The Kyoto Protocol and the Science of CO_2 Stabilization

AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2015

Topics for today:

- **Fossil Fuel Sources (continued)**
- **Obama / Xi Accord**
- **Kyoto Protocol**
- **Carbon Sequestration (a few options)**

433 students who are not doing a paper / presentation:
Please have a look at Problem Set 6, which has been posted

Lecture 18

21 April 2015

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CO_2 is long lived: society must reduce emissions soon or we will be committed to dramatic, future increases!

Curve that levels off at ~560 ppm has emissions peaking ~2030
Less than 20 years from now !

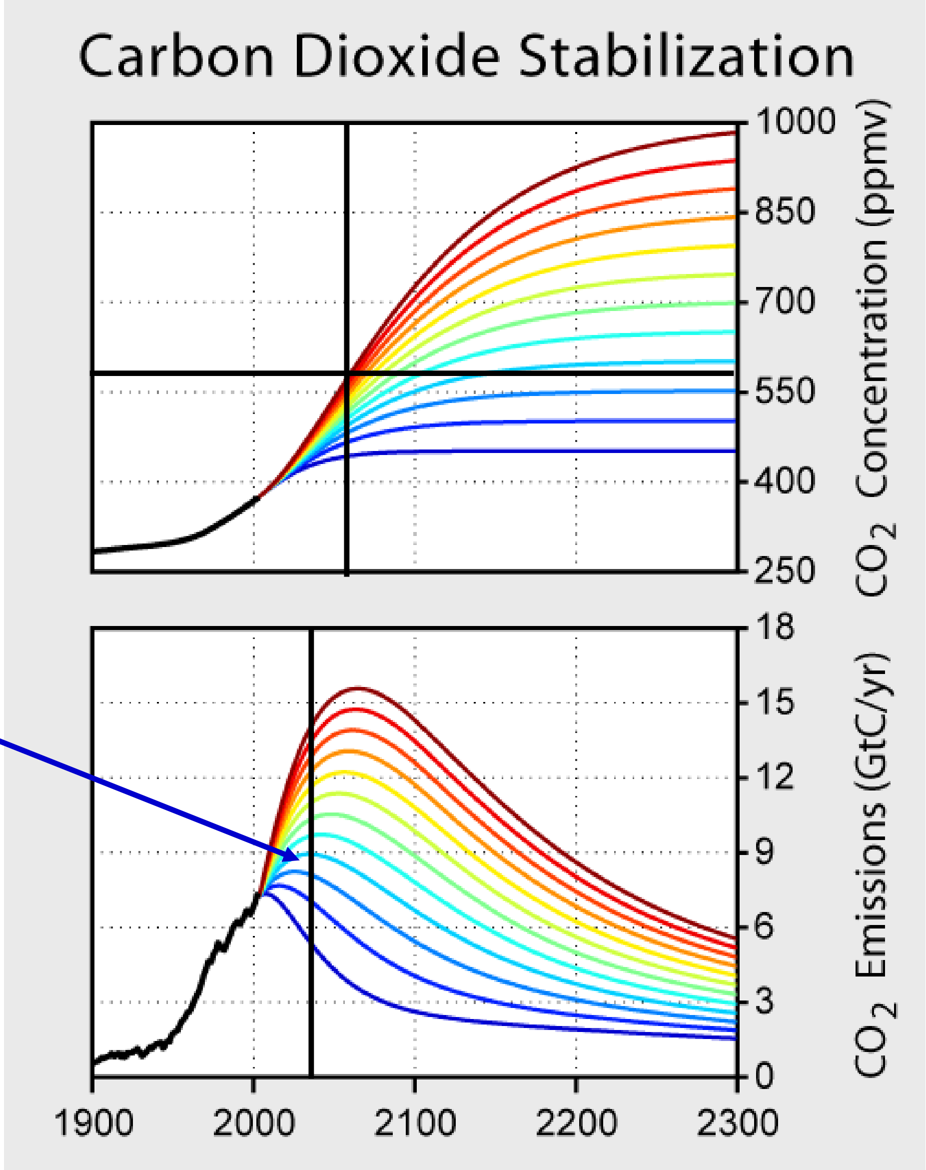

Image: "Global Warming Art" : http://www.globalwarmingart.com/wiki/Image:Carbon_Stabilization_Scenarios_png

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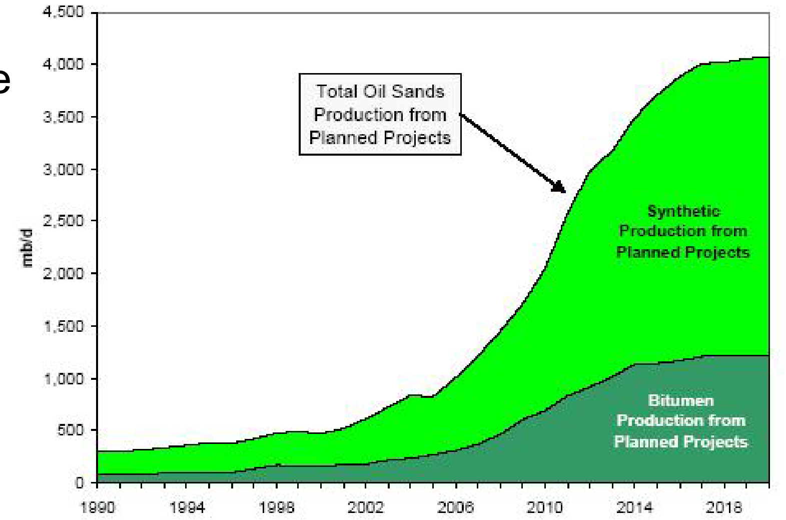
Canadian oil sands (tar sands)

- May represent 2/3 of world's total petroleum resource
- Not considered in many estimates of fossil fuel reserve
- Because of oil sands production, **Canada is largest supplier of oil to US**
- "Gold rush" like economic boom in Alberta Canada
- Fossil fuel extraction energy and water intensive: forests flattened and large waste water lakes created



RJ Research estimates and analysis

See http://en.wikipedia.org/wiki/Tar_sands and http://oilsands.alberta.ca/ for more info.

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Future Use of Fossil Fuels

• If society decides to continue to reply on fossil fuels, we will become increasingly reliant on (in the short term) and (in the long term)

Why is this a concern?

• Coal is a complex mixture of substances that can be approximated by the chemical formula $\mathbf{C_{135}H_{96}O_9NS}$. The elements come from prehistoric plant material.

• Coal may also contain, among other elements, copper, arsenic, lead, mercury, and uranium.

• Higher grades of coal, bituminous and anthracite, have been exposed to higher pressure and have less oxygen. Anthracite has less sulfur. **U.S. supply of anthracite is nearly exhausted.**

• The oxymoron “clean coal” means different things to different people

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Future Use of Fossil Fuels

- If society decides to continue to reply on fossil fuels, we will become increasingly reliant on **coal** (in the short term) and **oil sands** (in the long term)

Why else might reliance on coal and oil sands be a concern?

Fossil Fuel	GHG Output (pounds CO_2 per kWh)
Oil Sands	
Coal	
Oil	
Gas	

http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html
http://www.iop.org/EJ/abstract/1748-9326/4/1/014005

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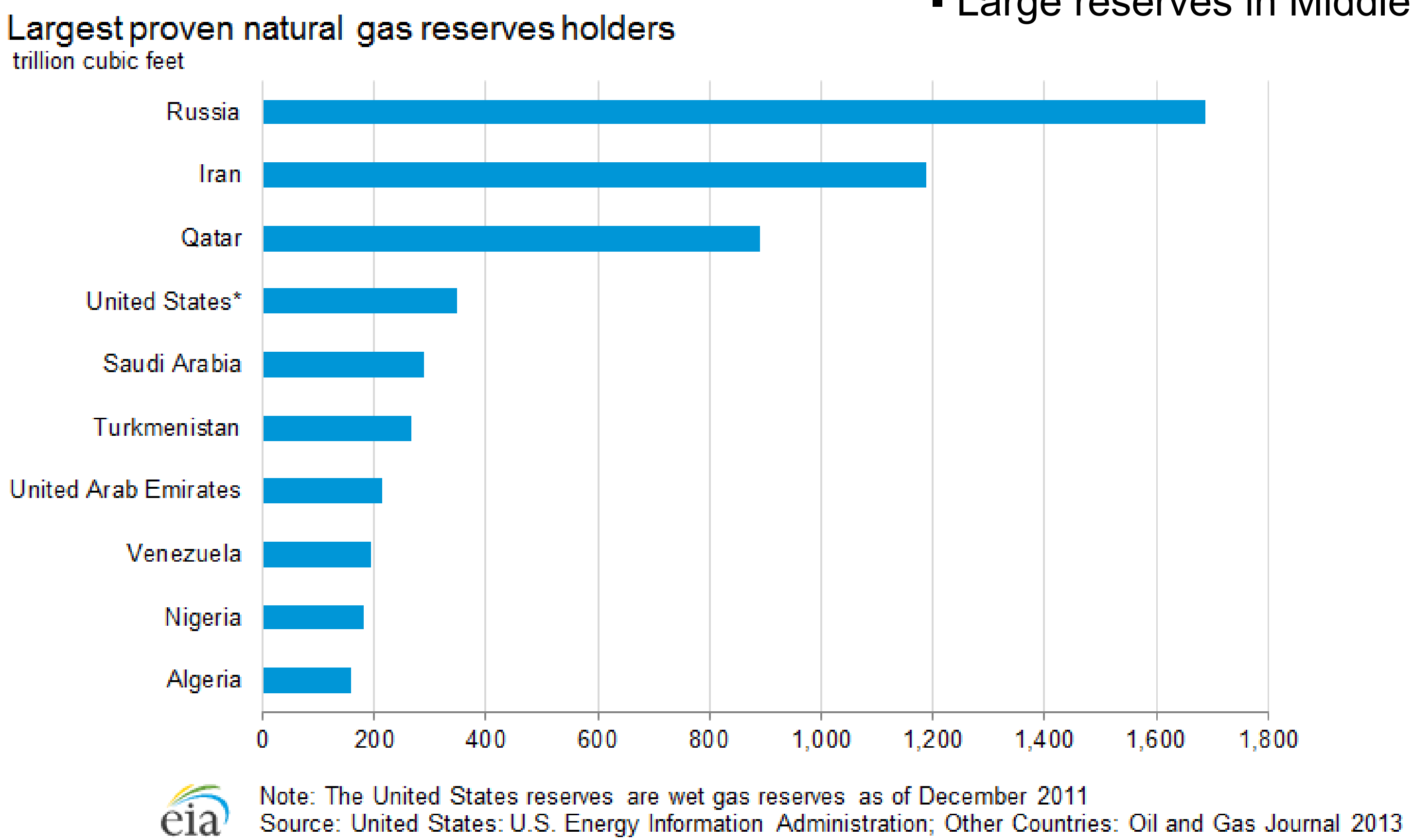
Natural Gas

- Large reserves in Middle East & Russia.



http://www.eia.gov/countries/cab.cfm?fips=rs

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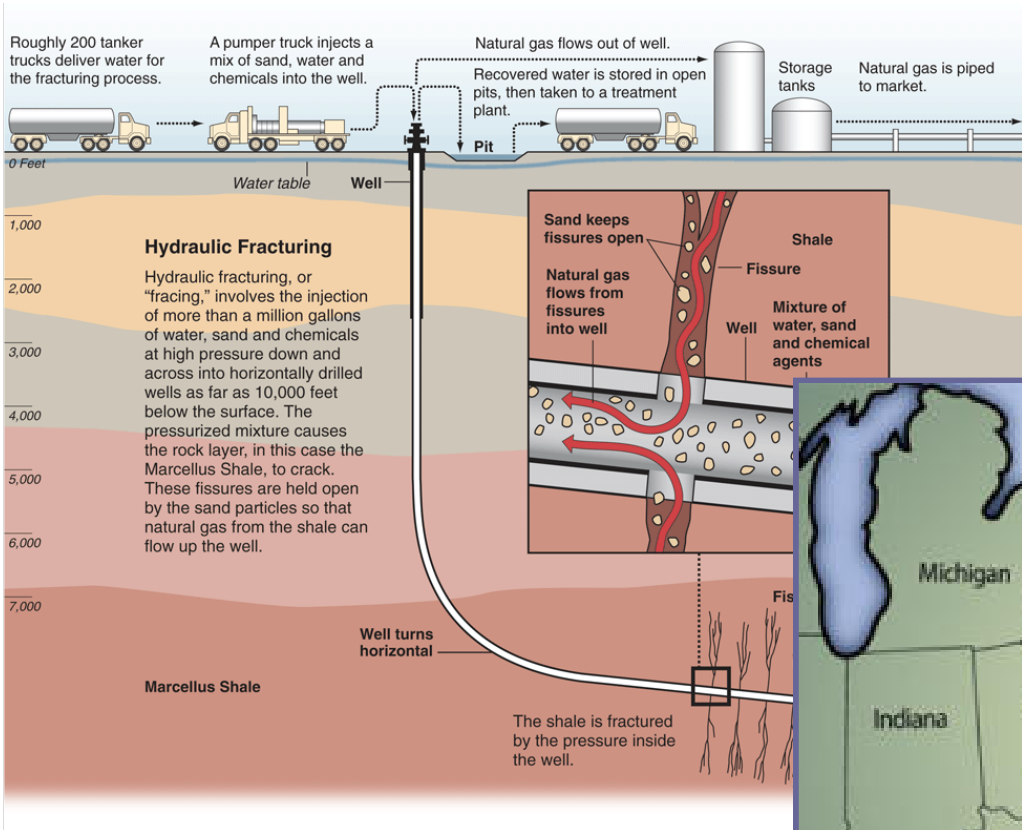
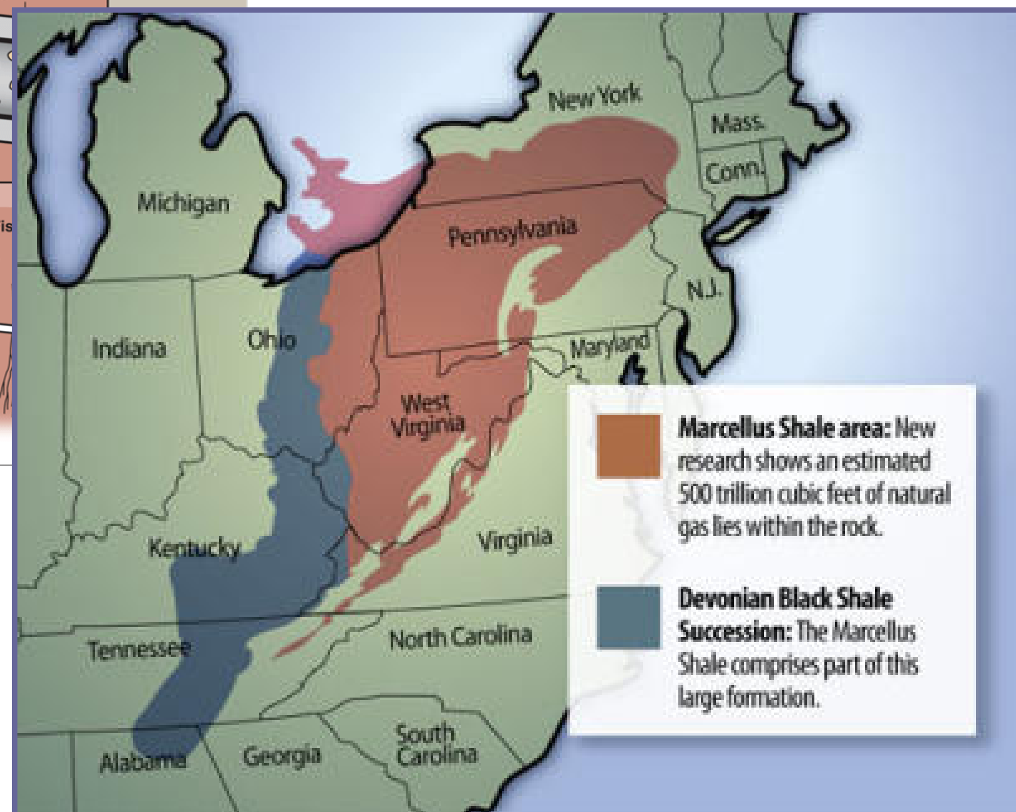
Natural Gas: Fracking



- Pumping of chemical brine to loosen deposits of natural gas from shale
- Marcellus Shale in Penn, NY and NJ is major source region



http://akrondave.files.wordpress.com/2011/01/marcellus-shale.jpg

We'll have a lecture devoted to fracking on Thurs, 30 April

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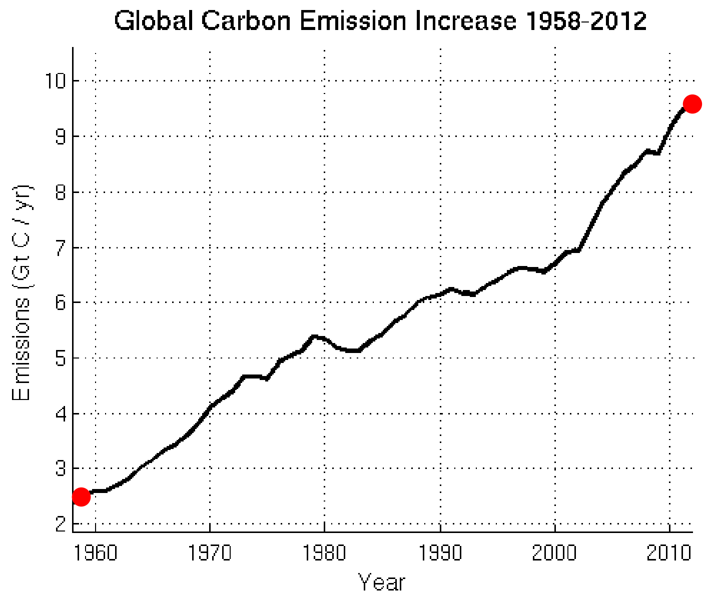
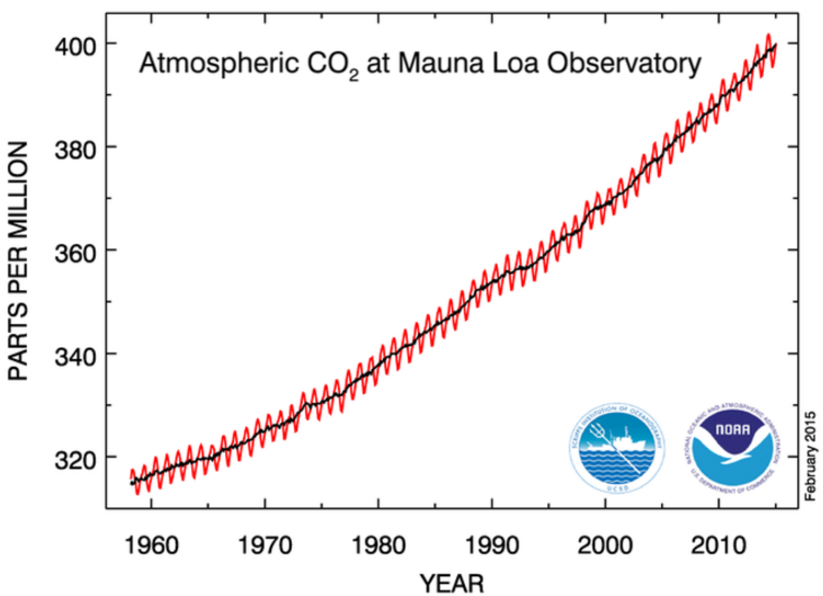
Fossil Fuel Emissions





Fossil fuel emissions, 1959 = **2.5** Gt C
2012 = **9.7** Gt C

What are the primary driving factors for this rise?

How can we quantify standard of living versus population growth contribution to this rise?

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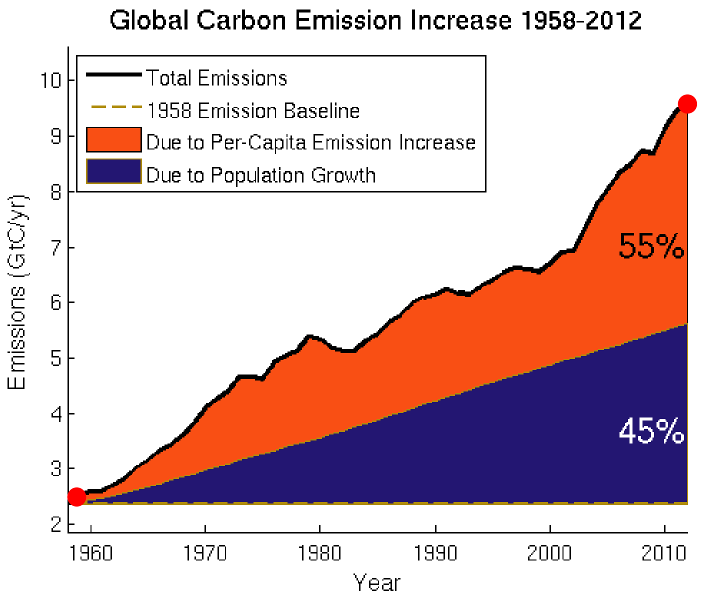
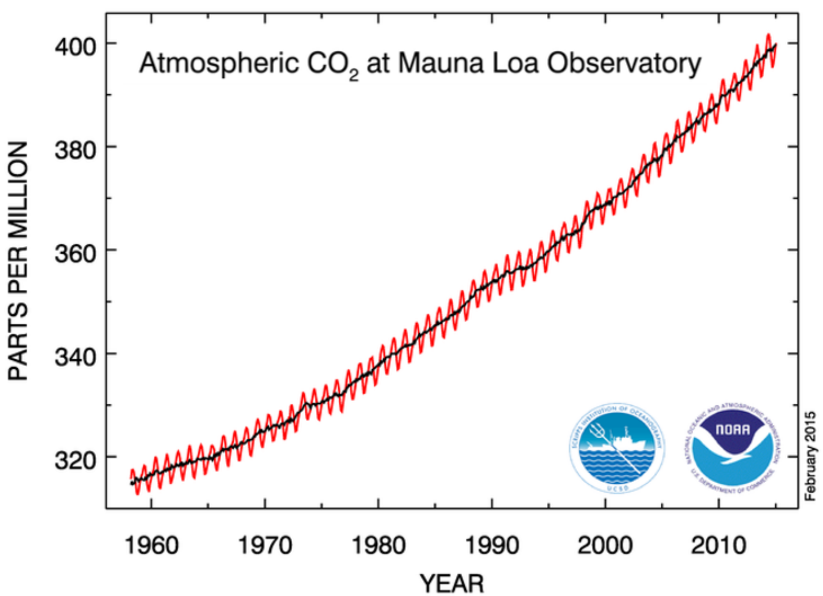
Fossil Fuel Emissions



Fossil fuel emissions, 1959 = **2.5** Gt C
2012 = **9.7** Gt C

Population increase & **per-capita rise** both contribute, with per-capita rise being somewhat more important



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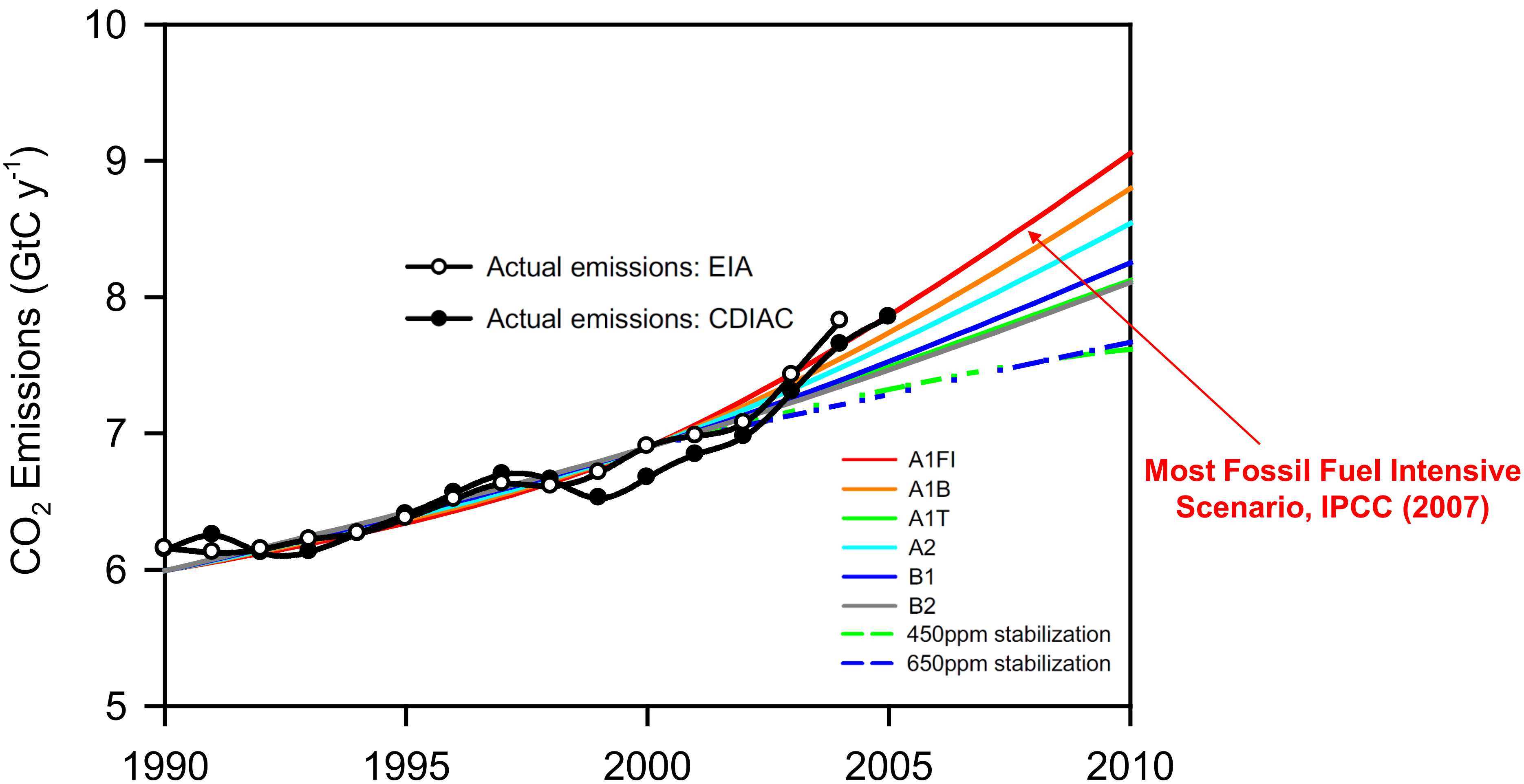
Global Fossil Fuel Emissions



Raupach *et al.*, *PNAS*, 2007

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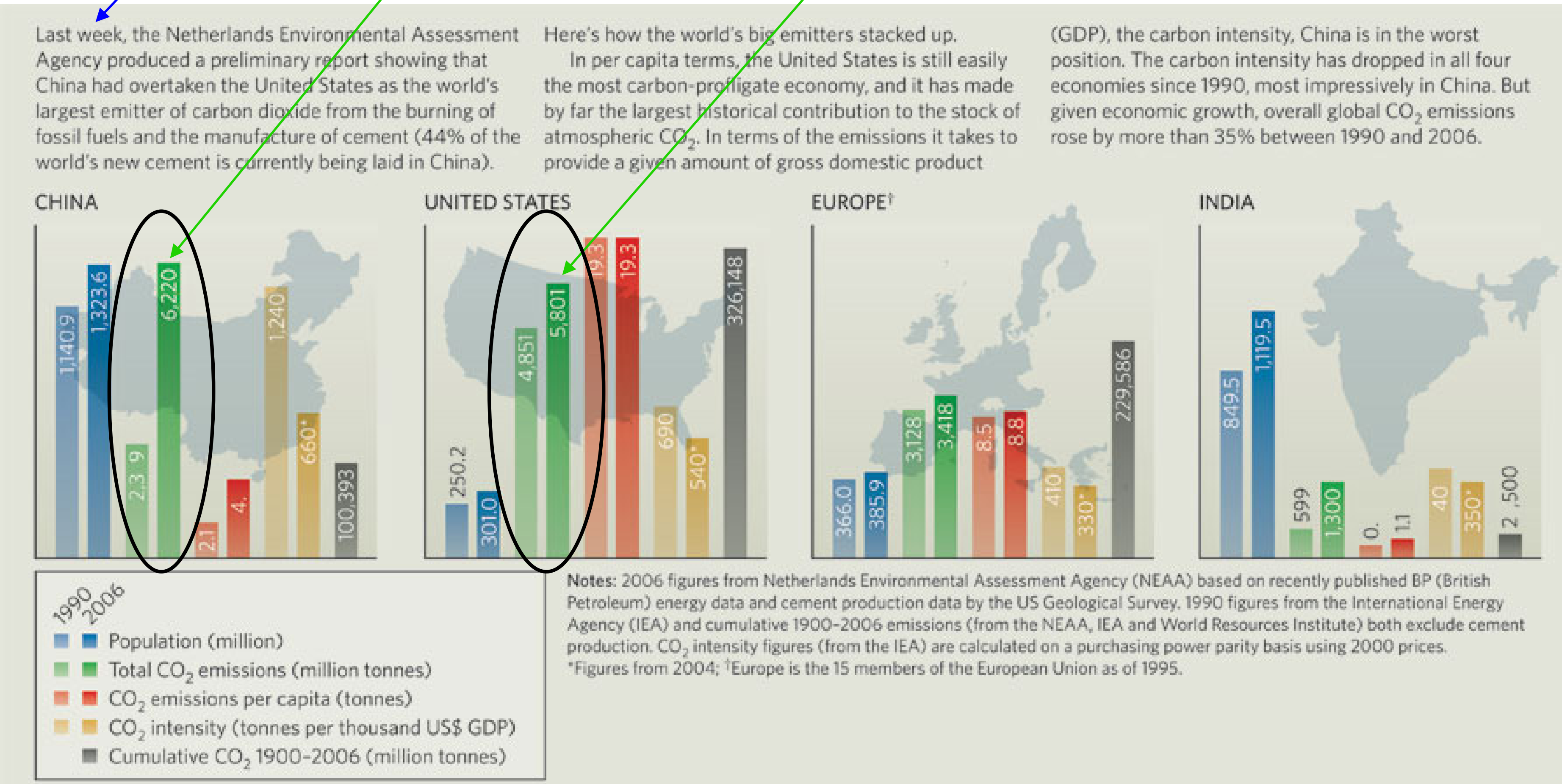
World Carbon Emissions

20 June 2007

China: 1.70 Gt C per year **US: 1.58 Gt C per year**



Source: http://www.nature.com/nature/journal/v447/n7148/fig_tab/4471038a_F1.html

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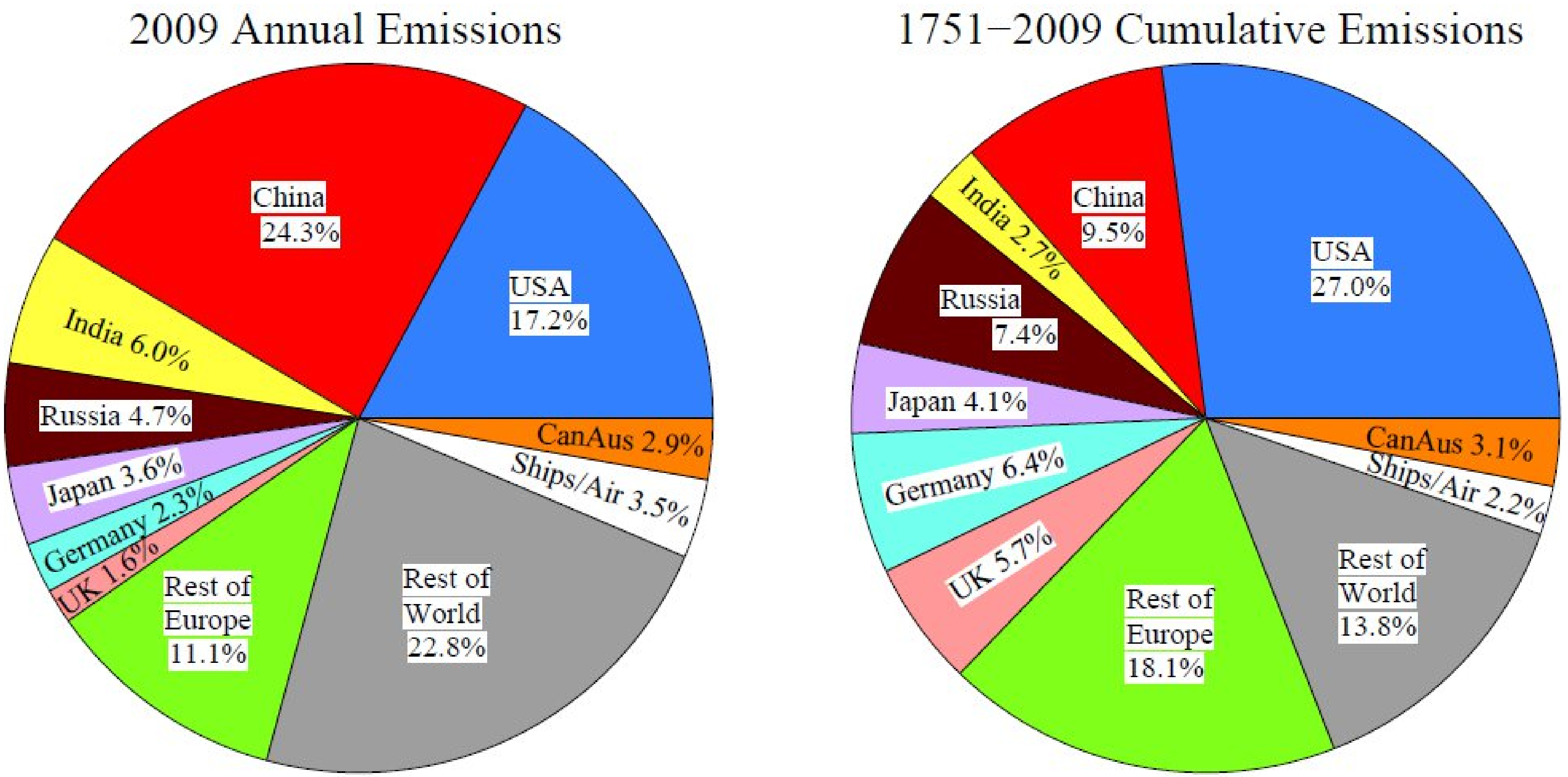
Carbon Emissions



http://transitionvoice.com/wp-content/uploads/2010/12/Hansen-12-6-10-figure-1.jpeg

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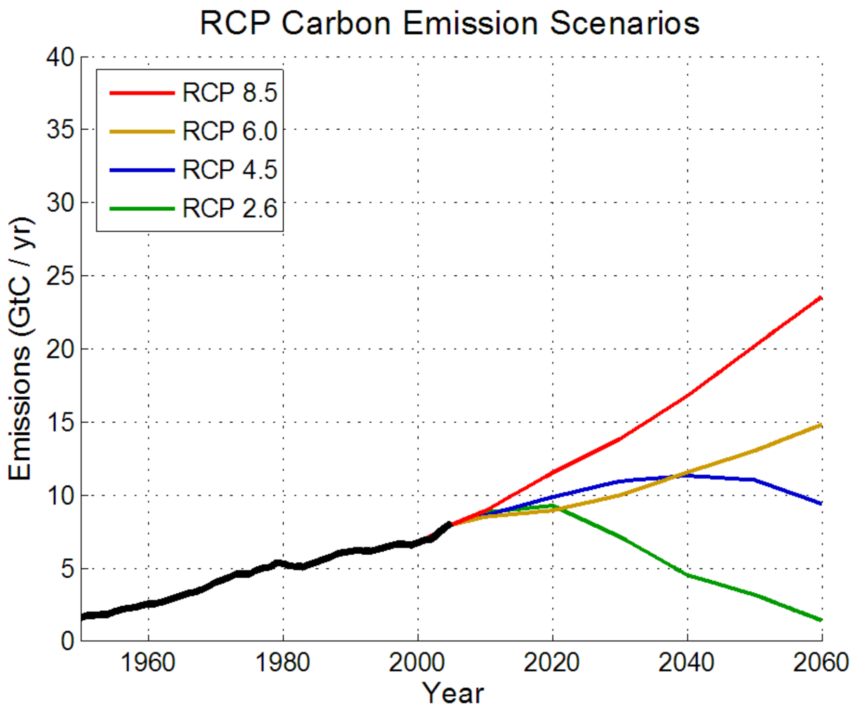

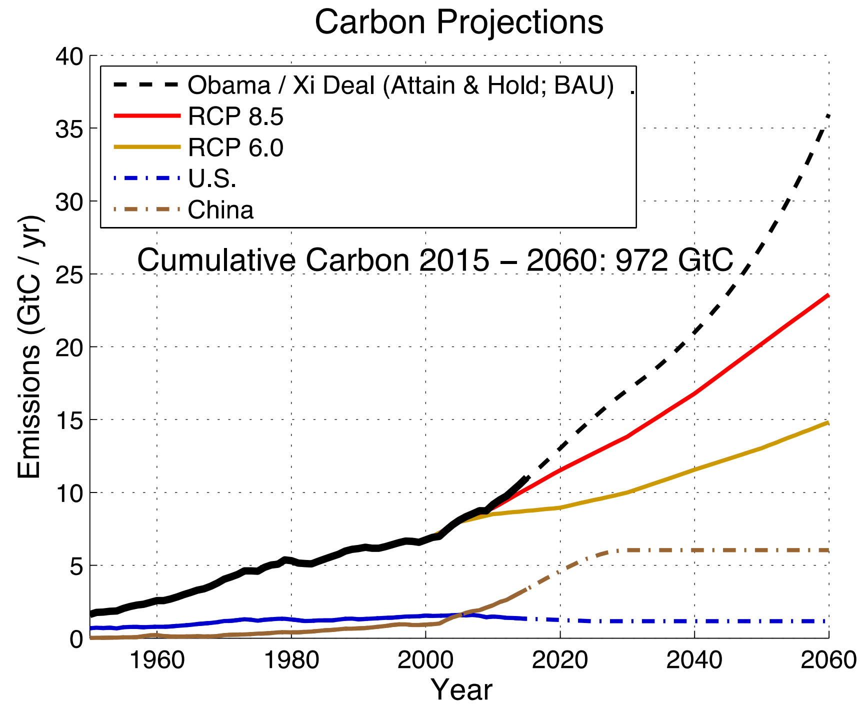

Tribett et al., in prep, 2015

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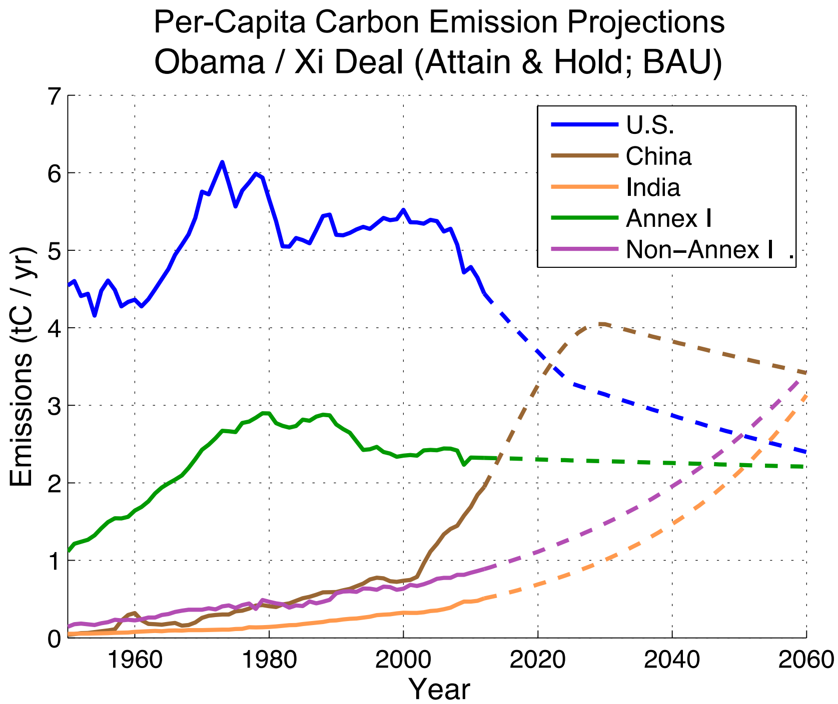

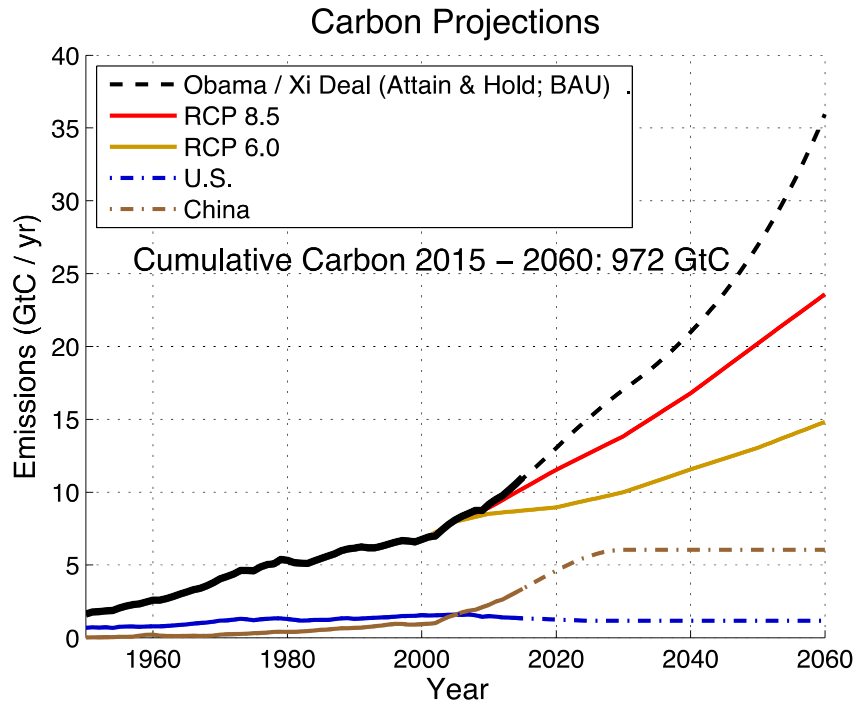

Tribett et al., in prep, 2015

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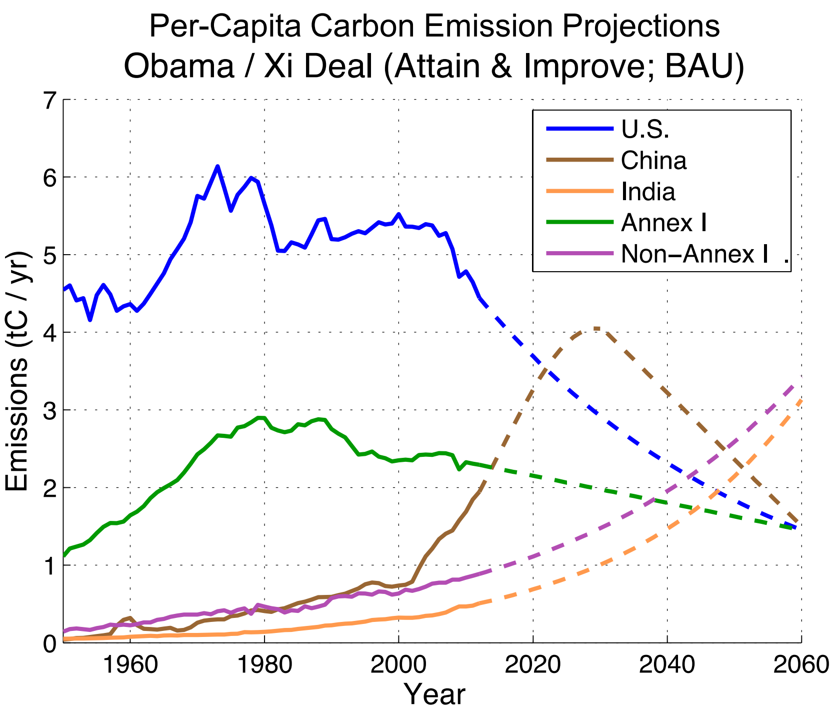

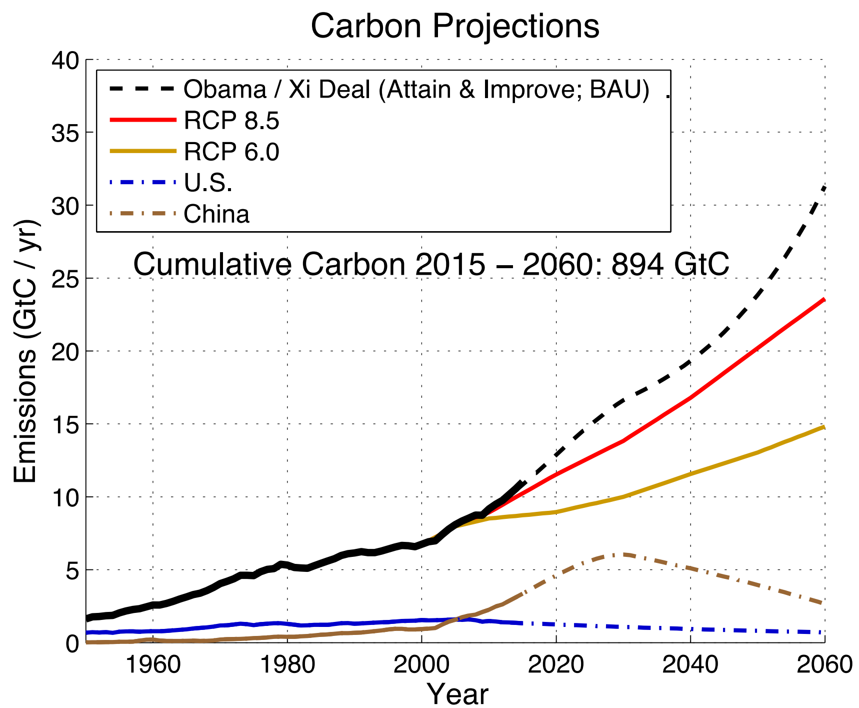

Tribett et al., in prep, 2015

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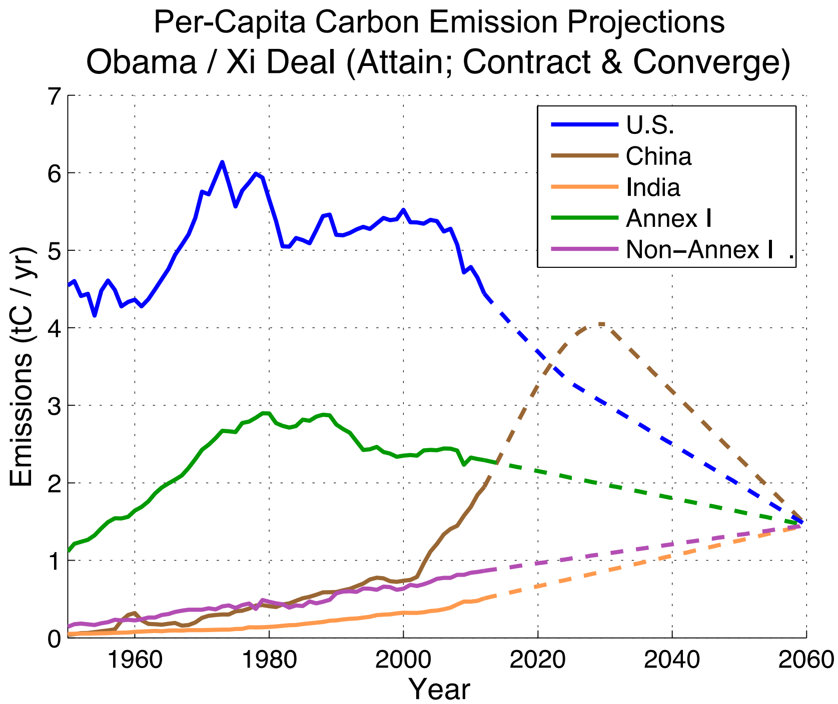

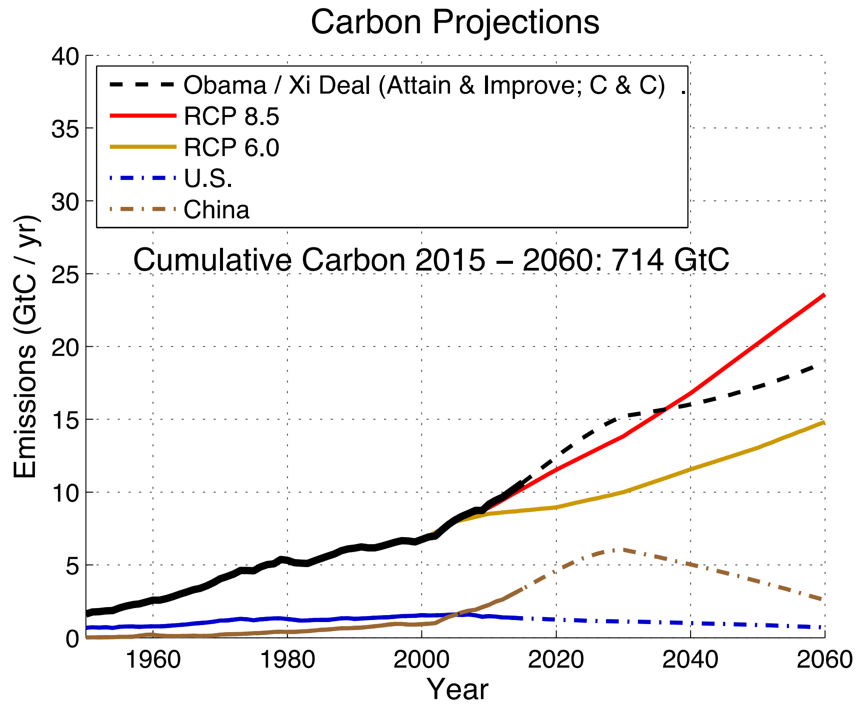

Tribett et al., in prep, 2015

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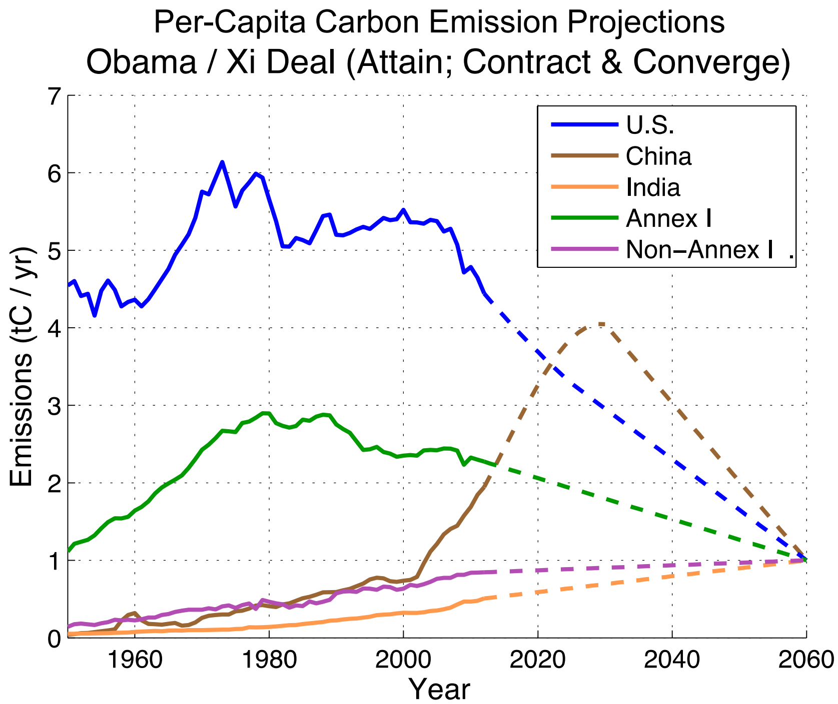

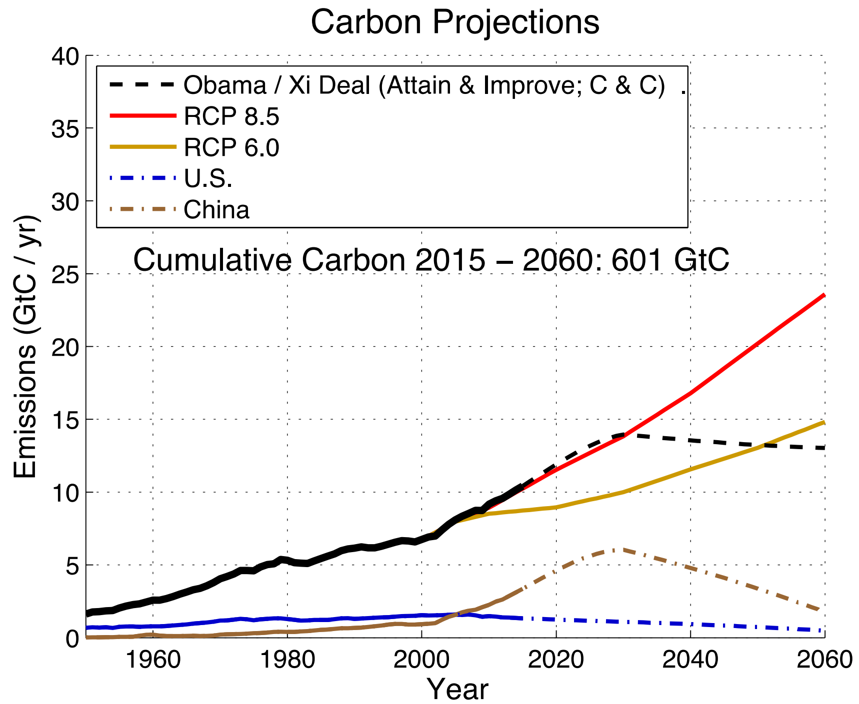

Tribett et al., in prep, 2015

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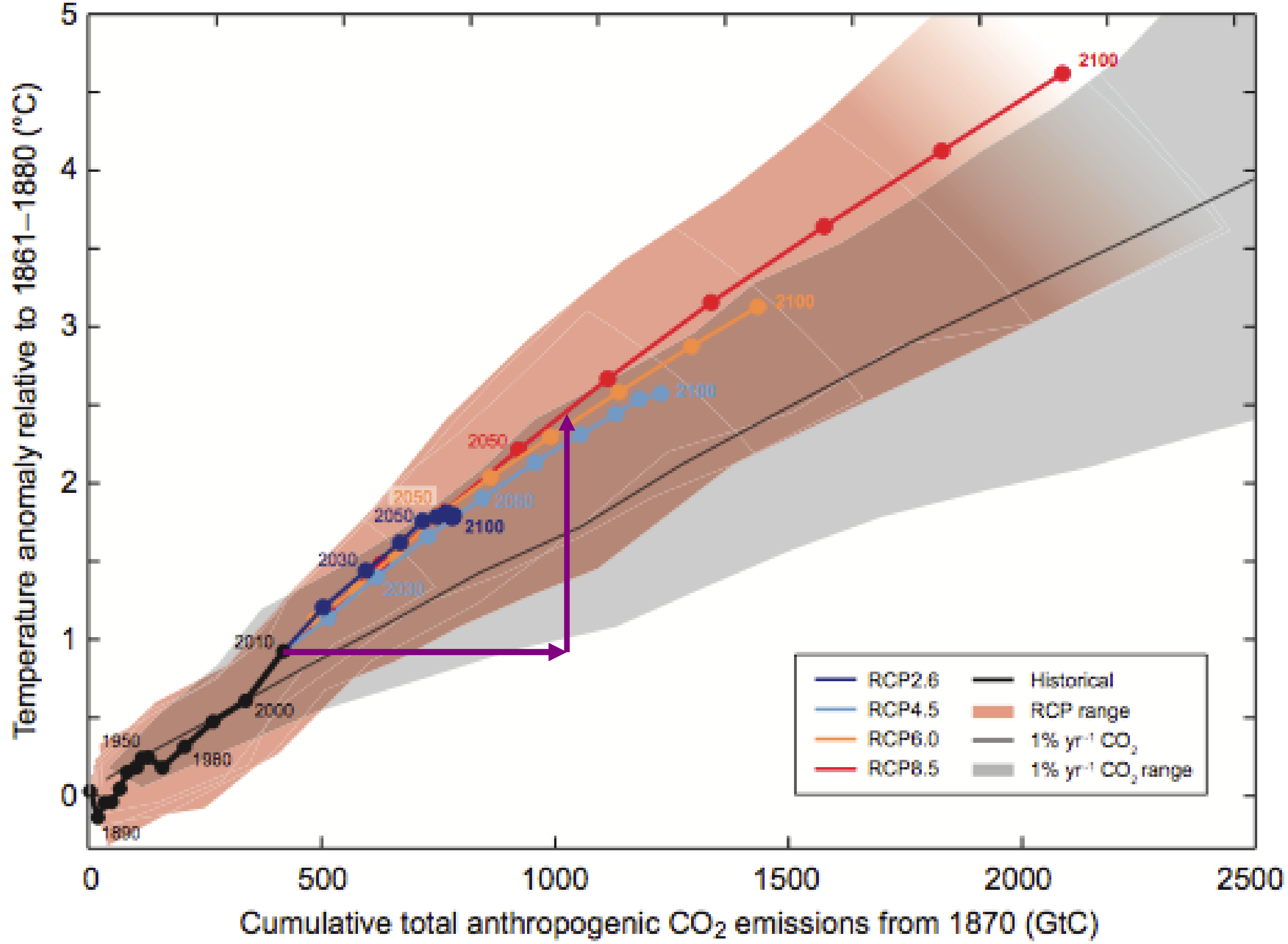
IPCC (2013) Links Rise in GMST to Total Cumulative C Emissions



IPCC AR5 SPM.10

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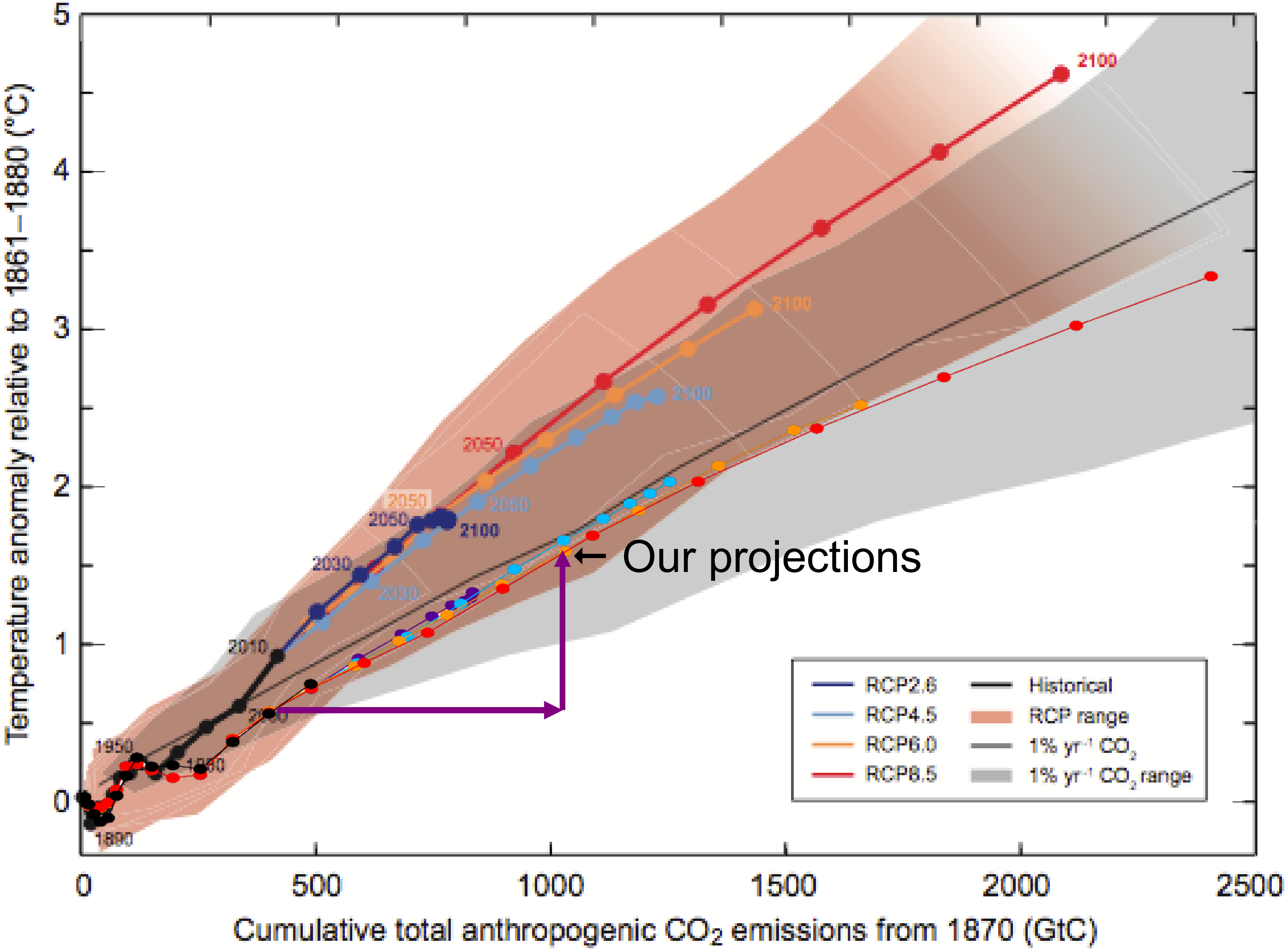

IPCC AR5 SPM.10

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Kyoto Protocol

- Negotiated in Kyoto, Japan in November 1997
  - Annex I countries: Developed countries (Table 10.1 of Houghton) with varying emission targets, 2008-2012 relative to 1990, ranging from +10% (Iceland) to –8% (EU-15)

Table 10.1 *Emissions targets (1990*–2008/2012) for greenhouse gases under the Kyoto Protocol*

Country	Target (%)
EU-15**, Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Romania, Slovakia, Slovenia, Switzerland	−8
USA***	−7
Canada, Hungary, Japan, Poland	−6
Croatia	−5
New Zealand, Russian Federation, Ukraine	0
Norway	+1
Australia	+8
Iceland	+10

* Some economies in transition (EIT) countries have a baseline other than 1990.

** The fifteen countries of the European Union have agreed an average reduction; changes for individual countries vary from −28% for Luxembourg, −21% for Denmark and Germany to +25% for Greece and +27% for Portugal.

*** The USA has stated that it will not ratify the Protocol.

Houghton, Global Warming: The Complete Briefing, 3d Edition, 2004

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  - Annex II countries: sub-group of Annex I countries that agree to pay cost of technology for emission reductions in developing countries
    Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States of America
  - Developing countries: all countries besides those in Table 10.1 of Houghton
- Went into effect in 16 February 2005 after signed by __________
- Annex I countries:
  - agree to reduce GHG emissions to target tied to 1990 emissions. If they cannot do so, they must buy emission credits or invest in conservation
- Developing countries:
  - no restrictions on GHG emissions
  - encouraged to use new technology, funded by Annex II countries, to reduce emissions
  - can not sell emission credits

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Kyoto Protocol

KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

UNITED NATIONS

1998

Article 3

1. The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article, **with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012**.

2. Each Party included in Annex I shall, by 2005, have made demonstrable progress in achieving its commitments under this Protocol.

3. The **net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990**, measured as verifiable changes in carbon stocks in each commitment period, **shall be used to meet the commitments** under this Article of each Party included in Annex I. **The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner** and reviewed in accordance with Articles 7 and 8.

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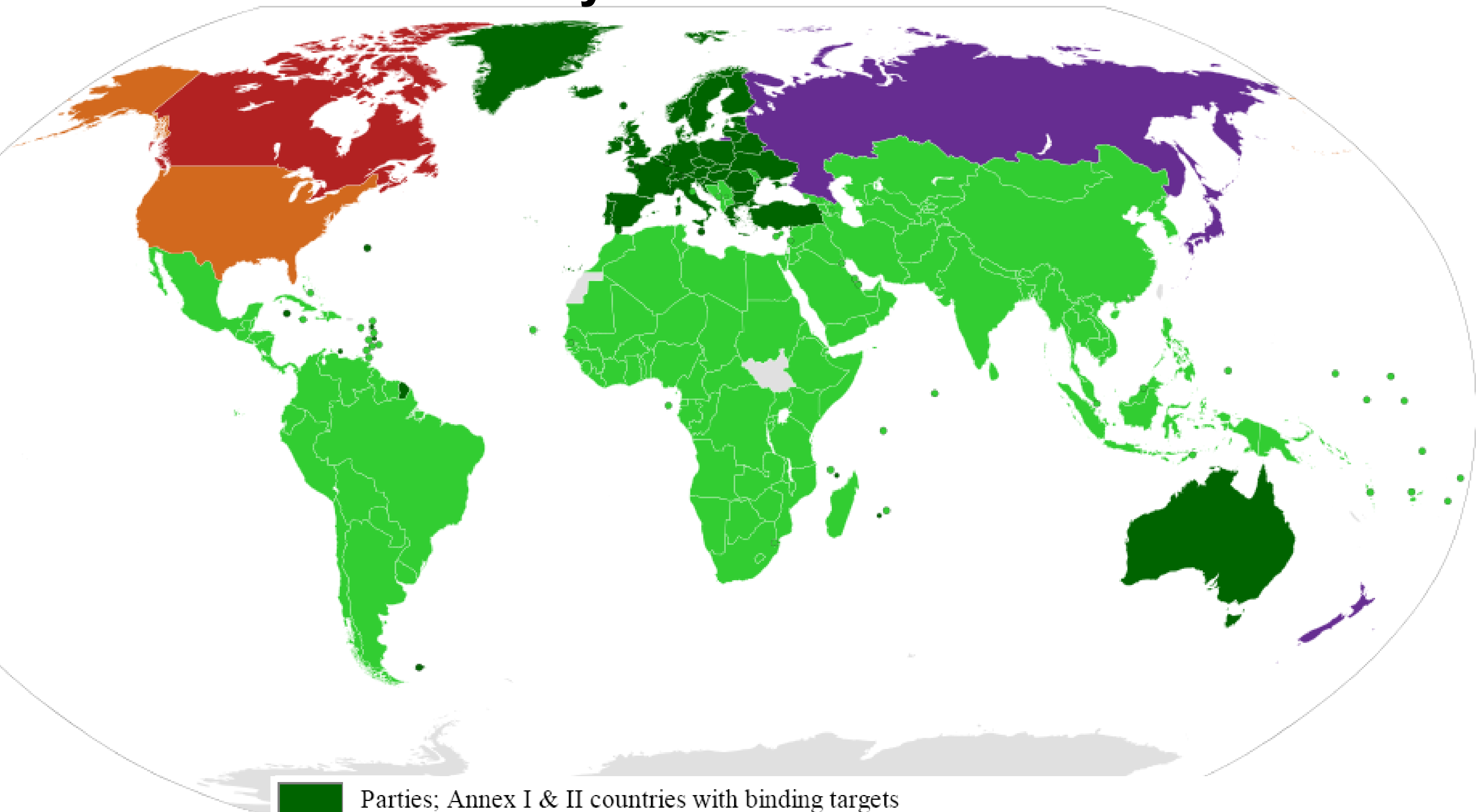
Kyoto Protocol



- Parties; Annex I & II countries with binding targets
- Parties; Developing countries without binding targets
- States not Party to the Protocol
- Signatory country with no intention to ratify the treaty, with no binding targets
- Countries that have denounced the Protocol, with no binding targets
- Parties with no binding targets in the second period, which previously had targets

http://schools-wikipedia.org/wp/k/Kyoto_Protocol.htm

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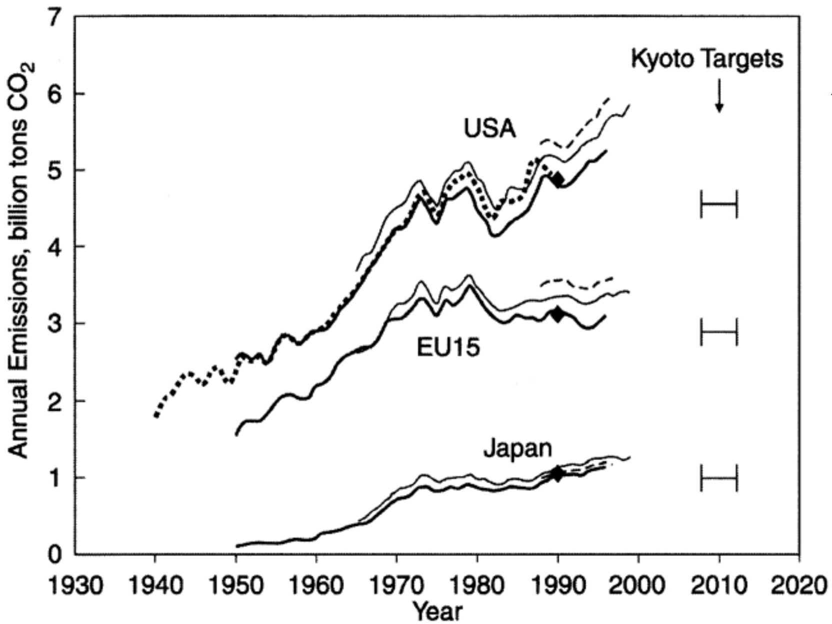
Kyoto Protocol Targets



CO_2 emissions

Does not include:

- **LULUCF (land use, land-use change and forestry)**
- **GHGs other than CO_2**

Kyoto target (2008 to 2012) for emissions of CO_2, relative to 1990 emissions selected locations

Australia	108%
EU15	92%
Iceland	110%
Japan	94%
New Zealand	100%
Norway	101%
Russia	100%
US	93%

The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming
David G. Victor, Princeton University Press, 2001.

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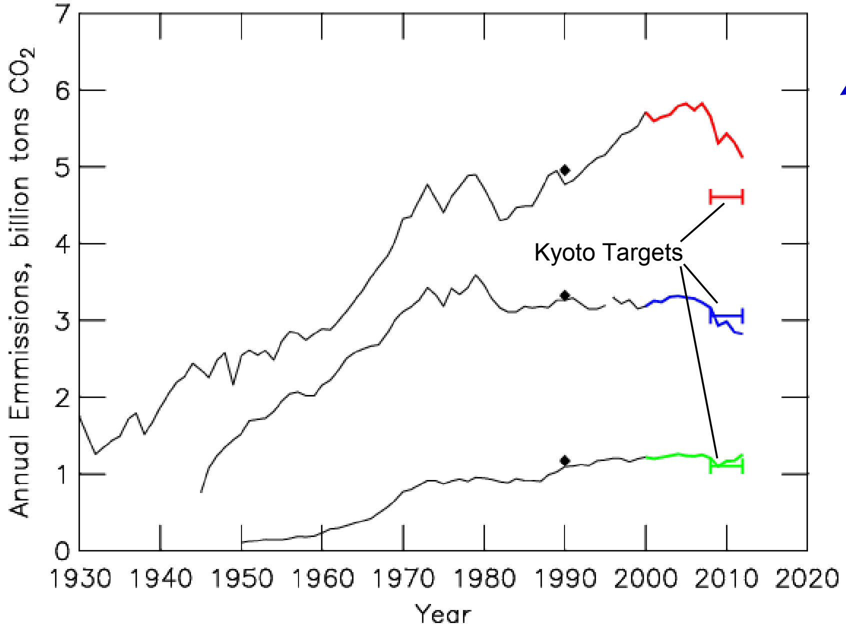
Kyoto Protocol Targets

CO_2 emissions



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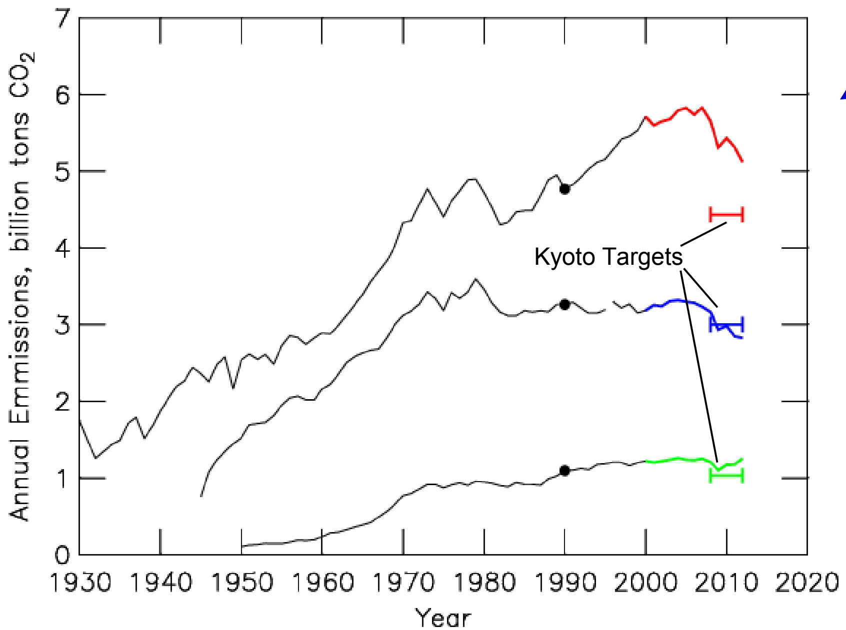
Kyoto Protocol Targets



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Kyoto Mechanisms

- Joint Implementation
  - Allows developed countries to implement projects that reduce emissions or increase natural GHG sinks in other *developed countries*; such projects can be counted towards the emission reductions of the investing country
- Clean Development Mechanism
  - Allows developed countries to implement projects that reduce emissions or increase natural GHG sinks in *developing countries*; such projects can be counted towards the emission reductions of the investing country
  - Australian Carbon Data Accounting Model
    http://www.climatechange.gov.au/en/government/initiatives/ncat.aspx
    being discussed as pilot for international metric for quantifying effects of reforestation on the carbon fluxes
- Emissions Trading
  - Annex I countries can purchase emission units from other *Annex I countries* that find it easier to reduce their own emissions

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Kyoto Emission Penalties

What happens if a country fails to reach its Kyoto emissions target?

The Kyoto Protocol contains measures to assess performance and progress.
It also contains some penalties. Countries that fail to meet their emissions targets by the end of the first commitment period (2012) must make up the difference plus a penalty of 30 per cent in the second commitment period

Their ability to sell credits under emissions trading will also be suspended

http://www.cbc.ca/news/background/kyoto/

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Kyoto Gases

GHG	GWP, 100-yr	Industrial Use	Lifetime
CO_2	1	Fossil fuel combustion; Land use changes	Multiple, ~172 yrs
CH_4	25	Fossil fuel combustion; Rice paddies; Animal waste; Sewage treatment and landfills; Biomass burning	~10 yrs
N_2O	298	Agriculture & river chemistry associated with pollution Biomass burning & fossil fuel combustion	~115 yrs
HFCs	124 to 15000	Refrigerant (HFC–134a: CH_2FCF_3), foam blowing agent, and by product of HCFC manufacture	Range from 1.5 to 270 yrs
PFCs	7400 to 12200	Aluminum smelting (CF_4) Semiconductor manufacturing (CF_4)	1000 to 50,000 yrs
SF_6	22800	Insulator in high voltage electrical equipment Magnesium casting Shoes and tennis balls (minor source)	3200 yrs

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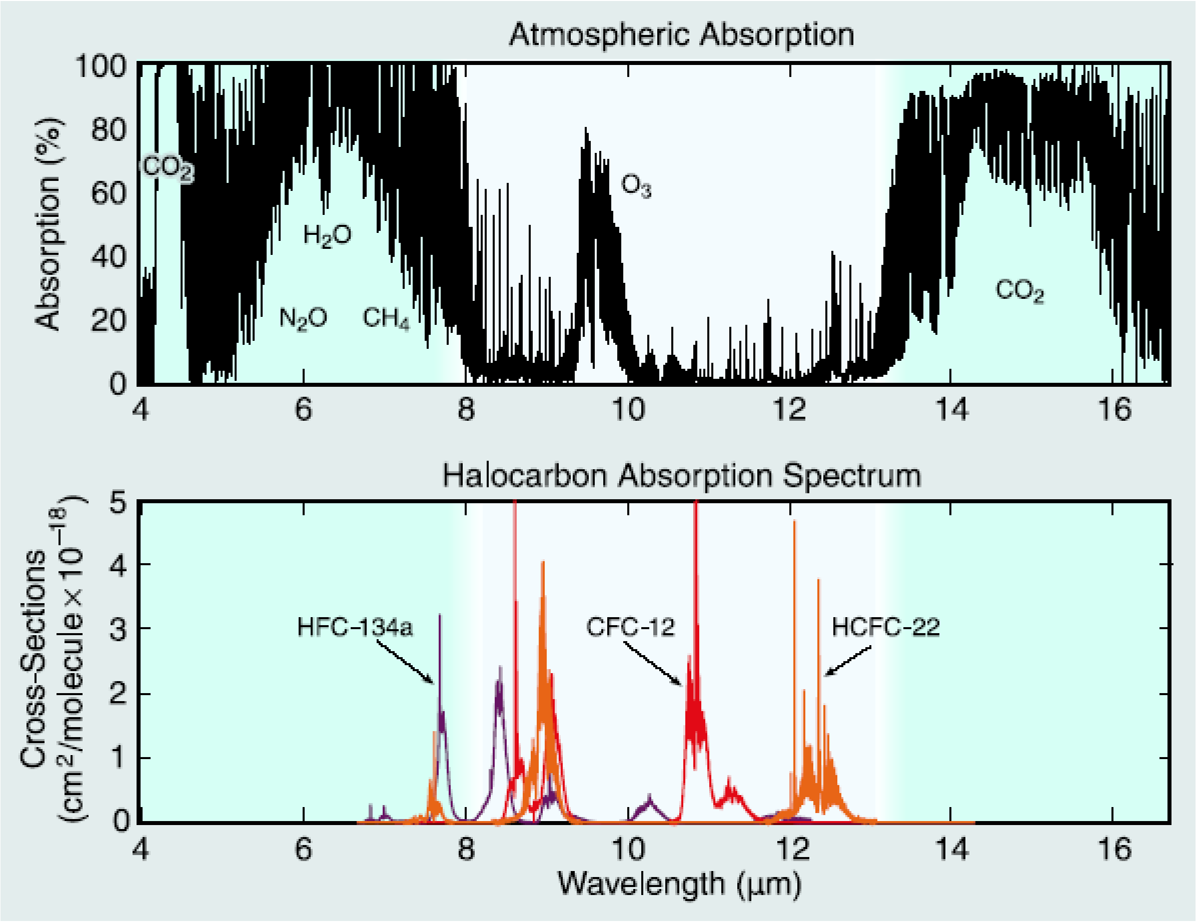
HFCs Spectra



IPCC "SROC": Special Report on Safeguarding the Ozone Layer and the Global Climate System

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

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GWP – Global Warming Potential

$$\text{GWP (HFC}-134\text{a)} = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\text{HFC}-134\text{a}} \times [\text{HFC}-134\text{a(t)]}\ \text{dt}}{\int_{\text{time initial}}^{\text{time final}} a_{\text{CO2}} \times [\text{CO}_2\text{(t) dt]}}$$

where:

$a_{HFC-134a}$ = Radiative Efficiency (W m^{-2} ppb^{-1}) due to an increase in HFC-134a

a_{CO2} = Radiative Efficiency (W m^{-2} ppb^{-1}) due to an increase in CO_2

HFC-134a (t) = time-dependent response to an instantaneous release of a pulse of HFC-134a

CO_2 (t) = time-dependent response to an instantaneous release of a pulse of CO_2

Note: HFC-134a is CH_2FCF
HCFC-22 is CH_3CClF_2

		GWP Time Horizon	
	τ (yr)	20-yr	100-yr
HFC-134a	13.4	3710	1300
HCFC-22	11.9		

Table 8.A.1, IPCC (2013)

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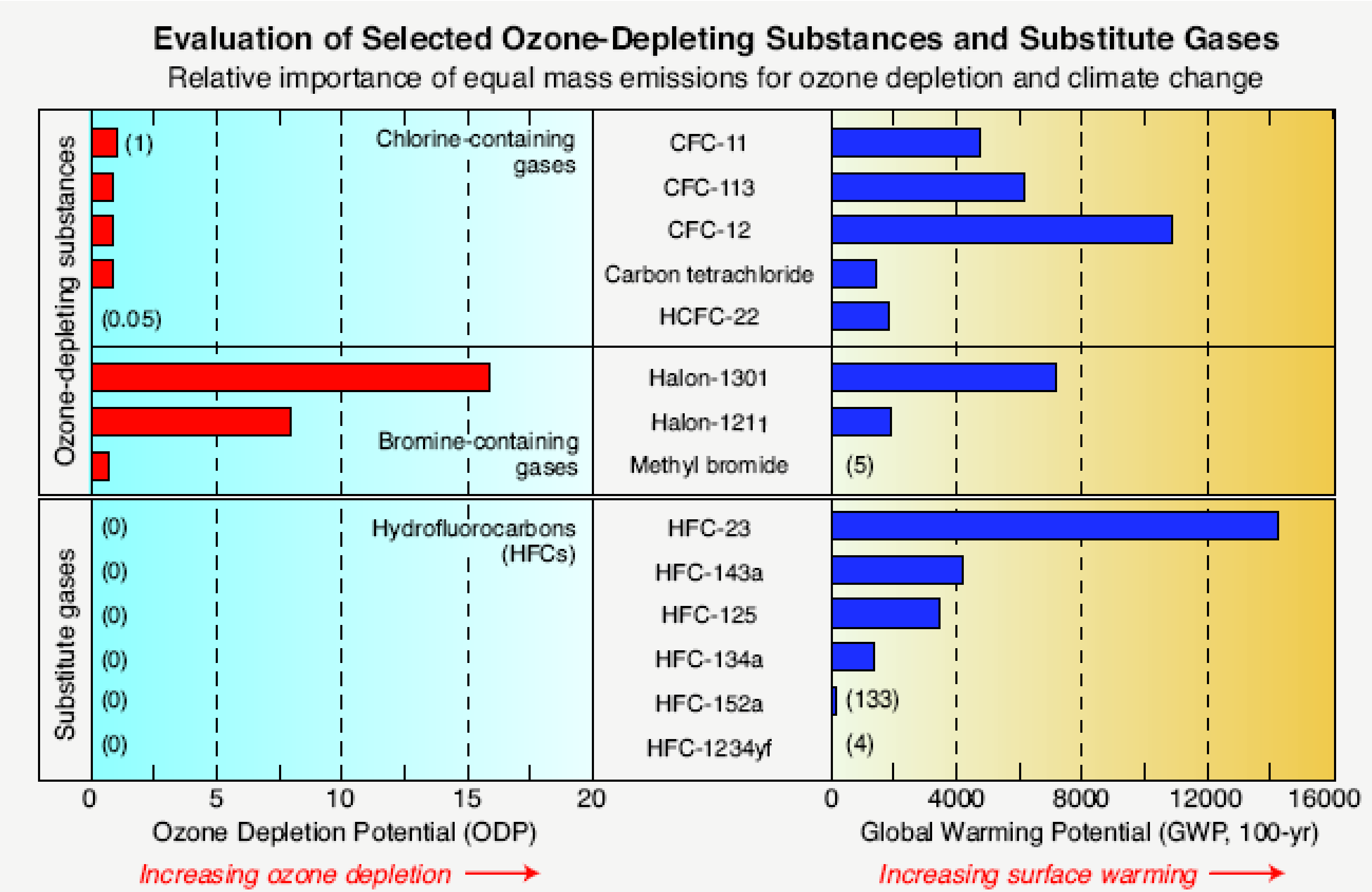
Not all HFCs are equal wrt Global Warming



WMO/UNEO 2011 “Twenty Questions”
http://esrl.noaa.gov/csd/assessments/ozone/2010/twentyquestions

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Radiative Forcing due to HFCs

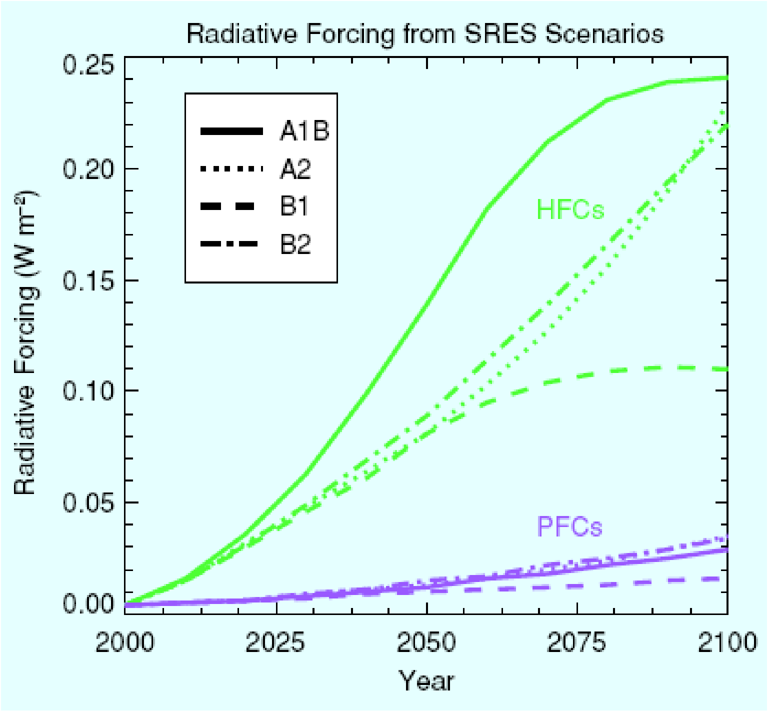
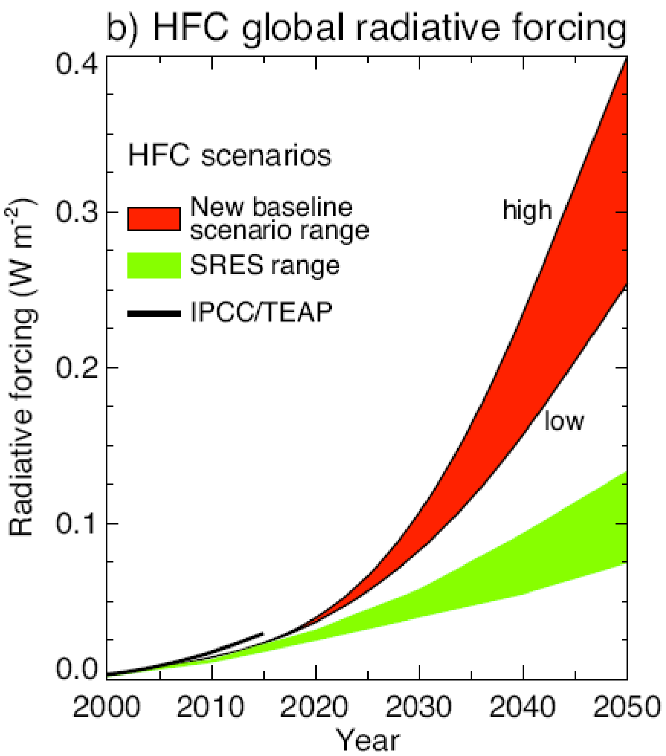


Fig 2.9



IPCC "SROC": Special Report on Safeguarding the Ozone Layer & Global Climate System, 2005

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

Velders et al., PNAS, 2009

SRES: Special Report on Emission Scenarios: used in past IPCC reports including IPCC (2007)
http://en.wikipedia.org/wiki/Special_Report_on_Emissions_Scenarios#SRES_scenarios_and_climate_change_initiatives

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Radiative Forcing due to PFCs

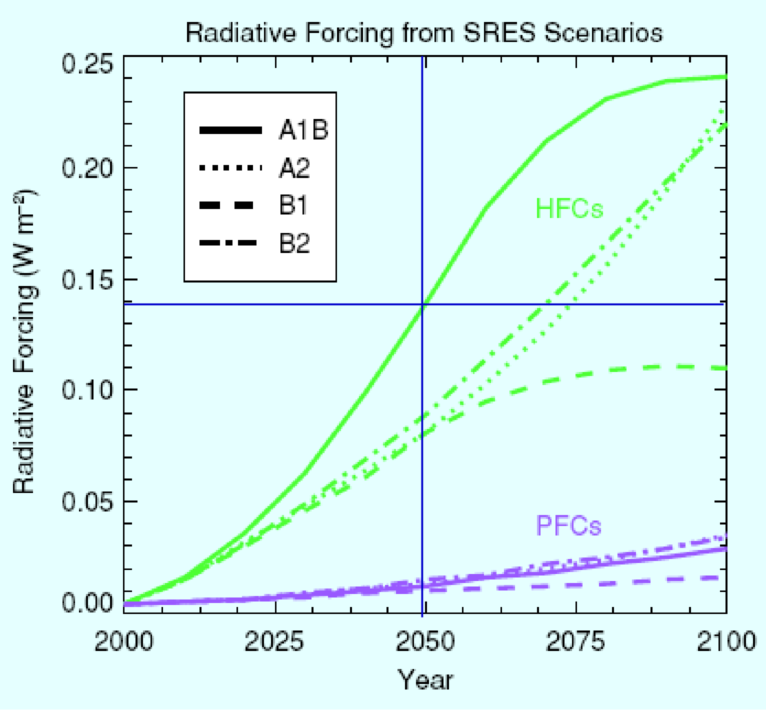

Fig 2.9

IPCC "SROC": Special Report on Safeguarding the Ozone Layer & Global Climate System, 2005

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

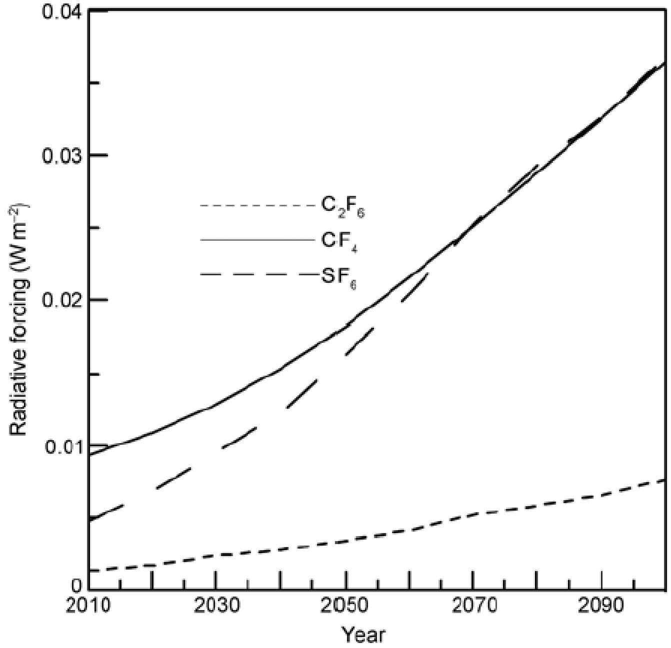

Figure 4 Radiative forcing of C_2F_6, CF_4, and SF_6 from 2010 to 2100.

Zhang et al., Sci China Earth Sci, 2011

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Climate News

- **Durban, South Africa (Dec 2011)**
  - Renewed the Kyoto Protocol in principle and a new process called the Durban Platform for Enhanced Cooperation (DPEC) was put in place
  - DPEC: countries will negotiate a new "outcome with legal force" by 2015 that would replace the Kyoto Protocol
- **Rio De Janeiro, Brazil (June 2012)**
  - 192 governments renewed their commitment to sustainable development, including a 49 page document, but commitment was non-binding
- **Doha, Qatar (Dec 2012)**
  - Amendment to Kyoto Protocol framed, for 2nd commitment period 1 Jan 2013 to 31 Dec 2020

	Ref Year	GHG reductions 2020
US*		
EU-15	1990	20 to 30%
Japan**		
Norway	1990	30 to 40%

* US did not participate
** Japan indicated that it does not intend to be under obligation of the second commitment period of the Kyoto Protocol

- **Paris (30 Nov to 11 Dec 2015)**
  - 11th session of the Conference of the Parties to the Kyoto Protocol

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Pacala and Socolow: CO_2 Stabilization Wedges

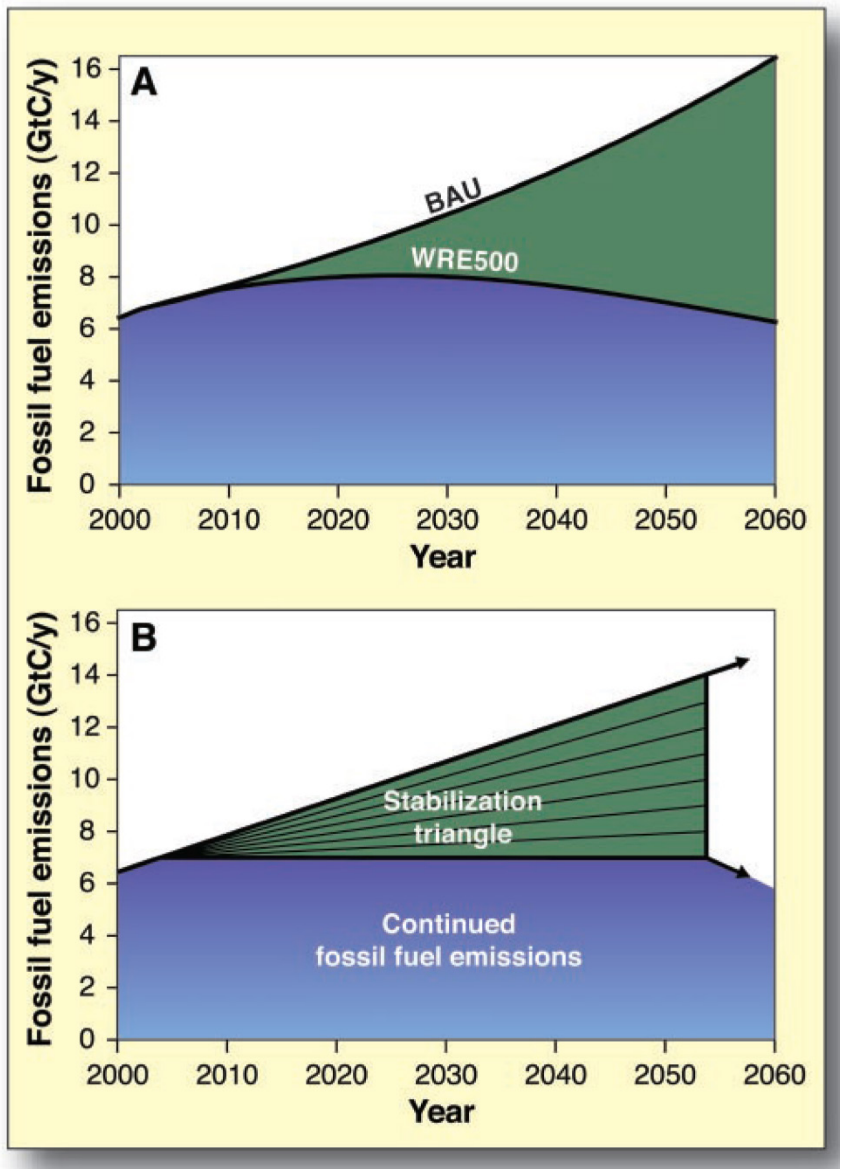

Fig. 1. (**A**) The top curve is a representative BAU emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500 ppm by 2125 akin to the Wigley, Richels, and Edmonds (WRE) family of stabilization curves described in (*11*), modified as described in Section 1 of the SOM text. The bottom curve assumes an ocean uptake calculated with the High-Latitude Exchange Interior Diffusion Advection (HILDA) ocean model (*12*) and a constant net land uptake of 0.5 GtC/year (Section 1 of the SOM text). The area between the two curves represents the avoided carbon emissions required for stabilization. (**B**) Idealization of (A): A stabilization triangle of avoided emissions (green) and allowed emissions (blue). The allowed emissions are fixed at 7 GtC/year beginning in 2004. The stabilization triangle is divided into seven wedges, each of which reaches 1 GtC/year in 2054. With linear growth, the total avoided emissions per wedge is 25 GtC, and the total area of the stabilization triangle is 175 GtC. The arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 GtC/year after 2054 to achieve stabilization at 500 ppm.

Pacala and Socolow, Science, 2004

http://www.princeton.edu/mae/people/faculty/socolow/Science-2004-SW-1100103-PAPER-AND-SOM.pdf

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Pacala and Socolow: CO_2 Stabilization Wedges

Action	Details
	Energy efficiency and conservation
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)
	Fuel shift
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)
	CO_2 Capture and Storage (CCS)
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)
8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture
Geological storage	Create 3500 Sleipners

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Pacala and Socolow: CO_2 Stabilization Wedges

Action	Details
	Nuclear fission
9. Nuclear power for coal power	Add 700 GW (twice the current capacity)
	Renewable electricity and fuels
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30×10^6 ha, on land or offshore
11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2×10^6 ha
12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)
13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250×10^6 ha (one-sixth of world cropland)
	Forests and agricultural soils
14. Reduced deforestation, plus reforestation, afforestation, and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)
15. Conservation tillage	Apply to all cropland (10 times the current usage)

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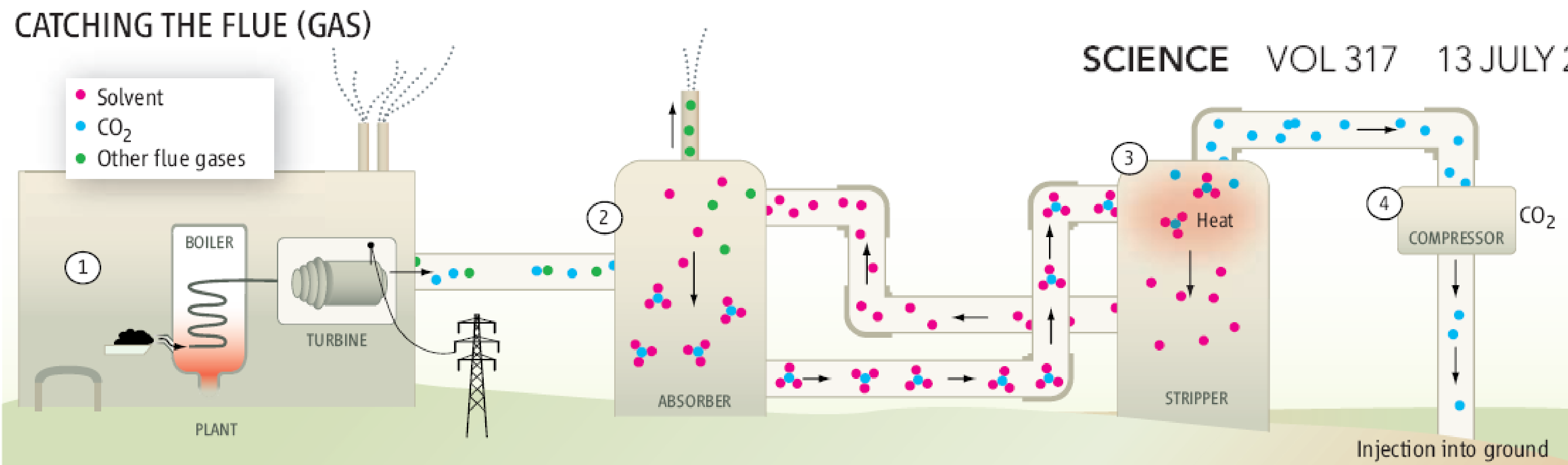
Carbon Capture & Sequestration



How a retrofit works. (1) Most coal plants burn coal to create steam, running a turbine that produces electricity. After treatment for pollutants, the flue gas, a mixture of CO_2 (blue) and other emissions (green), goes out a smokestack. To collect CO_2 for storage, however, the mixture of gases is directed to an absorber (2), where a solvent like MEA (pink) bonds with the CO_2 molecules. The bonded CO_2–solvent complexes are separated in the stripper (3), which requires heat. More energy is needed for the next step (4), which produces a purified CO_2 stream for ground storage as well as solvent molecules that can be reused. (Schematic not to scale.)

MEA-monoethanolamine $(CH_2CH_2OH)NH_2$ in an aqueous solution will absorb CO_2 to form ethanolammonium carbamate.

$$2RNH_2 + CO_2 + H_2O \rightarrow (RNH_3)_2CO_2$$

MEA is a weak base so it will re-release the CO_2 when heated

Kintisch, *Science*, 2007

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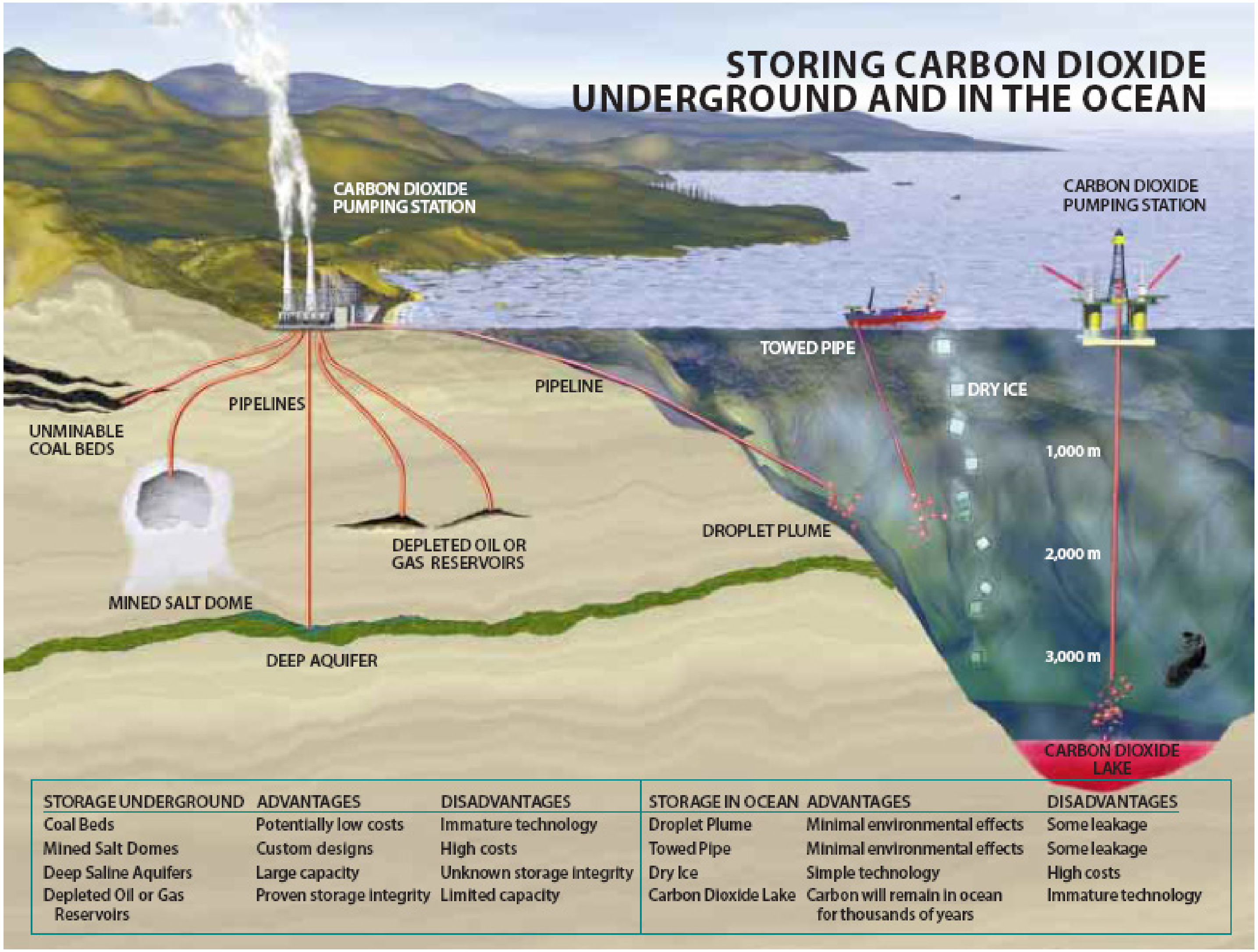
Where to Place the Sequestered Carbon?



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology
Mined Salt Domes	Custom designs	High costs
Deep Saline Aquifers	Large capacity	Unknown storage integrity
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity

STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Droplet Plume	Minimal environmental effects	Some leakage
Towed Pipe	Minimal environmental effects	Some leakage
Dry Ice	Simple technology	High costs
Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

STORAGE SITES for carbon dioxide in the ground and deep sea should help keep the greenhouse gas out of the atmosphere where it now contributes to climate change. The various options must be scrutinized for cost, safety and potential environmental effects.

Herzog *et al.*, *Scientific American*, 2000

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Carbon Sequestration in Action:

Sleipner, Norway

National Geographic, June 2008

- North Sea natural gas field: enormous capacity
- Captures ~90% of CO_2 that is generated
- CO_2 pumped into 200 m thick sandstone layer 720 m below sea floor
- Project initiated in response to $50 ton tax on CO_2 emissions instituted by Norwegian Government in 1996
- Investment in capital cost paid off in about one and a half years !

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CO_2 Capture and Storage (CCS) Costs:

CCS component	Cost range	
Capture from a power plant	15–75 US$/t$CO_2$ net captured	~$45/ ton
Capture from gas processing or ammonia production	5–55 US$/t$CO_2$ net captured	
Capture from other industrial sources	25–115 US$/t$CO_2$ net captured	
Transportation	1–8 US$/t$CO_2$ transported per 250km	~$4.5/ ton
Geological storage	0.5–8 US$/t$CO_2$ injected	~$4.5/ ton
Ocean storage	5–30 US$/t$CO_2$ injected	
Mineral carbonation	50–100 US$/t$CO_2$ net mineralized	

⇧ Back of the envelope analysis ⇦

Cost of capture: **~$54 / ton** CO_2 × 10 × 10^9 tons C / yr = **$ 540 billion**

Present cost of fossil fuel: $ 56 / barrel ≈ **$ 484 / ton**

World GDP, 2010: **$ 75.6 trillion** CO_2 capture = 0.7 % of world GDP
= 11 % of cost, barrel of oil

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)

WMO   UNEP

Carbon Dioxide Capture and Storage

http://www.ipcc.ch/pdf/presentations/briefing-montreal-2005-11/presentation-special-report-co2.ppt

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Afforestation

- If 100,000 km^2 (size of Ireland) was re-planted every year, for 40 years (size of Australia) would sequester between 20 and 50 Gt of C from the atmosphere

- ⇨ between **5** and **10** % of emissions, 2015 to 2055

http://www.worldlandtrust.org/images/places/brazil/wetland-before-after-joy-and-mick-braker-vl.jpg

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Afforestation

- If 100,000 km^2 (size of Ireland) was re-planted every year, for 40 years (size of Australia) would sequester between 20 and 50 Gt of C from the atmosphere
- ⇨ between **5** and **10** % of emissions, 2015 to 2055
- Land available ✓   Cost ✓

http://www.worldlandtrust.org/images/places/brazil/wetland-before-after-joy-and-mick-braker-vl.jpg

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Sequestration of CO_2 from the Atmosphere: Carbon Burial

- Prof Ning Zeng (UMCP) advocates planting, harvesting, and burial of rapidly growing trees (proposal is to collect dead trees on forest floor and selectively log live trees)

- Meetings have been held to discuss this idea:

Ecological carbon sequestration via wood burial and storage: A strategy for climate mitigation and adaptation
September 9-10, 2010, the Heinz Center, Washington, DC

- A UMd Gemstone Project has addressed this issue

http://teams.gemstone.umd.edu/classof2010/carbonsinks

- Statements from Zeng, Carbon Sequestration Via Wood Burial, *Carbon Balance and Management*, 2008 http://www.cbmjournal.com/content/3/1/1 :
  - Here I suggest an approach in which wood from old or dead trees in the world's forests is harvested & buried in trenches under a layer of soil, where the anaerobic condition slows the decomposition of the buried wood.
  - Because of low oxygen below the soil surface, decomposition of buried wood is expected to be slow

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Cap and Trade vs Carbon Tax

Extra Slide

From an economic point of view, these two policies are vastly different

Cap and trade regulates <u>amount emitted</u>

Carbon tax regulates <u>price of emission</u>

Comparison of Architectures for Greenhouse Gas Regulation

Instrument	*Economic wisdom*	*Allocation*	*Monitoring*	*Enforcement*
General approach:				
Cap and Trade (Kyoto)	**Pro:** Best way to empower market forces to control a "threshold" problem, but **Con:** tight quantity limits could force the economy to bear high costs **Con:** Identification and agreement on a dangerous threshold are not imminent	**Con:** Perhaps impossible to negotiate an allocation that would not cause some major emitting nations to withdraw	**Pro:** Easy to monitor permit trades; easy to monitor emissions if trading is restricted to fossil fuel CO_2 only **Con:** Kyoto Protocol includes six greenhouse gases—impossible to monitor all fluxes reliably if trading	**Pro:** Can rely on national legal systems in "liberal" nations if buyer liability is the rule. **Con:** If sellers are liable for noncompliance then system will require international enforcement institutions of unprecedented strength
Coordinated taxes	**Pro:** Most Efficient instrument when managing a "stock" problem; risks of climate change are mainly a function of the slowly growing "stock" of CO_2 in the atmosphere	**Pro:** Easier to allocate commitments because not distributing semipermanent assets	**Con:** Very difficult to monitor real impact of taxes that are applied to economies in tandem with other tax and investment policies	**Con:** Requires strong and intrusive international institutions

The Collapse of the Kyoto Protocol
and the Struggle to Slow Global Warming
David G. Victor, Princeton University Press, 2001

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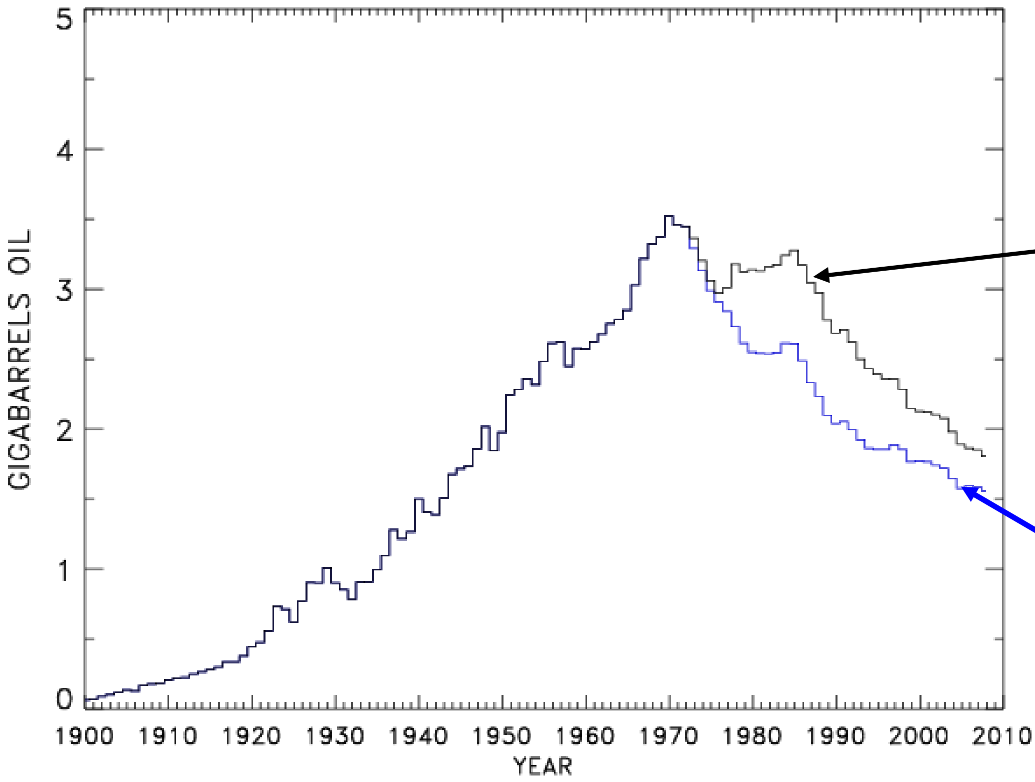
Peak Oil

In the 1950s, Dr. M King Hubbert applied this analysis to the lower 48 United States. By estimating oil reserves and the maximum production rate, he predicted that US oil would peak in the early 1970's.



The addition of oil from Alaska adds a secondary peak in the mid 1980s. However, oil is still decreasing.

Lower 48 states

United states annual rate of production

http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm

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Mathematics of Peak Oil

Extra Slide

We'll use a symmetric, bell shaped curve to represent production rates over time. In this case, production corresponds to

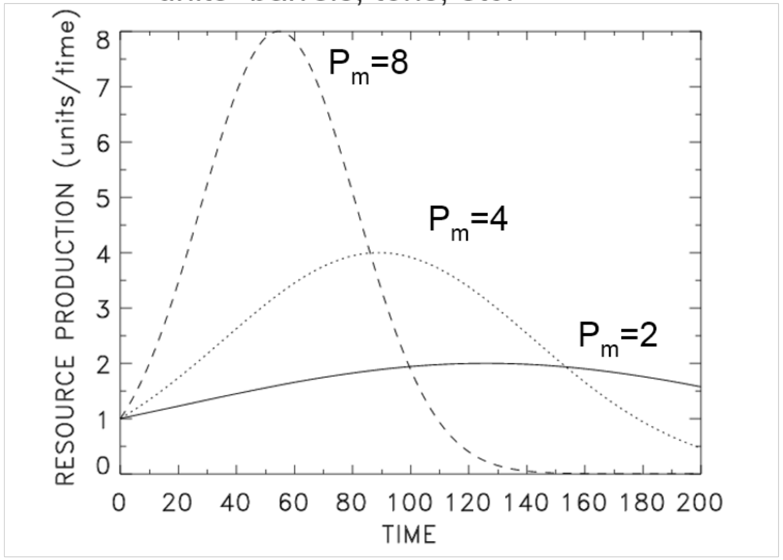
$$P = P_m \exp\left[-\frac{1}{2}\left(\frac{t - t_m}{\sigma}\right)^2 \right]$$

P_m = maximum production rate
t_m = time when max. production occurs
σ = standard deviation

As before, we'll solve for Q, the total amount of resource produced,

$$Q_\infty = \int_{-\infty}^{\infty} P_m \exp\left[-\frac{1}{2}\left(\frac{t - t_m}{\sigma}\right)^2 \right] dt = \sigma P_m \sqrt{2\pi}$$

units=barrels, tons, etc.



All three of these curves have the same area!!

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