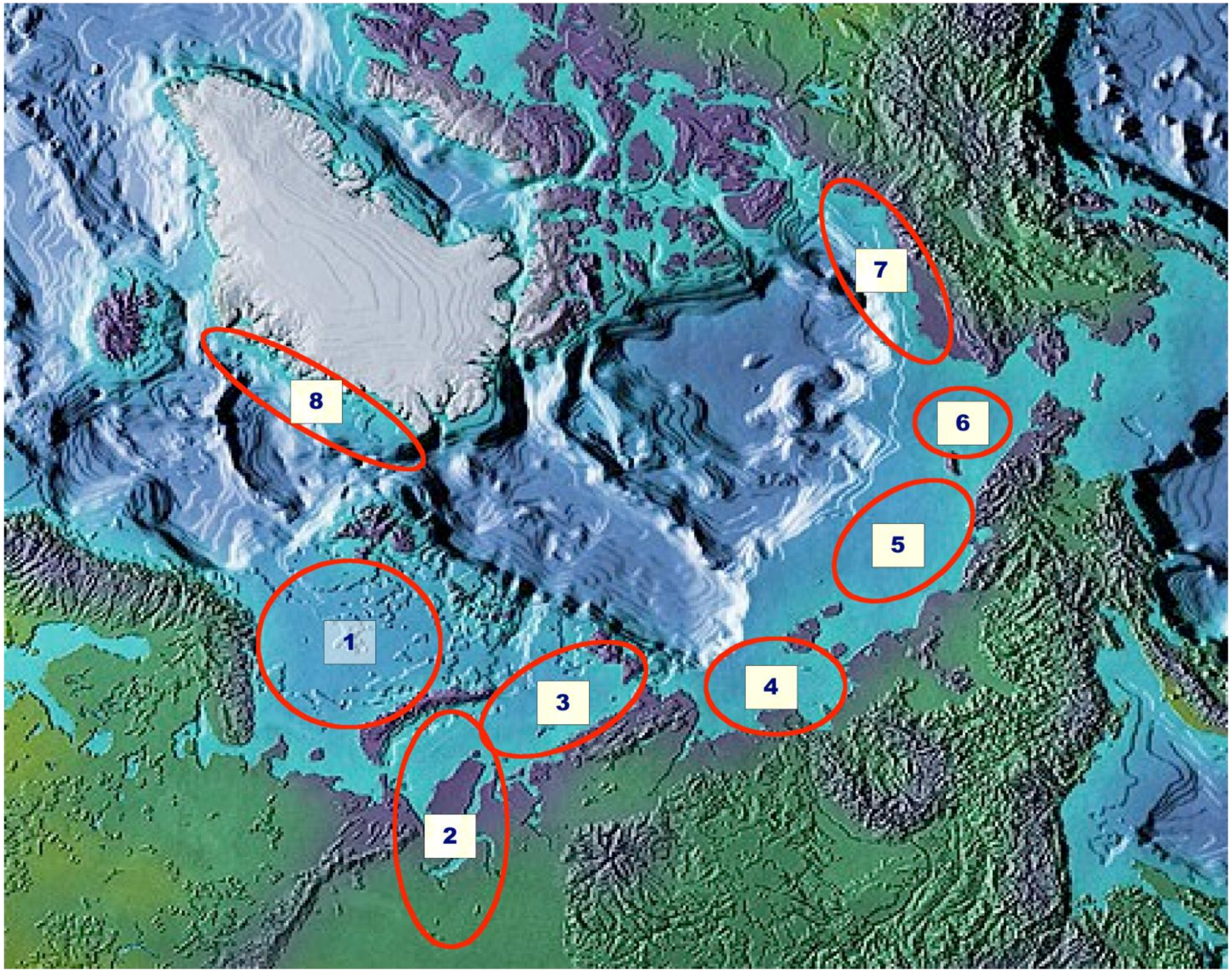
Some economic benefits of a shrinking arctic ice cap

IMPACTS OF A WARMING ARCTIC



Worlds Petroleum Potential



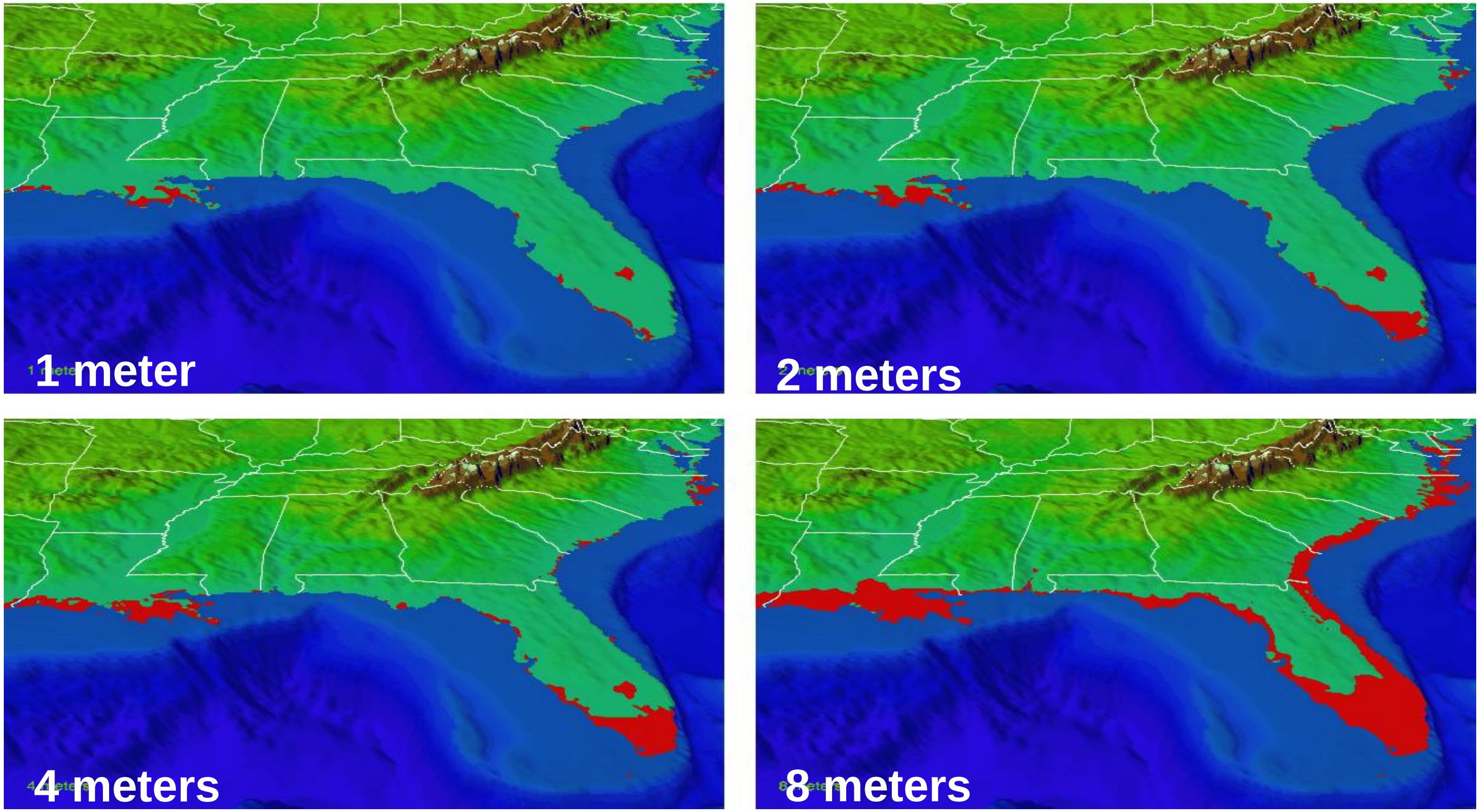


1. Barents Sea
2. Southern Kara Sea and Western Siberia
3. Northern Kara Sea
4. Laptev Sea
5. East Siberian Sea
6. Chukchi Sea
7. Alaska North Slope
8. East Greenland

ACIA

Greenland: 7 meters.
West Antarctica : 5 meters

Sea Level Rise



A falling sea level would also be disruptive!

Source is not McCarthy

Source: T. Knutson, Geophysical Fluid Dynamics Laboratory, NOAA. See: http://www.gfdl.noaa.gov/~tk/climate_dynamics/climate_impact_webpage.html#section4

Adaptation to rising sea level

Dikes, seaport reconstruction

Moving municipal water supplies further inland to avoid salinity

Moving cities inland

Our current geography is privileged

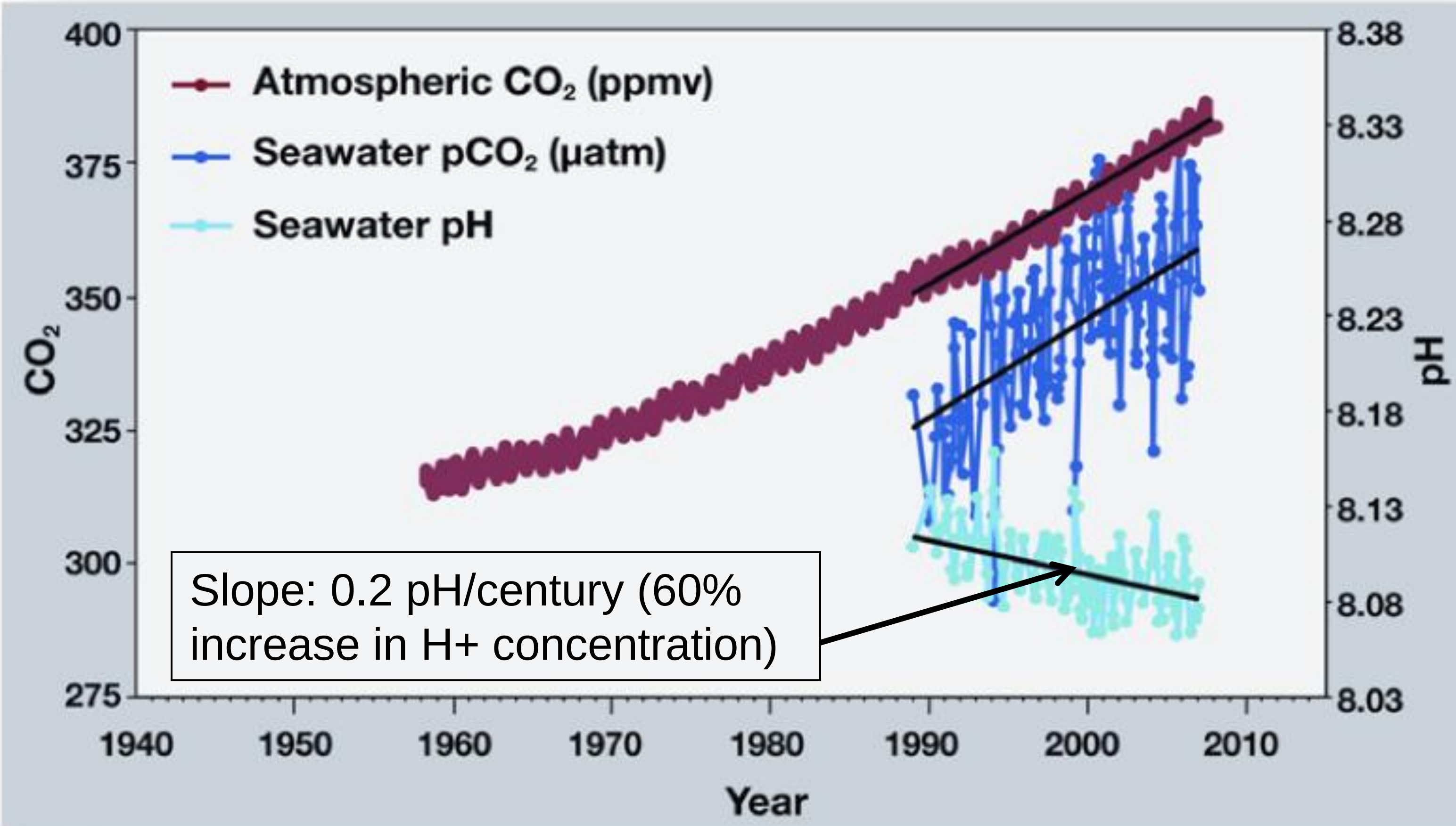
There are few beneficiaries of a rising sea level.

We planted crops where the rain fell and built our cities near rivers and coasts. So, we will grow different crops and move inland and perhaps abandon some very warm places. (A *falling* sea level would have required much dredging of harbors.)

Much disruption lies ahead.

Changes in Ocean Chemistry

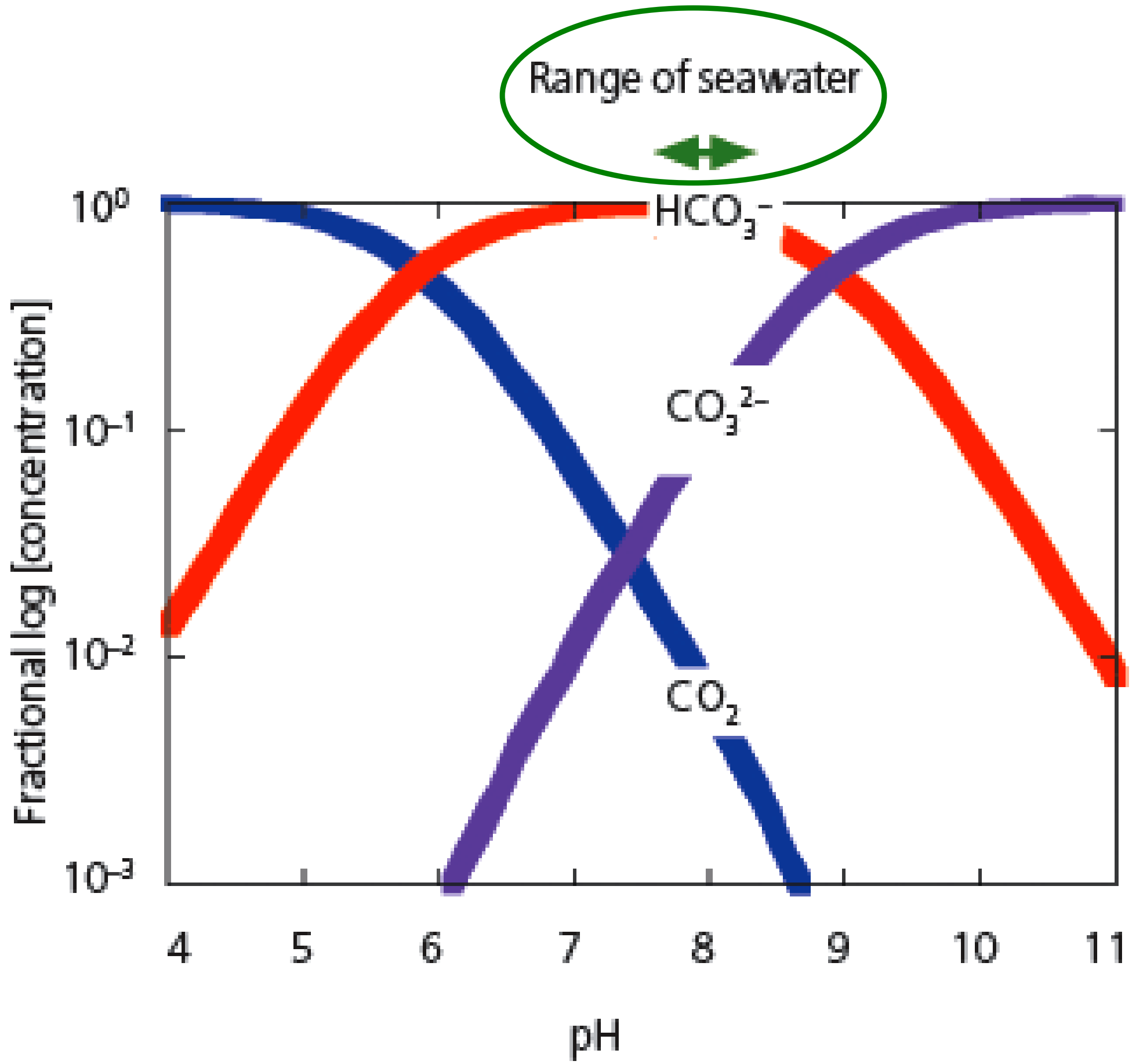
Ocean pH time series



CO_2 level in atmosphere at Mauna Loa; CO_2 level and pH in nearby ocean at Station Aloha.

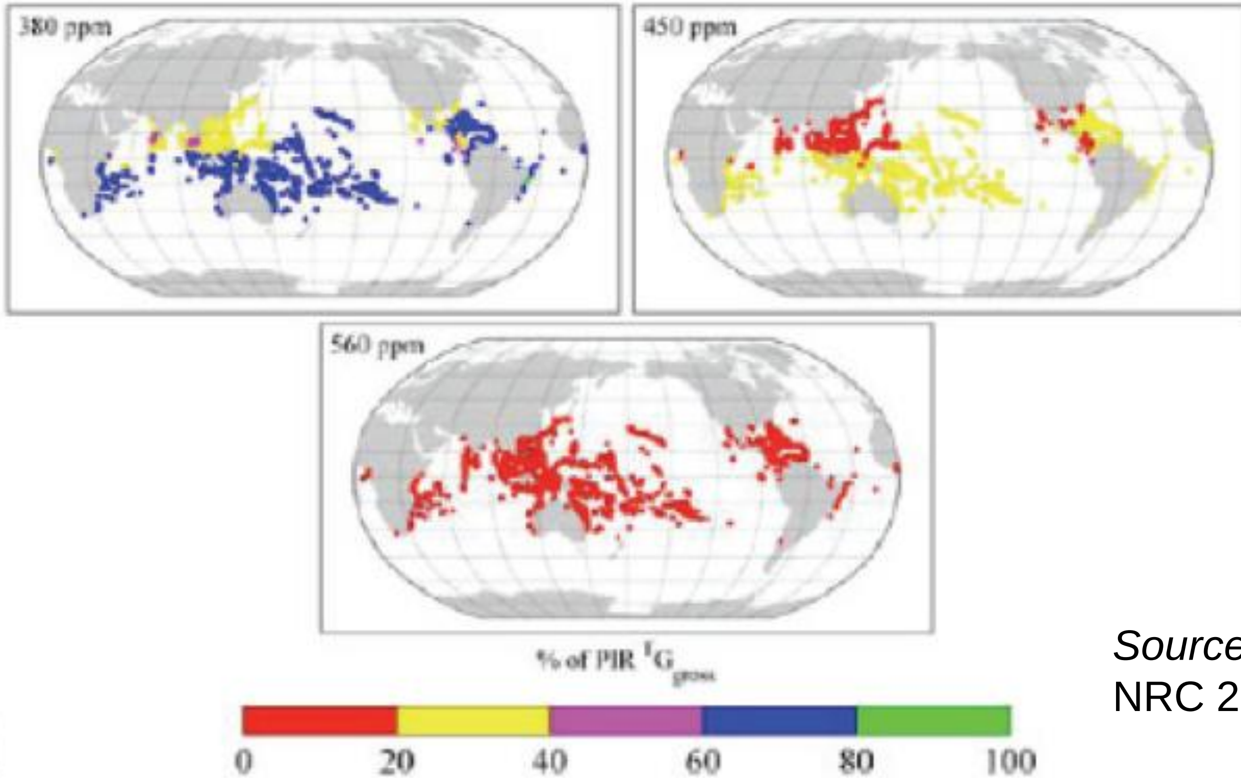
Modified after R.A. Feely, Bulletin of the American Meteorological society, July 2008. *Website*: Pacific Marine Environmental Laboratory, NOAA, http://pmel.noaa.gov/co2/files/hitimeseries2.jpg

Figure A. Relative proportions of the three inorganic forms of CO_2 dissolved in seawater. Note the ordinate scale (vertical axis) is plotted logarithmically.



Royal Society 2006

Ocean acidification and coral



Source: Solomon et al., NRC 2010

For each global coral reef location, at CO_2 stabilization levels of 380, 450 and 560 ppm, the biological production of calcium carbonate skeleton or shell material, as a percent of its pre-industrial rate (280 ppm).

Ocean acidification, thermal bleaching, and the loss of algal symbionts in response to warming and other stressors are taken into account (from Silverman et al. 2009).

Adaptation to changes in ocean chemistry

Aquariums for coral and their associated fish
(similarly, zoos for endangered non-aquatic species)

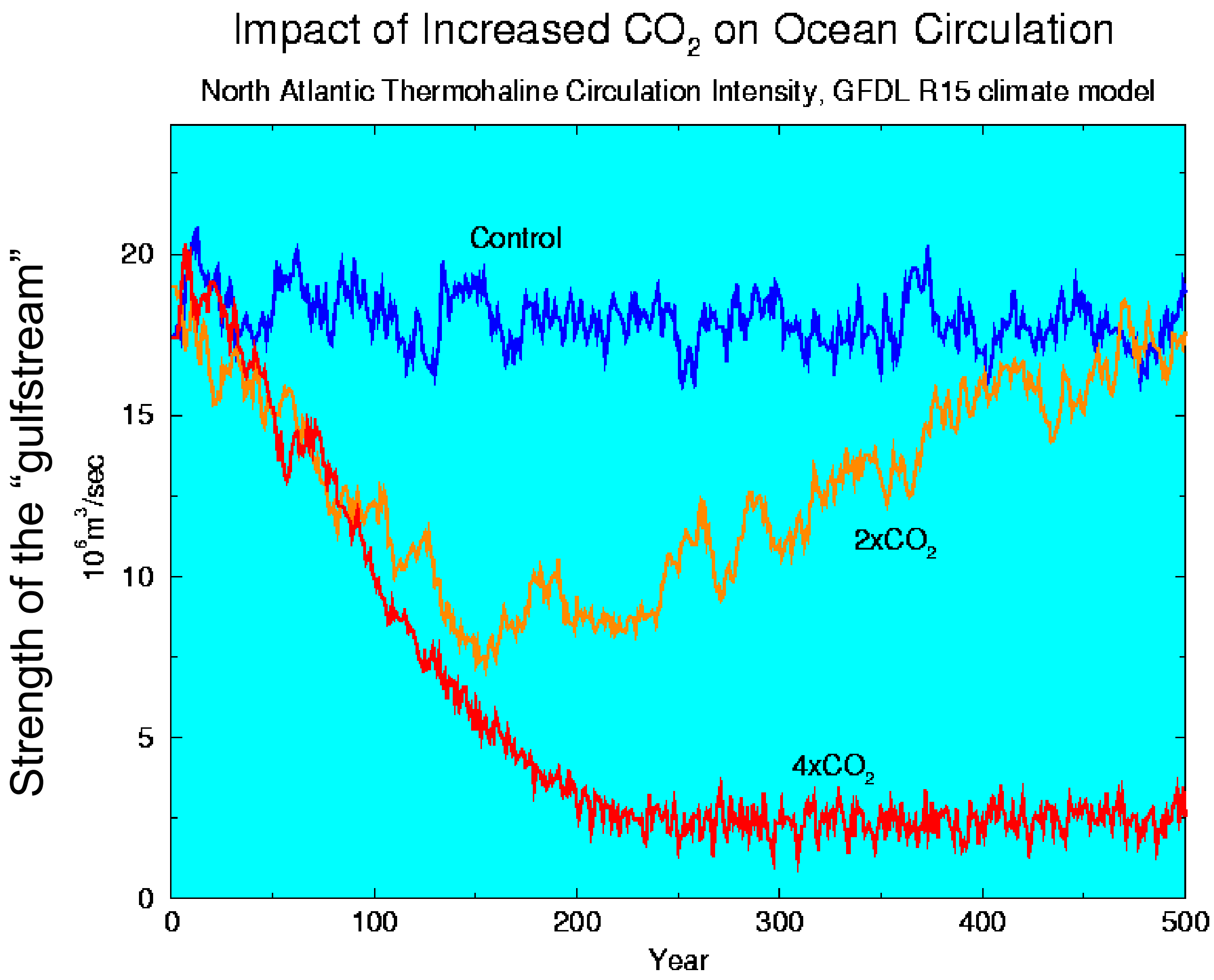
No other ideas that I am aware of.

Changes in Ocean Dynamics

A weaker gulfstream?

This particular “monster” looks less fierce, relative to a decade ago, as a result of new measurements and modeling

Two-state systems and irreversibility



$2xCO_2$: +1%/yr for 70 years, then hold

$4xCO_2$: + 1%/yr for 140 years, then hold

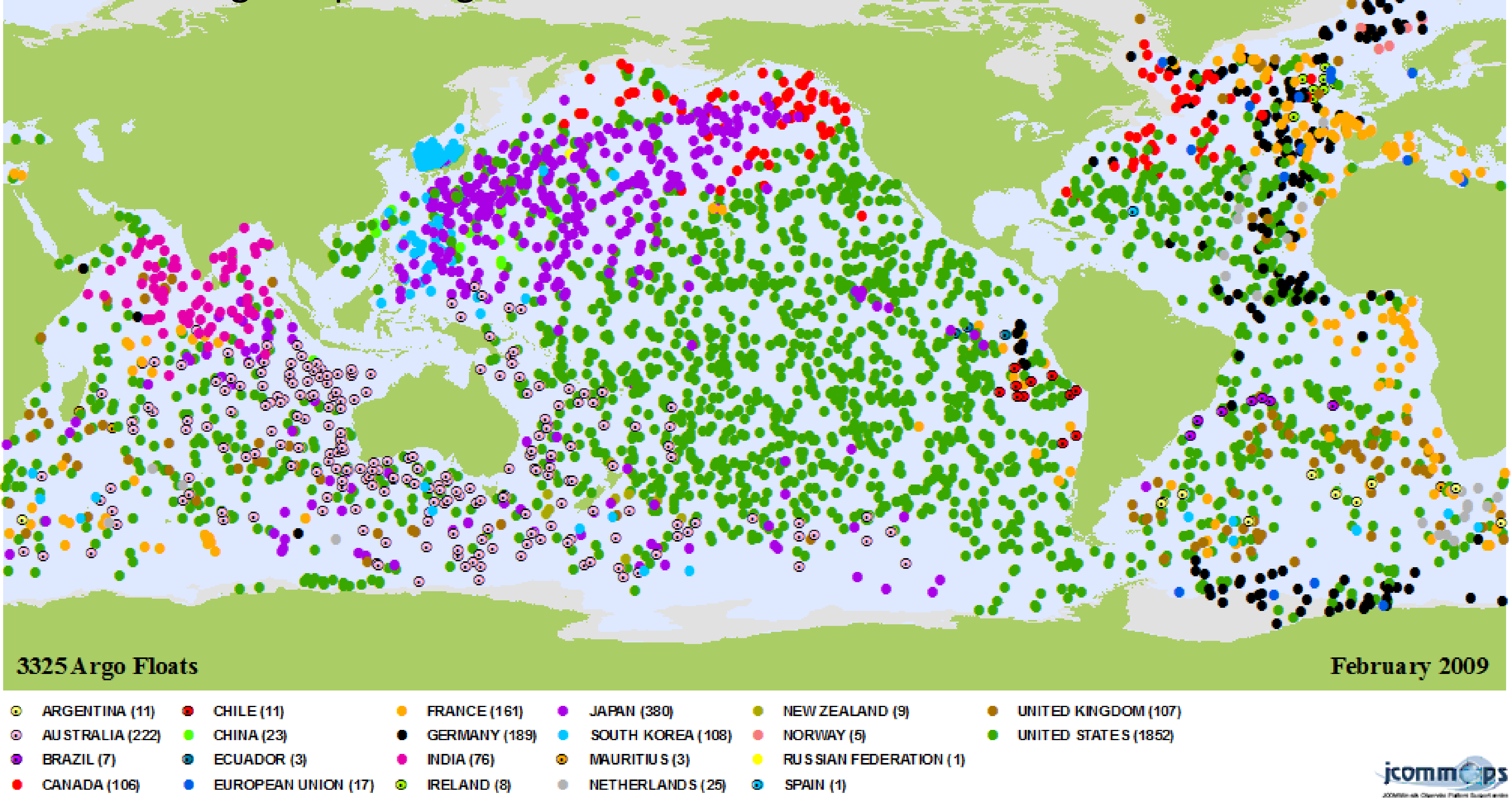
Small push: system is restored.

Large push: system shifts to another state.

Adaptation to changes in ocean dynamics

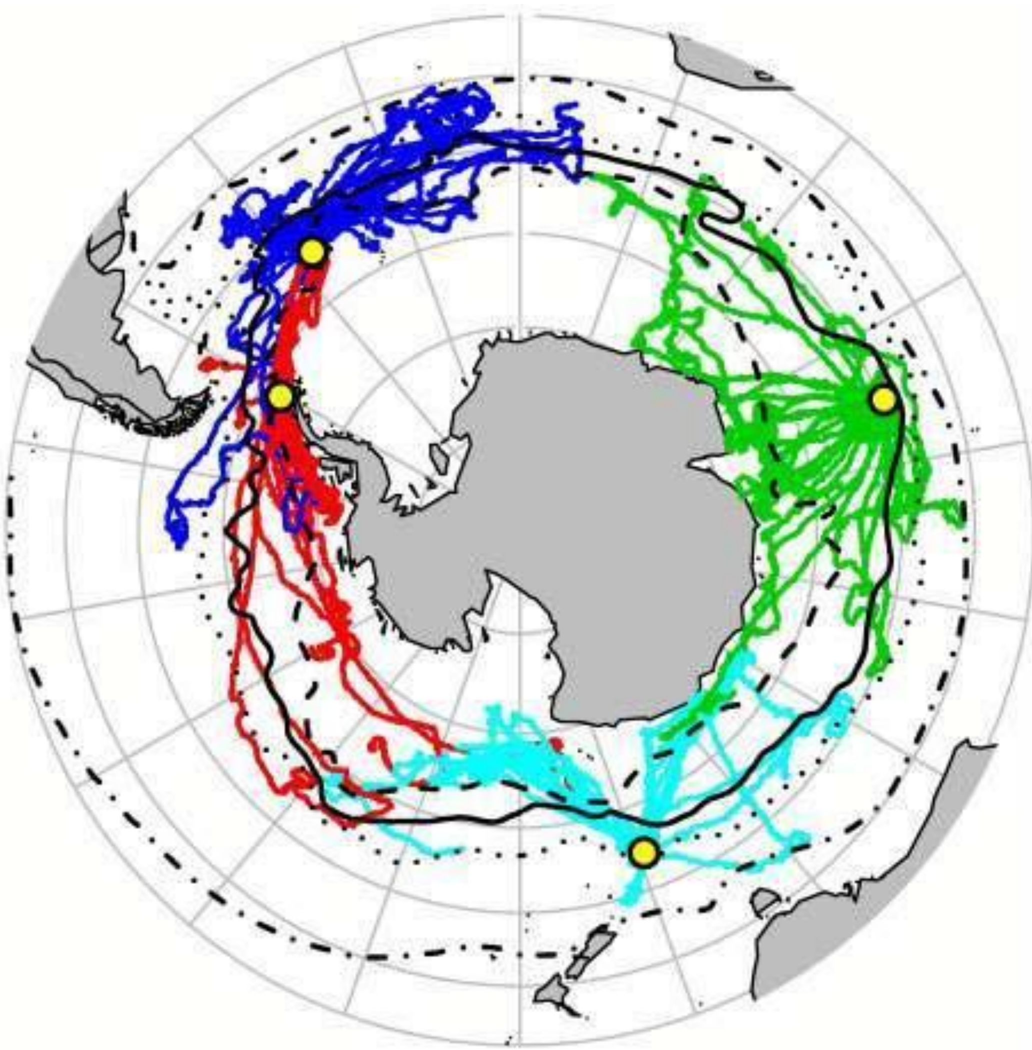
No ideas that I am aware of.

ARGO drifting and profiling instruments



Profile upper 2000m every 10 day. 3325 floats deployed (8/23/10).
22 participating nations.

Instruments for Temp and Salinity on Diving Elephant Seals



Expanded program in Southern Ocean under an NSF 2013 award to Prof. Jorge Sarmiento, later rescinded.

SCAR 2009

BREAK

Required readings, Week 3: Primary energy, global oil (1 of 2)

1919, "How long will the oil last?" *Scientific American* (2 pages).

Rogner, H., 1997, "An assessment of world hydrocarbon resources." *Annu. Rev. Energy Environ*. (45 pages).

National Academy of Sciences, *America's Energy Future*. Read section on Oil, Gas and Coal Reserves in Chapter 7 (pp. 331-357).

Fitzpatrick, T.M. & Spohn, K. (2009) A 25th Anniversary Redux of the Simon and Ehrlich Global Sustainability Wager. *Journal of International Business and Cultural Studies*: pp.1-7.

Yergin, D. 1991, *The Prize: The Epic Quest for Oil, Money, and Power*. [Read Prologue (pp. 11-16), and chapter 35 "Just Another Commodity?" (pp. 715-744)].

Required readings, Week 3: Primary energy, global oil (2 of 2)

Lizza, R. (September 16, 2013). “The President and the Pipeline: The campaign to make the Keystone XL the test of Obama’s resolve on climate change”. *The New Yorker magazine*, pp. 38-51.

U.S. Energy Information Administration (June 2013). *Technically Recoverable Shale Oil and Shale Gas Resources*. *[Browse through, noting in particular China's very large technically recoverable shale gas resources!]*

Andrew Revkin (2013). “The Silent Partner Behind the Energy Boom – Taxpayers”. Available at: http://dotearth.blogs.nytimes.com/2013/07/31/the-silent-partner-behind-the-shale-energy-boom-taxpayers/?src=recg&_r=0.

Recommended readings for Week 3: Primary energy, global oil

Deffeyes, Kenneth, *Hubbert's Peak*, Princeton University Press, 2001

Gorelick, Steven M. *Oil Panic and the Global Crisis: Predictions and myths*. Wiley-Blackwell, 2010.

MIT (2011) The Future of Natural Gas: An interdisciplinary MIT study. [Read Chapter 2: Supply, pp. 17-48].

Reschedule two classes

Week 4: Wed Oct 2 to Mon Oct 7 evening?

Week 7: Wed Oct 23 to Mon Oct 21 evening?

Exactly which evening hours?

Food committee?

Outline for Lecture 2

A short preamble on greenhouse gas quantities.

What are the impacts of climate change?

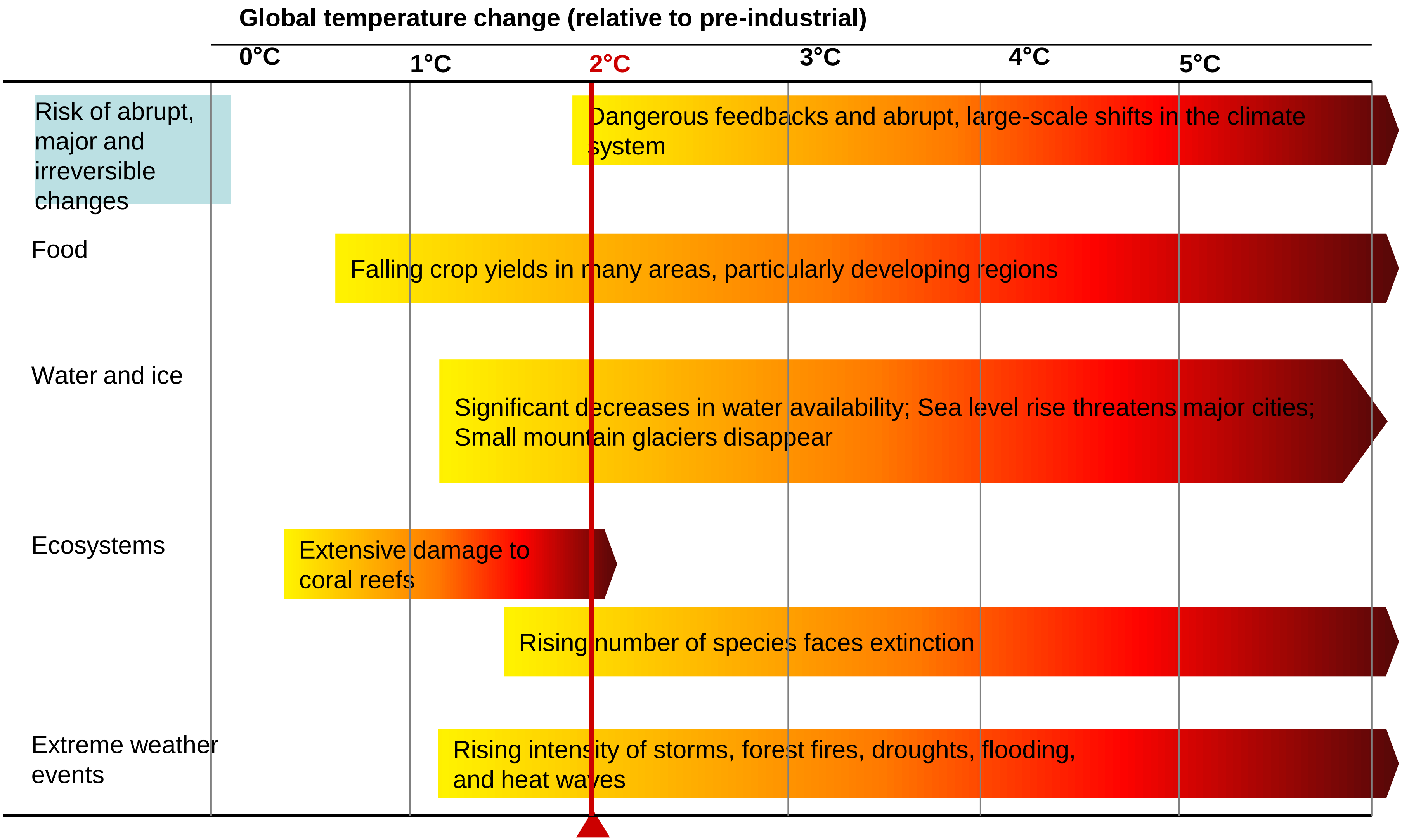
How are goals being formulated that would constrain emissions?

“Dangerous anthropogenic interference”

The United Nations Framework Convention on Climate Change (1992) challenges the nations of the world to stabilize greenhouse gas concentrations “at a level that would prevent dangerous anthropogenic interference with the climate system.”

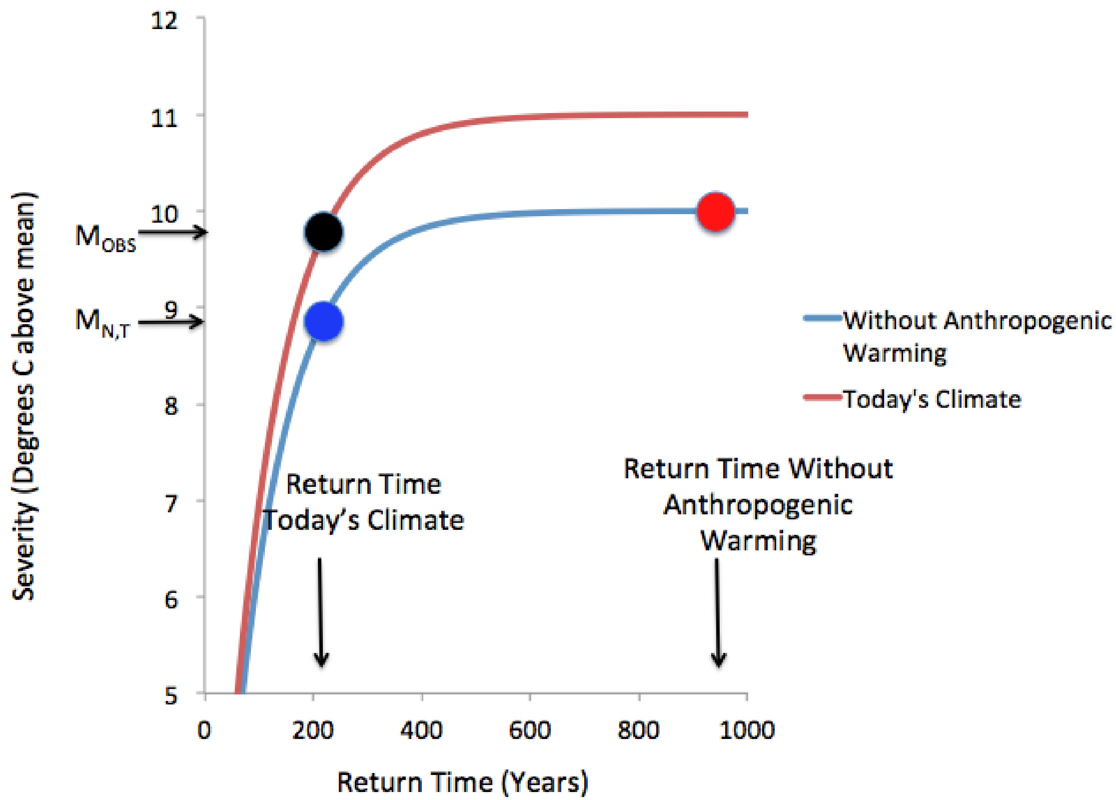
What is “dangerous”?

The “burning embers” figure



***Source*: adapted from Stern Review, 2006. Not included in AR4. Watch for it in AR5.**

Attribution of extremes to climate change



Climate change is bringing the same nasty event much more often.
It is bringing only somewhat nastier events.

Source: S. Pacala, to be published. Do not cite!

First targets: stabilized concentration

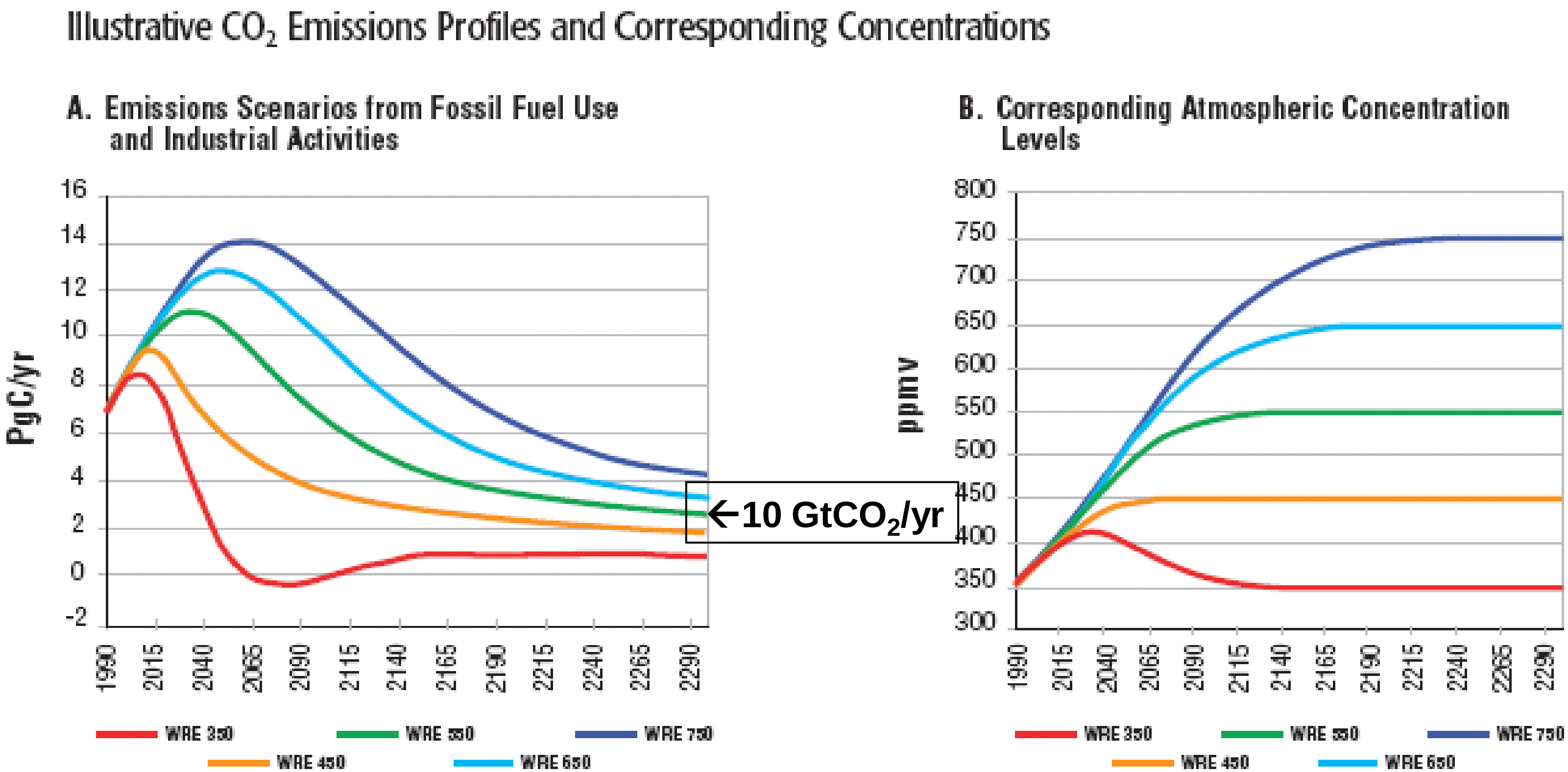
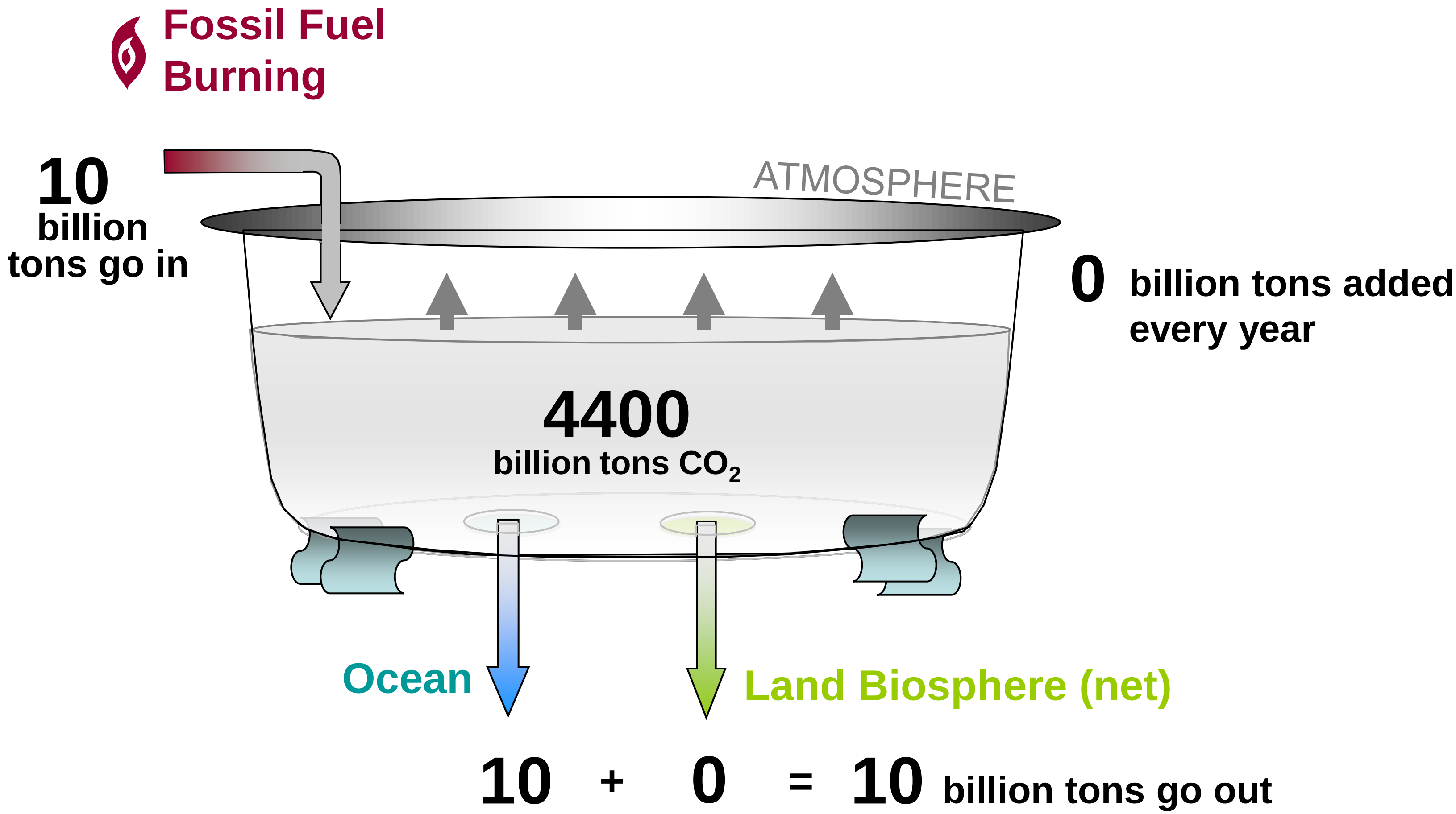


Figure 3-10. Illustrative CO_2 Emissions Profiles and Corresponding Concentrations

These are the WRE stabilization scenarios (1996).
"WRE" is Wigley, Richels, and Edmonds.

Source: Captured from US DOE, *CCTPSP*, Sept. 2006,. p. 36.

At "stabilization," allowed emissions are about one-third of today's.



Shown here: Stabilization at double the pre-industrial concentration.

“Stabilization”: 1 ton CO_2/yr per capita

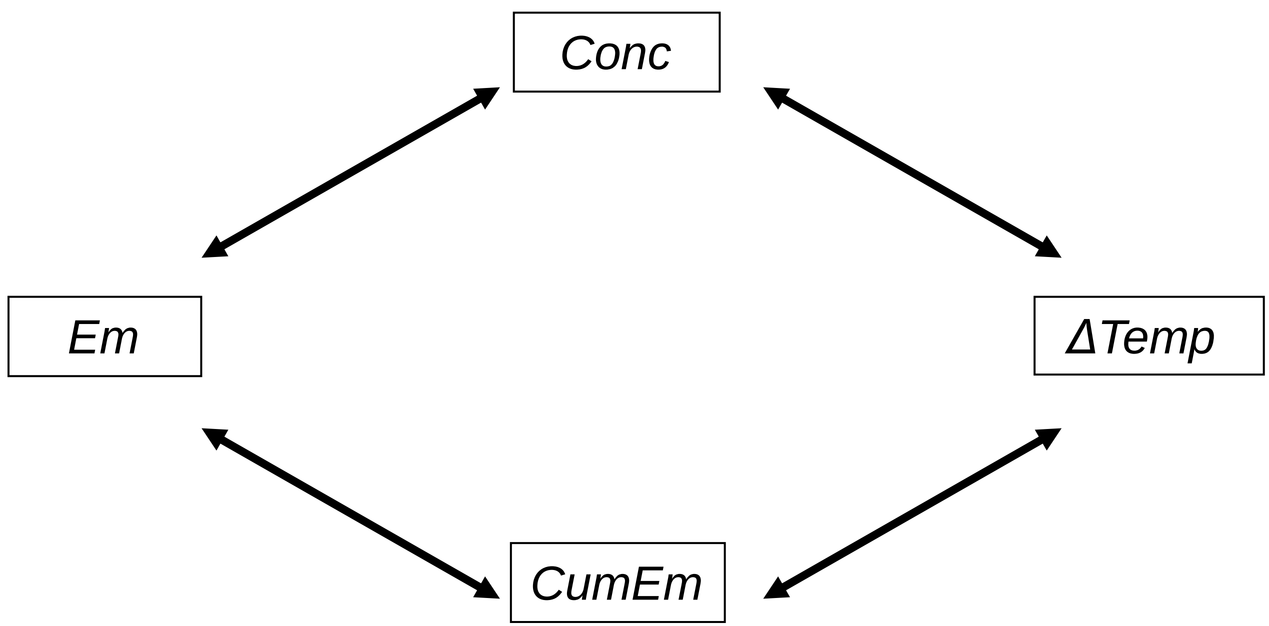
It is *not* sufficient to limit emissions in the prosperous parts of the world and allow the less fortunate to catch up. Such an outcome would overwhelm the planet.

The emissions of the future rich must eventually equal the emissions of today’s poor, …

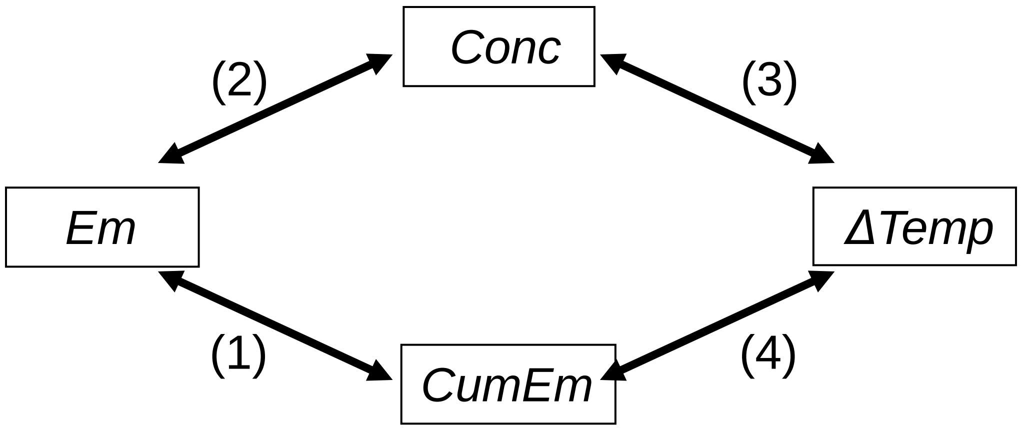
…not the other way around.

Alternative versions of targets

Em: Emission rate at some date (tCO_2/yr)
Conc: Concentration or “forcing” at some date (ppm or W/m^2)
CumEm: Cumulative emissions (“budget”) for an interval (tCO_2)
Temp: Maximum allowed average surface temperature increase relative to pre-industrial times (^oC)



Relationships among global targets



(1): *dCumEm/dt = Em*

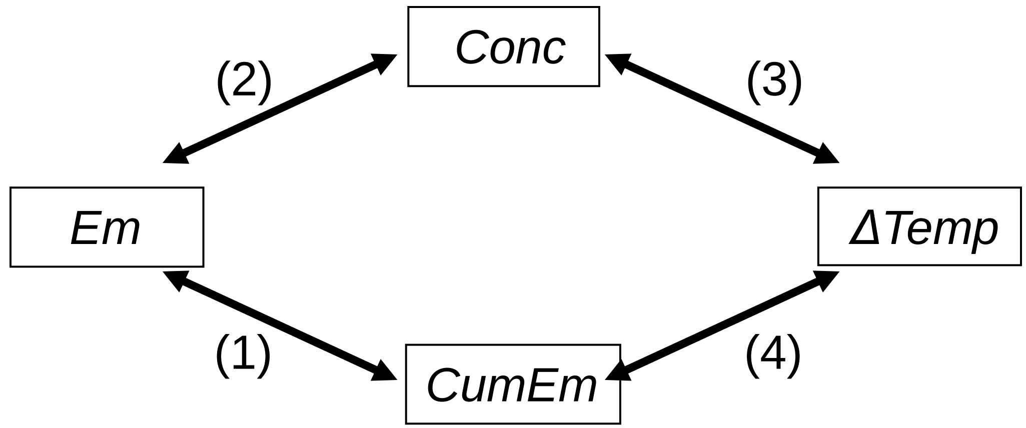
(2): *dConc/dt = λ*Em*, *λ* ≈ 0.5 ("Half Stays In")

Within the "*Conc*" box: Radiative forcing (RF) is approximately logarithmically related to concentration:

$$RF = \alpha * \ln(Conc/Conc_o),\ C_o = 275 \text{ ppm},\ \alpha = 5.35 \text{ W/m}^2$$

Here, $Conc_o$ is the pre-industrial concentration.

Relationships among global targets



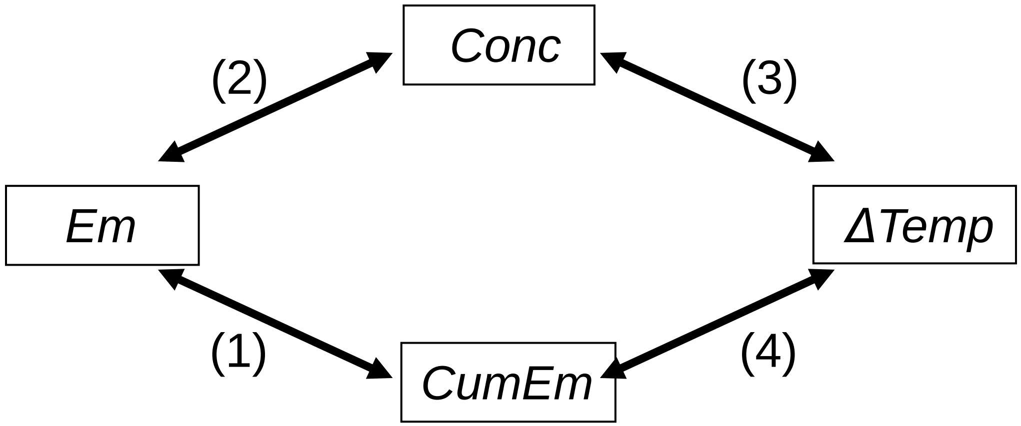
(3): $\Delta Temp = CS*ln(Conc/Conc_o)/ln2$,

where *ΔTemp* is the average surface temperature rise since pre-industrial times,
$Conc_o$ is the pre-industrial concentration ≈ 2200 $GtCO_2$ or 280 ppm, and
CS is the climate sensitivity. (Two references for $Conc_o$, 280 ppm and 275 ppm!)

Note that $\Delta Temp = CS*RF/(3.7\ W/m^2)$. The logarithmic dependence of both the "forcing" and the temperature rise on the concentration derives from the dominance of line-broadening warming.

In *AR4*, the central value of *CS* is 3.0^{o}C and the 66% interval: 2.0^{o}C < *CS* < 4.5^{o}C.
At CS = 3^{o}C, a "quadrupling" to 1120 ppm produces a warming of 6^{o}C.

Relationships among global targets

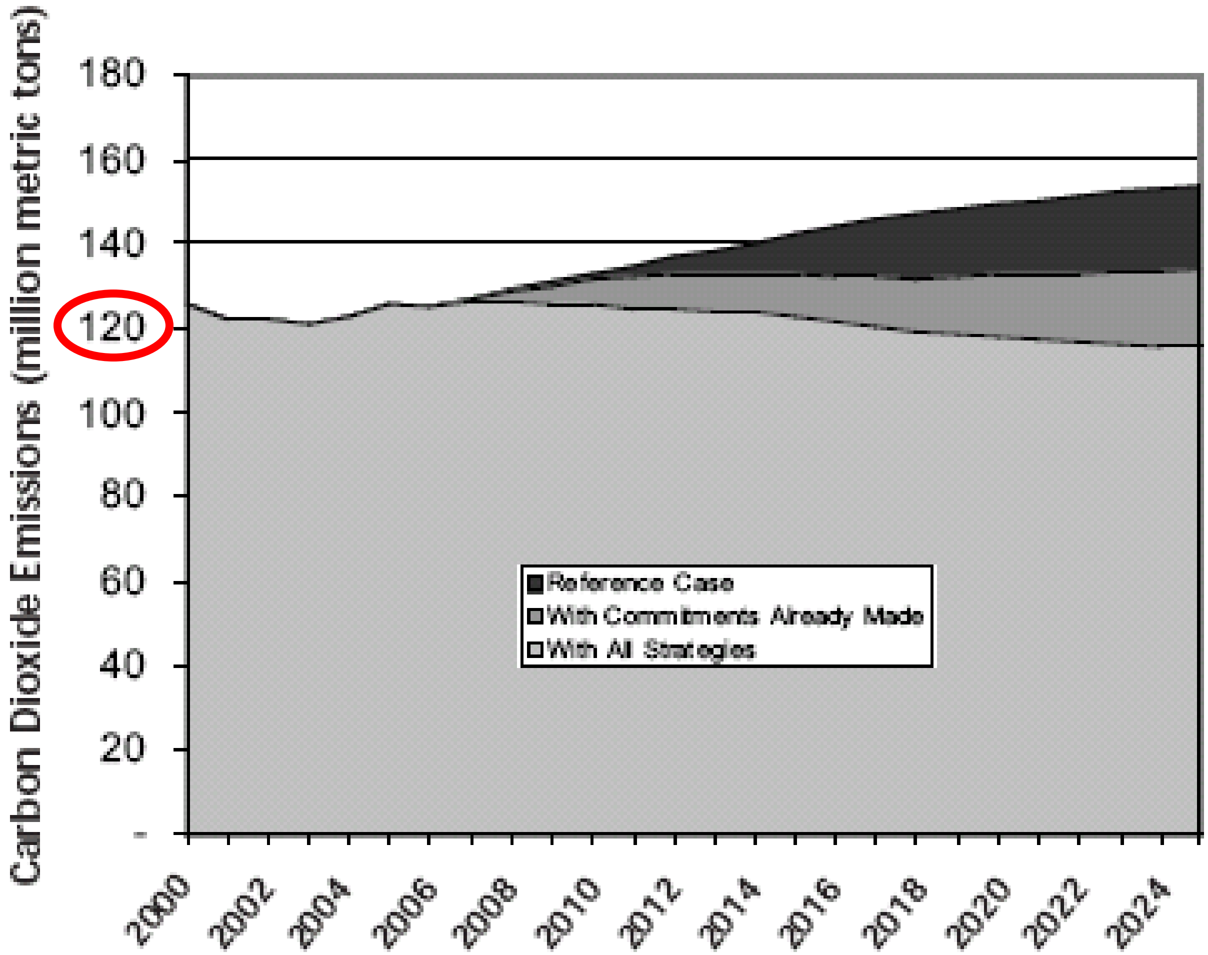


(4): $\Delta Temp = K{*}CumEm_{\infty}$, where
$CumEm_{\infty}$ extends from pre-industrial time to infinity.

This has been newly proposed as the preferred relationship, rather than (3). The problem with (3) is that to sustain the same concentration after stabilization requires further emissions, and temperature then keeps rising. The finding from models is that *Temp* is insensitive to the interval over which *CumEm* occurs.

K, of course, has its own probability distribution. In units of $^{o}C/1000GtCO_2$, the central value of *K* is 0.48: 90% interval: $0.27 < K < 0.68$. (Solomon et al., National Academy Press, 2010)

NJ CO_2 emissions goals



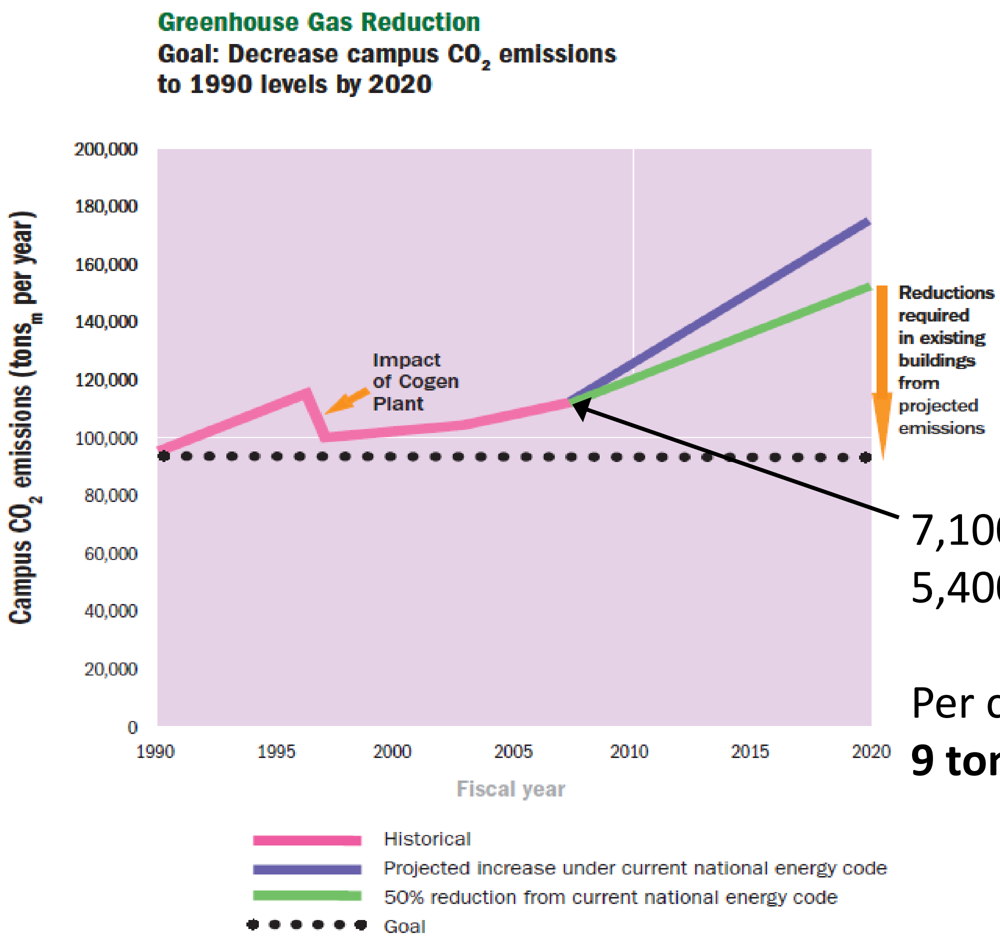
Not included: CO_2 emissions from 28% imported power

Source: *A Blueprint for Action: Policy Options to Reduce New Jersey's Contribution to Global Warming*, Environment New Jersey Research and Policy Center, September 2006.

Total: 120 $MtCO_2$/yr = 2% of U.S., 0.5% of world

Per capita: (120 $MtCO_2$/yr)/8.7 M people = 13.8 tCO_2/yr, 2/3 of U.S., 3x world.

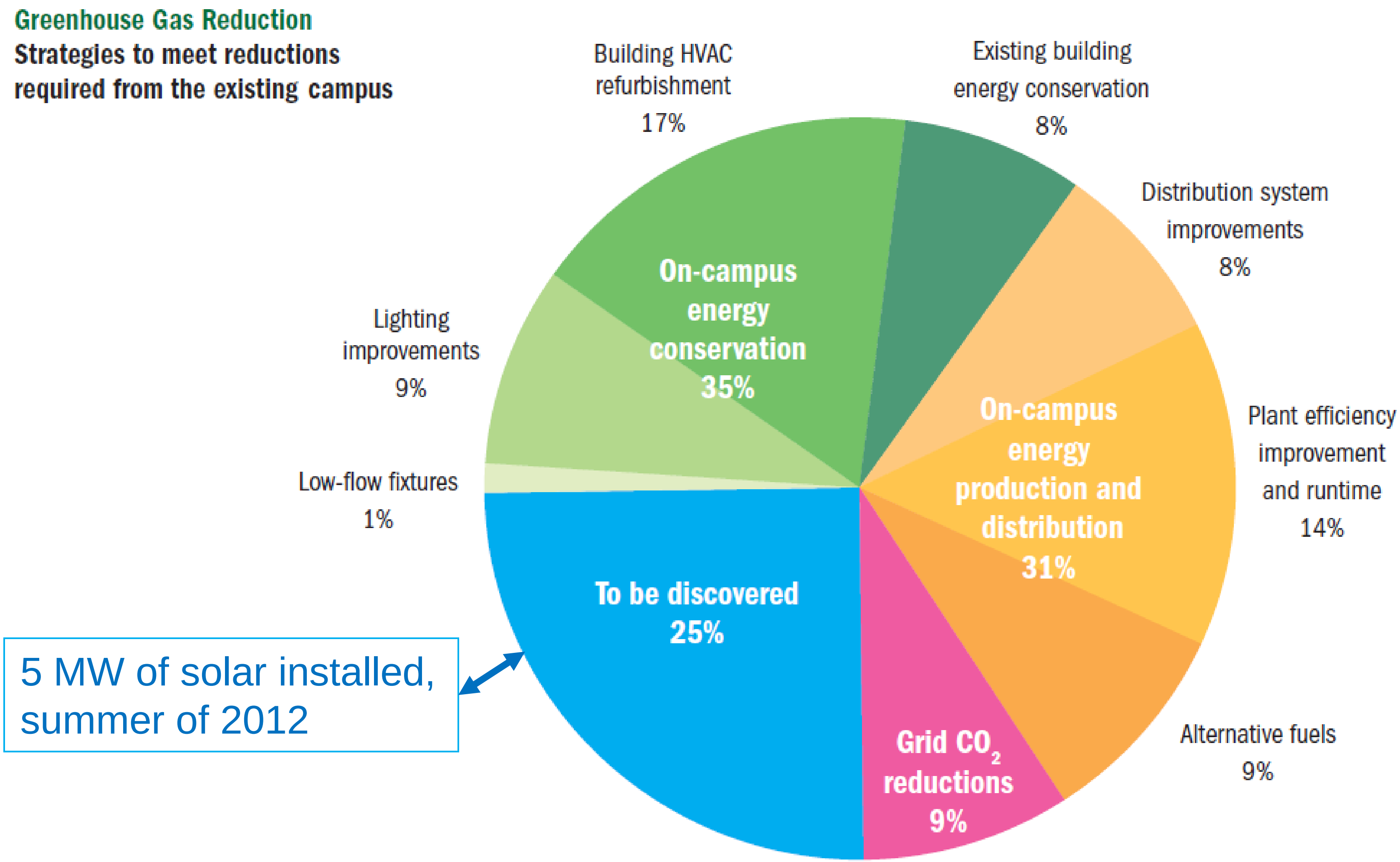
Princeton's CO_2 emissions goal



7,100 students
5,400 employees

Per capita emissions:
9 $tons_m$ CO_2 per year

Included: On-campus and external energy for cogeneration plant, fuel for vehicle fleet, but *no travel*. *Note*: Princeton expects to add almost 2 million square feet of building space in the next 10 years.



- Reduction of CO_2 emissions by 75,000 tons$_m$ per year in 2020
- No purchasing of emissions “offsets”
- Voluntary “CO_2 tax” when developing new building projects

What's in the way of action?

Important factors have been beyond the control of the environmental community:

- The recent recession
- The political influence of the fossil fuel industries and the beneficiaries of low-cost power (e.g., the coal-power states)
- Economic development imperatives in countries undergoing industrialization.

However, advocates for prompt action, of whom I am one, also bear responsibility for the poor quality of the discussion and the lack of momentum. We could and should have acknowledged that:

- The news is unwelcome
- The science is incomplete
- "Solutions" can bring serious problems of their own.

Might these three domains of political discourse be seedbeds for the restarting of serious discussion and ensuing action?

The news is unwelcome.

Never in history has the work of so few led to so much being asked of so many!

- The “few” are today’s climate science researchers.
- The “many” are the rest of us.
- We are asked to reduce our emissions promptly and substantially.

John Donne, *The First Anniversary*

Published a few months after Galileo's *Starry Messenger* (1610)

And new philosophy calls all in doubt,
The element of fire is quite put out;
The sun is lost, and th'earth, and no man's wit
Can well direct him where to look for it.
And freely men confess that this world's spent,
When in the planets and the firmament
They seek so many new; they see that this
Is crumbled out again t'his atomies.
'Tis all in pieces, all coherence gone,
All just supply, and all relation;
Prince, subject, father, son, are things forgot,
For every man alone thinks he hath got
To be a phoenix, and that there can be
None of that kind, of which he is, but he.
This is the world's condition now…

Copied from David Wootton, *Galileo: Watcher of the Skies*, Yale University Press, 2010, p. 5.

“Shooting the messenger”? No surprise.

The messenger has been shot before.

- Galileo argued that the earth wasn’t at the center of the universe and was excommunicated.
- Darwin argued that human beings were part of the animal kingdom and was cruelly mocked.

The idea that humans can’t change our planet is as out-of-date and wrong as the earth-centered universe and the separate creation of Man.

But all three ideas have such appeal that they will fade away only very slowly.

The science is incomplete

1. Neither mild nor severe climate change can be ruled out, given our poor understanding of feedbacks.
2. The probability of very bad outcomes is poorly known.
3. Breakthroughs are not imminent. We are not only flying blind, but the fog is not about to lift.

Uncertain feedback effects underlie uncertainties of climate forecasting

- Water vapor feedback
- Cloud feedback
- Biosphere feedback
- Ice-albedo feedback
- Aerosol feedback
- Ocean circulation feedback

Iterative risk management: the basis for a renewed commitment

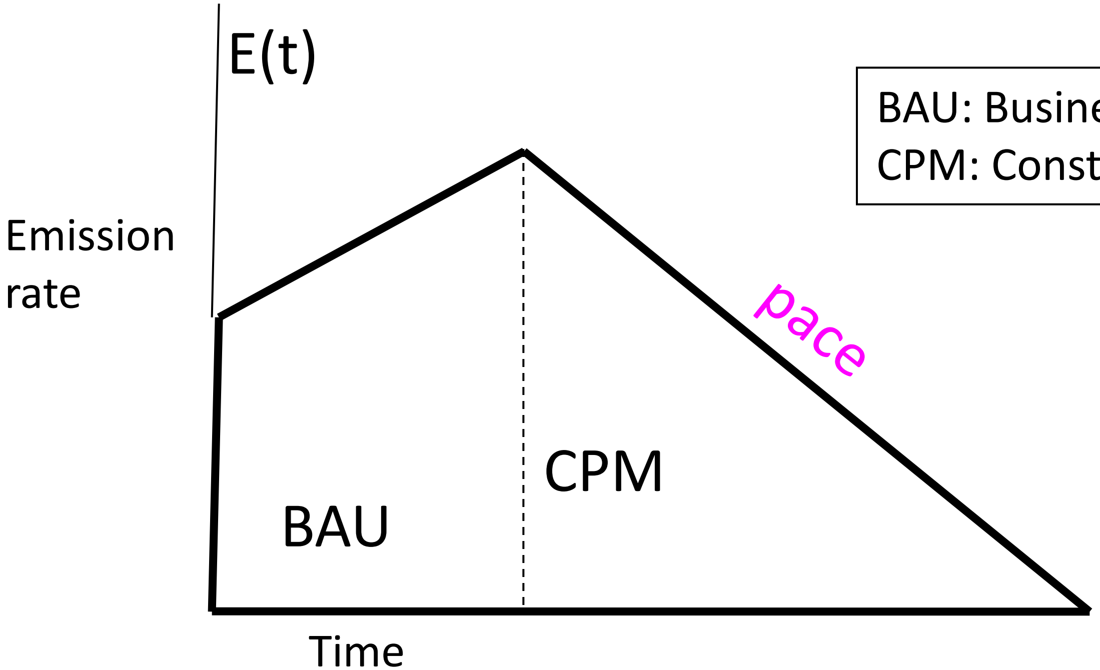
In another decade we'll know a lot more about the earth, both because of new climate science and because of what the earth tells us about itself.

We’ll also know more about the solutions themselves, thanks to both R&D and field experience.

All this argues for making decisions *iteratively*.

- Specifically, we can wait at least a decade before deciding whether 1) flat emissions are as heroic an outcome as we can achieve safely and equitably, or 2) whether we can achieve still more.

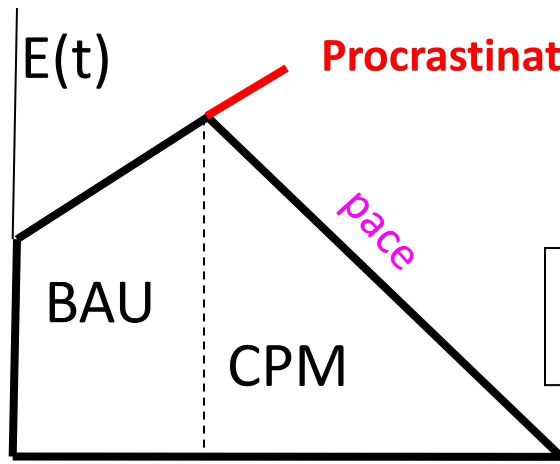
An idealization of mitigation



BAU: Business As Usual
CPM: Constant-Pace Mitigation

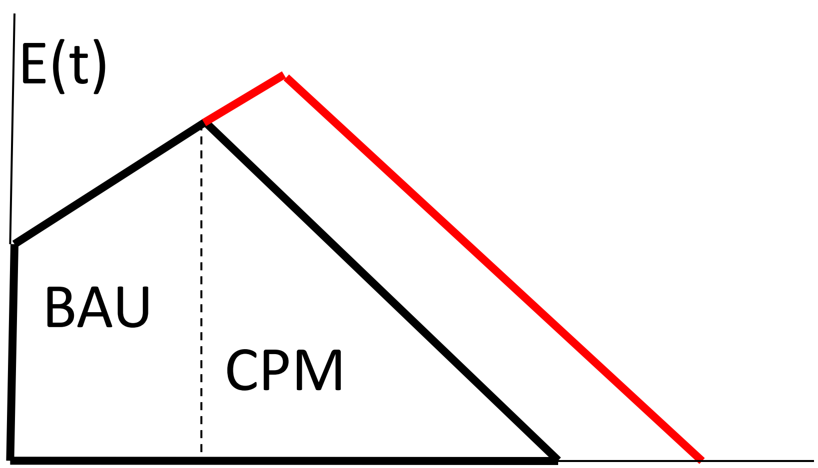
Today, approximately half of emissions are retained in the atmosphere and half move to other reservoirs.

Procrastination and “Pace”

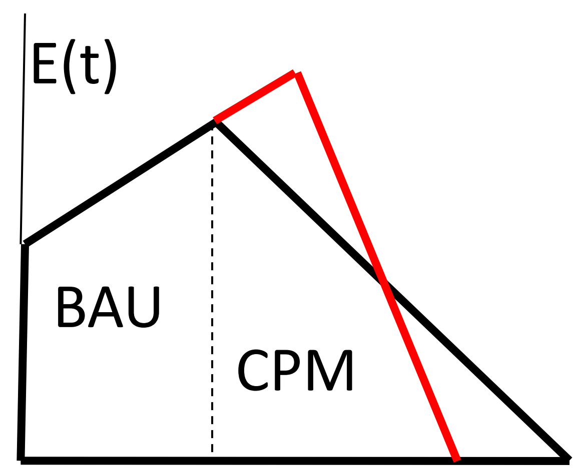


Procrastination can lead to…

BAU: Business As Usual
CPM: Constant-Pace Mitigation



(1) Extra total emissions, because pace cannot be increased,



OR (2) Constant total emissions, with a faster pace.

Arguments for Delay (1 of 2)

SCIENCE

- We don't know the science. Human activity may be having a negligible effect, swamped by natural variation.
- We may be having an effect, but the impacts are, on balance, favorable.

TECHNOLOGY

- We do not yet have the tools to solve the problem.
- The tools to solve the problem that we have are far inferior to the tools we will have if we conduct R&D for a few decades.
- We have tools that could solve the problem, but they are too dangerous. The cures are worse than the disease.

Arguments for Delay (2 of 2)

POLITICS, ECONOMICS

- The costs of mitigation are too high, relative to any willingness to pay.
- Government makes a mess of things when it intervenes in the economy.
- The world has more important things to do, notably to deal with world poverty.
- It is wasteful to engage developing countries in mitigation now, given that they will have much greater capacity for implementation later.
- Mitigation will hurt the poor in every country. Wait till we are richer.
- The net result will be to transfer wealth from rich to poor, not good policy.

PHILOSOPHY

- Government should not run our lives.
- People aren’t ready to tackle climate change – the issue is too abstract.
- Whatever the impacts, we can adapt to them.
- We should not play God. We should not control nature.

Surrogate Goals (1 of 3)

Definition of a surrogate goal

A person who holds Goal A strongly and Goal B weakly, but believes that achieving Goal B will also achieve Goal A, can pursue Goal B as a *surrogate* for Goal A.

Usually, Goal A will be revealed only in special circumstances. Recognizing that a multiplicity of surrogate goals is at play has considerable explanatory power.

Surrogate Goals (2 of 3)

Surrogate goals and climate change

In the formulation of policy to deal with climate change, the general objective of slowing the rate of climate change is often a surrogate for more strongly held goals, such as:

- Augmenting financial transfers to developing countries
- Bringing the fossil fuel era to a close
- Curtailing consumerism and human centeredness
- Promoting self-sufficiency, autonomous communities
- Diminishing the power of technological elites
- Promoting environmental science
- Encouraging entrepreneurship

Surrogate Goals (3 of 3)

A problem arises when an action in support of the surrogate goal negates the person’s more strongly held goal.

- Capturing and storing CO_2 prolongs the fossil fuel era.
- Large and distant solar arrays and windfarms do not promote local self-reliance.

EXTRA SLIDES #1

CO_2-equivalent concentration

Incremental radiative forcing (RF) for CO_2, relative to pre-industrial times, is:

$$RF = \alpha * \ln(C/C_o),\ C_o = 275 \text{ ppm},\ \alpha = 5.35 \text{ W/m}^2 \qquad (1)$$

For C = 385 ppm, RF = 1.80 W/m^2.

Invert this equation:

$$C = C_o \exp(RF/\ \alpha) \qquad (2)$$

Add a second gas, say CH_4. Its incremental RF is found in some fashion. (For a saturated gas, like methane, perhaps from an expression like (1); for gases with unsaturated absorption lines, from a linear expression.)

Sum the RF's: $RF_{tot} = RF_{CO2} + RF_{CH4}$. More generally, with *i indexing the gases:*

$$RF_{tot} = \Sigma\, RF_i \qquad (3)$$

Calculate CO_{2e} by inserting RF_{tot} into (2):

$$CO_{2e} = C_o \exp(RF_{tot}/\alpha) \qquad (4)$$

Specifically, CO_{2e} = (275 ppm)exp[RF_{tot}/(5.35 W/m_2)]. For example, if RF_{tot} = 2.2 W/m^2, then CO_{2e} = 415 ppm; and if RF_e = 3.0 W/m^2, then CO_{2e} = 482 ppm.

In many definitions of CO_{2e}, aerosols are excluded. When they are *included*, $RF_{tot} \approx RF_{CO2}$

CO_{2e} is a product of factors, one for each gas

The forcing quantities for the various gases or aerosols affecting climate forcing act additively, which is why RF_{tot} (the total incremental radiative forcing) is a straightforward concept.

Awkward but true, the CO_2-equivalent concentration, CO_{2e} is a *product*, since RF_{tot} is a sum. Using (3) and (4), it can be written:

$$CO_{2e} = C_o * \Pi \exp(RF_i/\alpha), \qquad (5)$$

where the index i runs over the various contributors to the forcing.

When some RF is much less than α, the multiplicative factor can be approximated by (1 + RF/ α).

Table: Multiplicative factor, exp(RF/α), for α = 5.35 W/m² and various values of RF.

Source: IPCC (SFP, p.4) central values for CO_2, CH_4, N_2O and the halocarbons are, respectively, (in W/m²): 1.66, 0.48, 0.16, and 0.34.

RF [W/m²]	exp(*RF/α*)
0.4	1.078
0.8	1.161
1.2	1.251
1.6	1.349
2.0	1.453

Global CO_2 budget

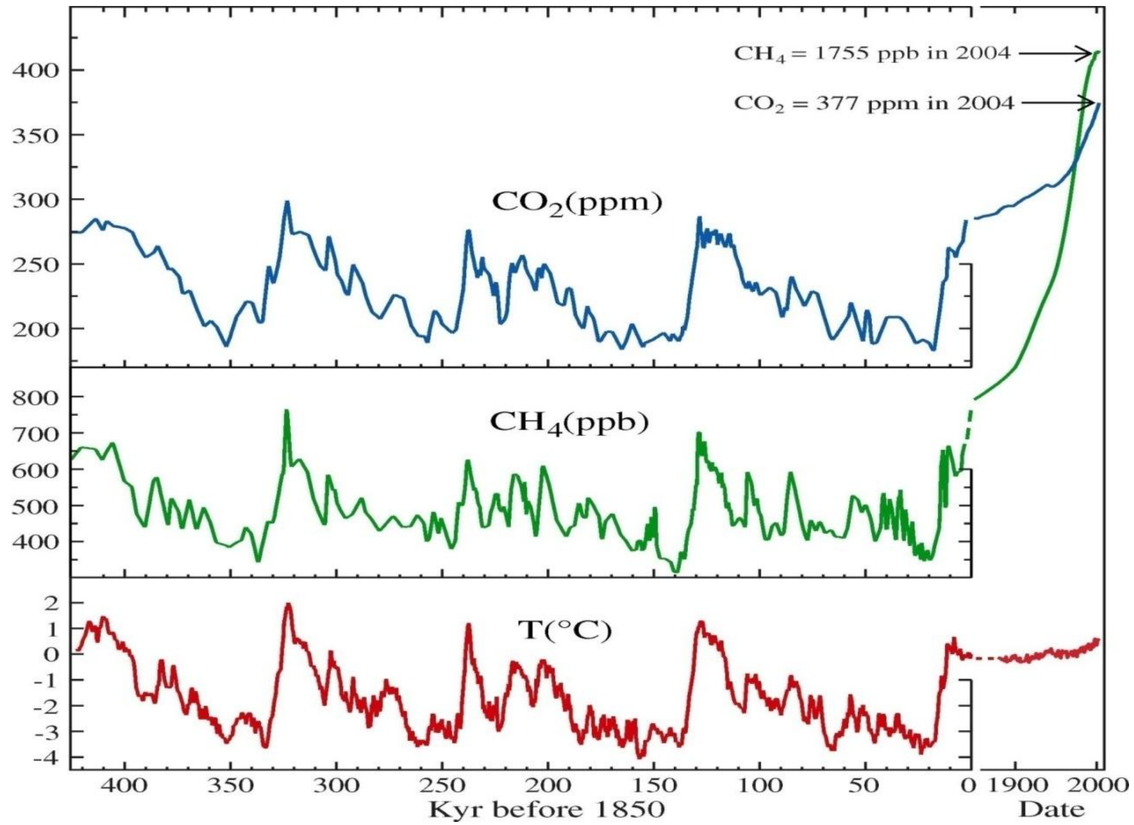
	2000-2008
Sources (Pg C/yr)	
Fossil fuel + cement	7.7 ± 0.4 (85%)
Land use	1.4 ± 0.7 (15%)
Sinks (Pg C y^{-1})	
Atmospheric growth	4.1 ± 0.1 (45%)
Ocean sink (models)	2.3 ± 0.4 (26%)
Land sink (models)	3.0 ± 0.9 (29%)
Residual (imbalance)	-0.3 ± 1.3

Source: Sarmiento, from Le Quéré et al. (2009)

Temperature, CO_2, methane track each other

CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era) 0 = 1880-1899 mean.

Source: Hansen, *Clim. Change*, **68**, 269, 2005.



Evidence for Abrupt Change: The Younger Dryas Cold Event

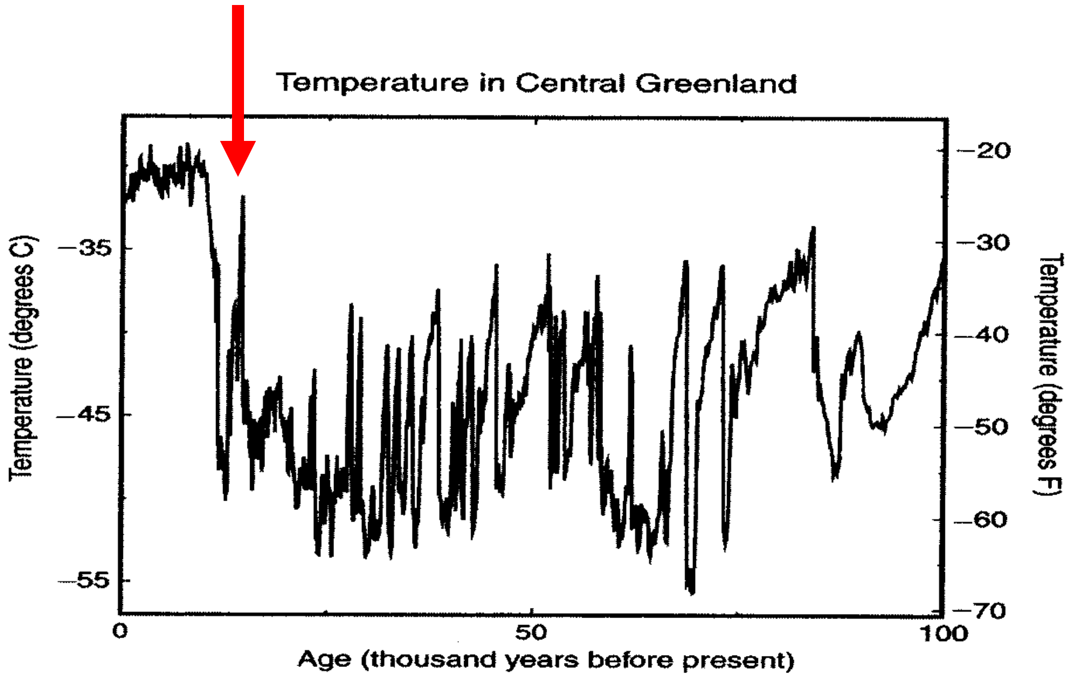
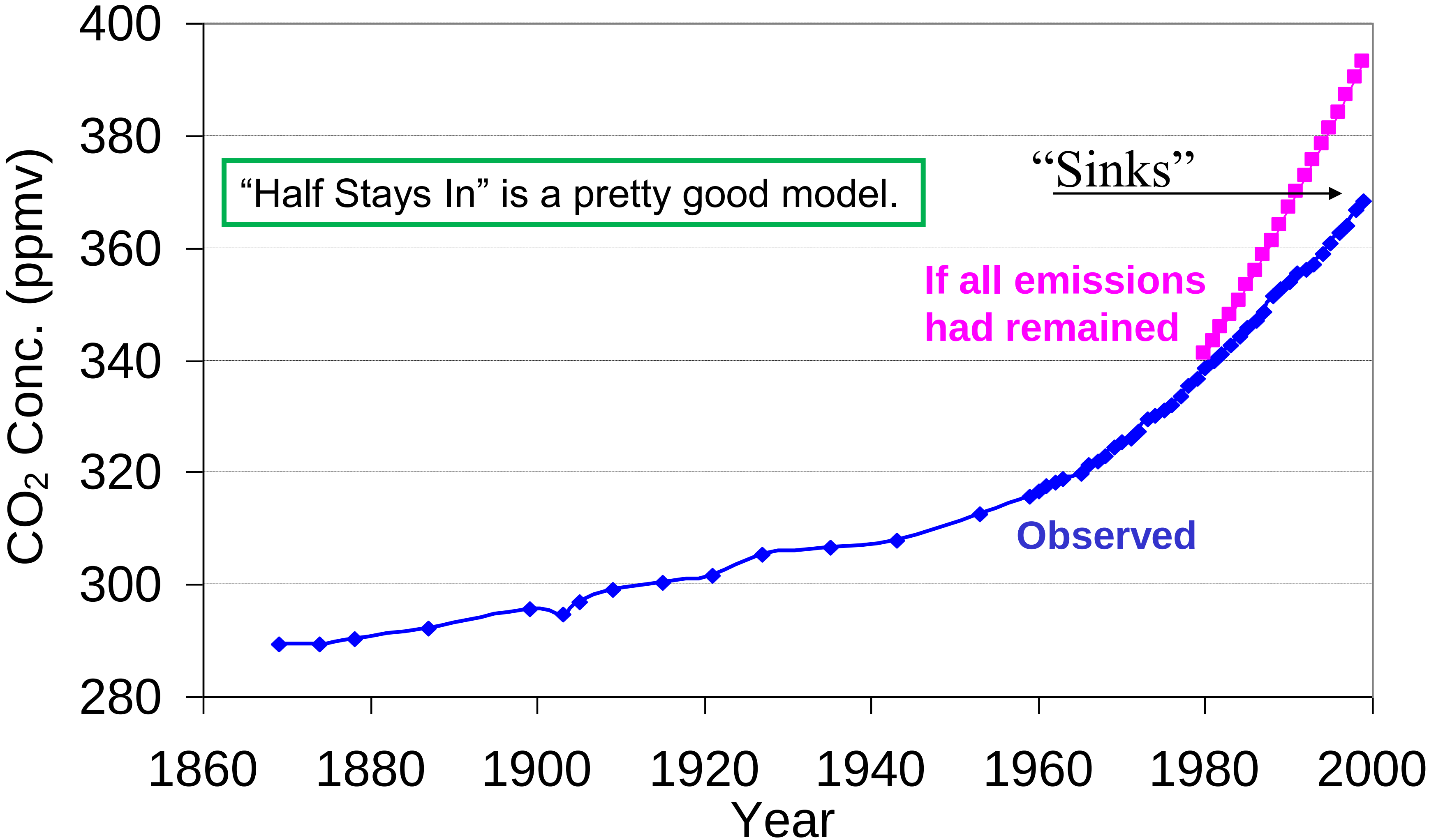
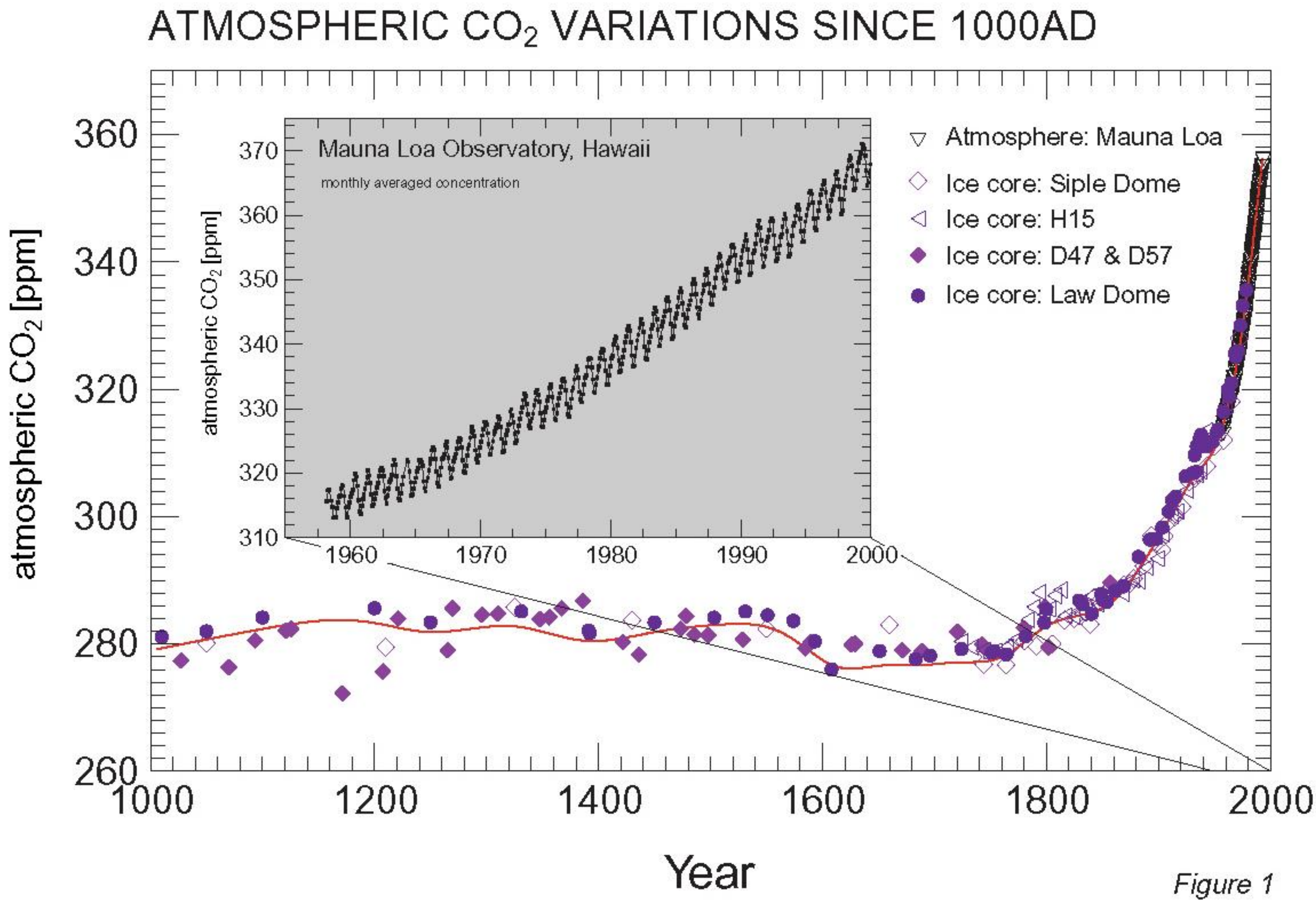


FIGURE 12.2
The history of temperature in central Greenland over the last hundred thousand years, from ice-isotopic values calibrated against borehole temperatures, using data from the 1997 paper by Cuffey and Clow. The prominent Younger Dryas cold event is now seen to be "business as usual," with similar events having dominated the record. Jumps have been smaller than usual around 20,000 years ago, when most of the world was in the coldest part of the ice age, and during the most recent few millennia, when most of the world was warm. Fahrenheit temperatures are shown on the right, and Celsius on the left.

The Two-Mile Time Machine, Richard B. Alley, p. 119.

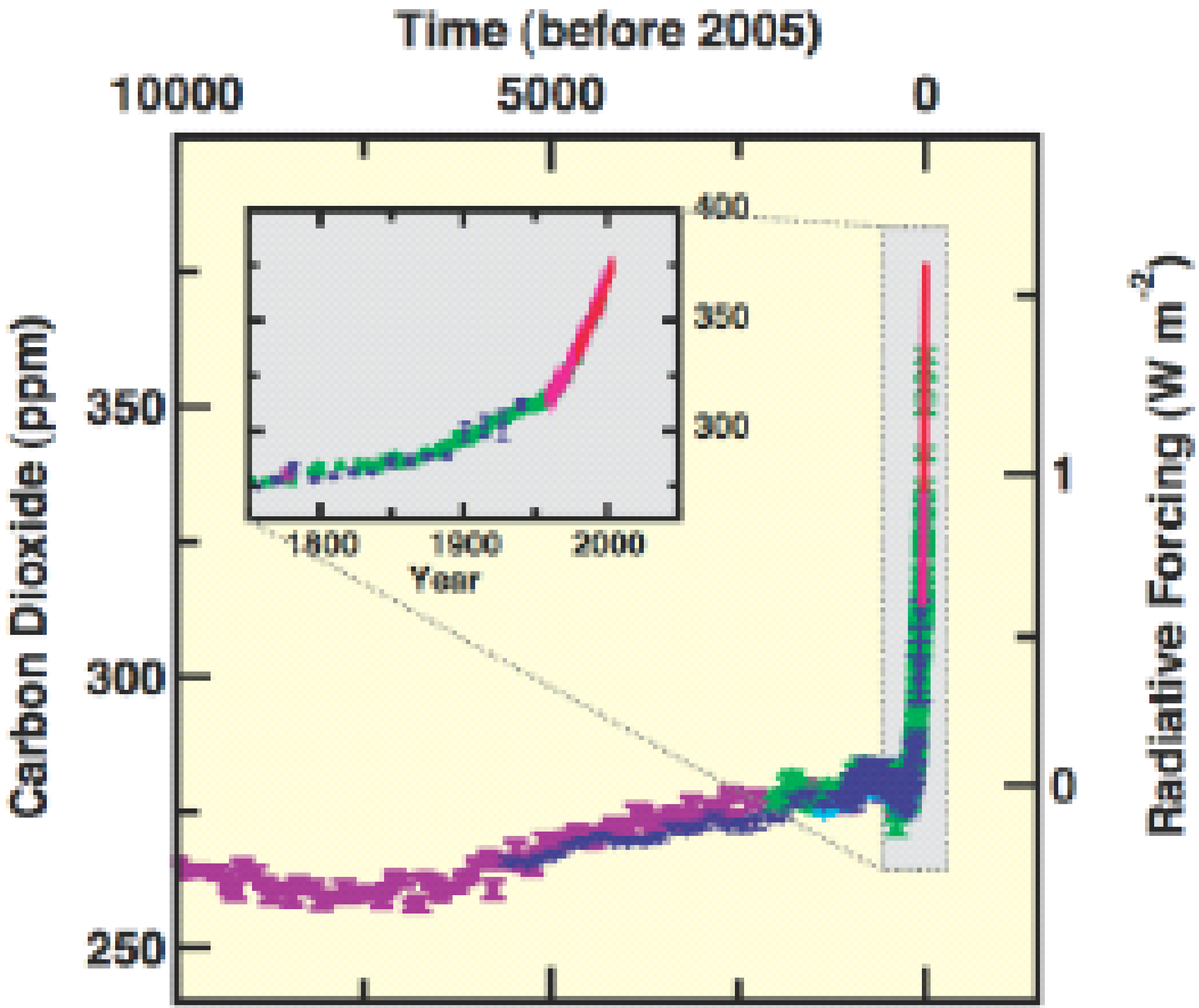
Atmospheric CO_2 Concentration with and without 1980-99 sinks



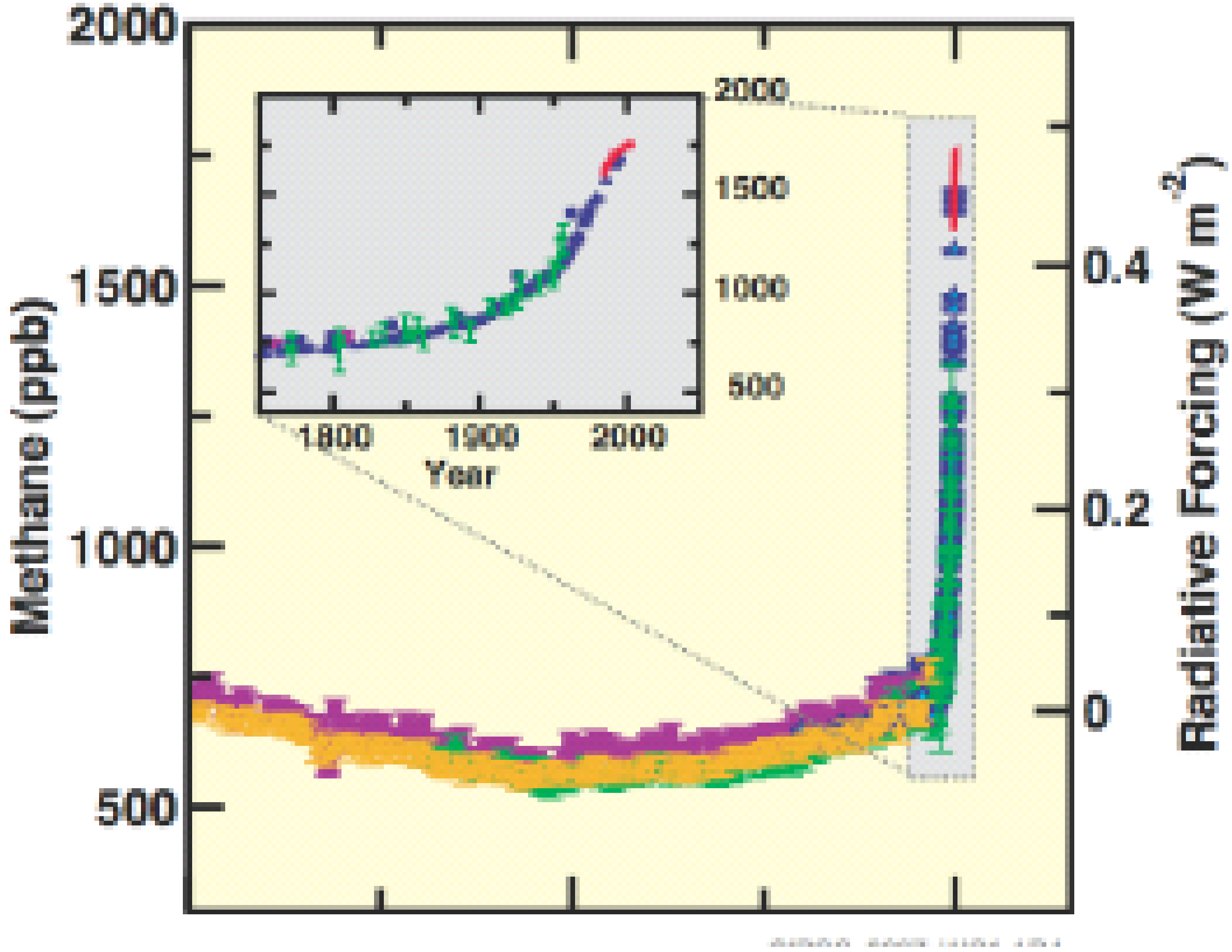


(Ice core data from Barnola, 1999; Mauna Loa from D. Keeling & T. Whorf, 2000)

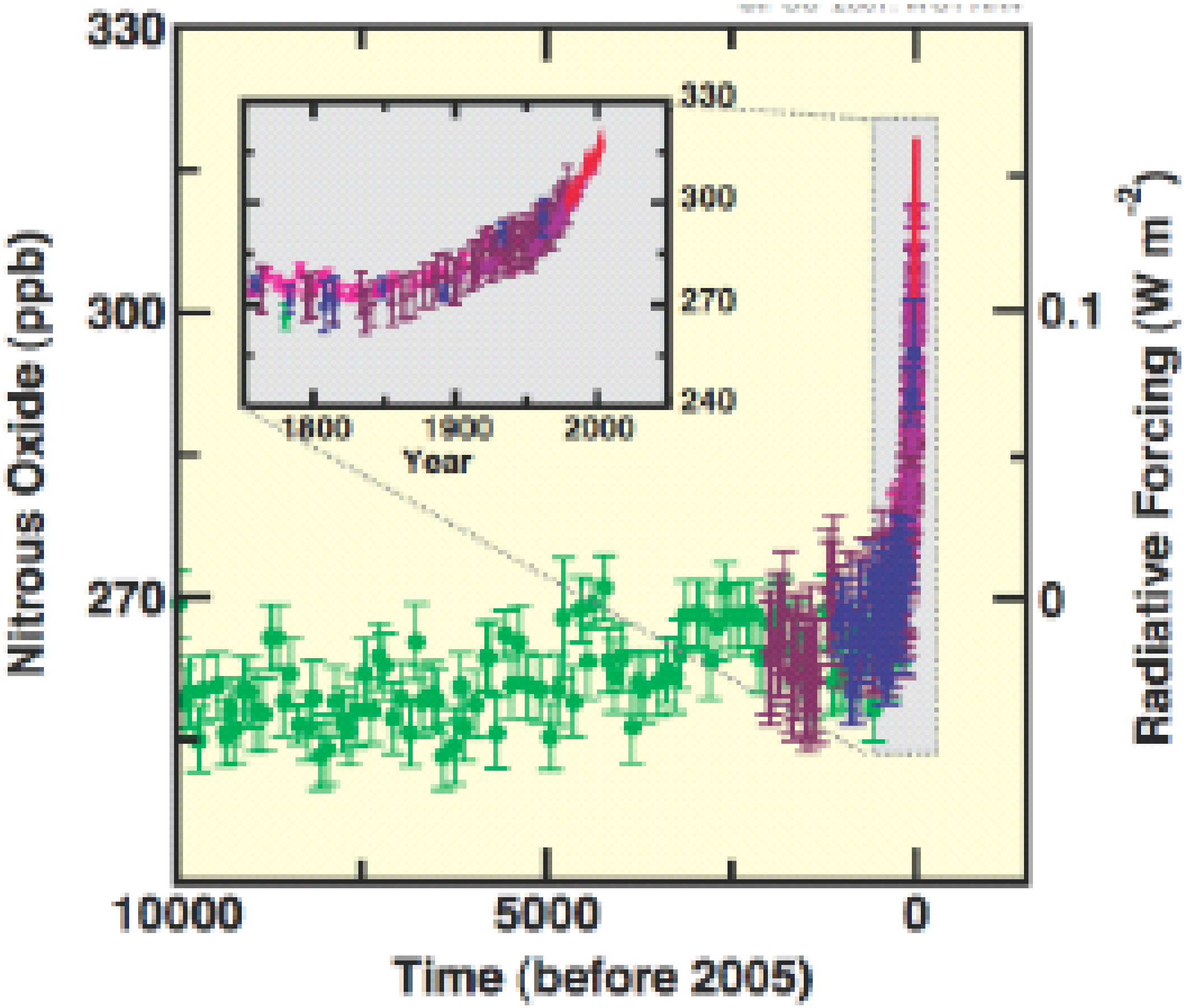
CO_2 Record (IPCC 2007)



CH_4 Record (IPCC 2007)



N_2O Record (IPCC 2007)



The benign alternative, AR4

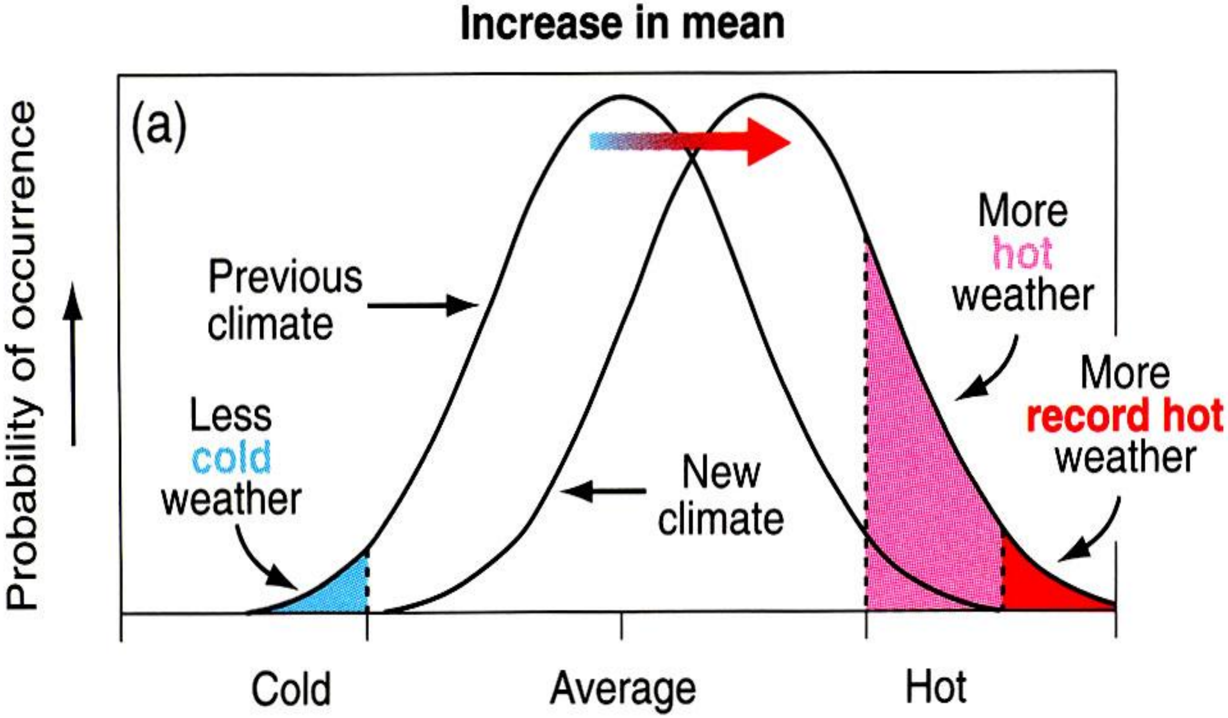
Phenomenon and direction of trend	Likelihood of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	*Virtually certain*
Warmer and more frequent hot days and nights over most land areas	*Virtually certain*
Warm spells/heat waves. Frequency increases over most land areas	*Very likely*
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	*Very likely*
Area affected by droughts increases	*Likely*
Intense tropical cyclone activity increases	*Likely*
Increased incidence of extreme high sea level (excludes tsunamis)	*Likely*

Virtually certain > 99% probability; Very likely > 90%; Likely > 66%

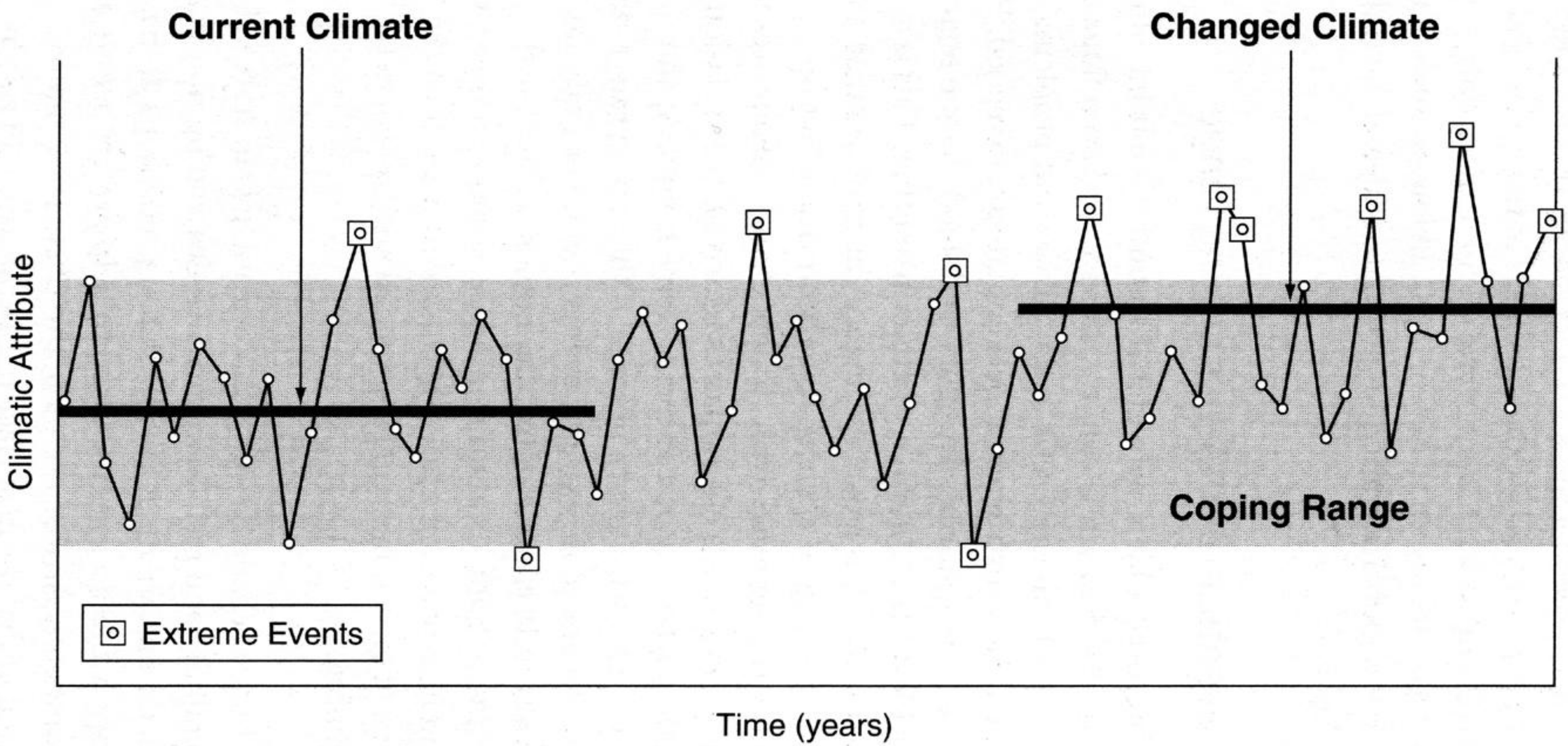
IPCC, WGI, SPM (2007)

Source: IPCC WG1 SPM, 2007

Changes in temperature extremes

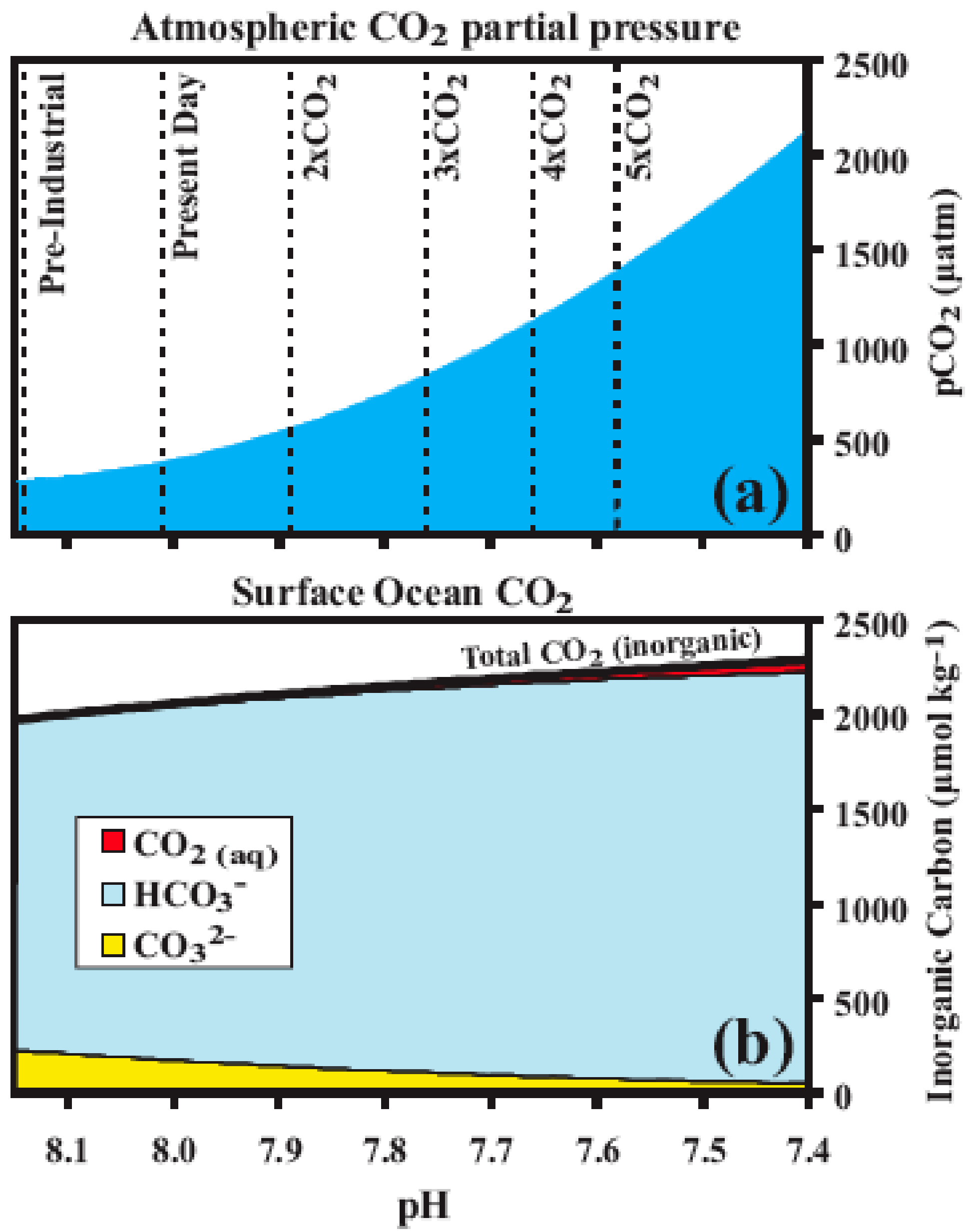


IPCC



17. Climate change, society's coping range, and extreme events

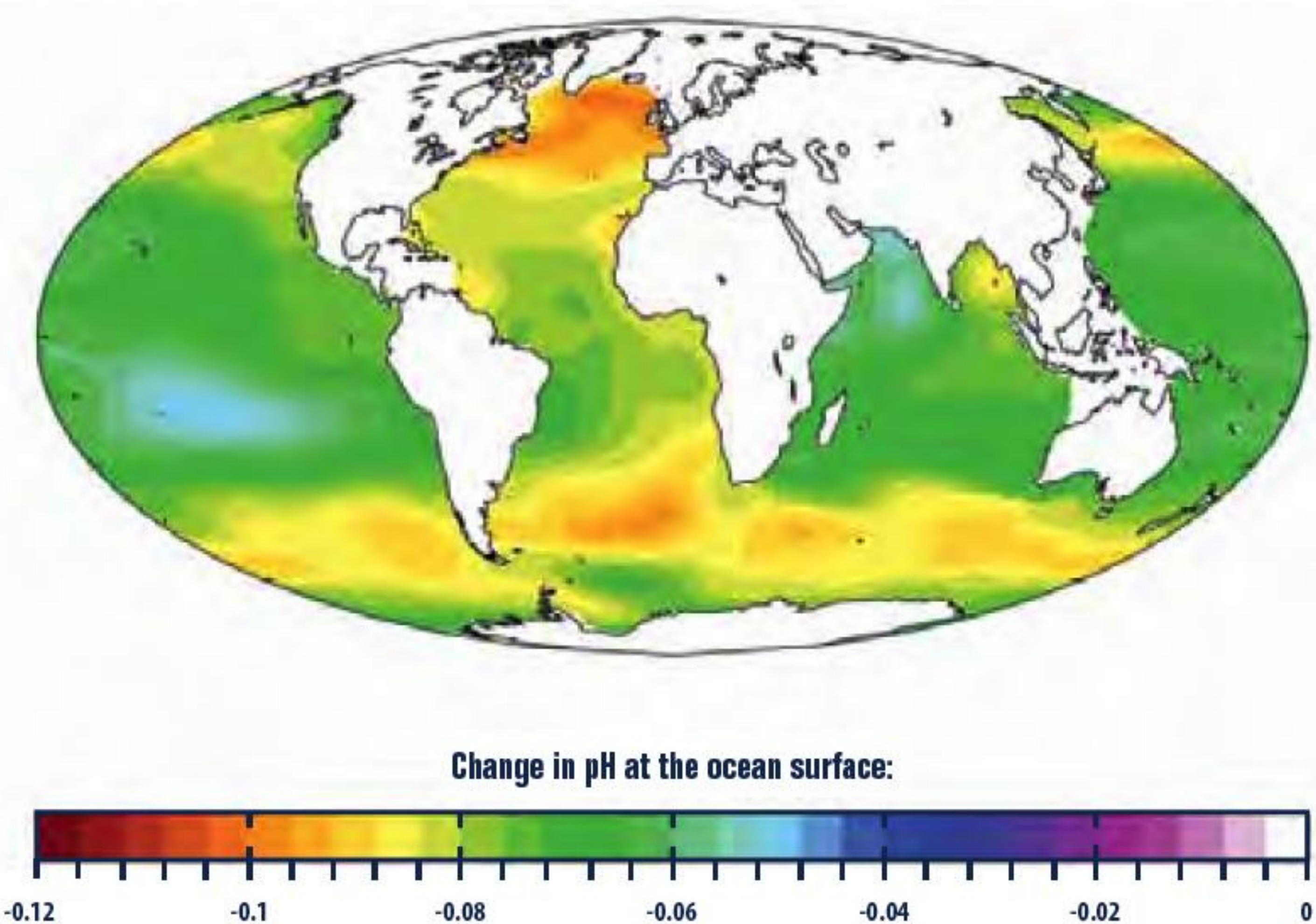
Maslin, M. *Global Warming* (2009)



Kleypas et al. 2006

Figure 2. Historical Changes in Ocean Acidity, 1700s–1990s

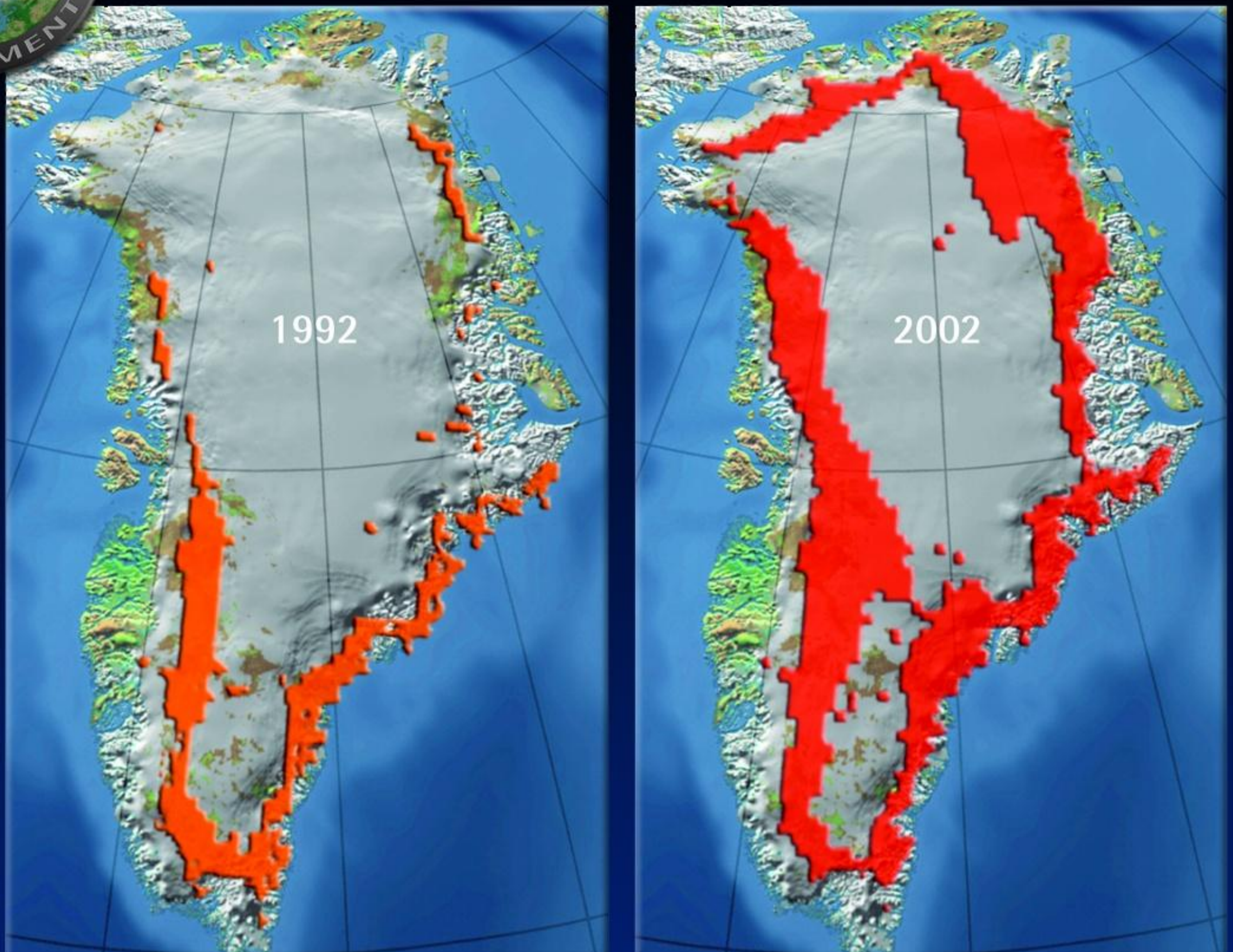
This figure shows changes in ocean pH levels around the world from pre-industrial times to the present based on modeled data.



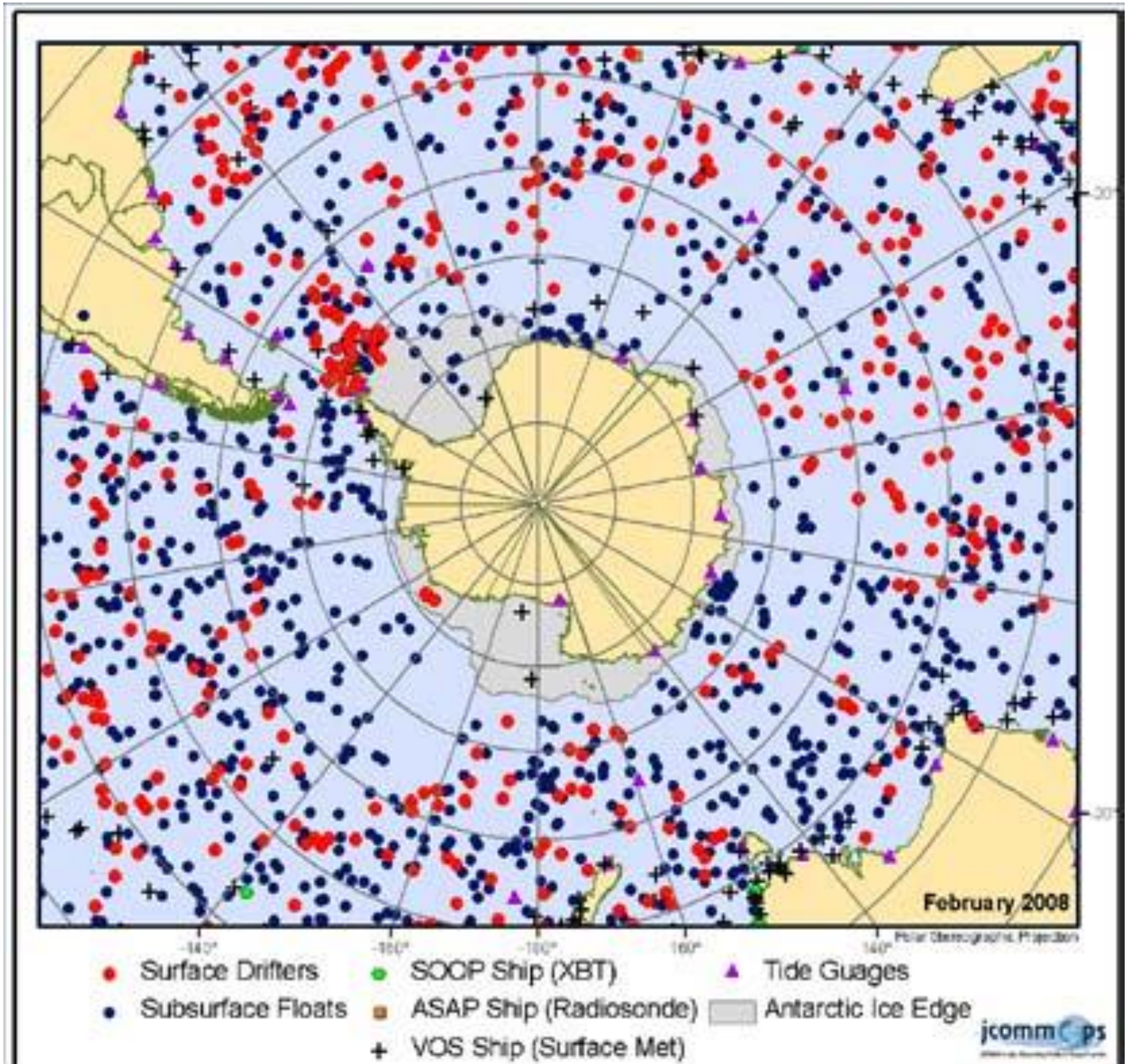
Data source: Yool, 2007[23]

IMPACTS OF A WARMING ARCTIC

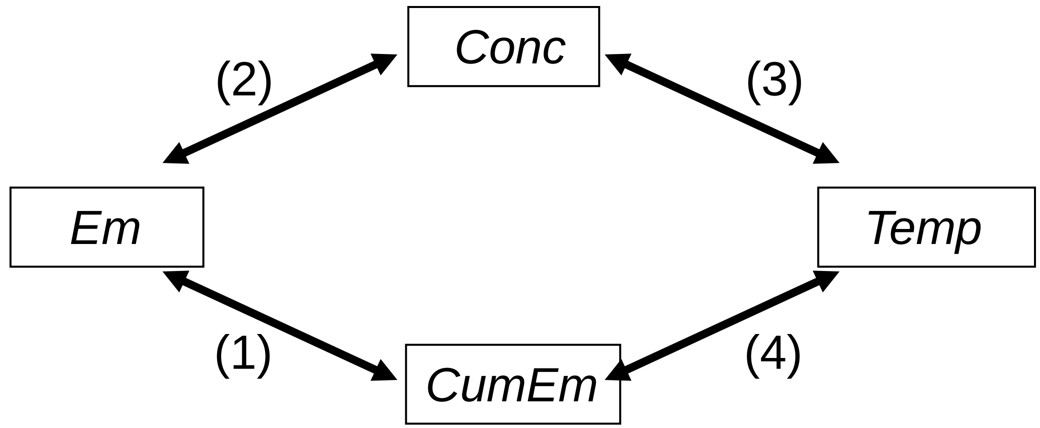
Greenland Ice Sheet Melt Extent



Ocean observing systems, as of February 2008



Relationships among global targets



(1): $dCumEm/dt = Em$

(2): $dConc/dt = \lambda{*}Em$, $\lambda \approx 0.5$ ("Half Stays In")

(3): $Temp = CS{*}ln(Conc/Conc_o)/ln2$,

where $Conc_o$ = pre-industrial concentration ≈ 2200 $GtCO_2$

and CS = climate sensitivity

(central value of CS is 3.0^{o}C; 66% interval: 2.0^{o}C < CS < 4.5^{o}C)

(4): $Temp = K{*}CumEm_\infty$,

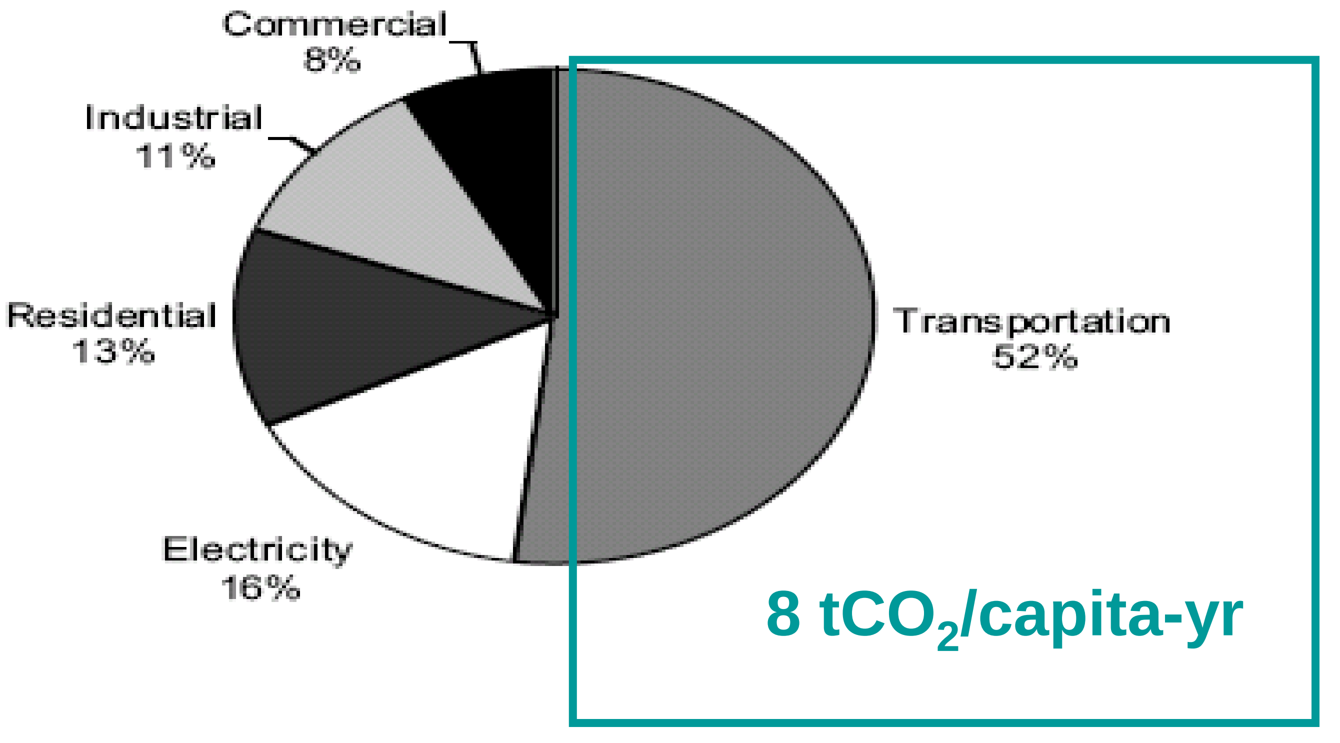
where $CumEm_\infty$ extends from pre-industrial time to infinity

and, in units of ^{o}C/1000$GtCO_2$, the central value of K is 0.48:

90% interval: 0.27 < K < 0.68.

Dominance of transport in NJ

Sectoral CO_2 emissions, 2002

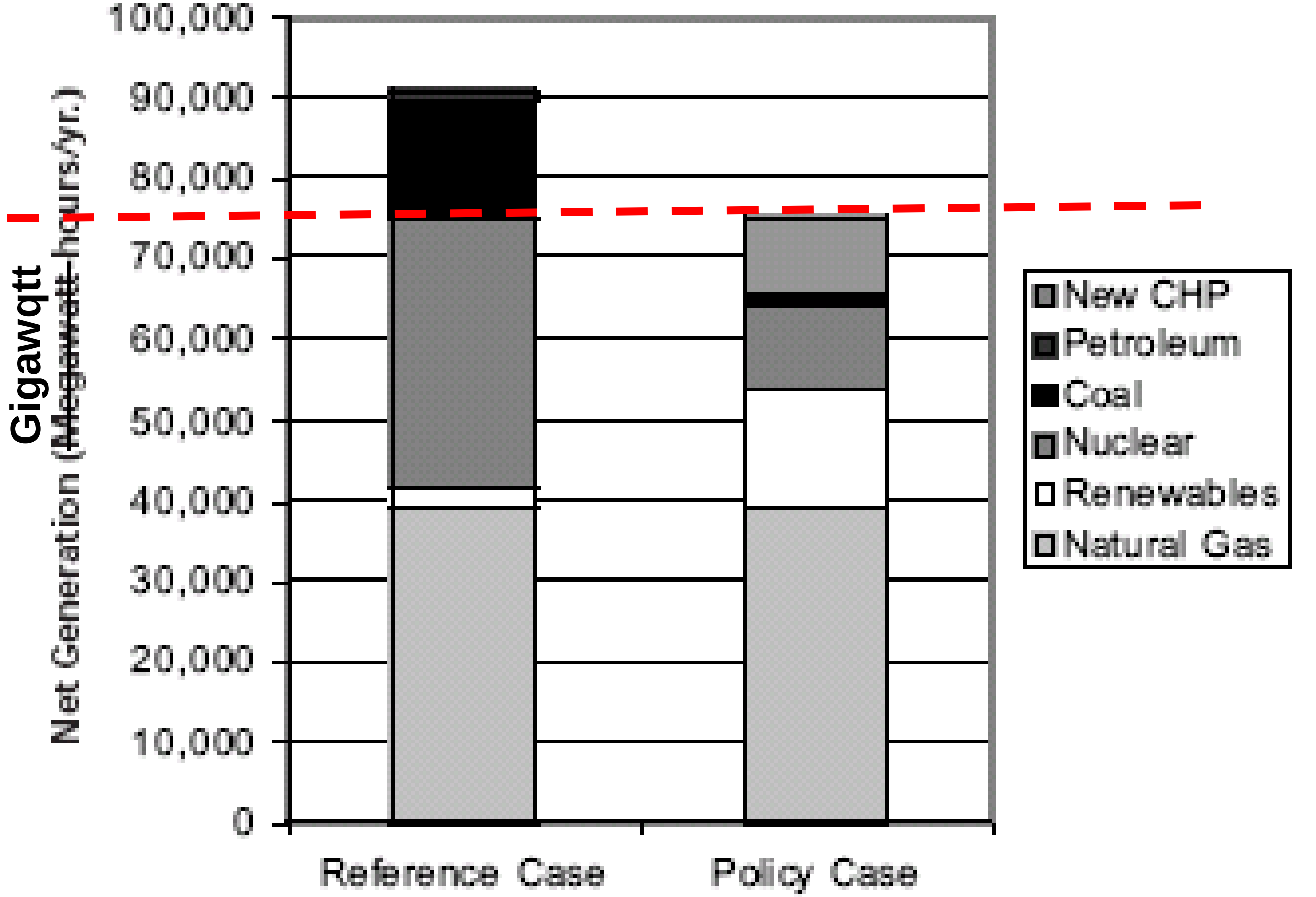


Source: *A Blueprint for Action: Policy Options to Reduce New Jersey's Contribution to Global Warming,* Environment New Jersey Research and Policy Center, September 2006.

Projected Net Generation of Electricity by Power Source, New Jersey, 2025

2006(?):

≈ 75,000 GWh/yr = 8600 kWh/cap-yr



Source: *A Blueprint for Action: Policy Options to Reduce New Jersey's Contribution to Global Warming,* Environment New Jersey Research and Policy Center, September 2006.

Princeton University CO_2 in 2007

University emissions*	112,000 tCO_2
12,500 participants**	
Per-capita emissions	9 tCO_2

*On-site cogeneration plant, purchased electricity, fuel for University fleet.
**7,100 students and 5,400 employees

Goal-setting at Princeton

GOALS

Princeton's Sustainability Plan sets ambitious goals in three areas:

1. greenhouse gas emissions reduction,
2. resource conservation,
3. research, education, and civic engagement.

Slides from "Examining Climate Change: the University Perspective," in-class presentation from Matt Escarra, Matt Tilghman, and Matt Isakowitz, October 1, 2008.

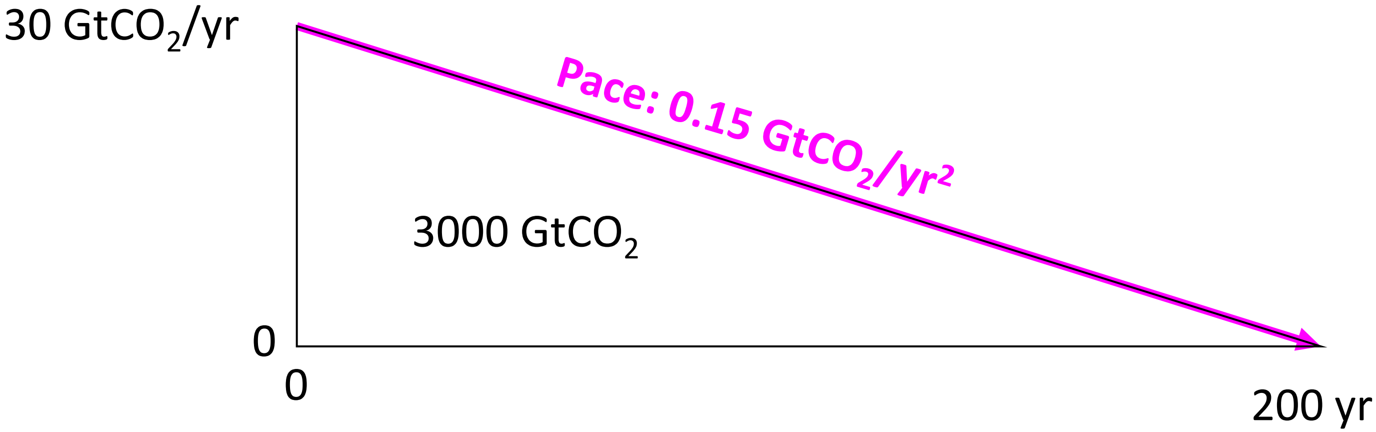
Sources:

Princeton sustainability brochure at http://www.princeton.edu/sustainability/plan/SustainabilityBrochure.pdf

Princeton sustainability plan at http://www.princeton.edu/sustainability/plan/Sustainability-Plan-Doc.pdf

Constant-Pace Mitigation (CPM)

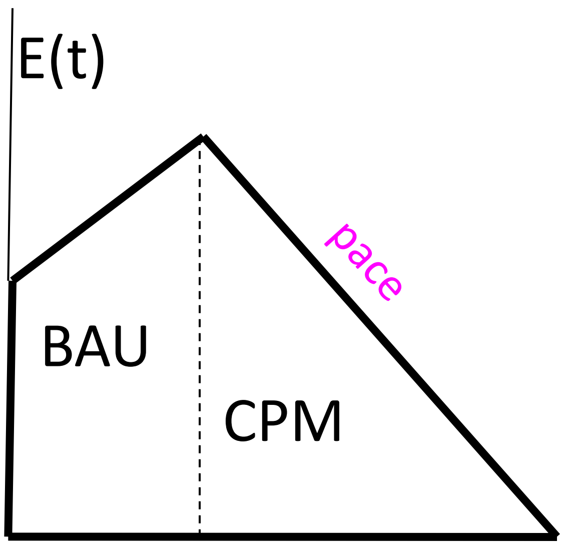
Example: Stabilize at 4500 $GtCO_2$ (double pre-industrial).
Start today (3000 $GtCO_2$). Assume “Half Stays In.”
Then can emit 3000 $GtCO_2$ more.
With CPM, emissions run for 200 years

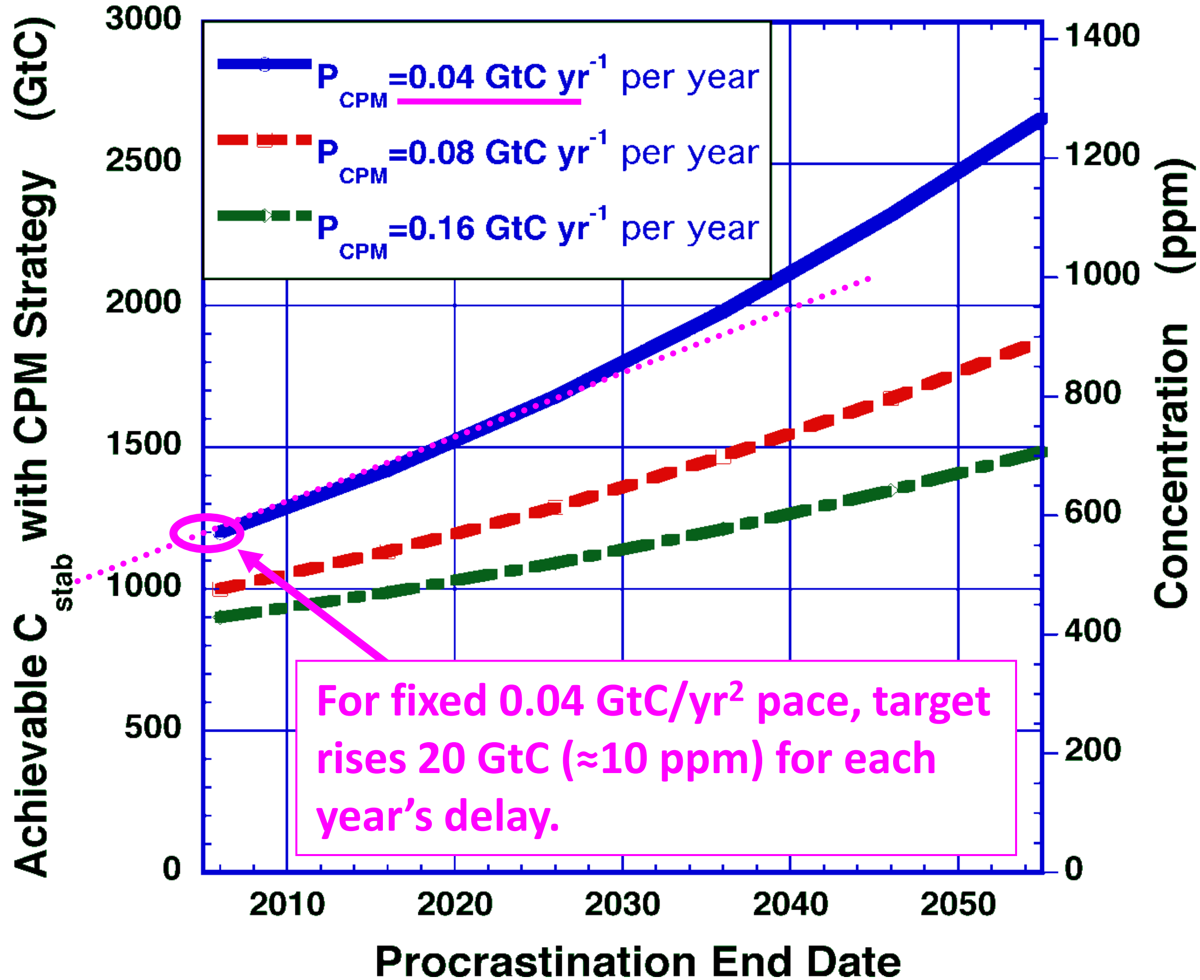


See: R.H. Socolow and S.H. Lam, “Good enough tools for global warming policy making,” *Phil. Trans. R. Soc*. A (2007) 365, 897–934

Procrastination and pace fix the target

Note: tC, not CO_2!





Stabilization target (C_{stab}) when Constant-Pace-Mitigation (CPM) follows Business as Usual (BAU) procrastination. During BAU, d*E(t)/dt* = 0.16 GtC/yr^2. Throughout, half of CO_2 emissions stay in the atmosphere. *Source*: Socolow-Lam, 2007.

Representative Concentration Pathways (RCPs)

SRES and RCP emissions trajectories

SRES: *Special Report on Emissions Scenarios*, IPCC 2000

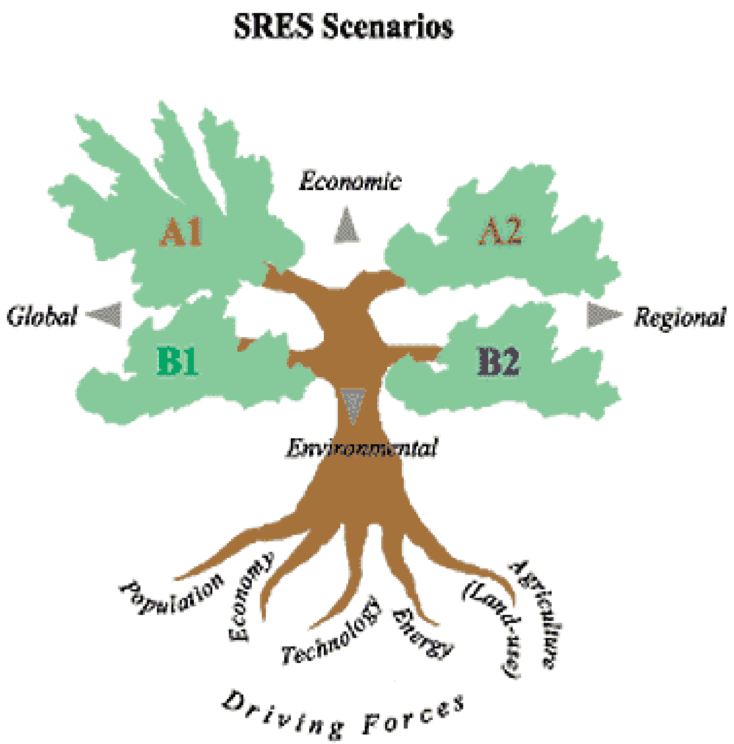
Starting point is a story. The world economy evolves in four very different directions, depending the level of coherence of global economic development and the level of priority given to environmental objectives. The end point is 2100.

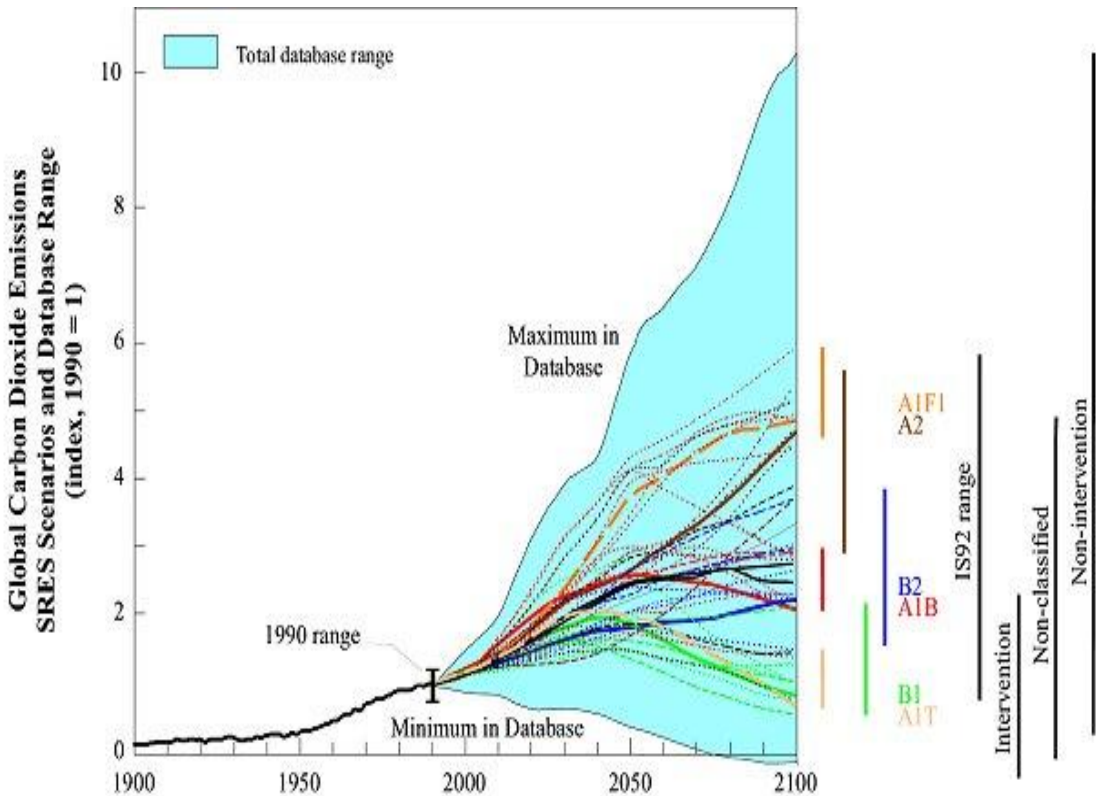
Business as Usual (BAU) is assumed in all cases, which means that climate change is not a driver of change. ("Stabilization scenarios" paired with the BAU scenarios have also been created.) Four story lines, plus alternative versions of each story (in all, 40 SRES scenarios). For the past decade, the SRES scenarios have served as inputs to climate modeling.

RCP: Representative Concentration Pathways, IPCC 2010

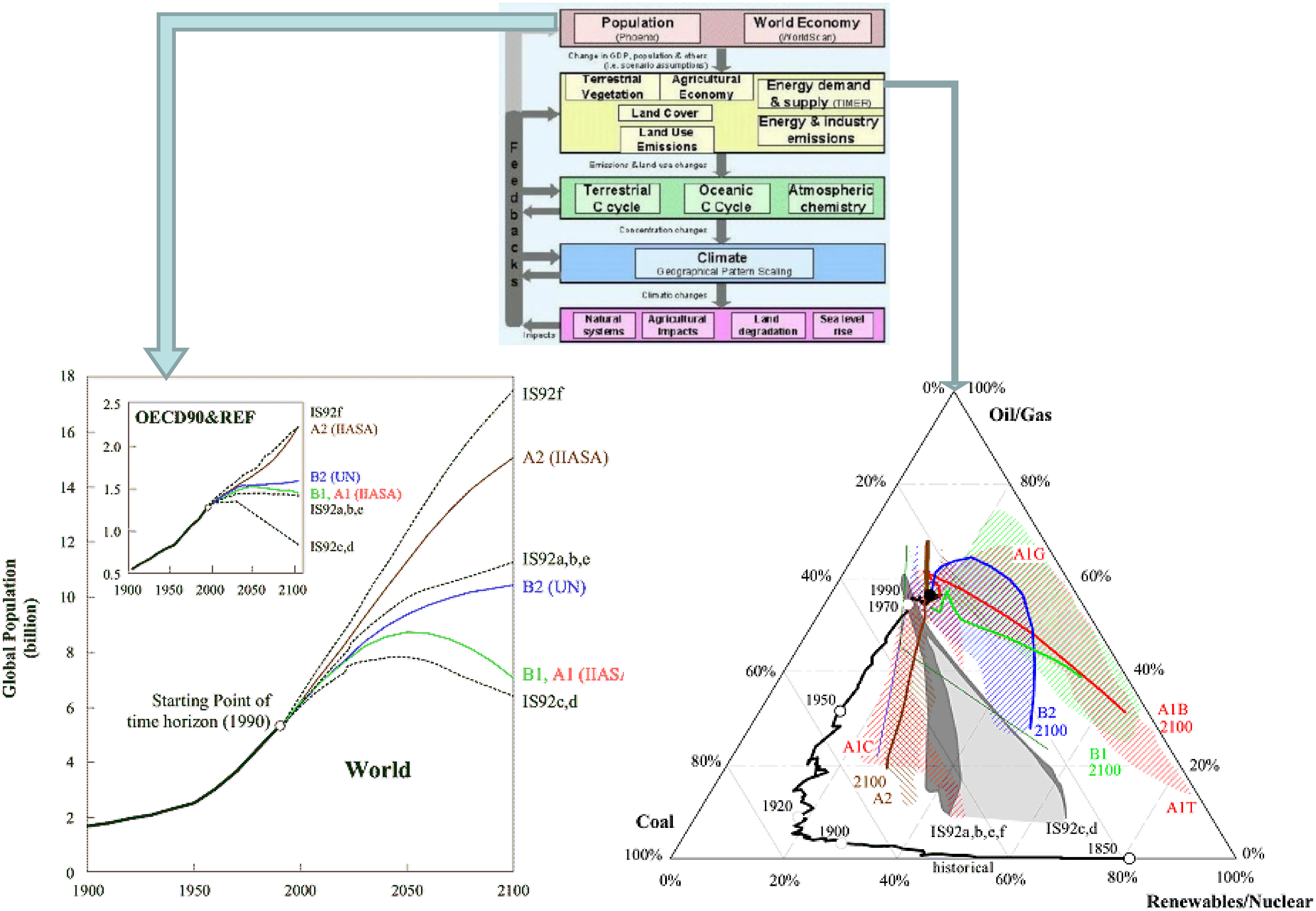
Starting point is a detailed emissions scenario: greenhouse gases, aerosols, land use. The end point is 2100, but there are extensions to 2300. SRES is dethroned. Goodbye to story lines, goodbye to Business as Usual. Just the facts, ma'am (the emissions). For now, just four RCPs.

SRES Scenarios: Four story lines



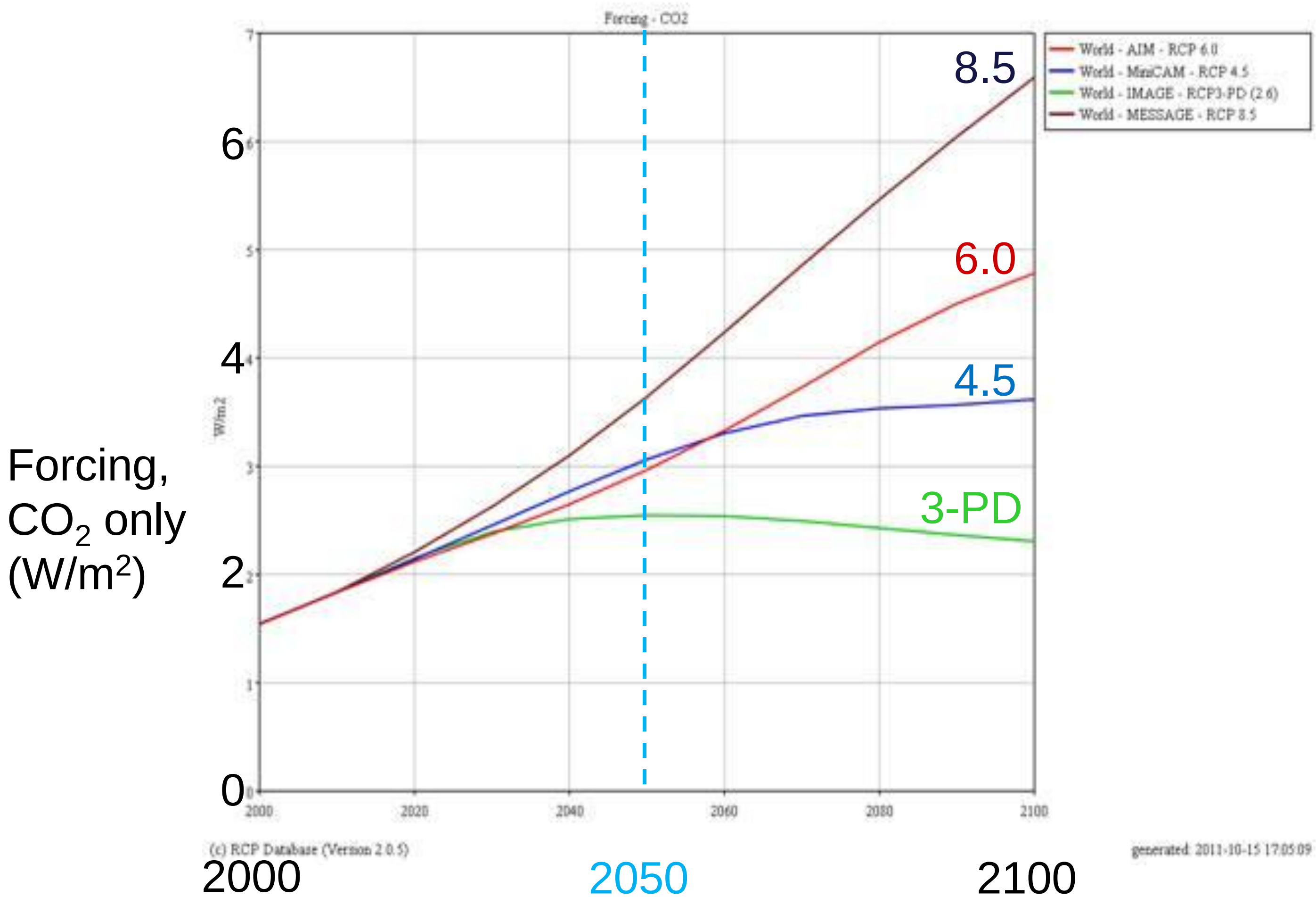


SRES: *Special Report on Emissions Scenarios*, IPCC. 2000



SRES: *Special Report on Emissions Scenarios*, IPCC. 2000

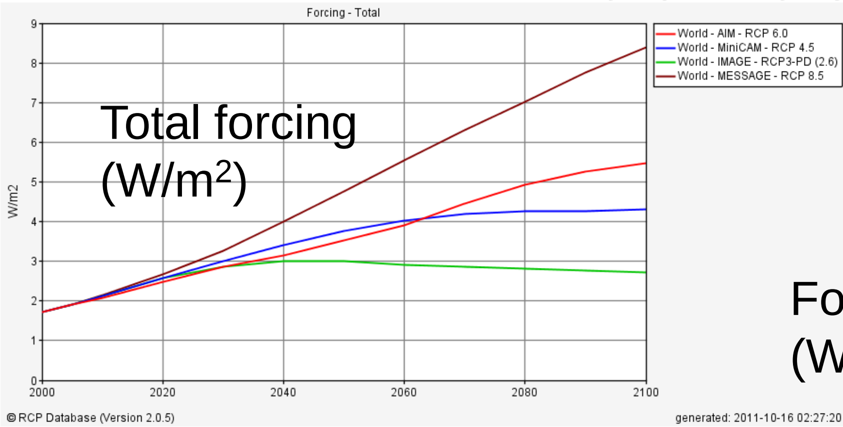
Representative Concentration Pathways



Data: http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about
Introduction: http://www.springerlink.com/content/f296645337804p75/fulltext.pdf

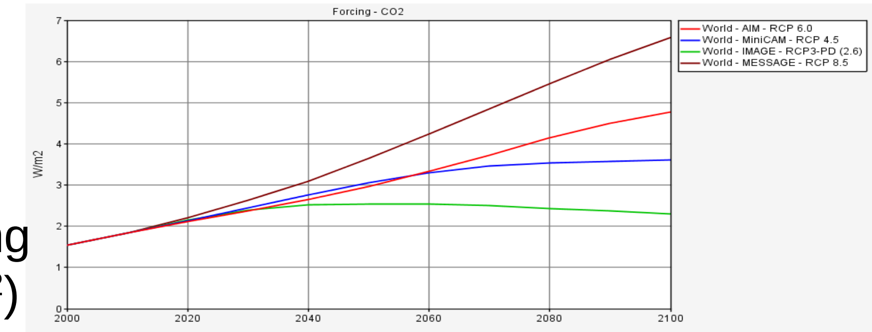
RCPs: Forcings and CO_2 concentrations

Total forcing (W/m^2)

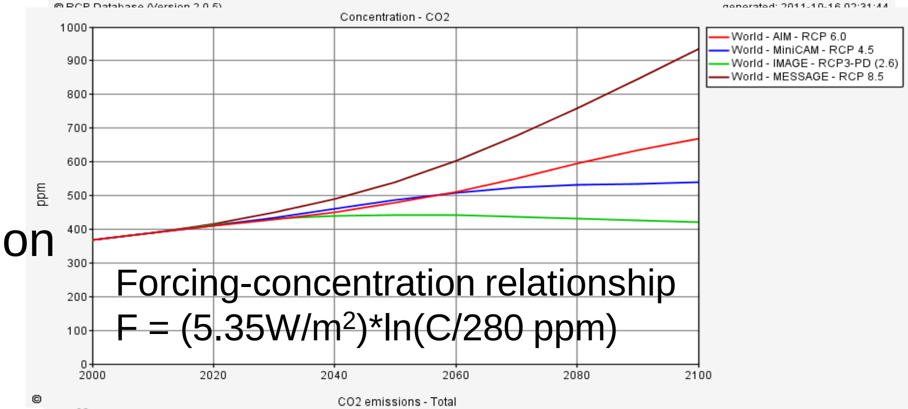


CO_2 only

Forcing (W/m^2)



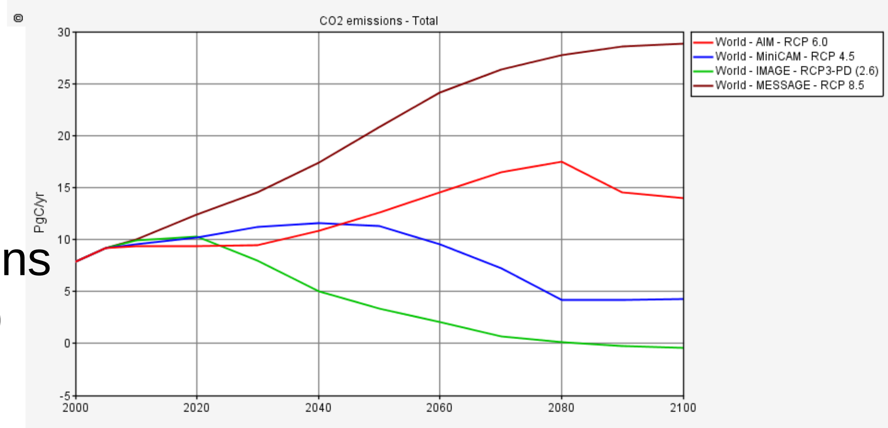
Concentration (ppm)



Forcing-concentration relationship

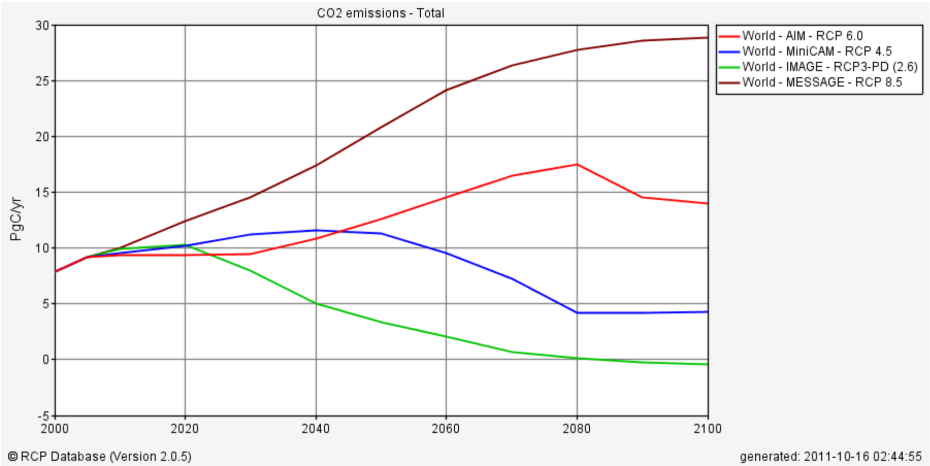
$F = (5.35 W/m^2)*\ln(C/280\ ppm)$

Emissions (GtC/yr)

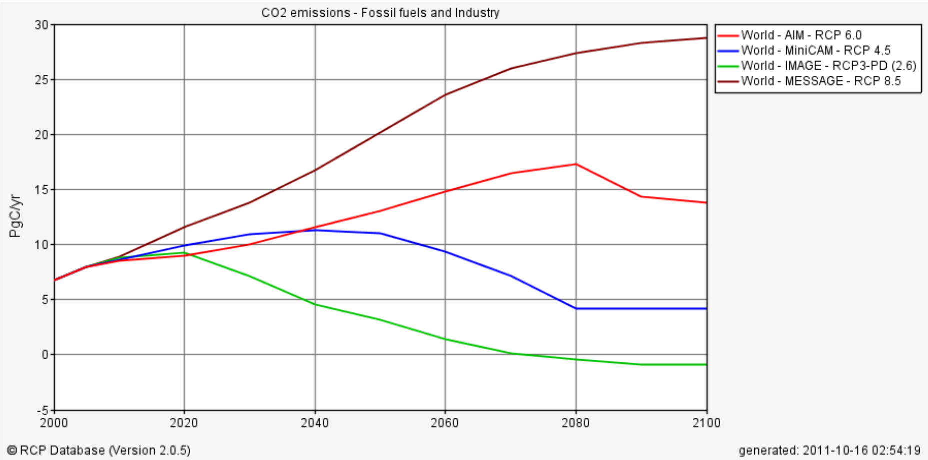


CO2 emissions in the RCPs

Total CO2 emissions (GtC/yr)

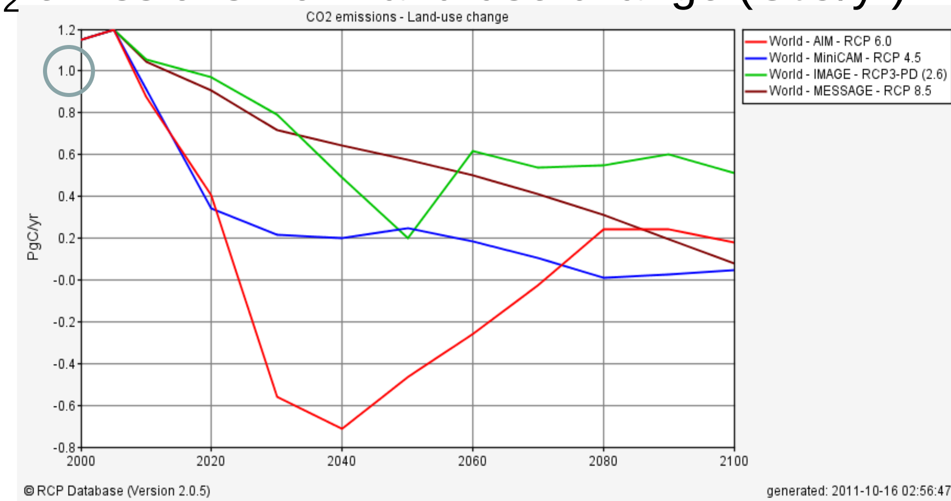


CO_2 emissions from fossil fuels and industry (GtC/yr)



“Total” = “Fossil fuel and industry” + “Land use change”

CO_2 emissions from land-use change (GtC/yr)



Representative Concentration Pathways

Pathway	RCP3.0 P-D	RCP4.5	RCP6.0	RCP8.5
Model	IMAGE	MiniCAM	AIM	MESSAGE
Group	Netherlands Environmental Assessment Agency (PBL)	Pacific Northwest National Laboratory (PNL, US): Joint Global Change Research Institute (JGCRI)	National Institute for Environmental Studies (NIES, Japan)	International Institute for Applied Systems Analysis (IAASA, Austria)
Forcing trajectory (W/m^2)	"P-D" is peak-decline. Peaks midcentury at 3.1, down to 2.6 in 2100	Stabilizes before 2100	Stabilizes after 2100	Continuous increase

Five Regions: OECD-90, Reforming Economies (REF), ASIA, Middle East and Africa (MAF), Latin America (LAM).

Note: OECD-90 is the 1990 membership, which includes Turkey and the Pacific island states. Joining OECD 1994-2000: Poland, Hungary, Czech Republic, Slovakia, Mexico, Republic of Korea; Joining OECD 2010: Chile, Slovenia, Israel, Estonia.

Create the RCPs first

With RCPs in hand*:

> "Climate modelers will use the …four RCPs in order to conduct new climate model experiments."
>
> "IAMs [Integrated Assessment Models] will explore a range of different technological, socio-economic and policy futures that could lead to a particular concentration pathway."

**See* http://www.springerlink.com/content/f296645337804p75/fulltext.pdf.

IAMs → RCPs → Climate model inputs

Durban (1 of 3)

U.N. Climate Talks End With Deal for New Emissions Treaty
By JOHN M. BRODER. Published: December 11, 2011

DURBAN, South Africa — Two weeks of contentious United Nations talks over climate change concluded Sunday morning with an agreement by more than 190 nations to work toward a future treaty that would require all countries to reduce emissions that contribute to global warming.

The result, coming as the sun rose after nearly 72 hours of continuous wrangling, marked a tentative but important step toward the dismantling of a 20-year-old system that requires advanced industrialized nations to cut emissions while allowing developing countries — including the economic powerhouses China, India and Brazil — to escape binding commitments.

The deal on a future treaty was the most contested element of a package of agreements that emerged from the extended talks here. The delegates also agreed on the creation of a fund to help poor countries adapt to climate change, and to measures involving the preservation of tropical forests and the development of clean-energy technology.

Durban (2 of 3)

The European Union had pushed hard for what it called a “road map” to a new, legally binding treaty against fierce resistance from China and India, whose delegates argued passionately against it. They said that mandatory cuts would slow their growth and condemn millions to poverty.

“Am I to write a blank check and sign away the livelihoods and sustainability of 1.2 billion Indians, without even knowing what the E.U. ‘road map’ contains?” asked India’s environment minister, Jayanthi Natarajan. “Please do not hold us hostage.”

The deal renews the Kyoto Protocol, the fraying 1997 emissions agreement that sets different terms for advanced and developing countries, for several more years. But it also begins a process for replacing it with something that treats all nations equally. The expiration date of the protocol — 2017 or 2020 -- and the terms of any agreement that replaces it will be negotiated at future sessions of the governing body, the United Nations Framework Convention on Climate Change.

Durban (3 of 3)

The United States never signed the Kyoto treaty because it did not accept its division of labor between developed and developing countries. Todd D. Stern, the chief American climate negotiator, said he was hopeful that negotiations in coming years would produce a more equitable arrangement.

The conclusion of the meeting was marked by exhaustion and explosions of temper, and the result was muddled and unsatisfying to many. Observers and delegates said that the actions taken at the meeting, while sufficient to keep the negotiating process alive, would not have a significant impact on climate change.

“While governments avoided disaster in Durban, they by no means responded adequately to the mounting threat of climate change,” said Alden Meyer, director of policy at the Union of Concerned Scientists. “The decisions adopted here fall well short of what is needed.”

David Kanter's 2012 cameo on non-CO_2 greenhouse gases

Readings for David Kanter's 2012 cameo on non-CO2 greenhouse gases

Montzka et al. (2011) "Non-CO_2 Greenhouse Gases and Climate Change", *Nature*

Kanter et al. (2012) "A post-Kyoto partner: Considering the Montreal Protocol as a tool to manage nitrous oxide" (please do not circulate)

UNEP (2011) "Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers"

Molina et al. (2009) "Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions", *PNAS*

David Kanter
Week 3

Geeta Persad
Week 2

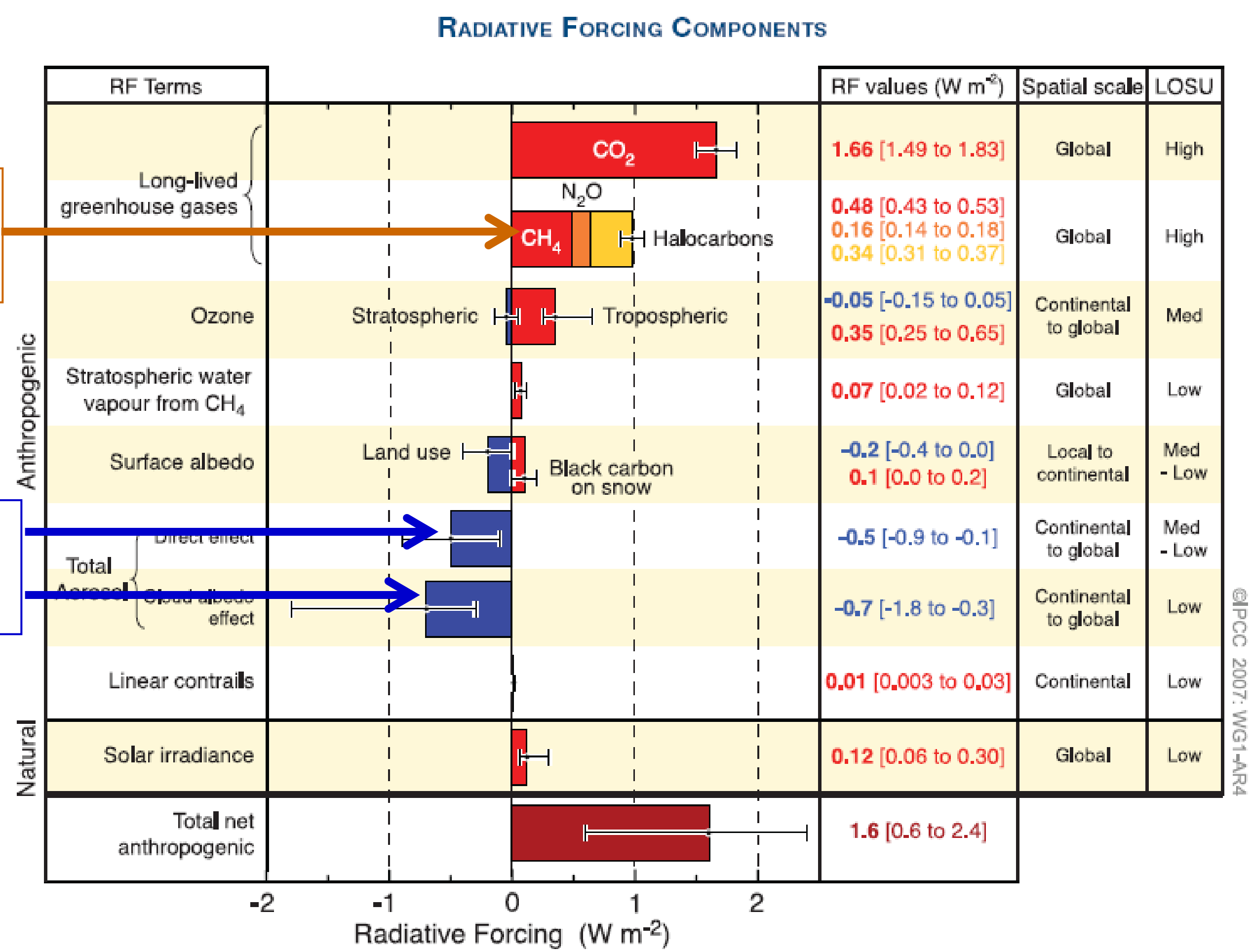
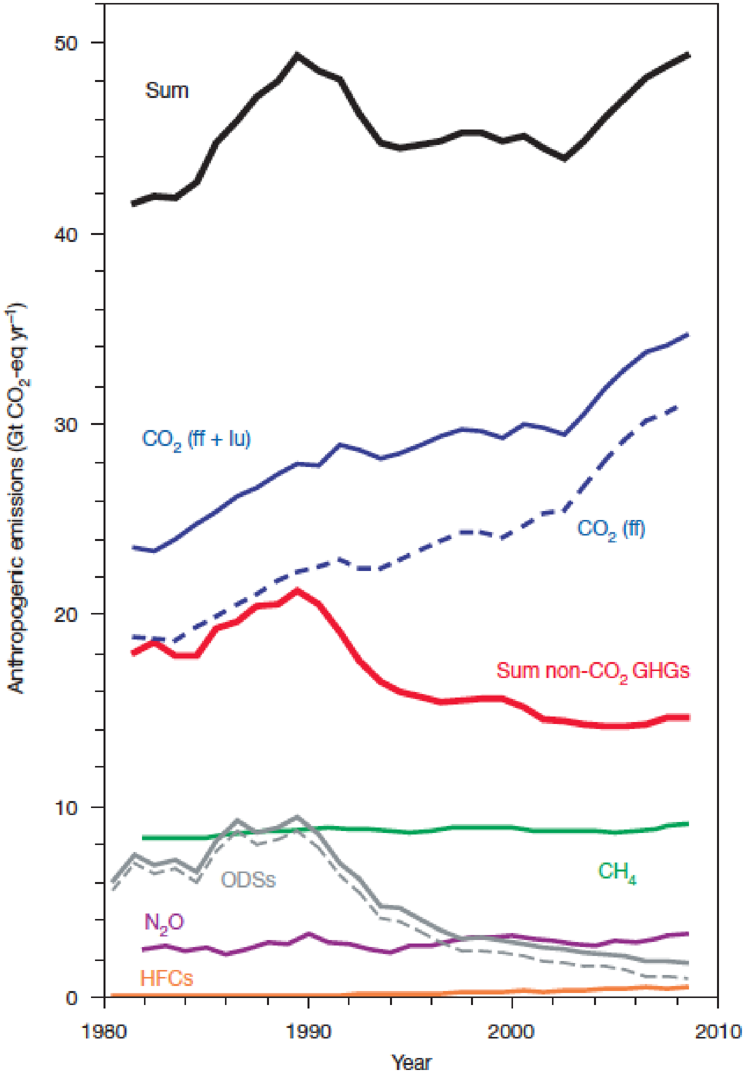


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

IPCC (2007) Summary for Policy Makers

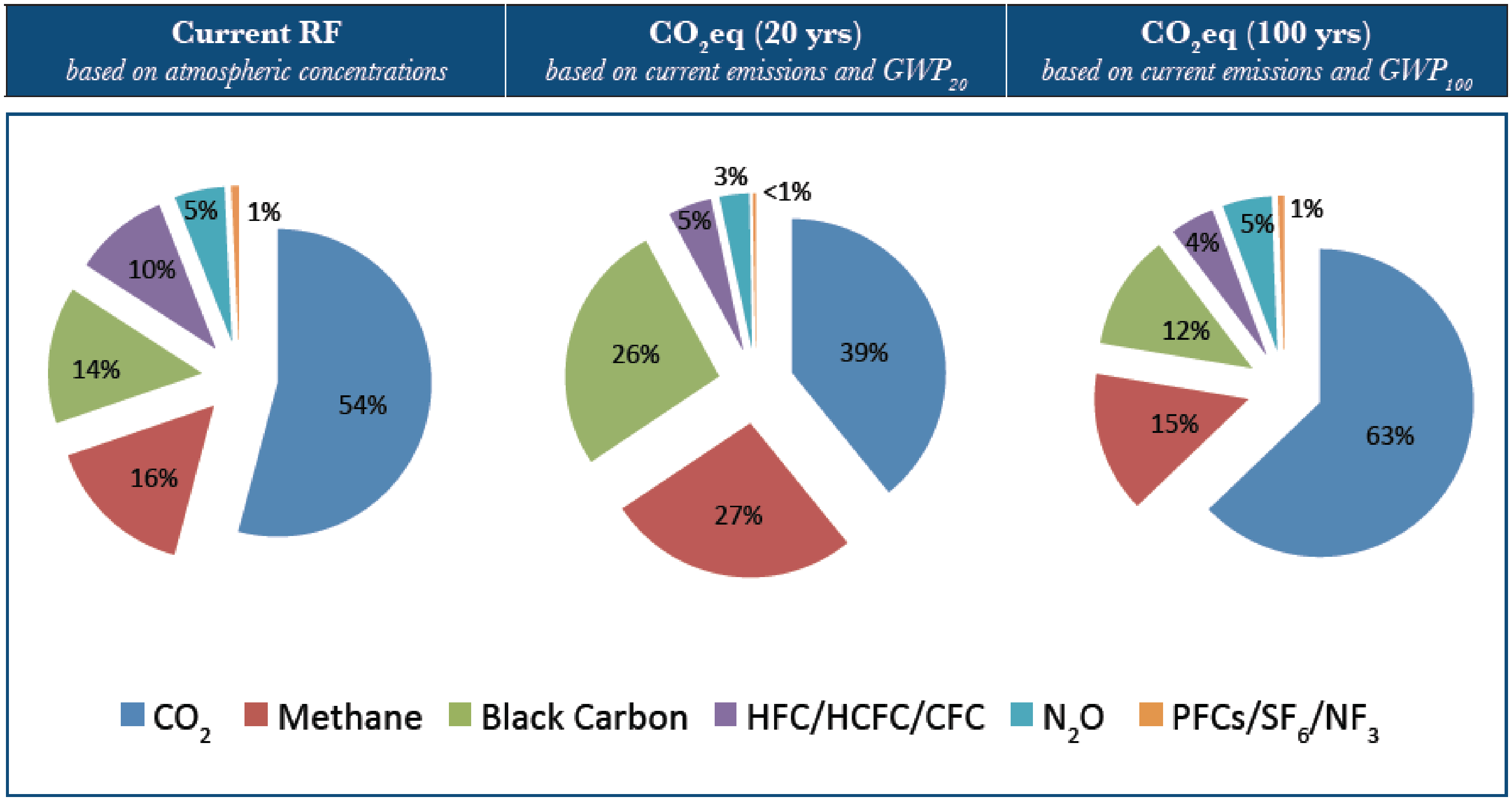
What are non-CO_2 climate forcers and how much do they contribute to climate change?



Montzka et al. 2011, *Science*

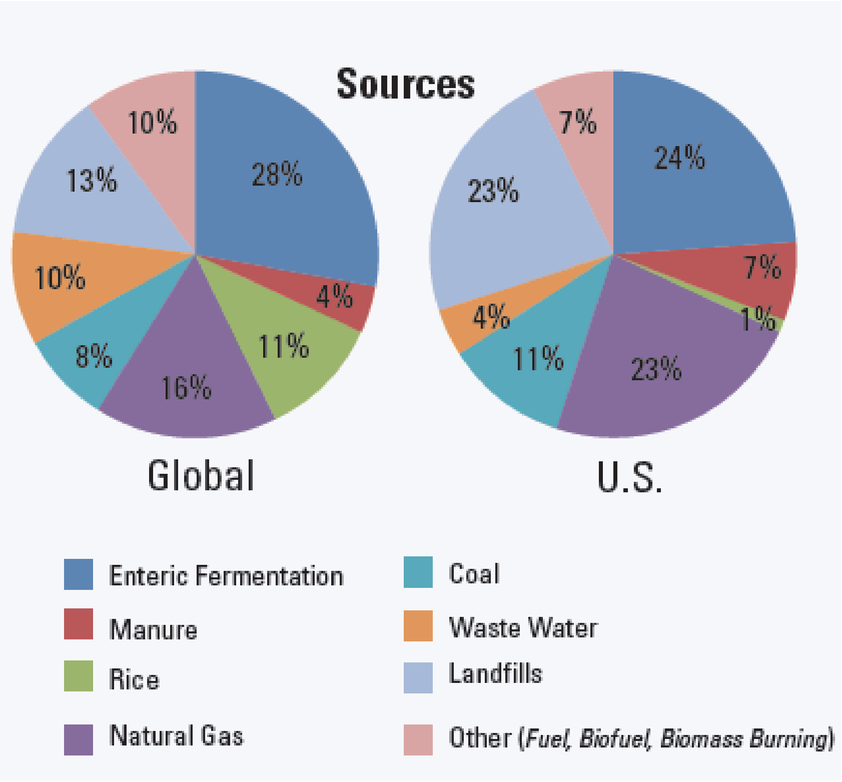
- CH_4, N_2O, HFCs, ODSs, SF_6, PFCs, NF_3, tropospheric O_3, black carbon…
- In 2008, non-CO_2 GHGs were responsible for 15 $GtCO_2e$ or 30% of all anthropogenic long-lived GHG emissions
- Climate impact often only one facet of their overall environmental impact

Timescale important



Princeton University (2011) “Complements to Carbon”

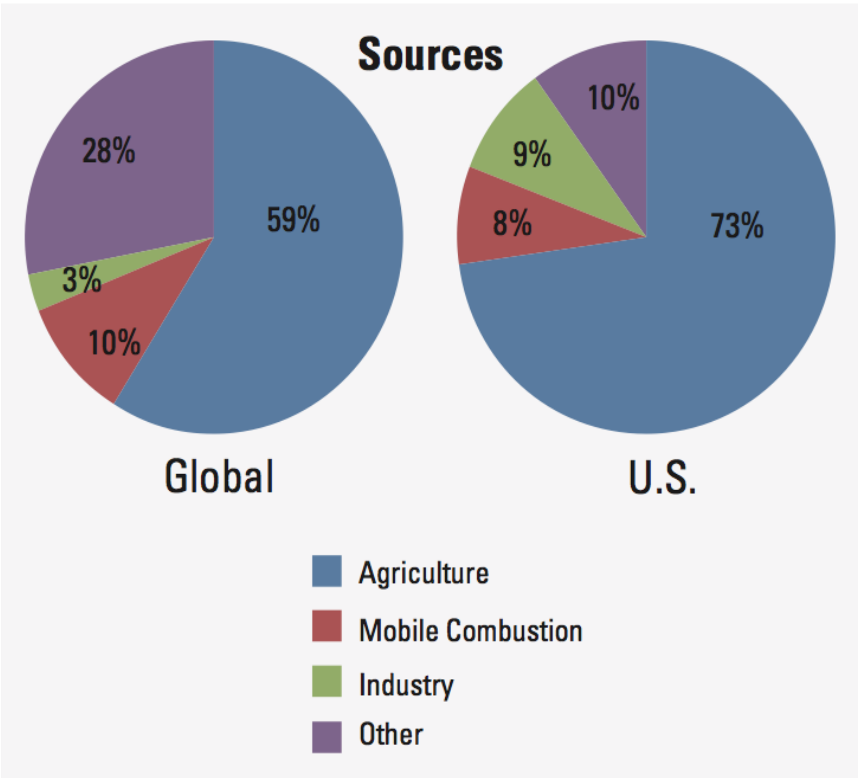
Methane (CH_4)



Princeton University (2011) "Complements to Carbon"

- Responsible for ~20% of our climate impact (excluding BC)
- Sources: 1/3 natural, 2/3 anthropogenic. Anthropogenic emissions have increased 250% since 1750.
- Life time ~ 9 years; GWP_{100} = 25
- Precursor to certain air pollutants e.g. tropospheric ozone. Reductions would have environmental side-benefits
- Mitigation opportunities include improved livestock & waste management, more efficient natural gas extraction

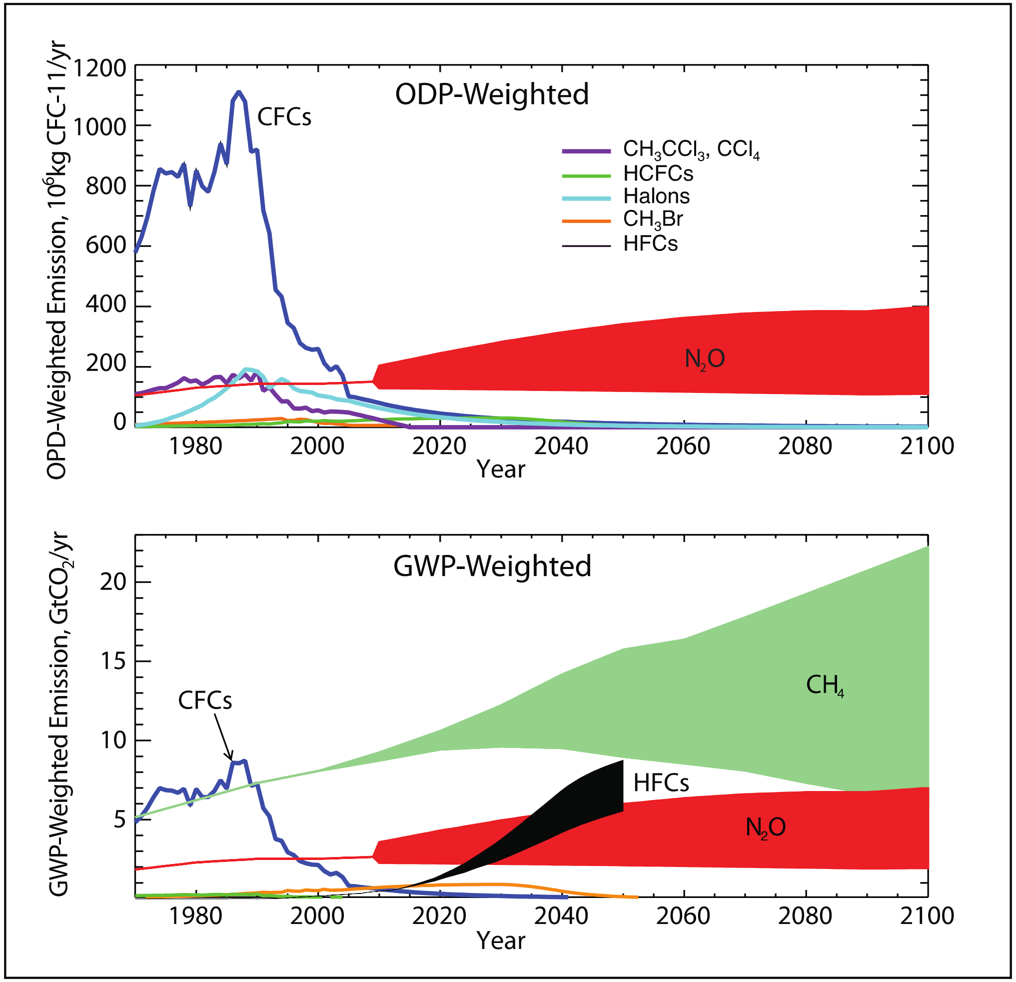
Nitrous oxide (N_2O)



Princeton University (2011) “Complements to Carbon”

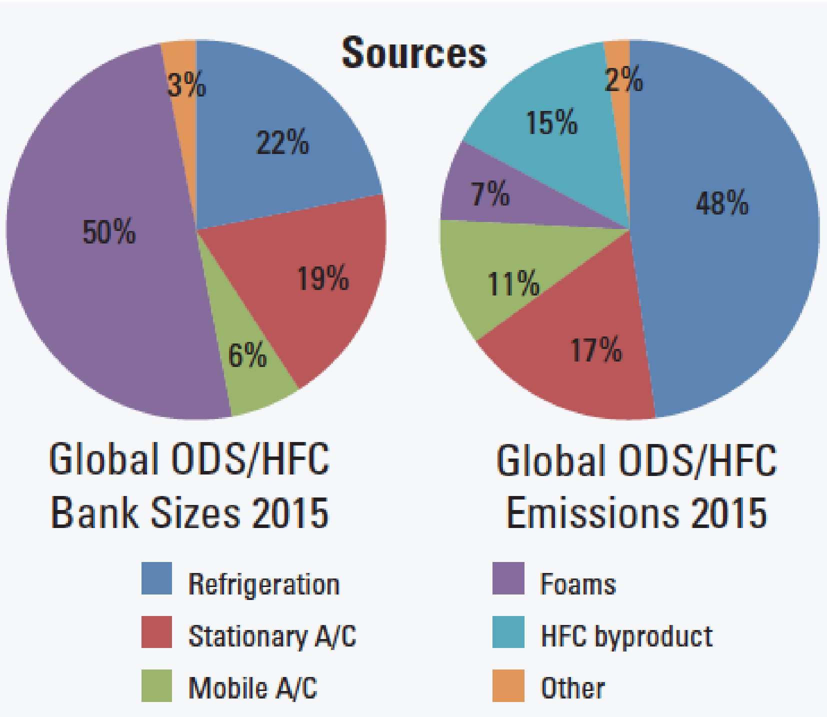
- Responsible for ~ 7% of our climate impact (excluding BC)
- Sources – ½ natural, ½ antropogenic. Anthropogenic emissions have increased 40%-50% since 1860.
- Lifetime: 114 years; GWP_{100}: 298 (*IPCC* 2007)
- Recently identified as largest remaining anthropogenic threat to the stratospheric ozone layer. Part of tightly coupled nitrogen cycle or ‘cascade’ (*Galloway et al.* 2003).
- Mitigation opportunities include add-on technologies for industrial sectors, and improved behavioral practices and technologies for agriculture

N_2O - Threat to climate & ozone



Ravishankara et al. 2009

HFCs



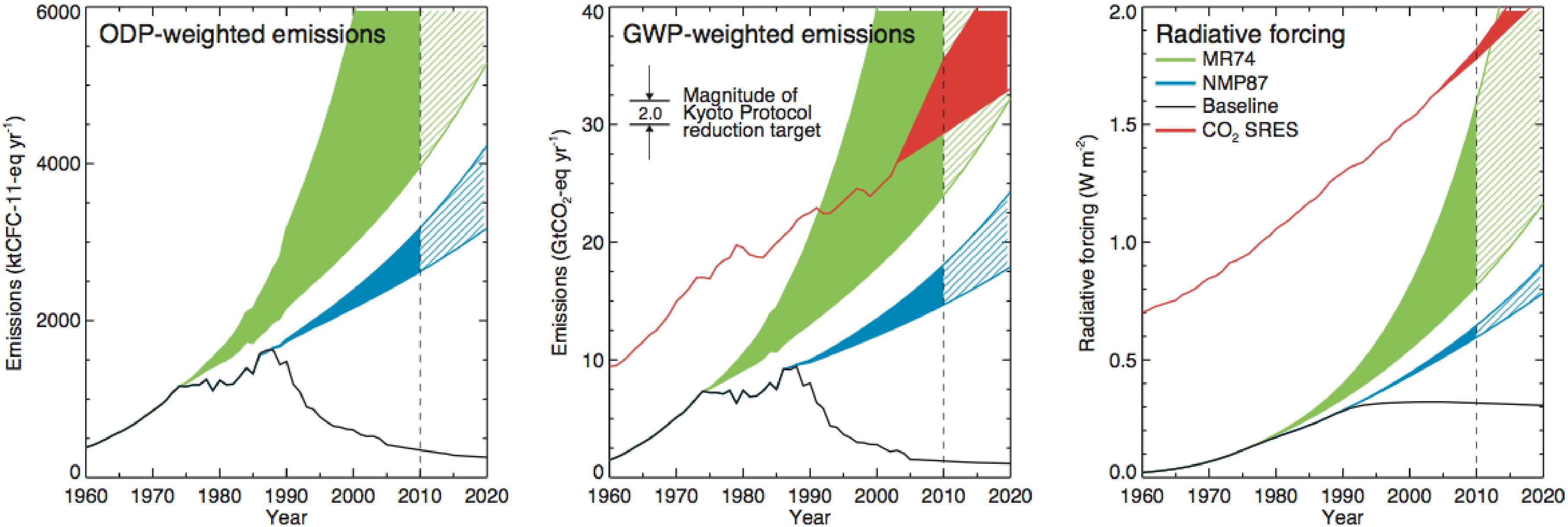
Princeton University (2011) "Complements to Carbon"

- Responsible for ~1% of our climate impact (excluding BC)
- Sources: 100% anthropogenic. Zero emissions pre-1990.
- Average lifetime: 21.7 years; Average GWP_{100}: 2362
- CO_2e emissions could increase to 19% of CO_2 emissions by 2050 if left unchecked (Velders et al. 2009)
- Mitigation technologies include more efficient appliance design (less leakage and load), and chemical alternatives (hydrocarbons, CO_2, ammonia, HFOs…)

Climate & Clean Air Coal

- A coalition of 17 countries with the EU and UNEP created in February, 2012 and spearheaded by US State Department, with a singular focus on short lived climate forcers: CH_4, black carbon, HFCs.
- Goal: raise awareness and improve scientific understanding of short-lived climate forcers, while implementing specific actions at national and regional level (e.g. reducing CH_4 from waste sector, promoting HFC alternative technologies etc.)
- Motive? Tackle low-hanging fruit with immediate pay-offs and environmental side-benefits, while avoiding UN negotiations and giving US a leadership role.

Montreal Protocol benefits for ozone & climate



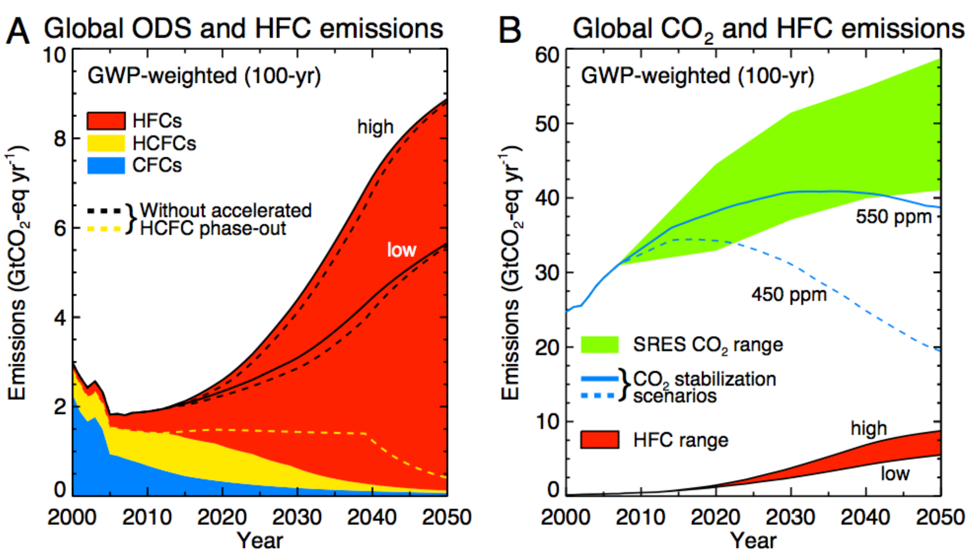
Velders et al. (2007), PNAS

The future

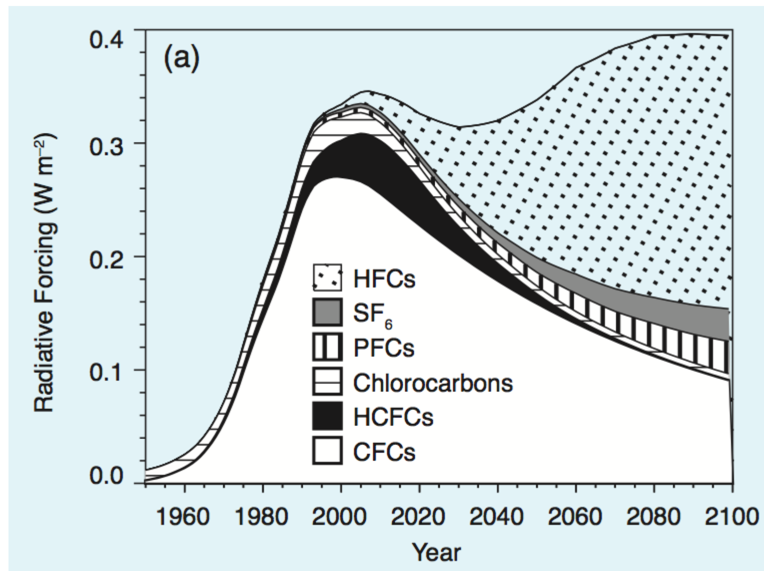
- Many lament: “If only Kyoto were more like Montreal”
- More interesting: what can the Montreal Protocol still do to help mitigate climate change and accelerate stratospheric ozone recovery?
  - Phase-down HFCs (second generation replacements to CFCs)
  - Manage N_2O (third most abundant GHG and largest remaining anthropogenic threat to stratospheric ozone layer)

Montreal Protocol & HFCs

- MP could become a net *contributor* to climate change if HFCs become the replacement of choice to HCFCs



Velders et al. (2009) *PNAS*



IPCC/TEAP (2005)

Montreal Protocol & N_2O

- Scientific case: N_2O is the largest remaining anthropogenic threat to the ozone layer
- Legal case: Montreal Protocol therefore has the authority to control it
- Technical case: Mitigation opportunities exist across all sectors, including agriculture
- Policy case: Montreal Protocol has well respected assessment panels, funding mechanism, has dealt with agricultural sector before (methyl bromide). N_2O contributes to global problems, needs global action
- Challenges: Food security, equity, nitrogen cascade