Paris Climate Agreement and the Science of CO_2 Stabilization

AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2017

Topics for today:

- **Hubbert Peak**
- **Kyoto Protocol**
- **Obama / Xi Accord**
- **Paris Climate Agreement**

Lecture 18

20 April 2017

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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 !

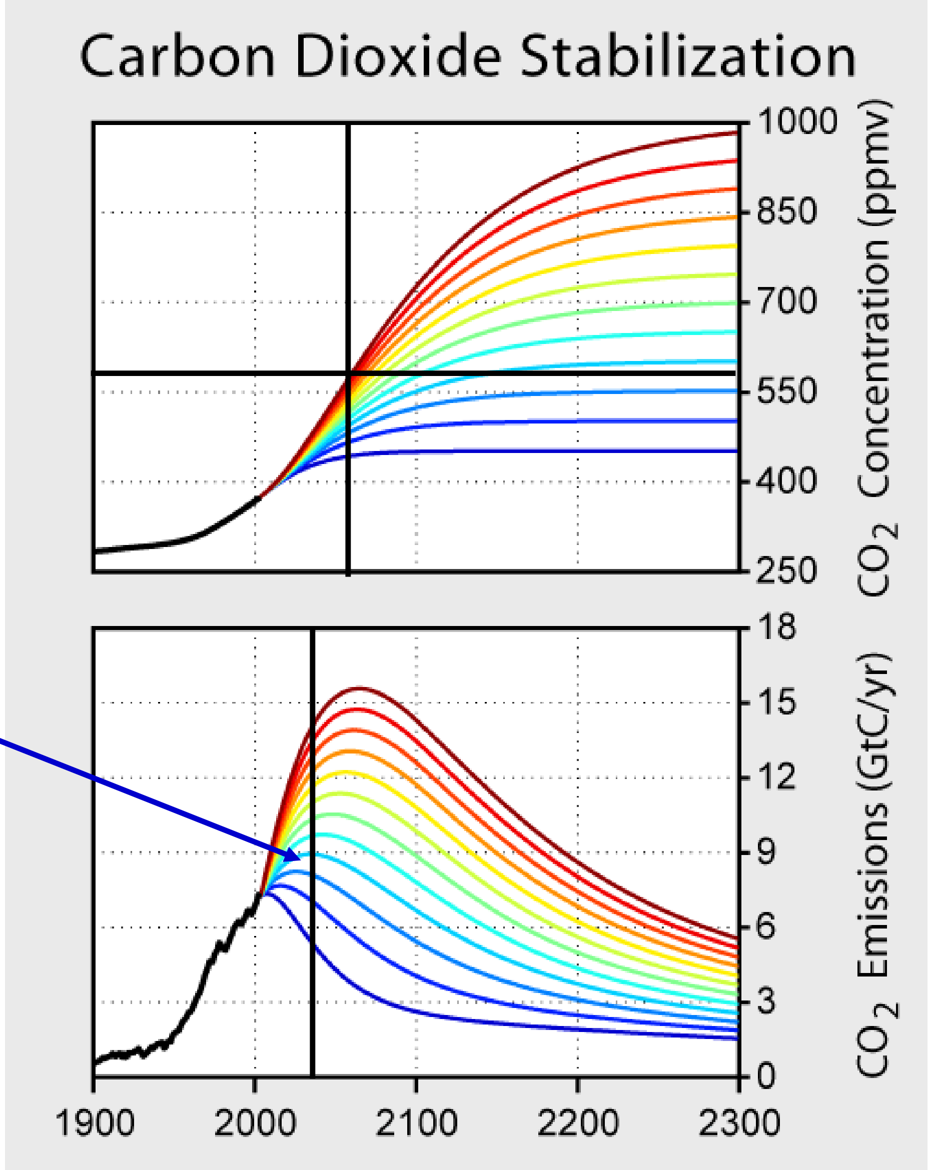

Image: "Global Warming Art" : http://www.globalwarmingart.com/wiki/Image:Carbon_Stabilization_Scenarios_png

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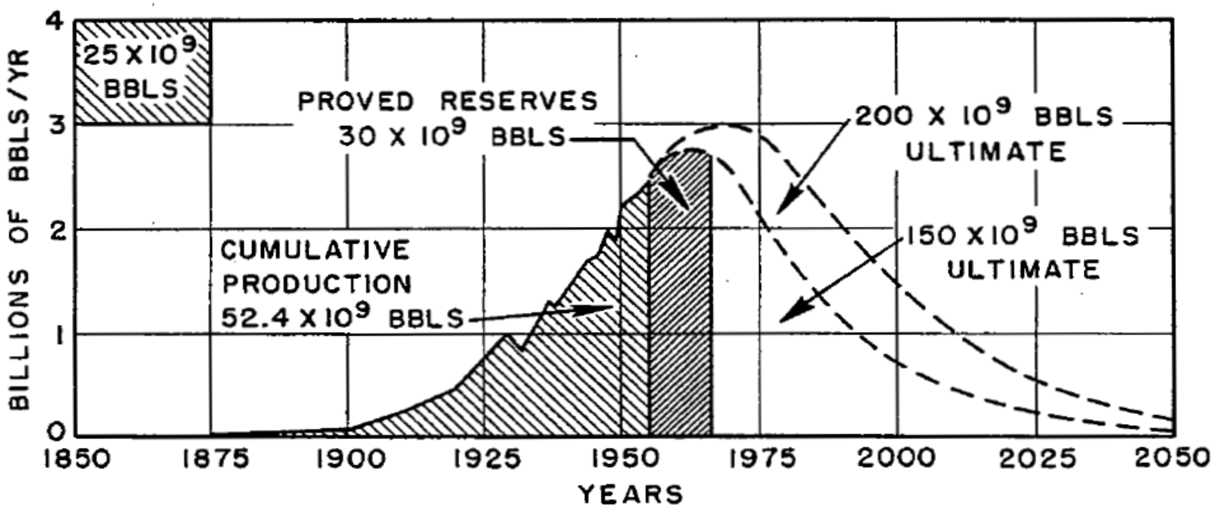
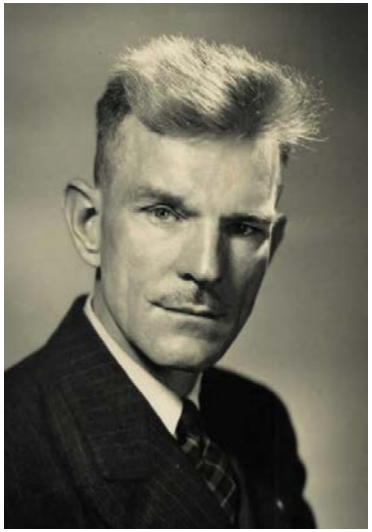
Hubbert's Peak



- **M. King Hubbert: Shell geophysicist**
- **1956 : presented a paper "Nuclear Energy and Fossil Fuels" that predicted US oil production would peak in 1970**
- **Paper was met with skepticism & ridicule**
- **But: *<u>this prediction was remarkably accurate</u>* !**



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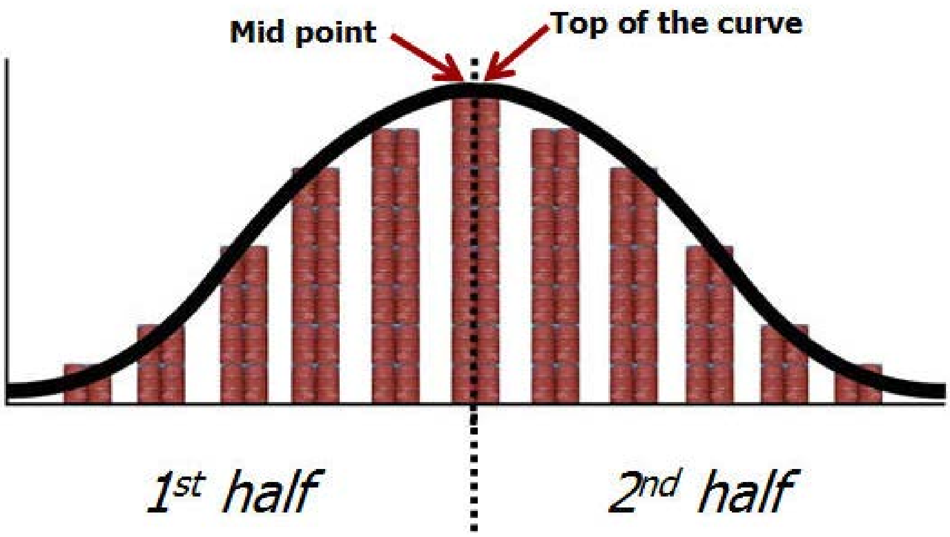
Mathematics of Resource Use

It is unlikely that an industry will go from full production of a resource to zero production the next year. It is reasonable to assume that production will follow an exponential growth while a resource is easy to find and relatively cheap to produce. As the resource becomes harder to find, prices rise, production rates peak, and then begin to decrease.



The area beneath this curve is the total amount of resource available.

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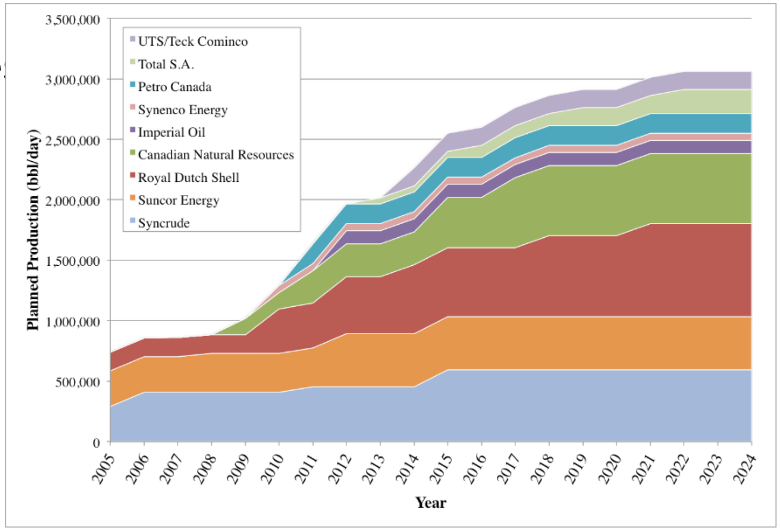
Canadian oil sands (tar sands)

- May represent 2/3 of world's total petroleum resource
- Not considered in many estimates of fossil fuel reserves
- 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



See http://en.wikipedia.org/wiki/Tar_sands 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 **coal** (in the short term) and **oil sands** (in the long term)

Coal (bad) and oil sands (terrible) in terns of CO_2 output per kWh of energy

Fossil Fuel	**GHG Output (pounds CO_2 per kWh)**
Oil Sands	**5.6**
Coal	**2.1**
Oil	**1.9**
Gas	**1.3**

https://www.eia.gov/electricity/annual/html/epa_a_03.html
http://www.iop.org/EJ/abstract/1748-9326/4/1/014005

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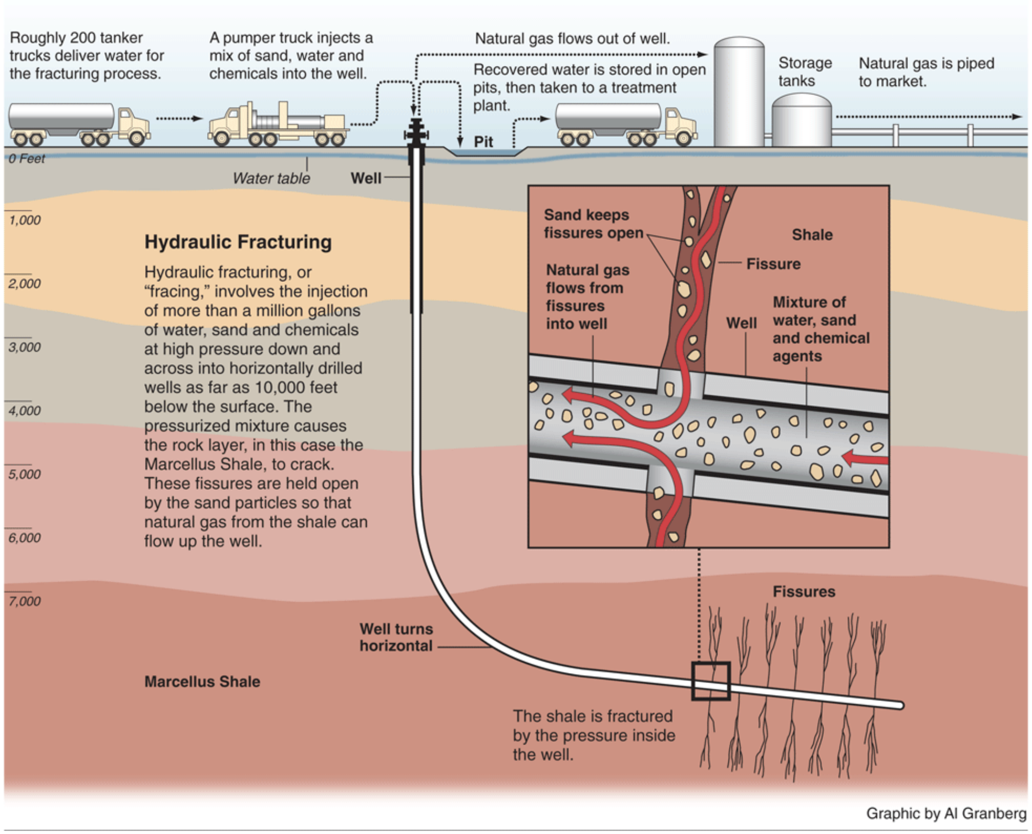
Natural Gas: Fracking



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

Image: http://www.propublica.org/images/articles/natural_gas/marcellus_hydraulic_graphic_090514.gif

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Natural Gas: Fracking

It is unclear whether increased use of CH_4 from fracking will truly be a transitional fuel on the way to renewables, as some contend, or if CH_4 will take over for coal In the long term.

From a climate change perspective, even though we can get about twice as much energy per CO_2 released from CH_4, compared to coal, **why might increased reliance on the use of CH_4 (natural gas) be a problem**?

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CO_2, CH_4, N_2O, & CFC-12

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Table 3.2 Examples of Greenhouse Gases

Name and Chemical Formula	Preindustrial Concentration (1750)	Concentration in 2008	Atmospheric Lifetime (years)	Anthropogenic Sources	Global Warming Potential
carbon dioxide CO_2	270 ppm	388 ppm	50-200*	Fossil fuel combustion, deforestation, cement production	1
methane CH_4	700 ppb	1760 ppb	12	Rice paddies, waste dumps, livestock	21
nitrous oxide N_2O	275 ppb	322 ppb	120	Fertilizers, industrial production, combustion	310
CFC-12 CCl_2F_2	0	0.56 ppb	102	Liquid coolants, foams	8100

*A single value for the atmospheric lifetime of CO_2 is not possible. Removal mechanisms take place at different rates. The range given is an estimate based on several removal mechanisms.

Chapter 3, *Chemistry in Context*

Table TS.2. *Lifetimes, radiative efficiencies and direct (except for CH_4) global warming potentials (GWP) relative to CO_2. {Table 2.14}*

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global Warming Potential for Given Time Horizon: SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153

IPCC (2007)

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CH_4 & N_2O

IPCC (2013) raises GWP of CH_4, lowers GWP of N_2O, and adds complexity of another GWP found upon consideration of Carbon Cycle Feedback

Table 8.7, IPCC (2013)

	Lifetime (years)		GWP_{20}	GWP_{100}
CH_4	12.4	No cc fb	84	28
		With cc fb	86	34
N_2O	121.0	No cc fb	264	265
		With cc fb	268	298

cc fb ⇨ Carbon Cycle Feedback

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Global Warming Potentials of CH_4 & N_2O

GHG	IPCC (1995)	IPCC (2001)	IPCC (2007)	IPCC (2013)
100 Year Time Horizon				
CH_4	21	23	25	28, 34*
N_2O	310	296	298	265, 298*
20 Year Time Horizon				
CH_4	56	62	72	84, 86*
N_2O	280	275	289	264, 268*
*Allowing for carbon cycle feedback				

Table 1.1 *Paris, Beacon of Hope*

Page 42 of Houghton states "the enhanced greenhouse effect caused by a molecule of methane is about eight times that of a molecule of carbon dioxide".
What, prey tell, is going on?

CO_2-equiv. emiss. = CO_2 (mass)+ × CH_4 (mass)+ ×N_2O (mass) etc.

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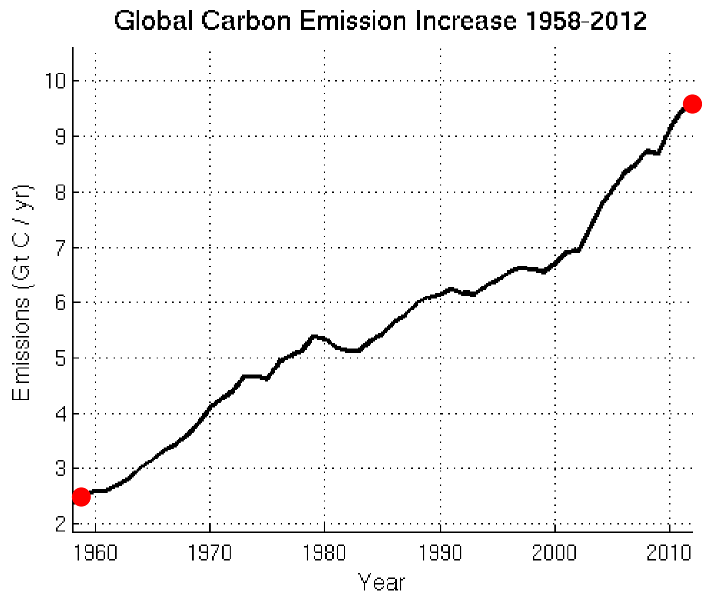
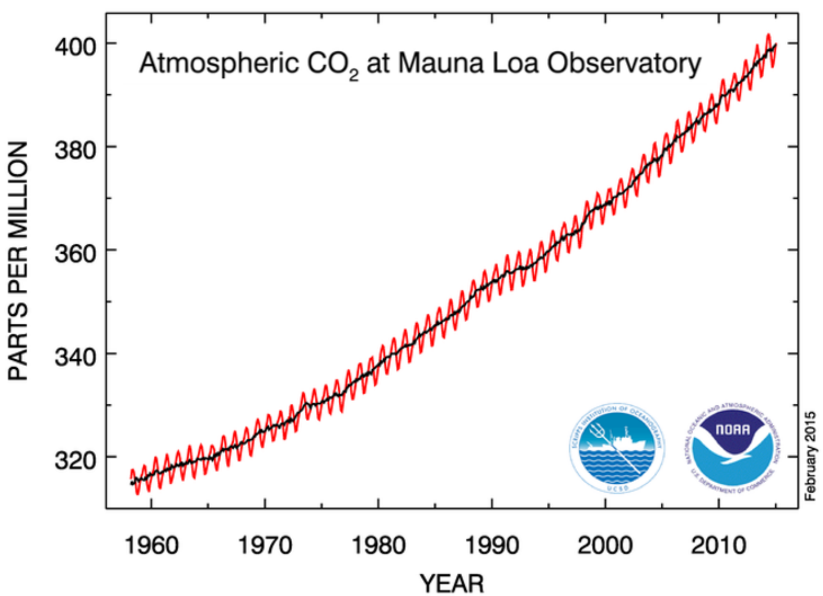
Fossil Fuel Emissions





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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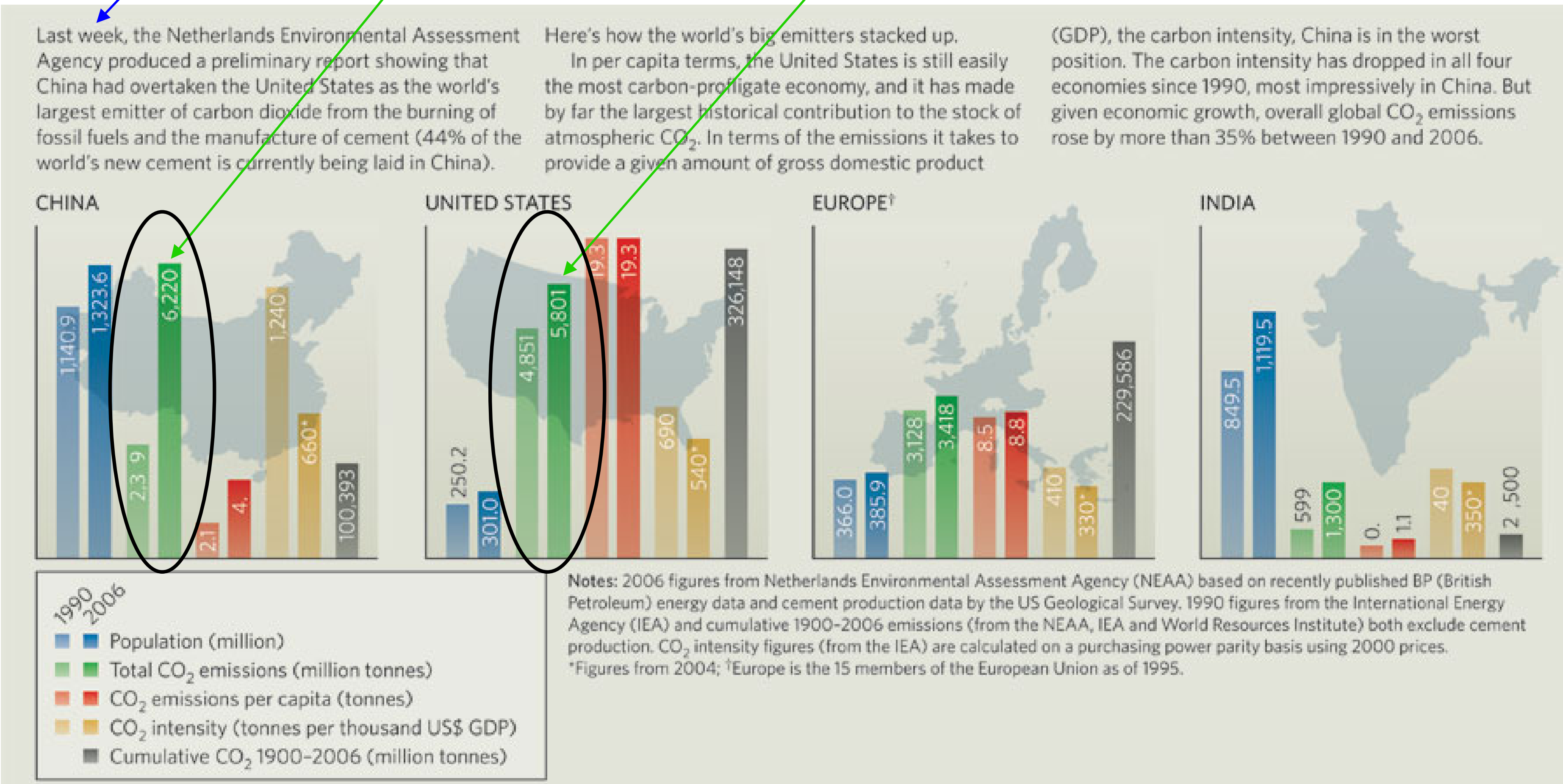
World Carbon Emissions

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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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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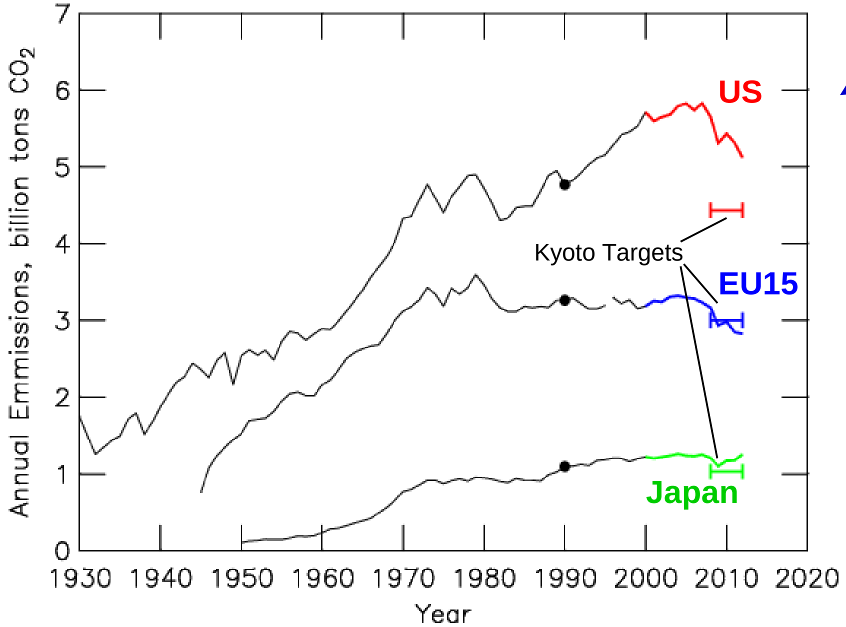
Kyoto Protocol Targets



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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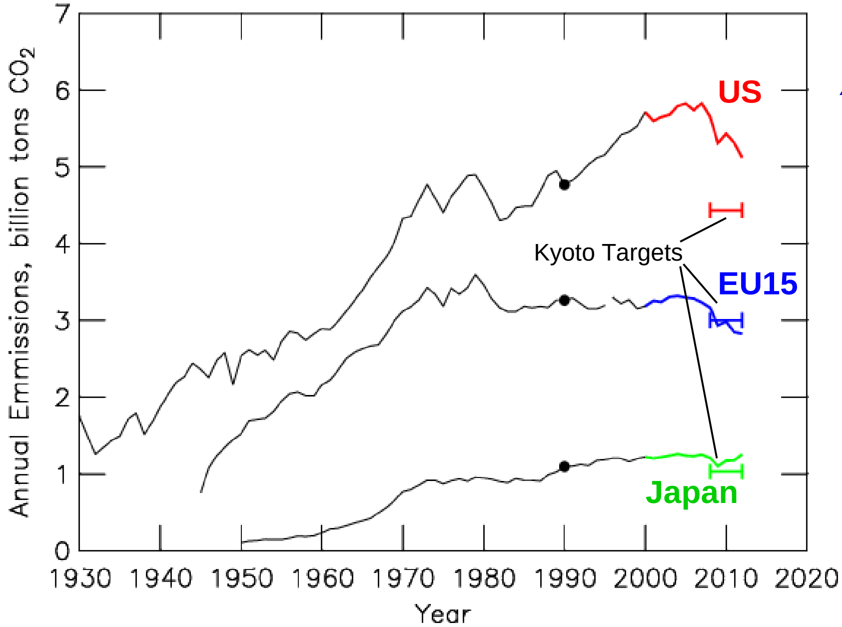
Kyoto Protocol Targets

CO_2 emissions



Does not include:
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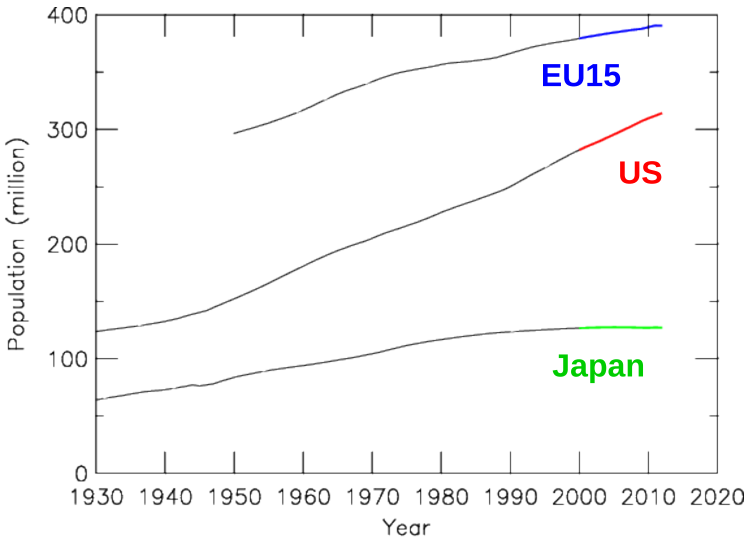

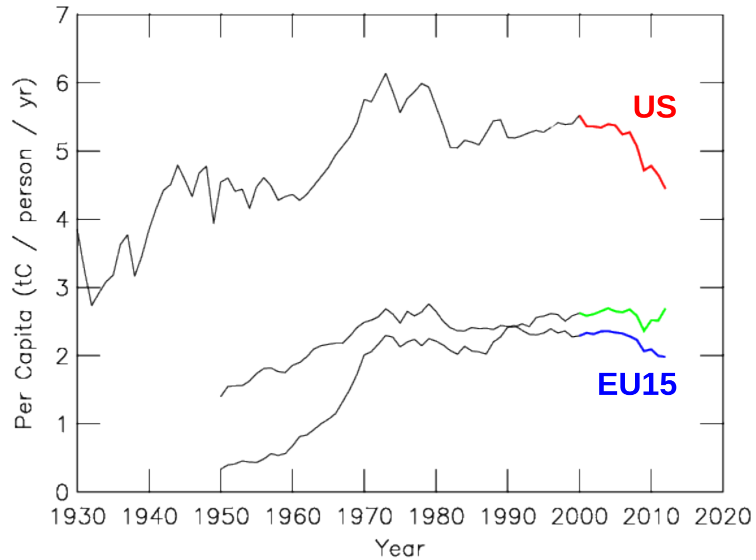

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Kyoto Mechanisms

- 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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UNFCCC 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

UNFCCC: United Nations Framework Convention on Climate Change

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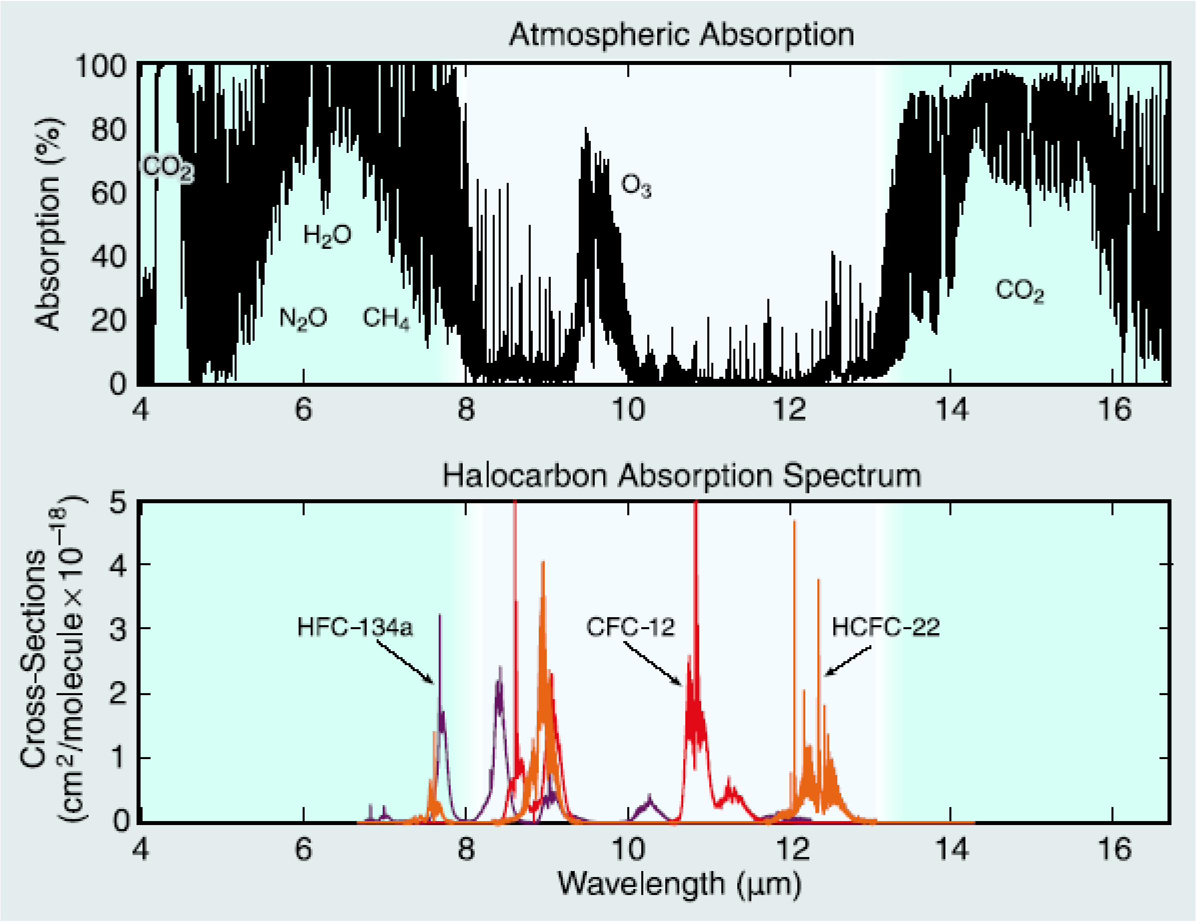
HFCs Spectra



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

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

where:

$a_{\text{HFC}-\text{134a}}$ = 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	5280	1760

Table 8.A.1, IPCC (2013)

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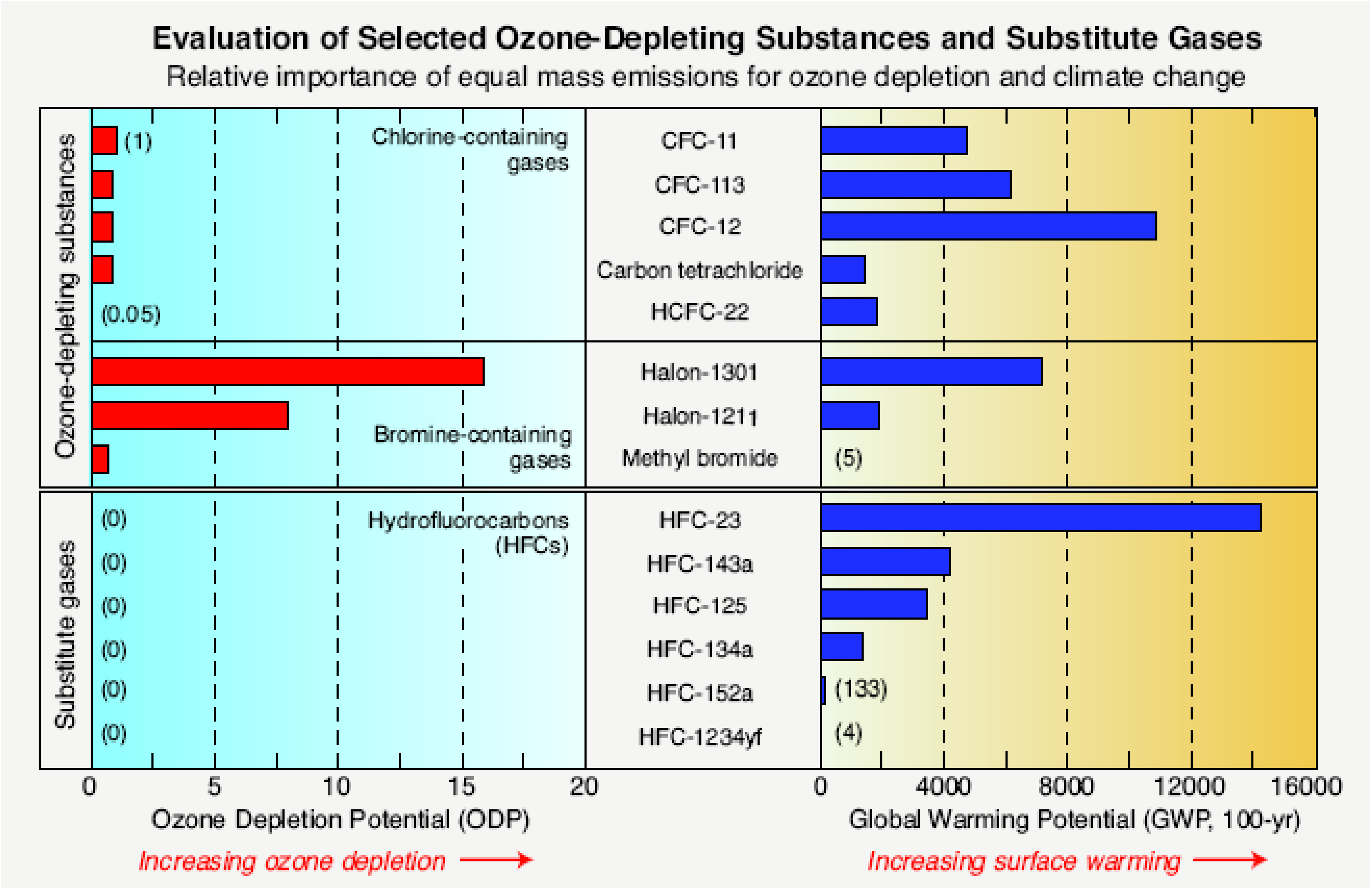
Not all HFCs are equal wrt Global Warming



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

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Radiative Forcing due to HFCs

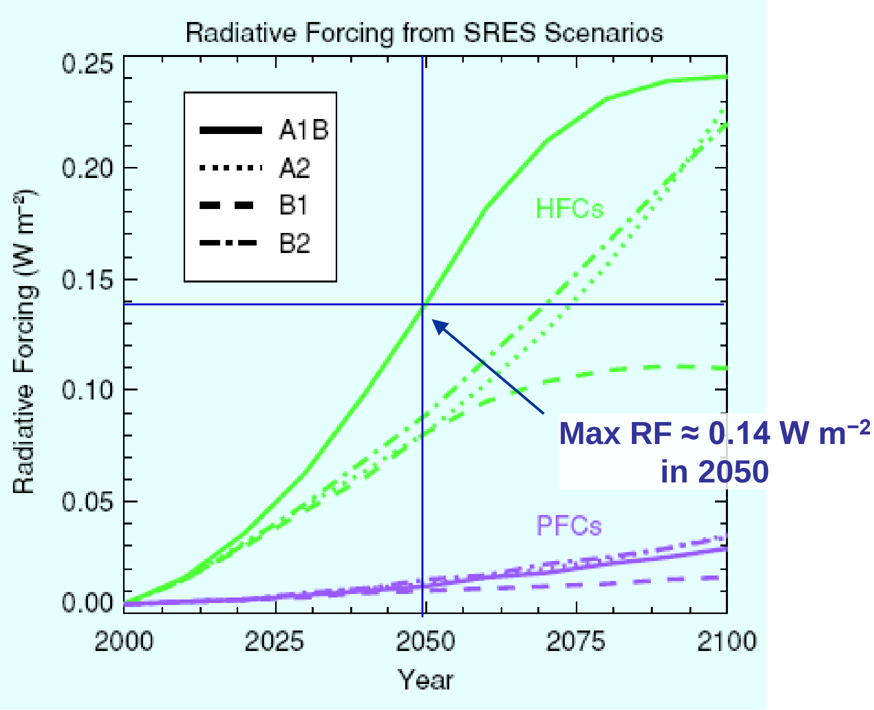
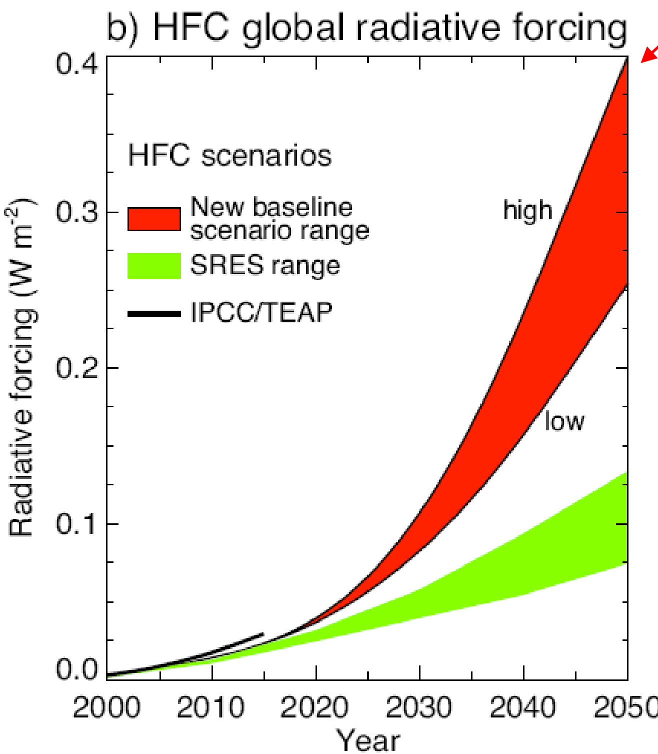


Fig 2.9

Max RF ≈ 0.40 W m^{-2} in 2050



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

Velders et al., PNAS, 2009

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

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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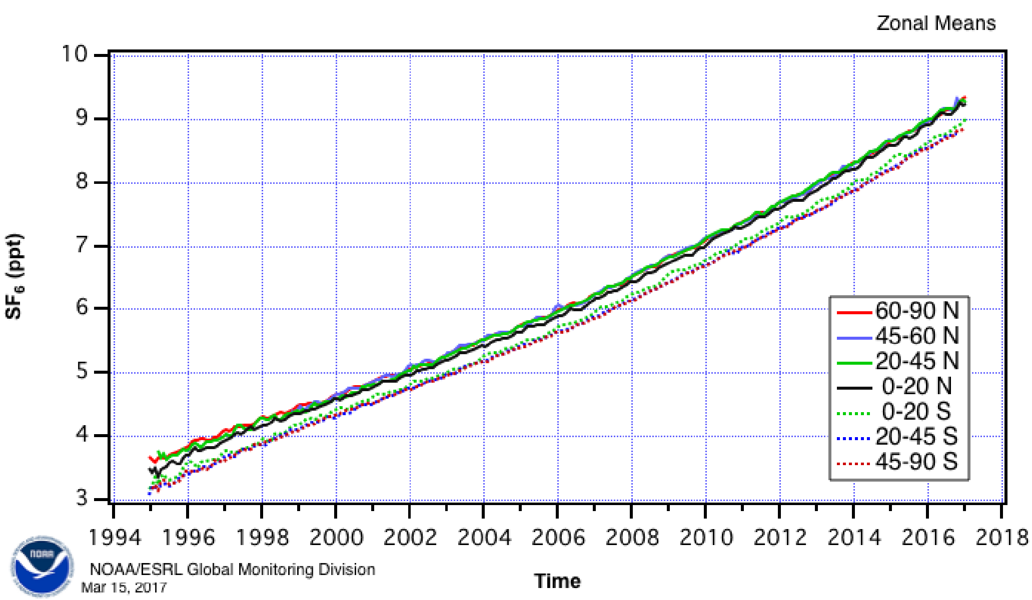
Radiative Forcing due to SF_6



https://www.esrl.noaa.gov/gmd/webdata/hats/combined/hats_sf6_zones.png

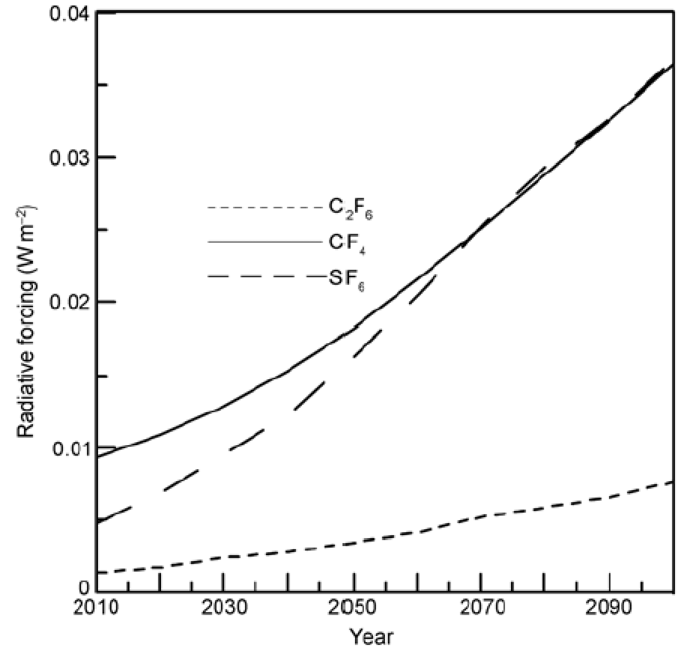


Figure 4 Radiative forcing of C_2F_6, CF_4, and SF_6 from 2010 to 2100.

Zhang et al., Sci China Earth Sci, 2011

SF_6: Sulfur hexafluoride

- τ_{SF6} = 3,200 yr
- Applications: gaseous dielectric in electrical transformers; insulator for windows; retina surgery
- Also had been used in sneakers but Nike has phased out this use:

http://americancarbonregistry.org/carbon-registry/projects/nike-sf6-substitution-project

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Two Super Heroes

US / China Announcement ⇒ Paris Climate Agreement

Nov 2014: Presidents Obama & Xi announced

U.S. would reduce GHG emissions to 27% below 2005 by 2025

China would peak GHG emissions by 2030 with best effort to peak early

Paris Climate Agreement:

Article 2, Section 1, Part a):

Objective to hold "increase in GMST to well below **2ºC** above pre-industrial levels and to pursue efforts to limit the temperature increase to **1.5ºC** above pre-industrial levels"

INDC: **I**ntended **N**ationally **D**etermined **C**ontributions to reduce GHG emissions

- Submitted prior to Dec 2015 meeting in Paris
- Consist of either **unconditional** (promise) or **conditional** (contingent) pledges
- Generally extend from present to year 2030

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Two Futures

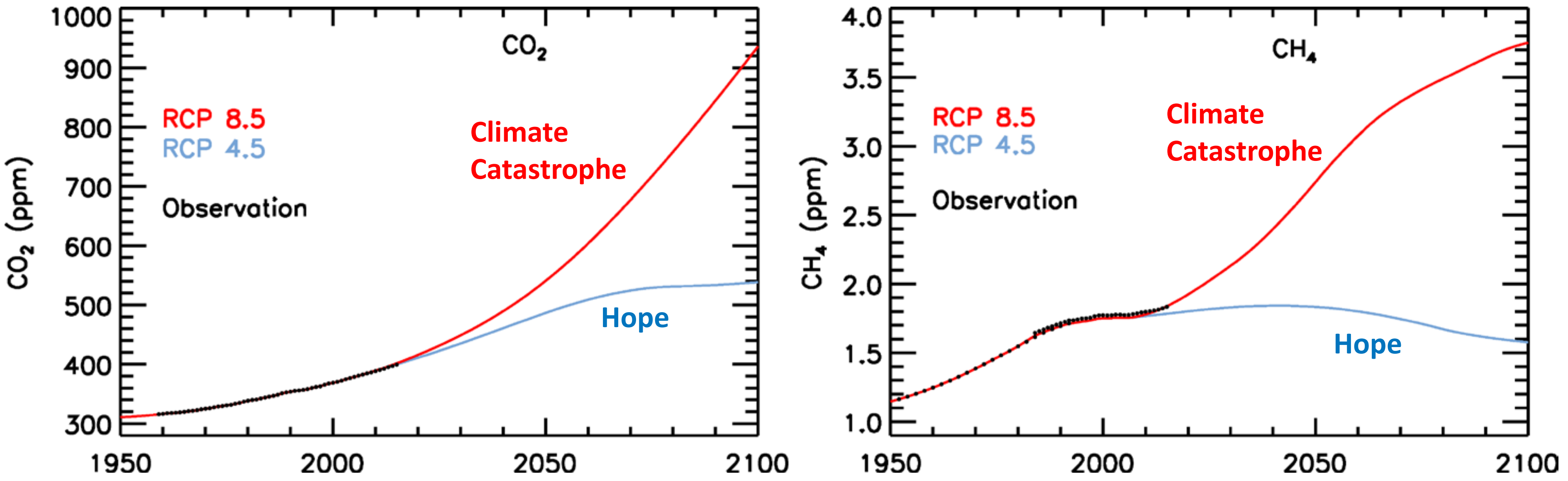

Fig 2.1

RCP: **R**epresentative **C**oncentration **P**athway

Number represents W m^{-2} RF of climate, units of Watts per square meter, that occurs at end of this century

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University of Maryland research indicates RCP 4.5 is the 2°C Pathway

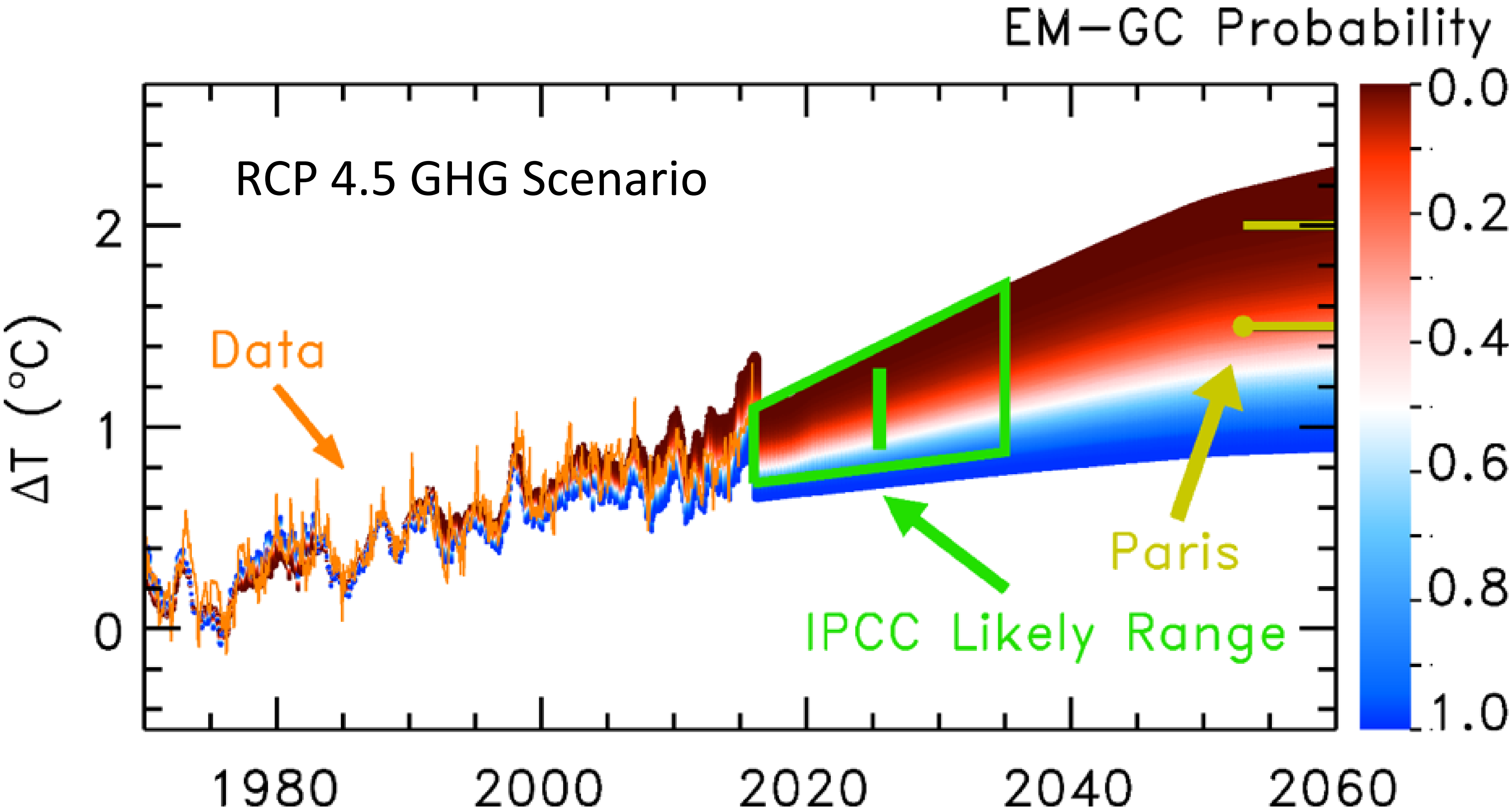

Fig 2.19

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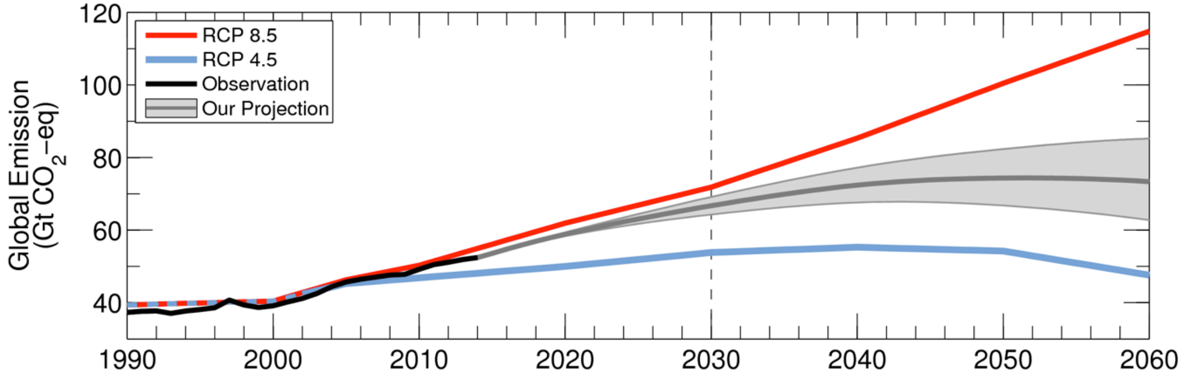
BAU: Business as Usual



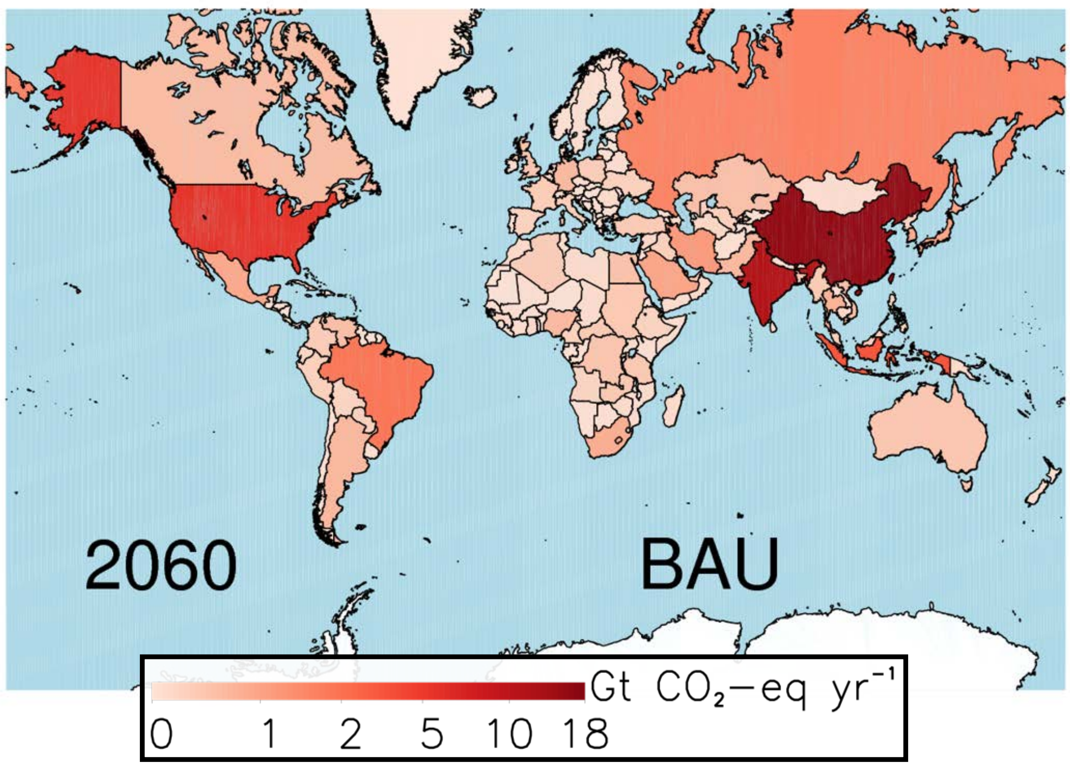


Fig. 3.8 & 3.13

CO_2-eq: Considers emissions of CO_2, CH_4, & N_2O

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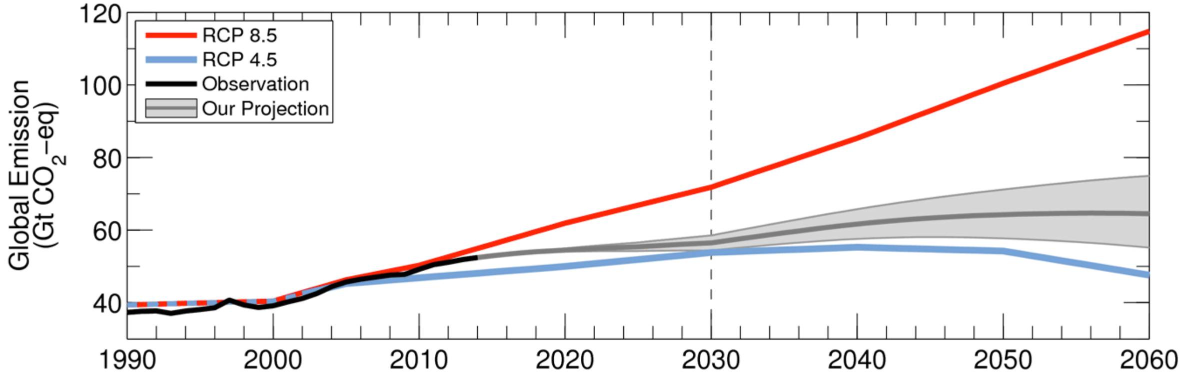
Attain & Hold, all Unconditional INDCs



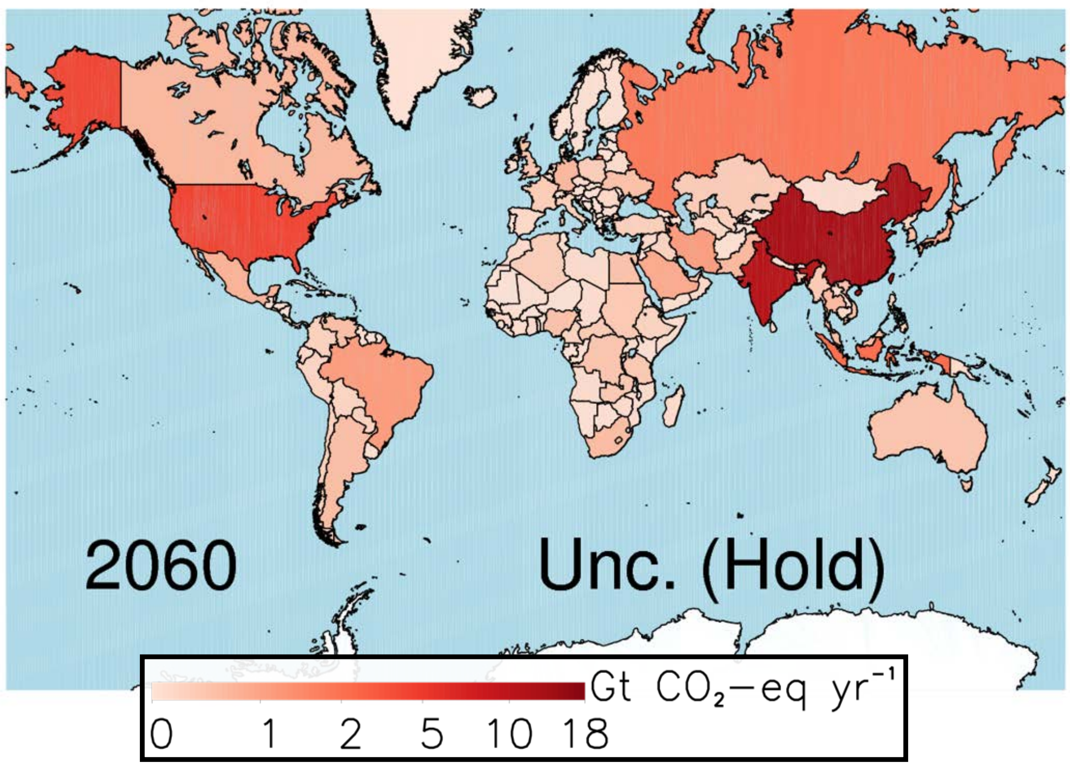


Fig. 3.9 & 3.13

CO_2-eq: Considers emissions of CO_2, CH_4, & N_2O

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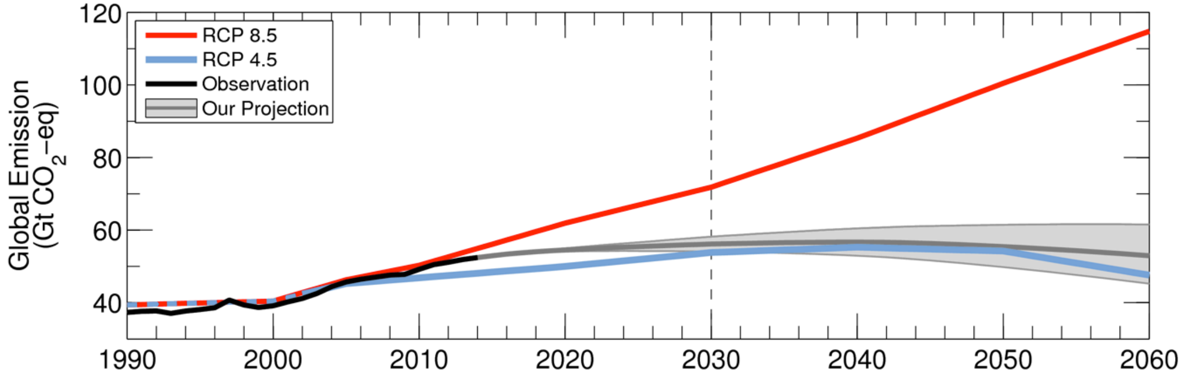
Attain & Improve, all Unconditional INDCs



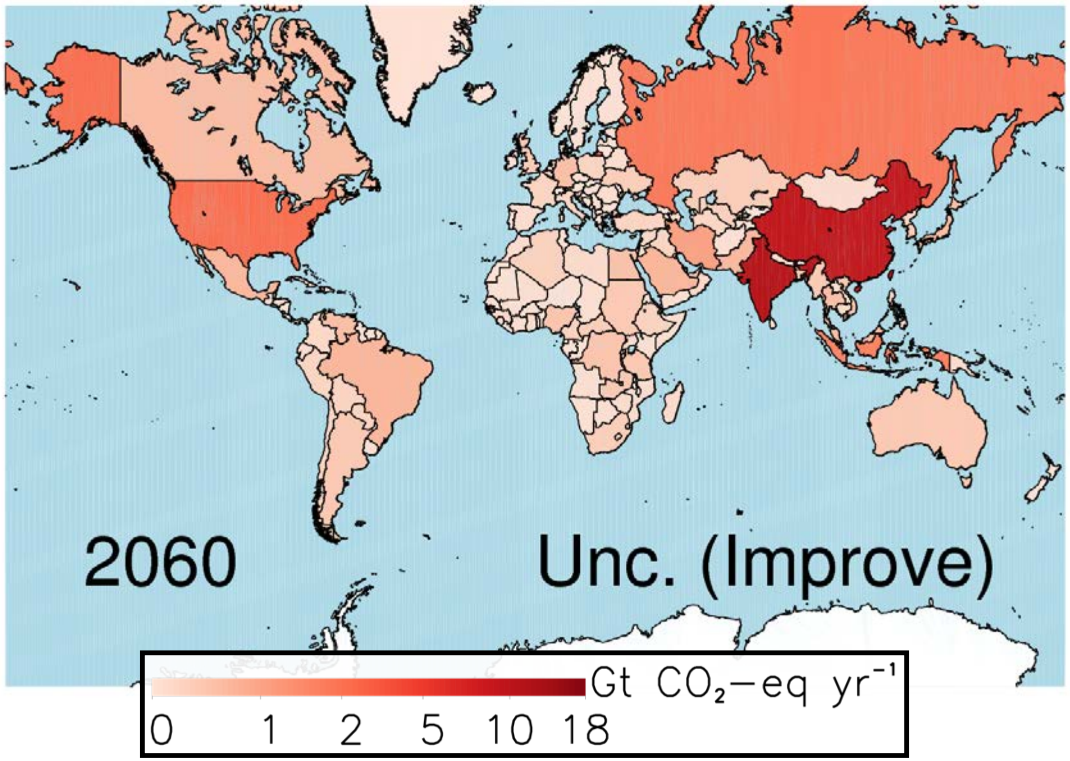


Fig. 3.10 & 3.13

CO_2-eq: Considers emissions of CO_2, CH_4, & N_2O

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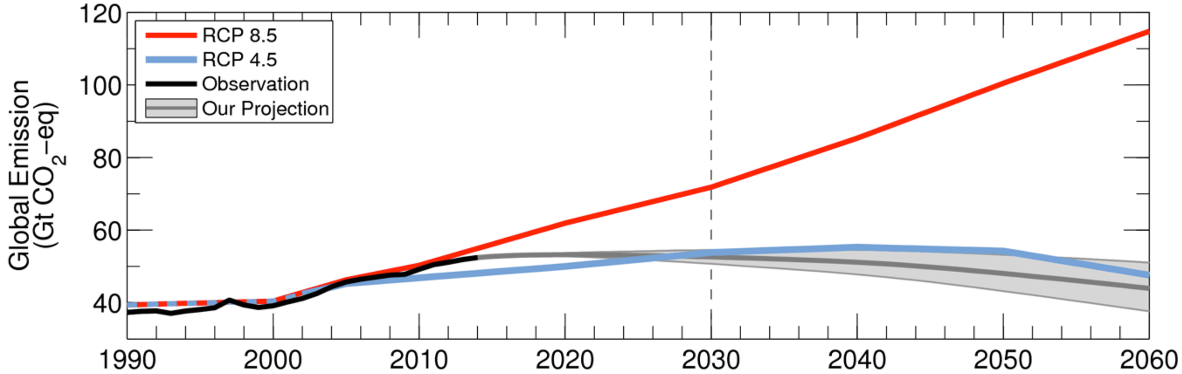
Attain & Improve, all Unconditional & Conditional INDCs



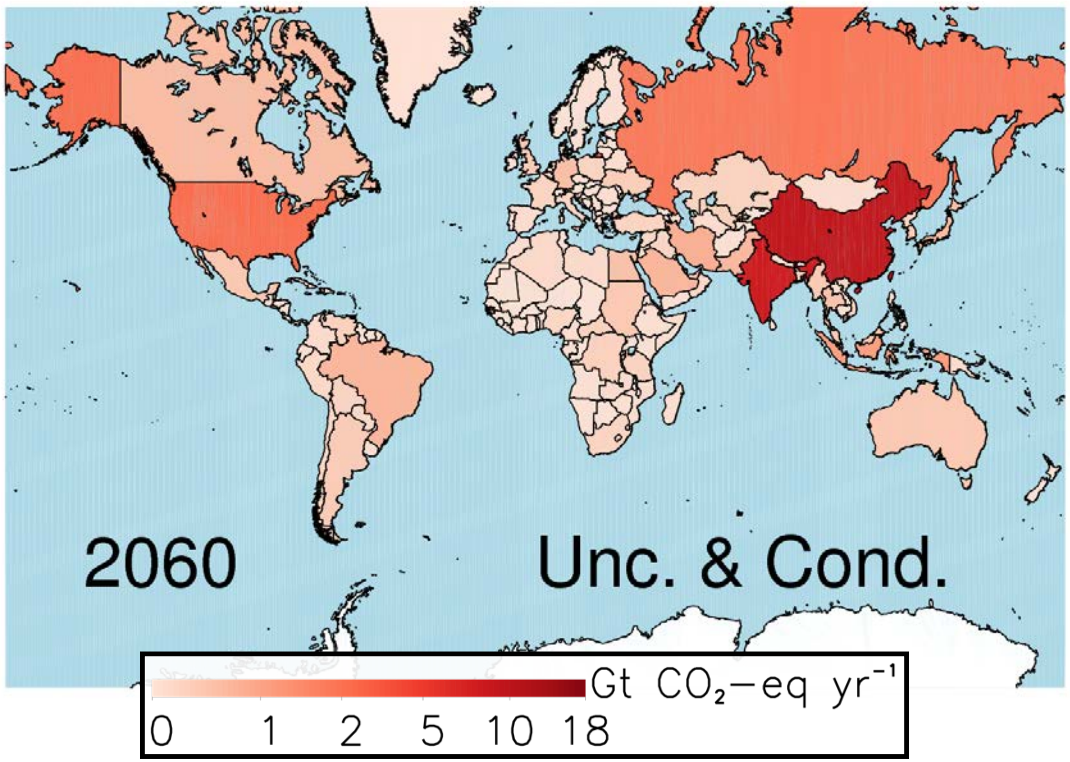


Fig. 3.11 & 3.13

CO_2-eq: Considers emissions of CO_2, CH_4, & N_2O

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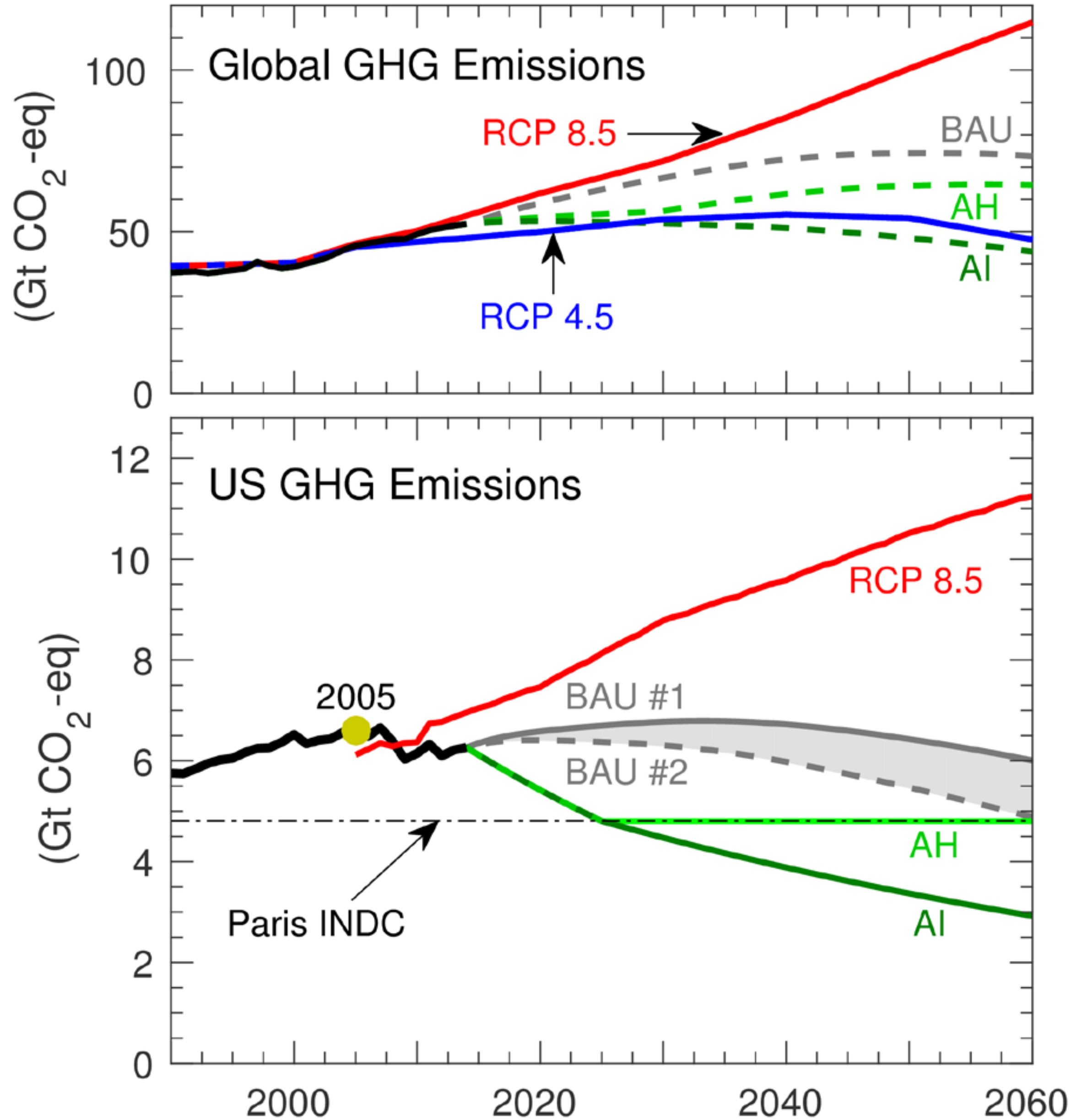

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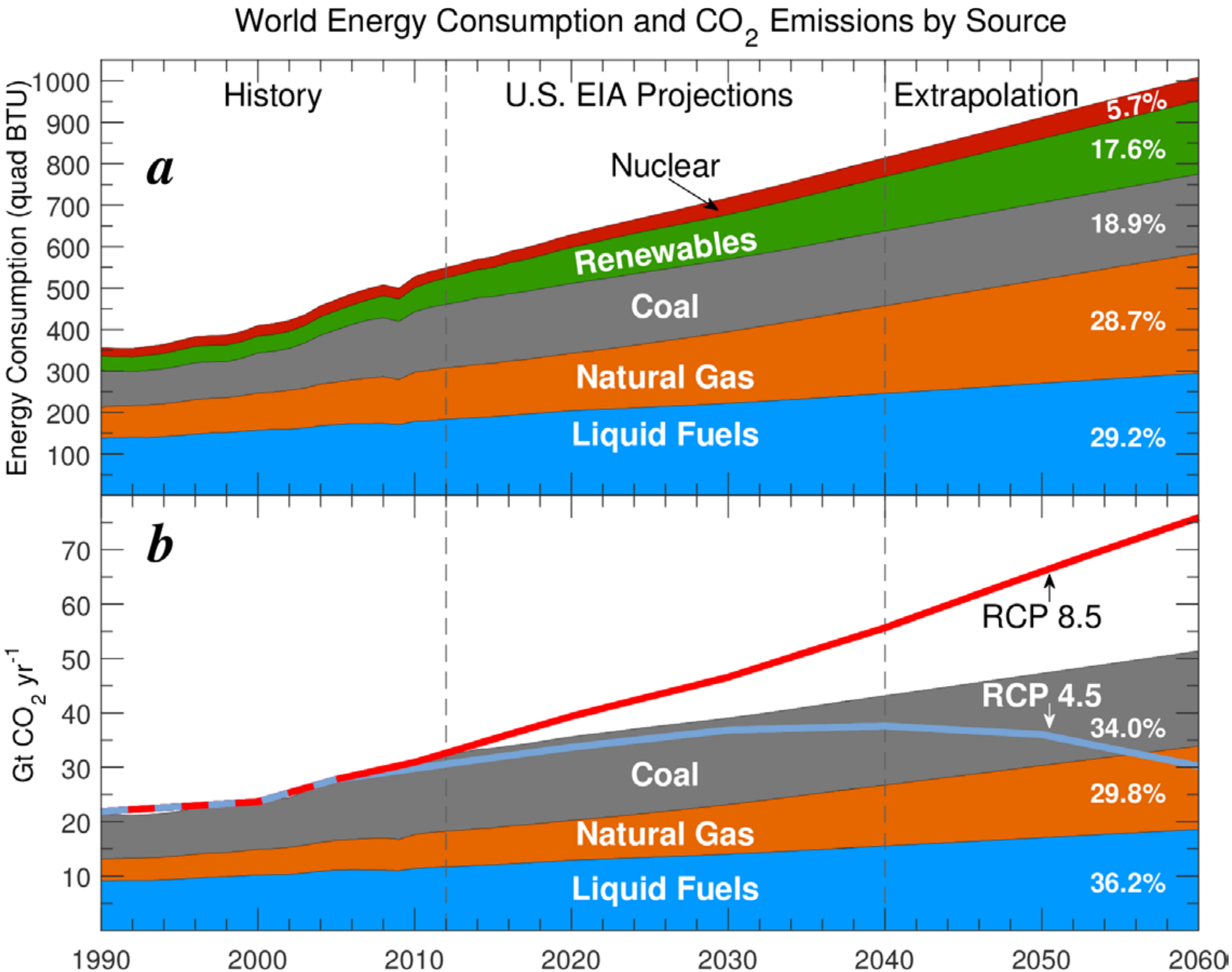

Fig. 4.2

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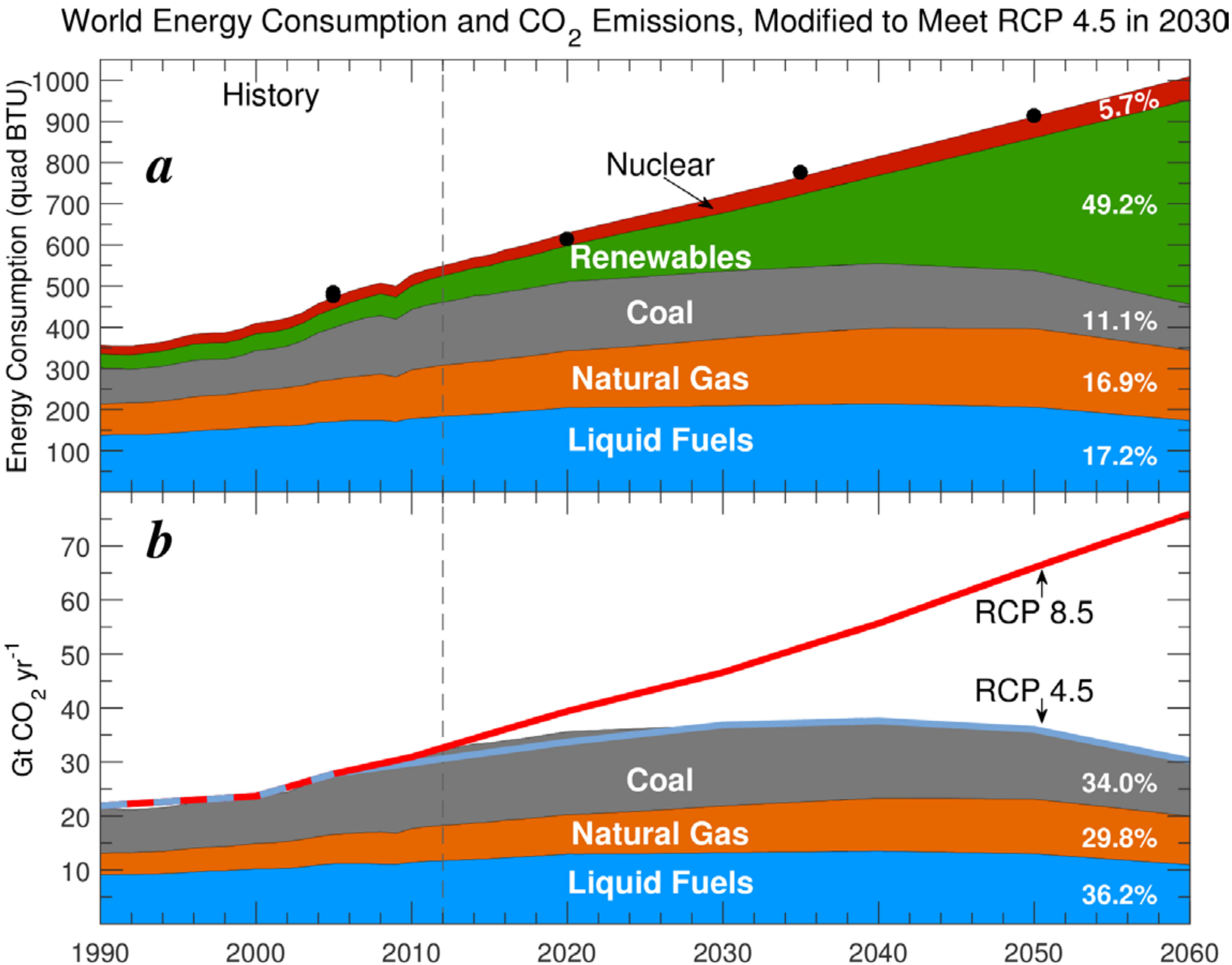

Fig. 4.3

Achieving RCP 4.5 requires *half of world energy* to be supplied by sources that do not emit GHGs, by year 2060

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CH_4 (methane aka natural gas) matters

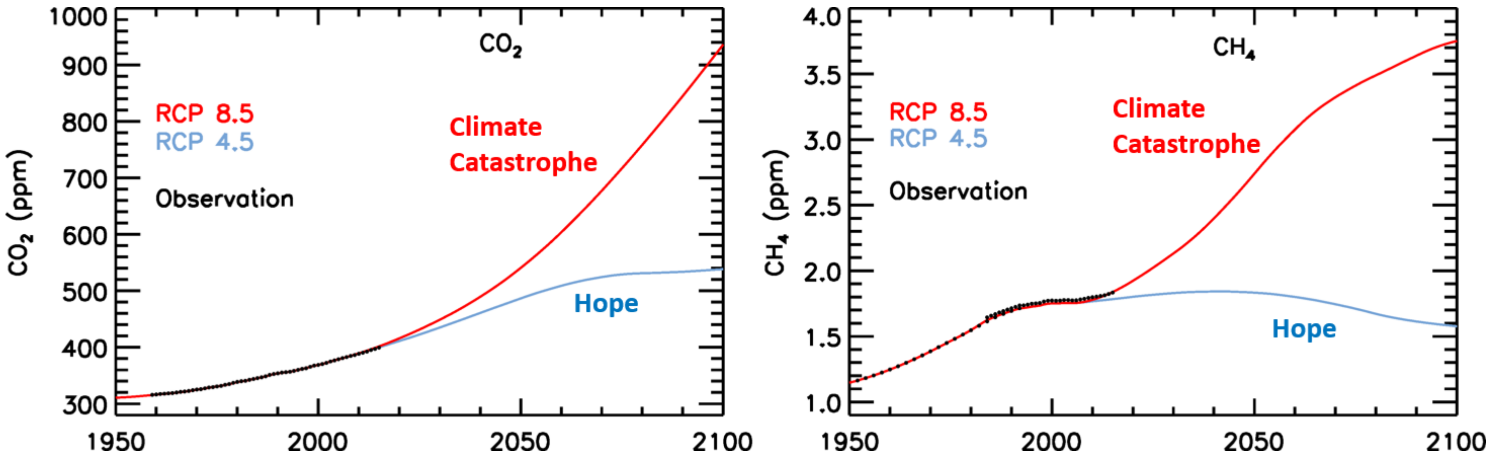
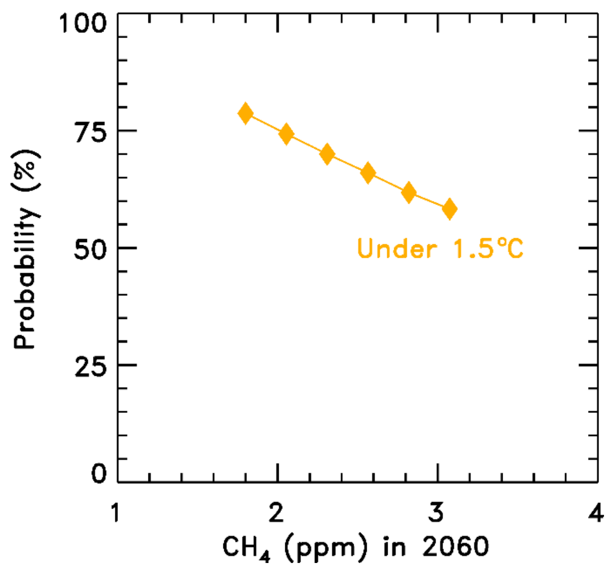


Fig 2.1

Fig 4.12



Prob. warming stays below 1.5°C for all GHGs following RCP 4.5 except CH_4, which is allowed to vary

RCP 4.5 requires immediate reduction in human release of methane.
If CO_2 were to follow RCP 4.5 but methane were to follow RCP 8.5,
the probability of achieving Paris goal of 1.5°C warming would substantially decline

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Pacala and Socolow: CO_2 Stabilization Wedges

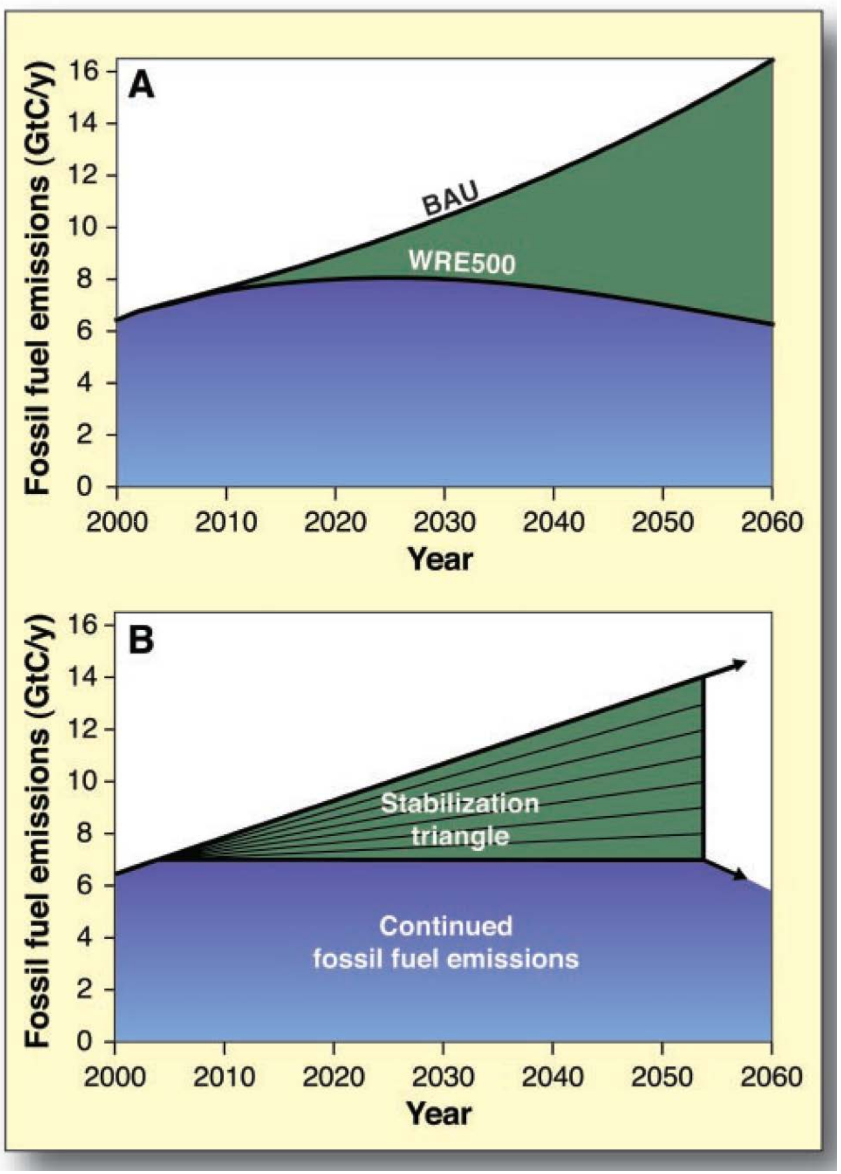

Fig. 1. (**A**) The top curve is a representative BAU emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization 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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