Kyoto Protocol and the Paris Climate Agreement

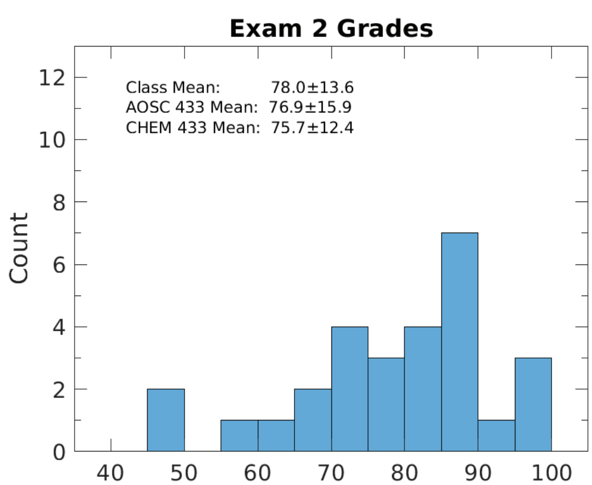
AOSC / CHEM 433 & AOSC 633

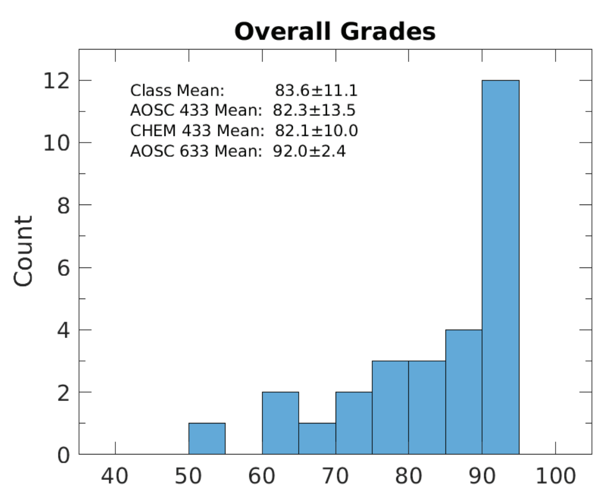
Ross Salawitch & Walt Tribett

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2019

Topics for today:
- **Kyoto Protocol**
- **Obama / Xi Accord**
- **Paris Climate Agreement**

Lecture 18
23 April 2019





Announcements

Interesting presentation on Wed, 24 April, 5:45 pm, ATL 2400
Preceded by a reception (⇒ free food) staring at 5:00 pm

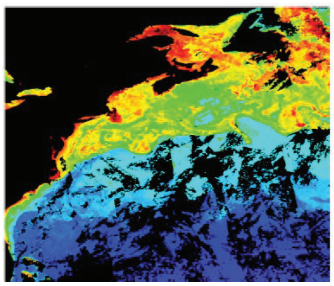
attendance is voluntary

Seminar will be ~an hour long

Ocean Acidification and Rising Ocean Temperature Impacts on Marine Ecosystems

Prof. Scott C. Doney
University of Virginia

What is the relationship between ocean acidification and rising temperatures and how do those phenomena affect sealife? How does ocean pollution exacerbate these environmental stressors and increase the susceptibility of marine organisms to disease and habitat disruptions? What is the future of marine ecosystems based on model predictions? These are among the many questions raised by the changing climate.



Chlorophyll concentration in the western North Atlantic in late-April, 2018 from the NASA MODIS Aqua satellite

https://www.atmos.umd.edu/seminar/semAbstract.php?event_id=272

Announcements

Will show Ozone Hole documentary on Thurs, 25 April, 6:00 pm, ATL 3400: attendance is voluntary

Documentary is 55 minutes long

Ozone Hole: How We Saved the Planet

OZONE HOLE: HOW WE SAVED THE PLANET
Courtesy of Windfall Films/NASA

Premieres Wednesday, April 10, 2019
10:00-11:00 p.m. ET on PBS

New Documentary Tells the Remarkable Story of How Scientists Discovered the Deadly Hole in the Ozone – and the Even More Remarkable Story of How the World's Leaders Came Together to Fix It

https://www.pbs.org/video/ozone-hole-how-we-saved-the-planet-ttwe2l

AT 17

Combustion of 1 gram of CH_4 results of 50.1 kJ of energy
Combustion of 1 gram of C results in 32.8 kJ of energy

Therefore, we might conclude natural gas is 50.1 / 32. 8 = 1.53 times more efficient, which I would right as 53% more efficient.
However, combustion of 1 gram of C results in 32/12 + 1 = 3.667 gram of CO_2 whereas combustion of 1 gram of CH_4 results in 12/16 (32/12+1) = 2.75 gram of CO_2

To place natural gas and coal (pure C) on equal footing, must first multiply energy yield from natural gas by (3.667/2.75) = 1.33, so that atmospheric CO_2 produced by both processes is identical.

We find natural gas is 1.33 × 50.1 / 32.8 = 2.0; i.e., about 100% more efficient than coal.

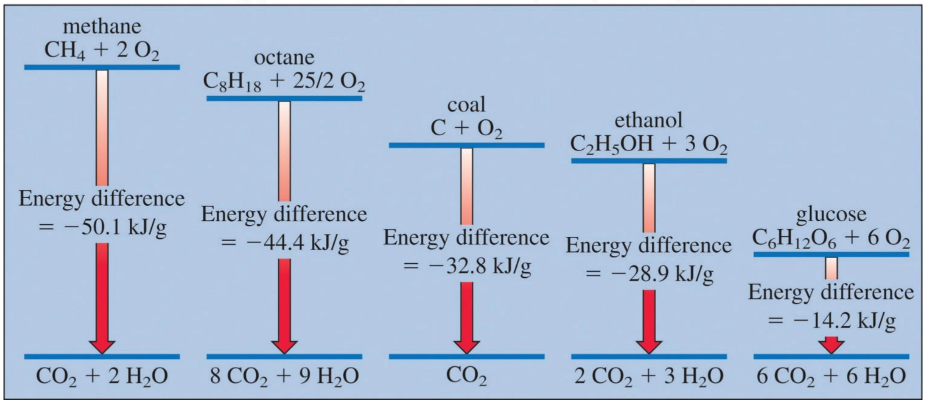


Fig 4.26. Energy differences (in kJ/g) for the combustion of methane (CH_4), n-octane (C_8H_{18}), coal (assumed to be pure carbon), ethanol (C_2H_5OH), and wood (assumed to be glucose).

AT 17

Combustion of 1 gram of CH_4 results of 50.1 kJ of energy
Combustion of 1 gram of C results in 32.8 kJ of energy

Alas, coal is not pure carbon in the real world. Rather, notational formula for coal is $C_{135}H_{96}O_9NS$ (page 162 of Chemistry in Context): i.e., coal has a carbon content of 85% by mass.

Therefore, we'd state:
natural gas is actually 1.33 × 50.1 / (32.8/0.85) = 1.73; i.e., 73% more efficient than coal.

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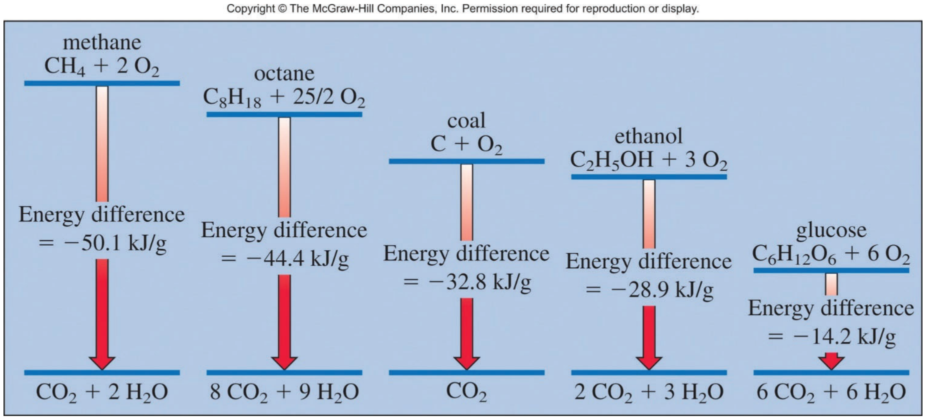

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Future Use of Fossil Fuels

Table shown last lecture

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

Natural gas produces (1/1.3) / (1/2.1) = 1.61; i.e., 61% more energy than coal, per CO_2 released
Natural gas produces (1/1.3) / (1/5.6) = 4.3; i.e., more than 4× more energy than oil sands, per CO_2 released

http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html
https://iopscience.iop.org/article/10.1088/1748-9326/4/1/014005/meta

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*

CO_2-equiv. emiss. = CO_2 (mass)+GWP_{CH4} × CH_4 (mass)+GWP_{N2O}×N_2O (mass) etc.

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

Kyoto Protocol

KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

UNITED NATIONS

1998

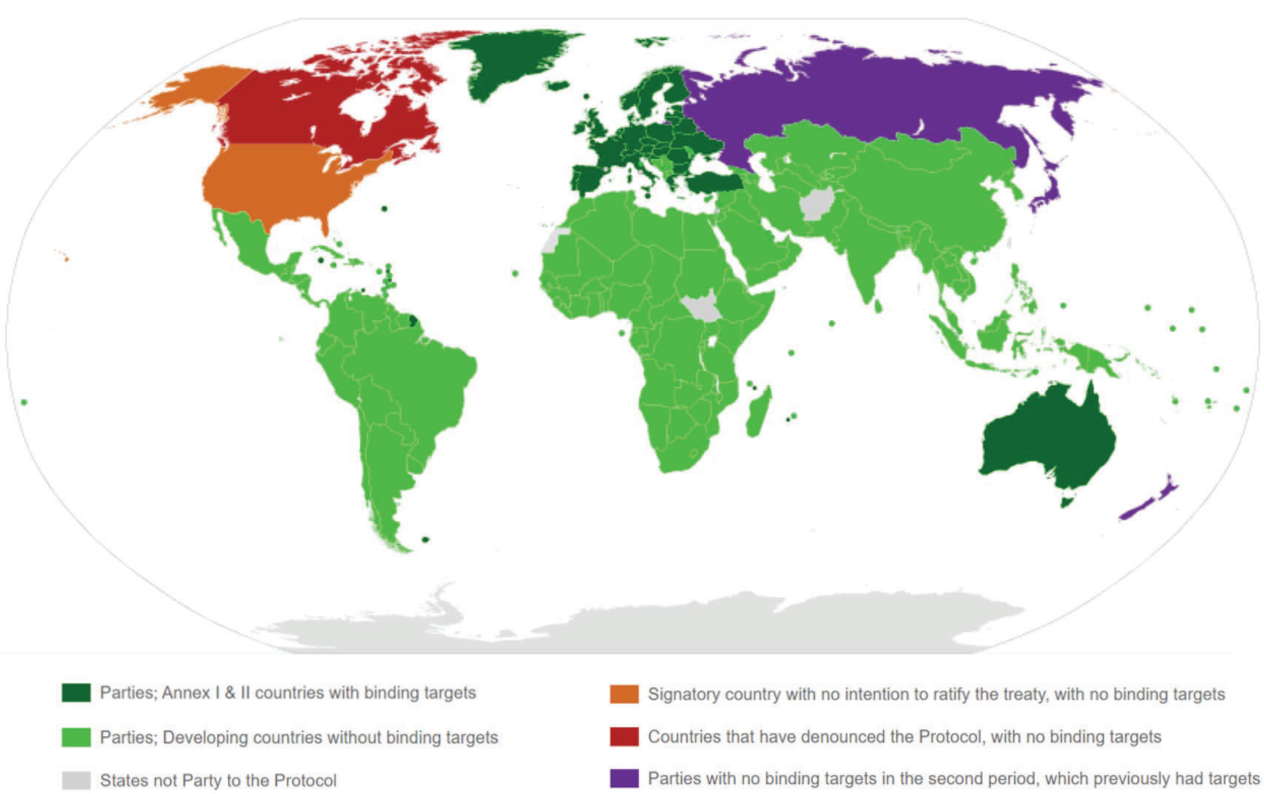
Article 3

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.

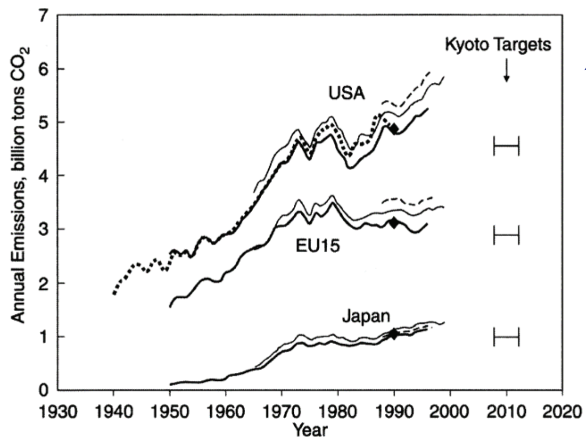
Kyoto Protocol



https://www.climate-change-guide.com/kyoto-protocol.html

Kyoto Protocol Targets

CO_2 emissions



Does not include:
- **LULUCF (land use, land-use change and forestry)**
- **GHGs other than CO_2**

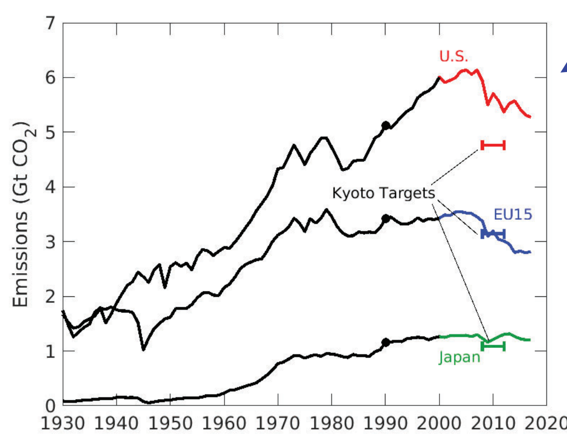
Kyoto target (2008 to 2012) for emissions of CO_2, relative to 1990 emissions
selected locations

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.

Kyoto Protocol Targets

CO_2 emissions



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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

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

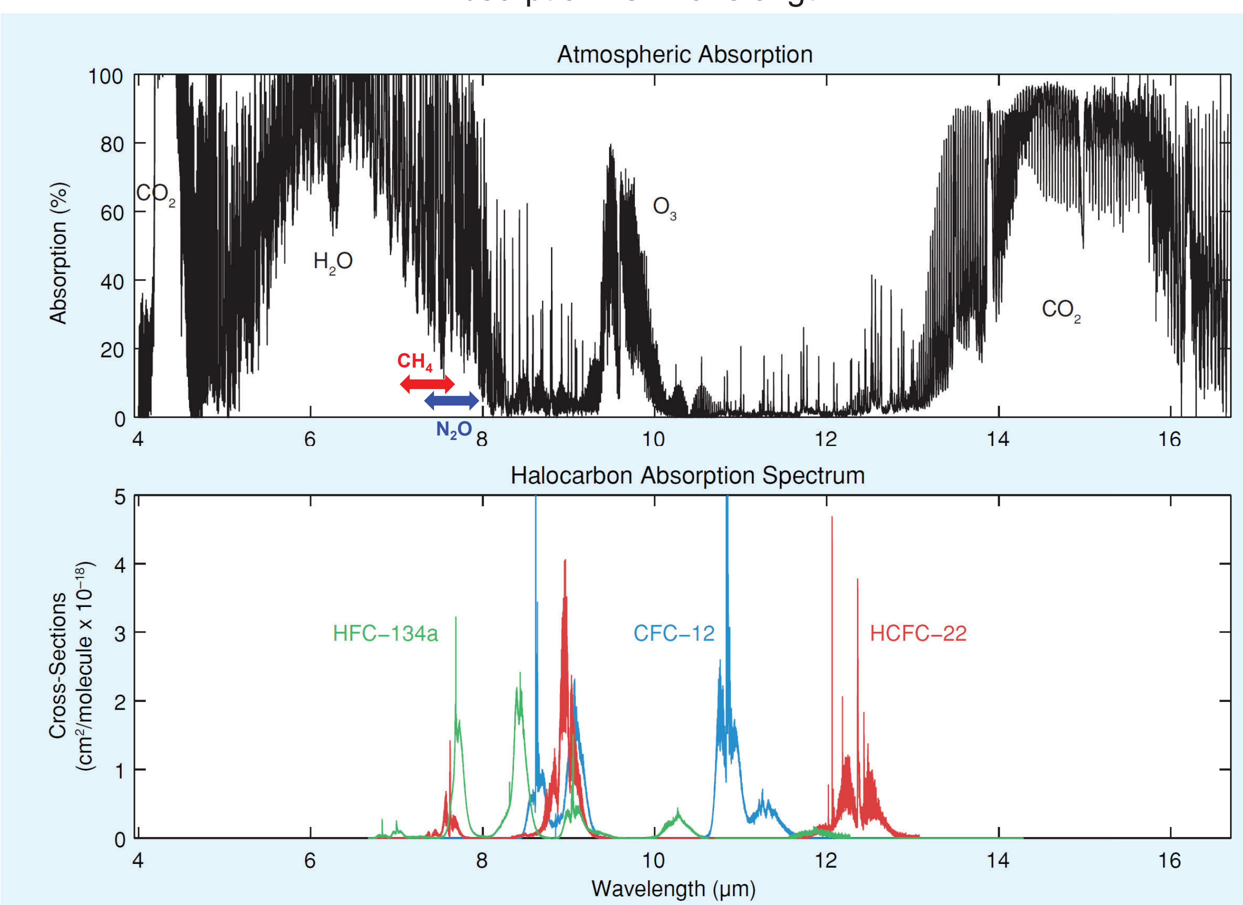
Their ability to sell credits under emissions trading will also be suspended

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

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−143a: $C_2H_3F_3$), 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

Absorption vs. Wavelength



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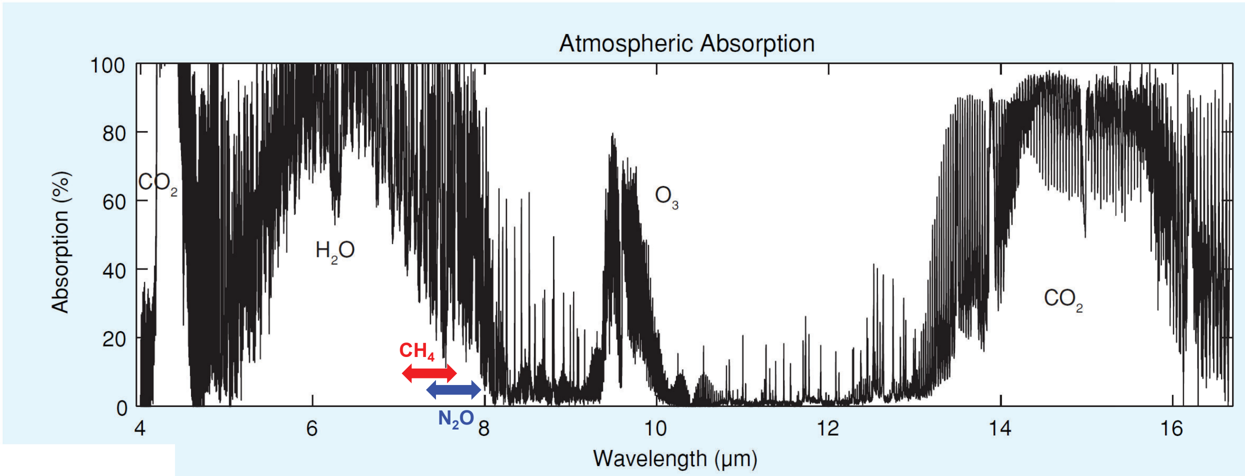
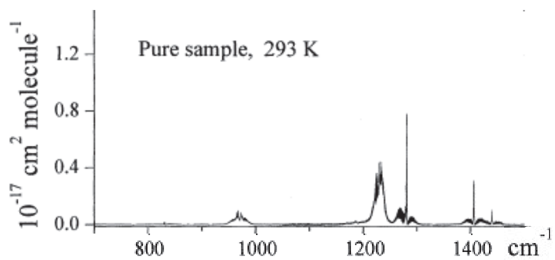




Absorption cross section of HFC-143a
DiLonardo and Masciarelli, 2000
https://www.sciencedirect.com/science/article/pii/S0022407399002125

GWP – Global Warming Potential

$$\text{GWP (HFC}-143\text{a)} = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\text{HFC}-143\text{a}} \times [\text{HFC}-143\text{a(t)}]\ \text{dt}}{\int_{\text{time initial}}^{\text{time final}} a_{\text{CO2}} \times [\text{CO}_2\text{(t) dt}]}$$

where:

$a_{HFC-143a}$ = Radiative Efficiency (W m^{-2} ppb^{-1}) due to HFC-143a

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

HFC-143a (t) = time-dependent response to an instantaneous release of a pulse of HFC-143a

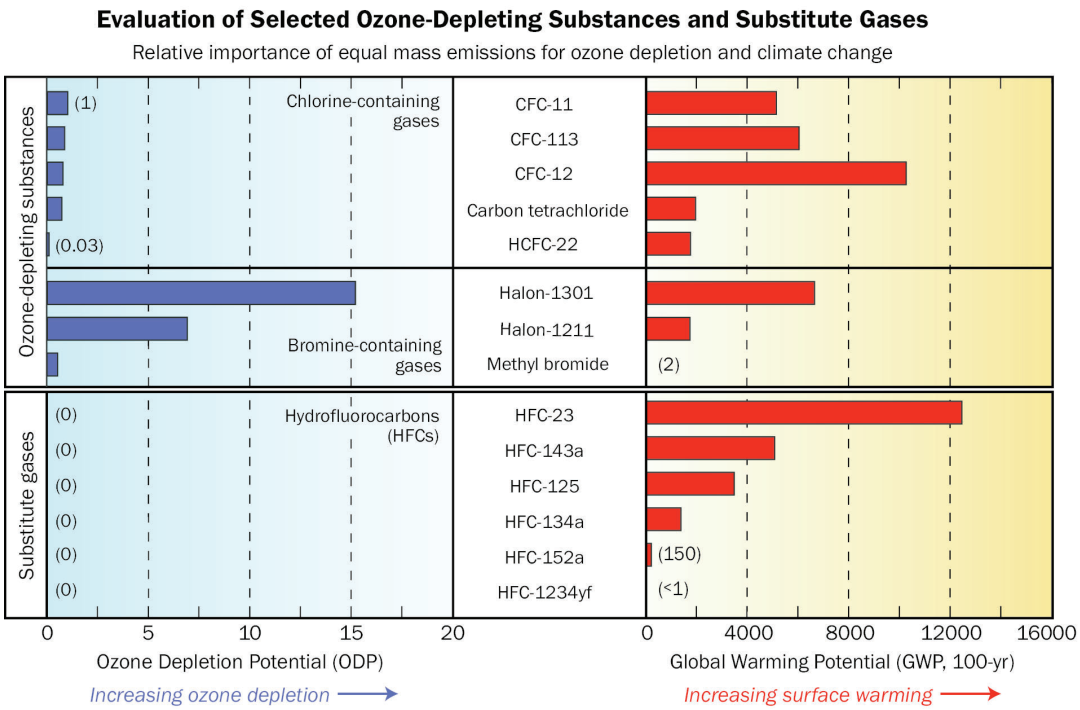
CO_2 (t) = time-dependent response to an instantaneous release of a pulse of CO_2

Note: HFC-143a is $C_2H_3F_3$
HCFC-22 is CH_3CClF_2

		GWP Time Horizon		ODP
	τ (yr)	20-yr	100-yr	n.a.
HFC-143a	51	7050	5080	0
HCFC-22	12	5310	1780	0.034
CFC-11	52	7090	5160	1.0

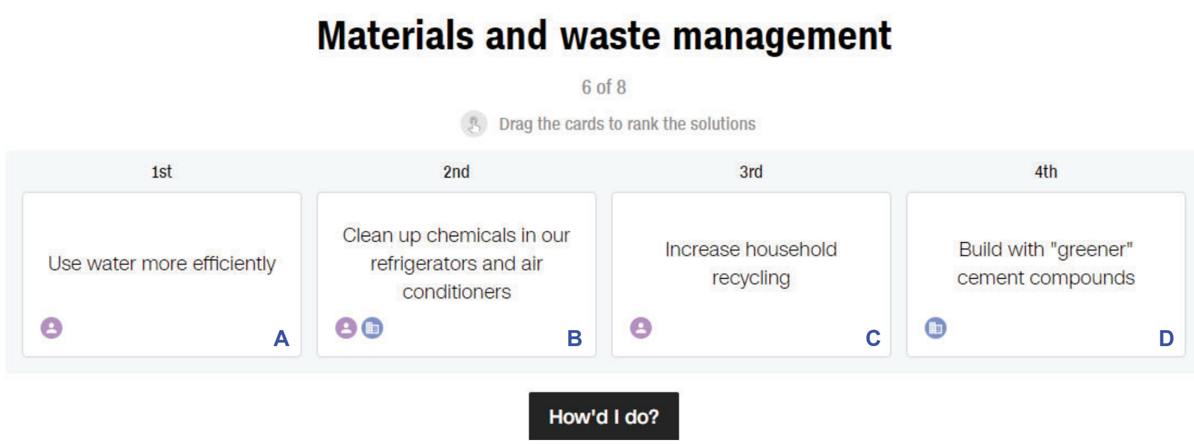
Table 8.A.1, IPCC (2013)

Not all HFCs are equal wrt Global Warming



WMO/UNEO 2014 "Twenty Questions"
http://esrl.noaa.gov/csd/assessments/ozone/2014/twentyquestions

CNN Climate Quiz



https://www.cnn.com/interactive/2019/04/specials/climate-change-solutions-quiz/index.html

Kigali Amendment to the Montreal Protocol

Kigali, Rwanda, October 2016

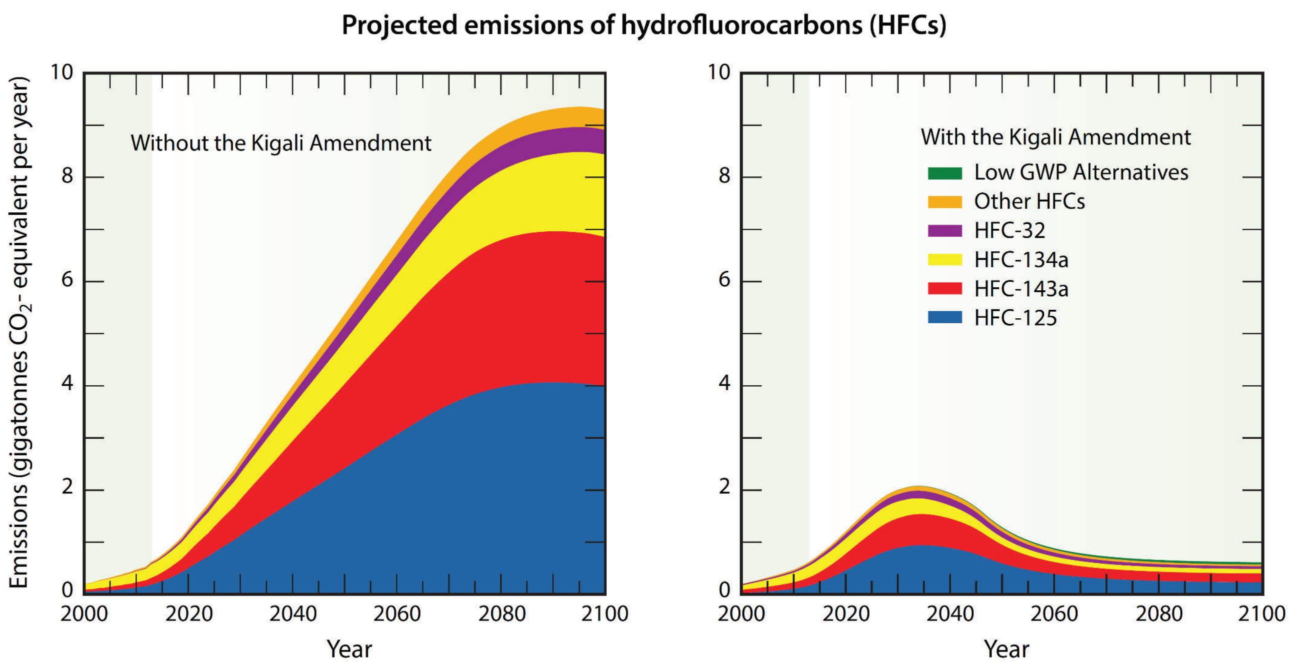
Placed HFCs, which have an ODP of 0.0, under the Montreal Protocol

https://www.unenvironment.org/news-and-stories/news/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate

Konstantina Birbili
Executive Secretary of the U.N. Vienna Convention for the Protection of the Ozone Layer
PhD in Environmental Management and Economics from Imperial College of Science, Technology and Medicine, London
https://en.wikipedia.org/wiki/Tina_Birbili

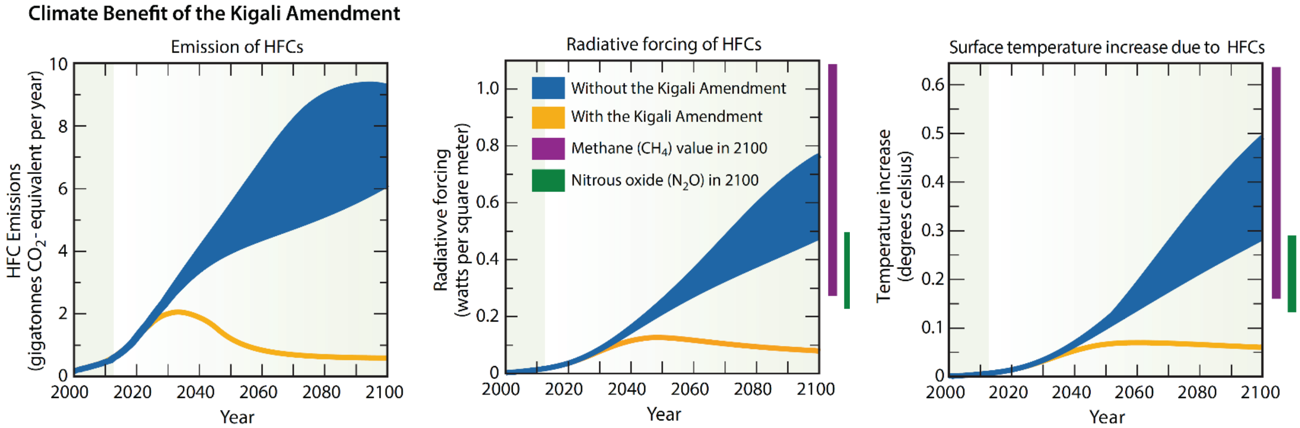
Vincent Biruta
Minister of the Environment, Rwanda
Physician; Masters in Planning and Management from University of Brussels, Belgium
https://en.wikipedia.org/wiki/Vincent_Biruta

Effect of the Kigali Amendment to the Montreal Protocol



Will appear in the next WMO/UNEP "Twenty Questions"

Effect of the Kigali Amendment to the Montreal Protocol



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Radiative Forcing due to PFCs

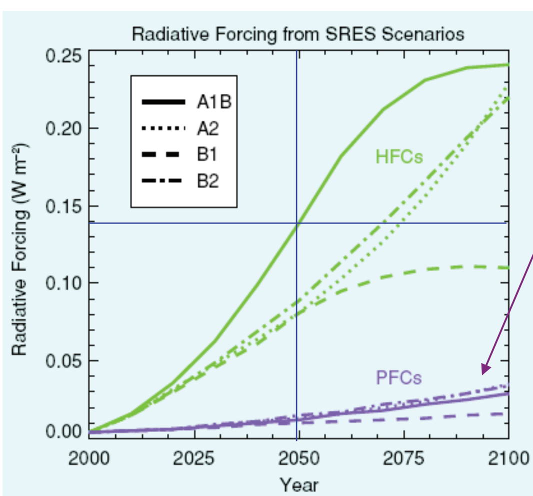


Fig 2.9

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

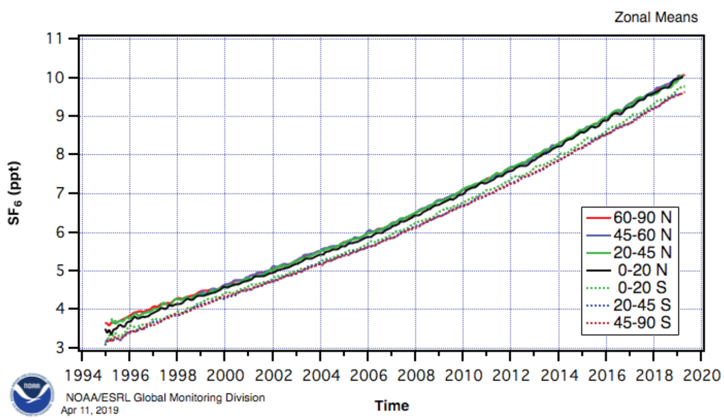
http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

PFC: Perfluorocarbons

- Contain only C & F
- Strong bonds: chemically stable
  τ_{CF4} = 50,000 yr !
- Applications: medical, electrical, cosmetics

https://www.sciencedirect.com/science/article/pii/S0950423001000675

Radiative Forcing due to SF_6



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

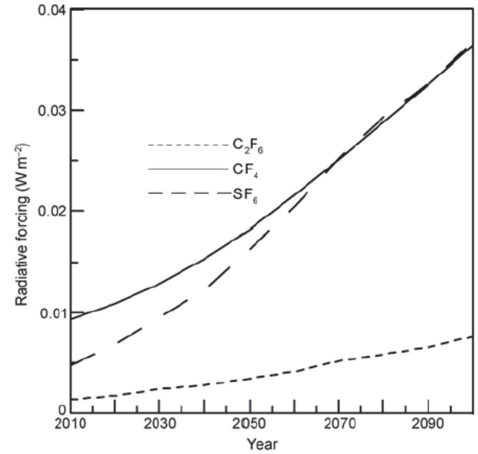


Figure 4 Radiative forcing of C_2F_6, CF_4, and SF_6 from 2010 to 2100.

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

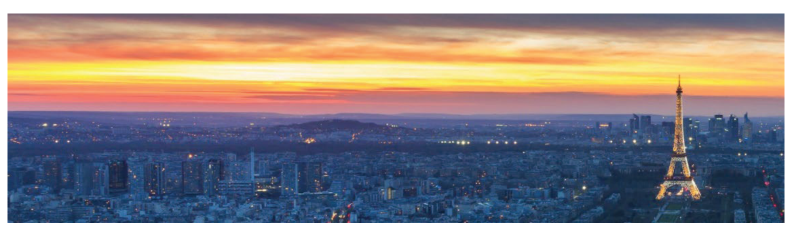
Two Super Heroes

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 **2°C** above pre-industrial levels and to pursue efforts to limit the temperature increase to **1.5°C** above pre-industrial levels"

INDC: Intended **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

Paris Climate Agreement, Dec 2015:

a) Negotiated as an “agreement” (unilateral pledges to reduce GHG emissions by by member nations) rather than a treaty to avoid the need for Senate approval

https://www.senate.gov/artandhistory/history/common/briefing/Treaties.htm

b) Based on language of ratification, U.S. committed to agreement until 4 November 2020

https://qz.com/996882/paris-climate-agreement-trumps-renegotiation-is-not-realistic-in-any-way

https://www.theatlantic.com/science/archive/2017/08/trump-and-the-paris-agreement-what-just-happened/536040

Summer 2017:

President Trump states US intends to withdraw from Paris Climate Agreement

- “withdrawal” symbolic in that US is committed to the agreement until 4 Nov 2020

August 2018:

- Obama’s plan for achieving the U.S. NDC had relied on implementation of the Clean Power Plan by the EPA
- Main gist of Clean Power Plan was transitioning power plants from coal to either natural gas or renewables
- Combustion of natural gas produces about 70% more energy per CO_2 released to the atmosphere than coal
- Clean power plan being abandoned by the US EPA

  https://psmag.com/environment/the-epa-publishes-its-proposed-replacement-for-the-clean-power-plan

  but the main reason natural gas has replaced coal for US power generation is economic, rather than regulatory

What will occur on 3 Nov 2020 ?!?

Three Futures

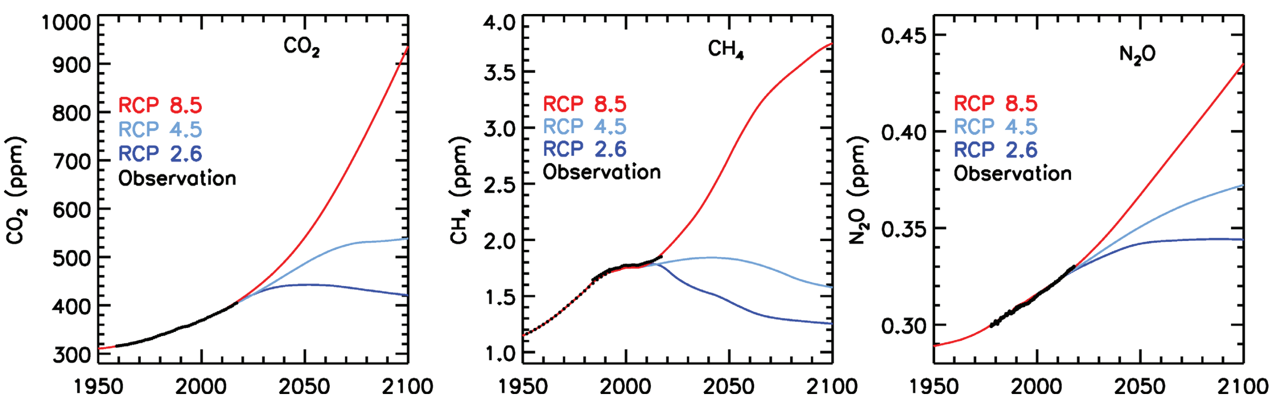


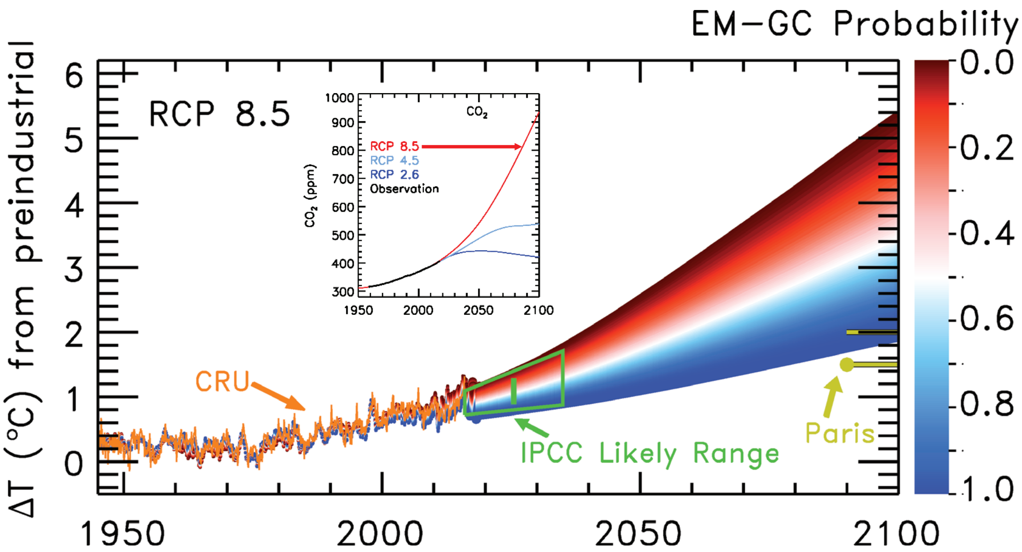
Fig 2.1, update
Paris Climate Agreement: Beacon of Hope

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

Number represents W m^{-2} RF of climate at end of century

Probabilistic Forecast of Human-Induced Rise in GMST for model trained on data acquired until end of 2017 and future GHG levels from RCP 8.5

Fig 2.20 (updated) ***Paris Climate Agreement: Beacon of Hope***

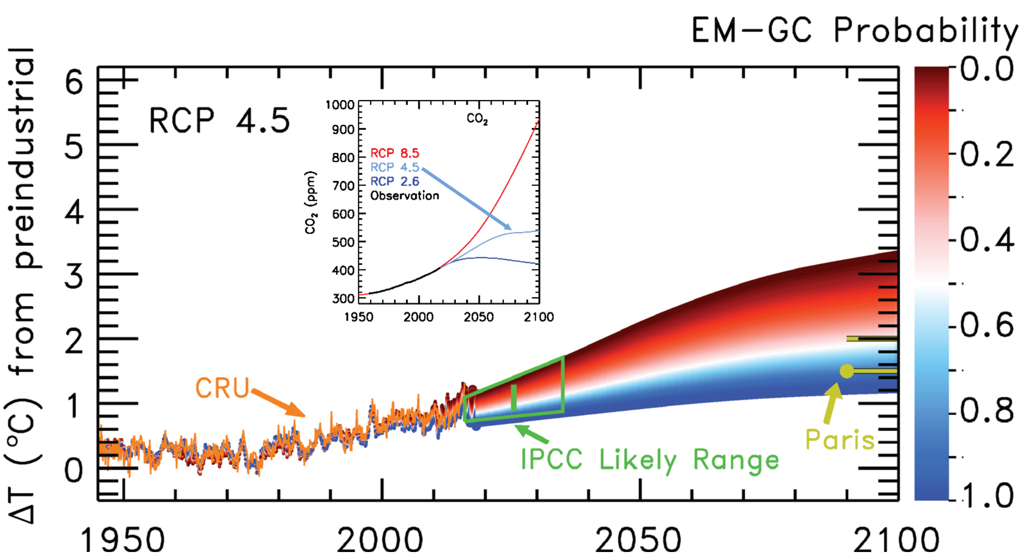


If GHGs follow RCP 8.5, **0%** chance rise GMST stays below **1.5°C** and **0.1%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT
IPCC Likely Range of ΔT : From Fig 11.25b of the 2013 Intergovernmental Panel on Climate Change Report

Probabilistic Forecast of Human-Induced Rise in GMST for model trained on data acquired until end of 2017 and future GHG levels from RCP 4.5

Fig 2.19 (modified) ***Paris Climate Agreement: Beacon of Hope***

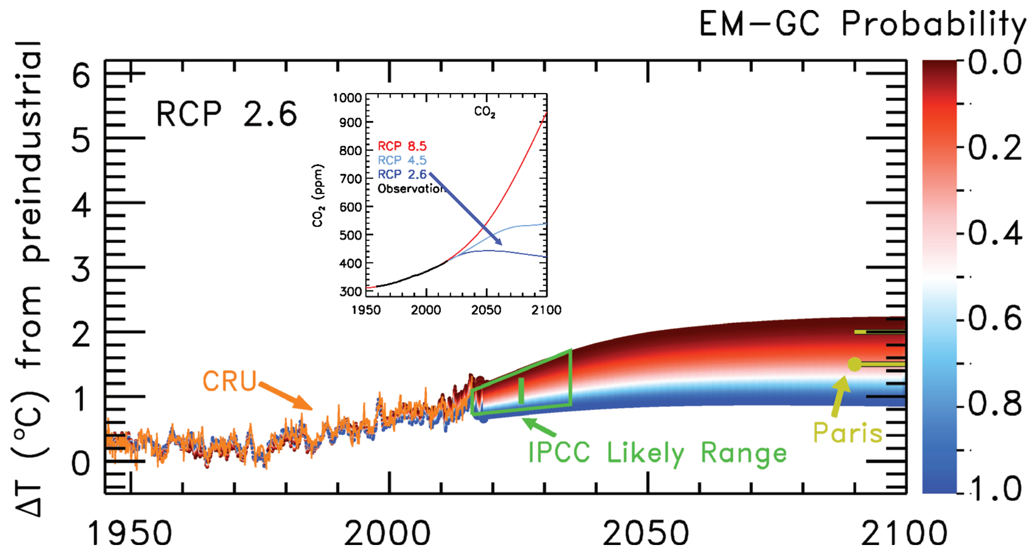


If GHGs follow RCP 4.5, **9%** chance rise GMST stays below **1.5°C** and **51%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT
IPCC Likely Range of ΔT : From Fig 11.25b of the 2013 Intergovernmental Panel on Climate Change Report

Probabilistic Forecast of Human-Induced Rise in GMST for model trained on data acquired until end of 2017 and future GHG levels from RCP 2.6

Fig 2.19 (modified) ***Paris Climate Agreement: Beacon of Hope***



If GHGs follow RCP 2.6, **68%** chance rise GMST stays below **1.5°C** and **96%** chance stays below **2.0°C**

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ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT
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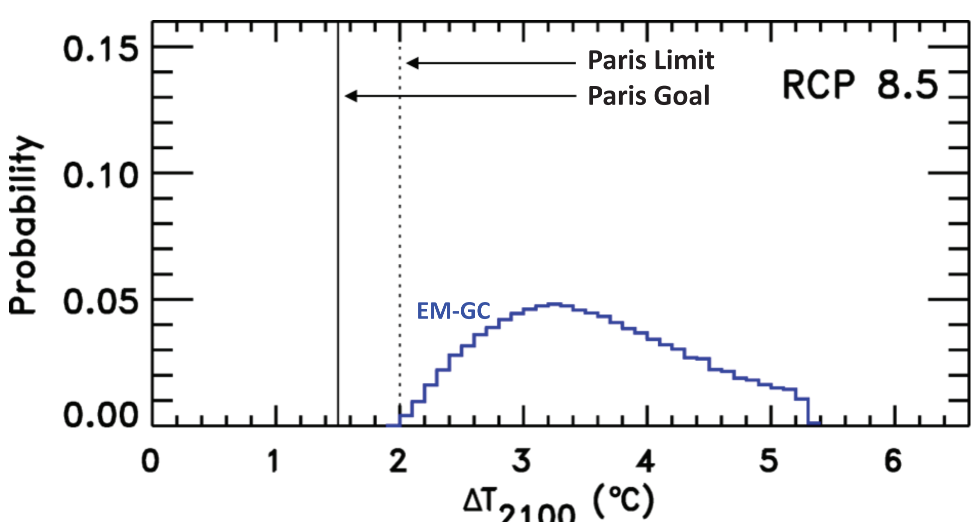


Fig 2.18 (updated)
Paris Climate Agreement: Beacon of Hope

If GHGs follow RCP 8.5

EM-GC: 0% chance rise GMST stays below **1.5°C** and **0.1%** chance stays below **2.0°C**

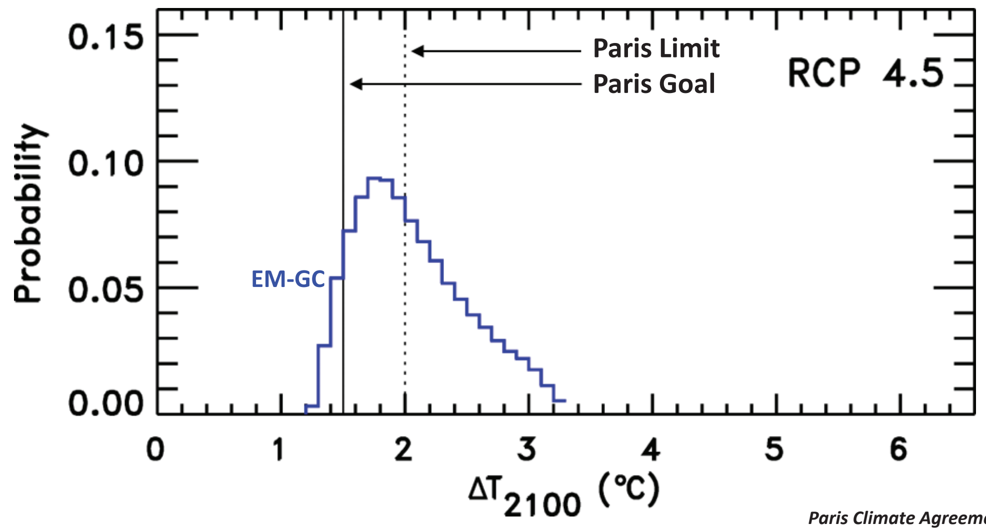


Fig 2.18 (updated)
Paris Climate Agreement: Beacon of Hope

If GHGs follow RCP 4.5

EM-GC: **9%** chance rise GMST stays below **1.5°C** and **51%** chance stays below **2.0°C**

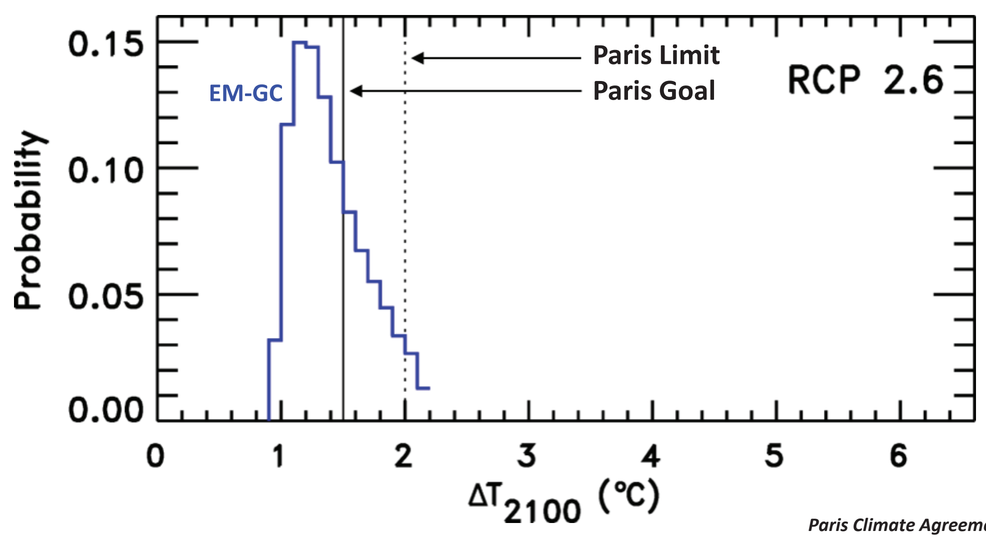


Fig 2.18 (updated)
Paris Climate Agreement: Beacon of Hope

If GHGs follow RCP 2.6

EM-GC: 68% chance rise GMST stays below **1.5°C** and **96%** chance stays below **2.0°C**

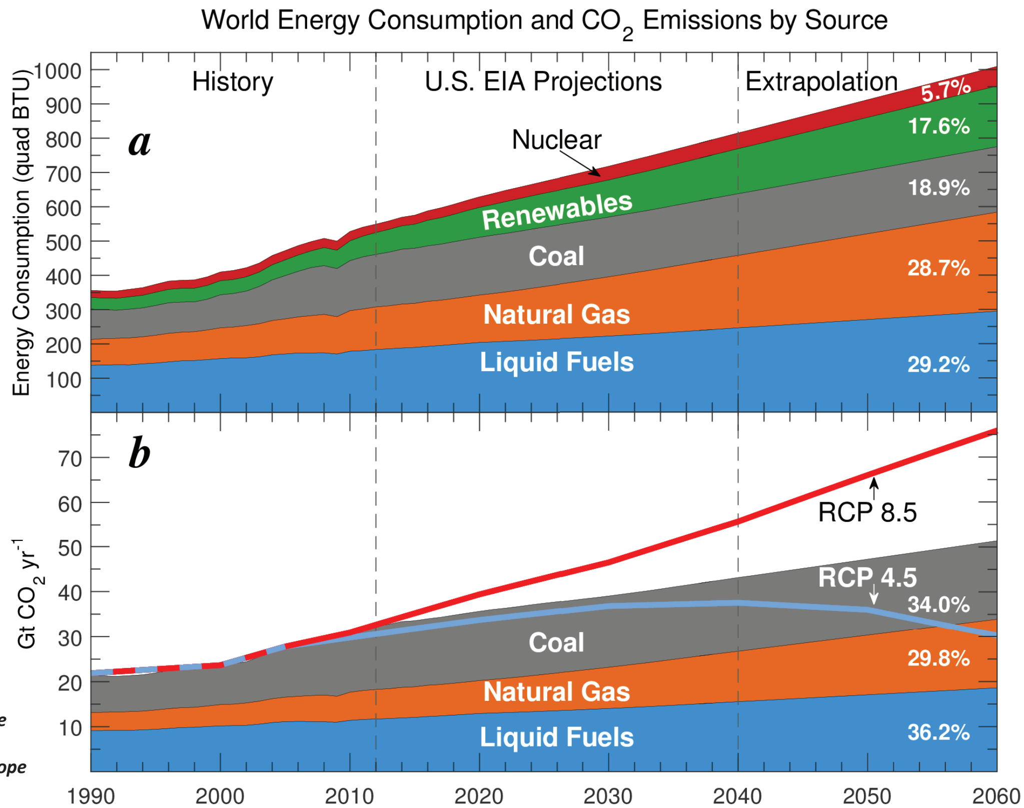


Fig 4.2
Paris Climate Agreement: Beacon of Hope

Business As Usual (i.e., projection of current trajectory) places the world in between RCP 4.5 and RCP 8.5 trajectories for global emission of CO_2

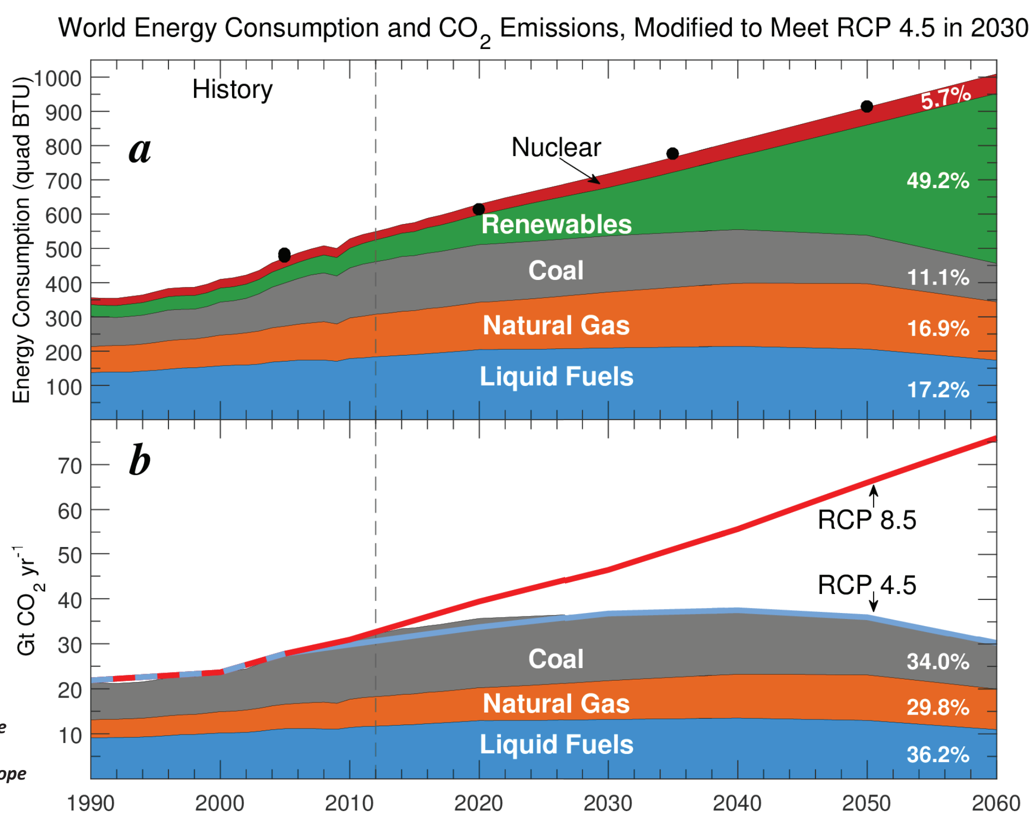


Fig 4.3
Paris Climate Agreement: Beacon of Hope

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

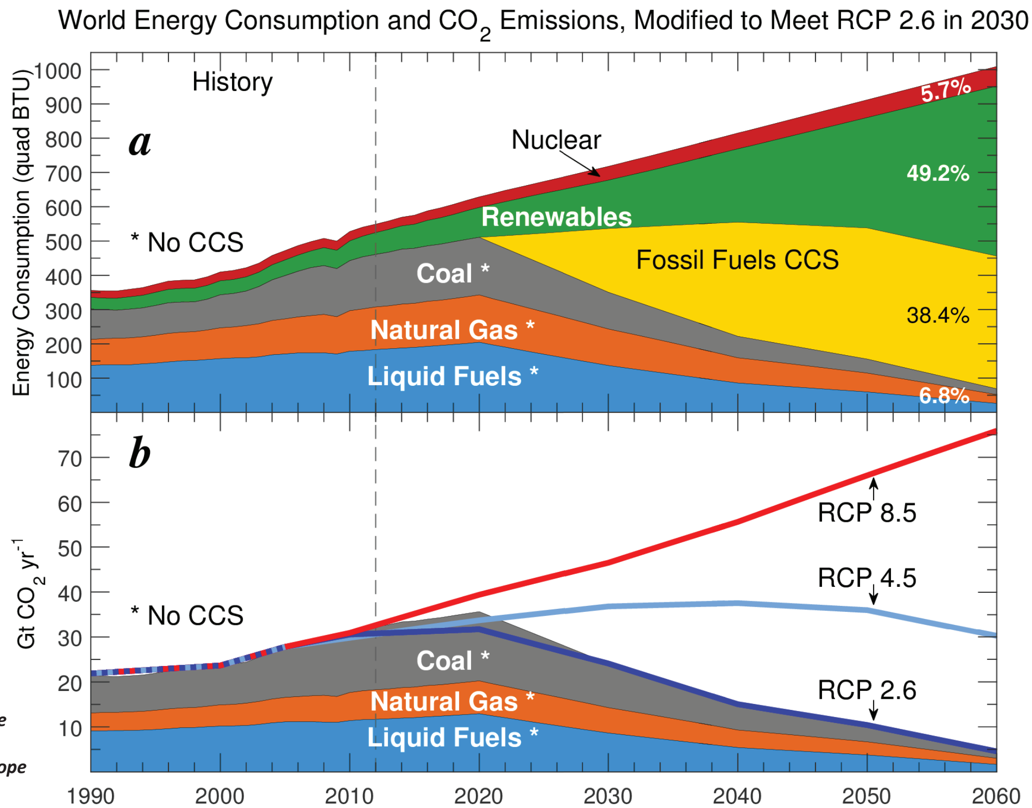


Fig 4.5
Paris Climate Agreement: Beacon of Hope

Achieving RCP 2.6 requires *half of total global energy* to be supplied by renewables/nuclear by 2060 coupled with massive Carbon Capture and Sequestration (CCS)

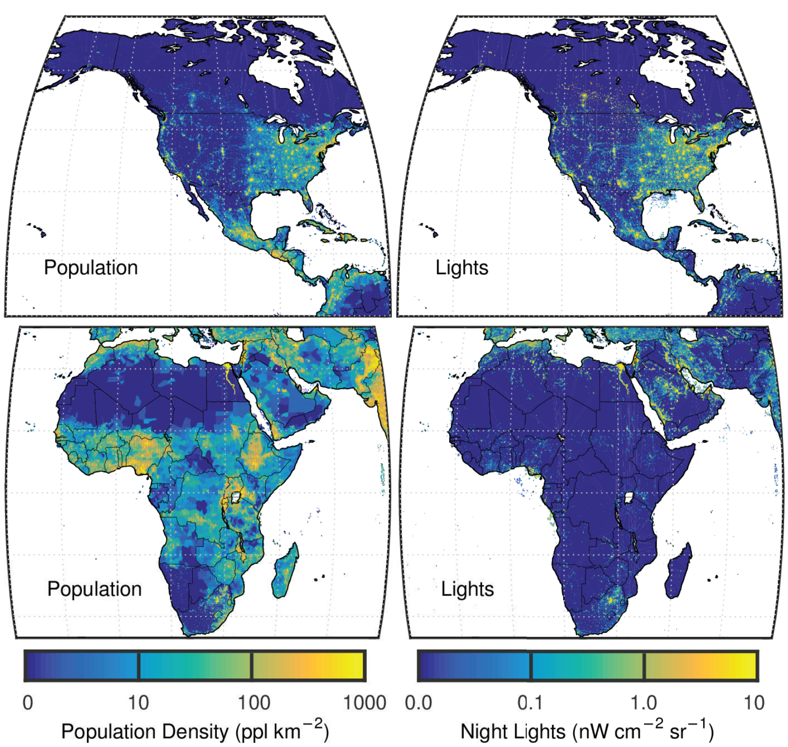


Fig 4.7
Paris Climate Agreement: Beacon of Hope

Limiting global warming to 2°C will require a massive transition to renewables and/or implementation of carbon capture and sequestration in the developed world and initial electrification of developing world by renewables (i.e., must bypass fossil fuels)

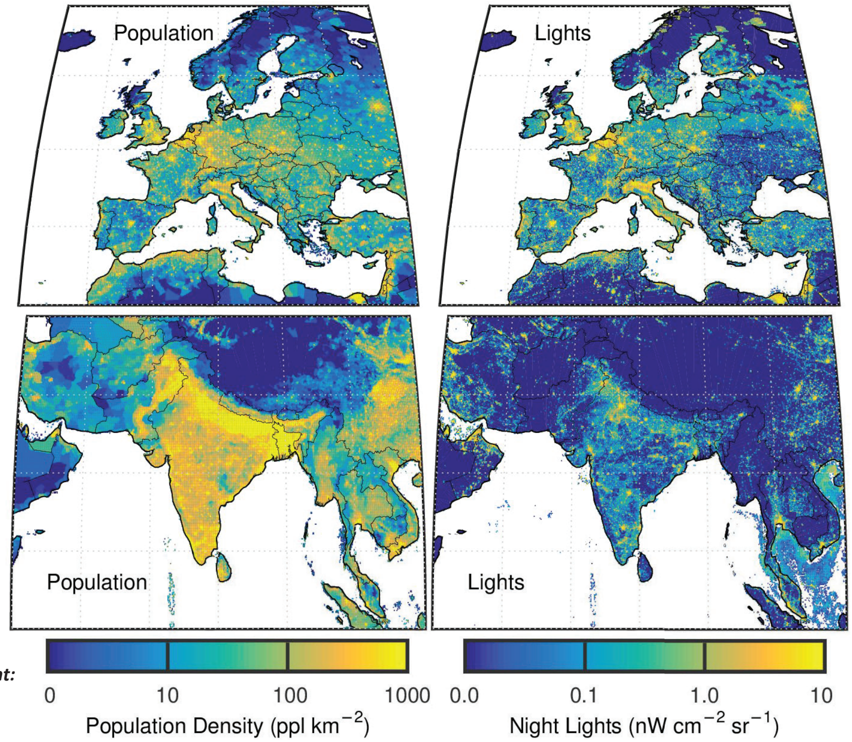


Fig 4.8
Paris Climate Agreement: Beacon of Hope

Limiting global warming to 2°C will require a massive transition to renewables and/or implementation of carbon capture and sequestration in the developed world and initial electrification of developing world by renewables (i.e., must bypass fossil fuels)

Released 21 October 2016 by National Geographic

Can watch free stream at https://archive.org/details/youtube-90CkXVF-Q8M

GHG Emission Projection

BAU: Business as Usual

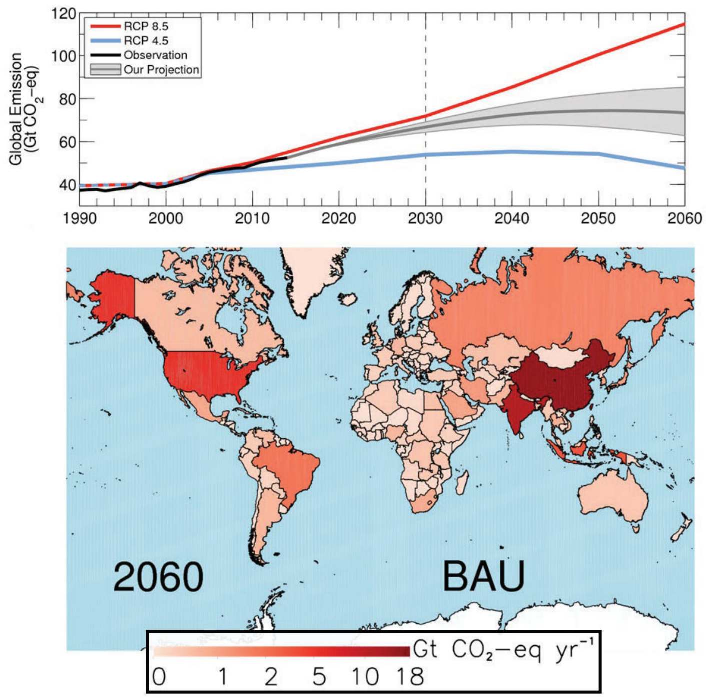


Fig. 3.8 & 3.13

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

RCP 4.5 & 8.5: GHG scenarios with 2.6., 4.5, and 8.5 W m^{-2} RF of climate in 2100

Uncertainty in "Our Projections" due to various population forecasts

Emissions for big 3 (U.S., China, & India) use Full Kaya Identity, whereas Simplified Kaya Identity used for other nations

https://en.wikipedia.org/wiki/Kaya_identity

GHG Emission Projection

Attain & Hold, all Unconditional INDCs

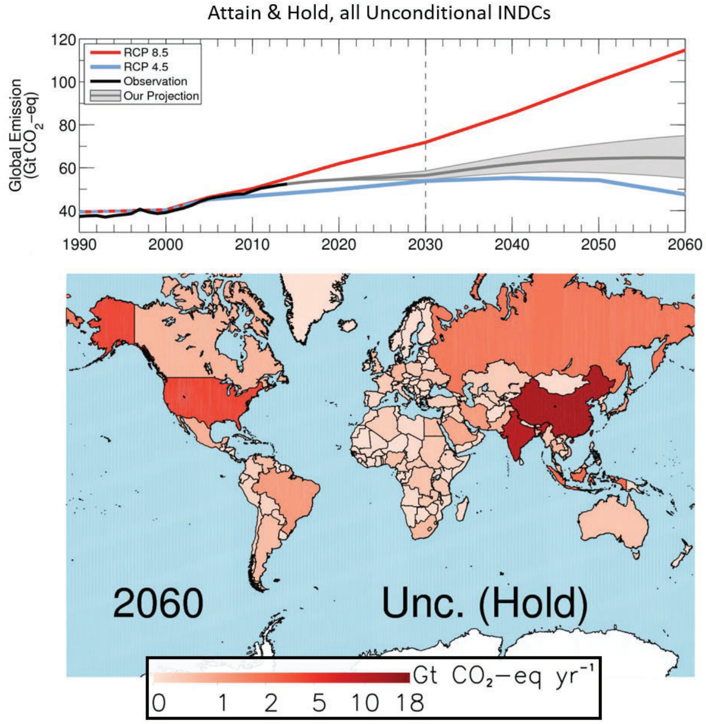


Fig. 3.9 & 3.13

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

INDC: Intended Nationally Determined Contribution (to reduce emissions of GHGs)

Unconditional: We promise, no matter what, to follow our INDC

GHG Emission Projection

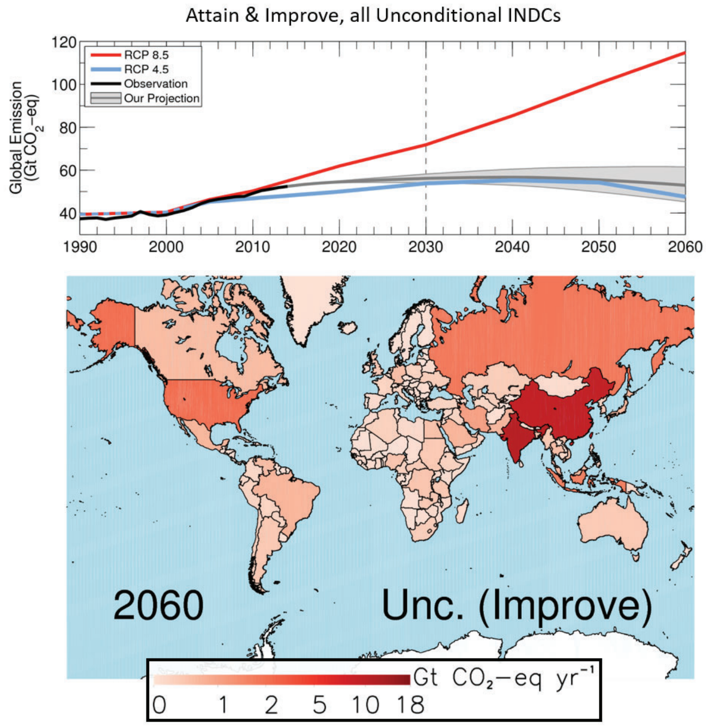


Fig. 3.10 & 3.13

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

INDC: Intended Nationally Determined Contribution (to reduce emission of GHGs)

Unconditional: We promise, no matter what, to follow our INDC and keep ***improving the carbon efficiency of our economy***

GHG Emission Projection

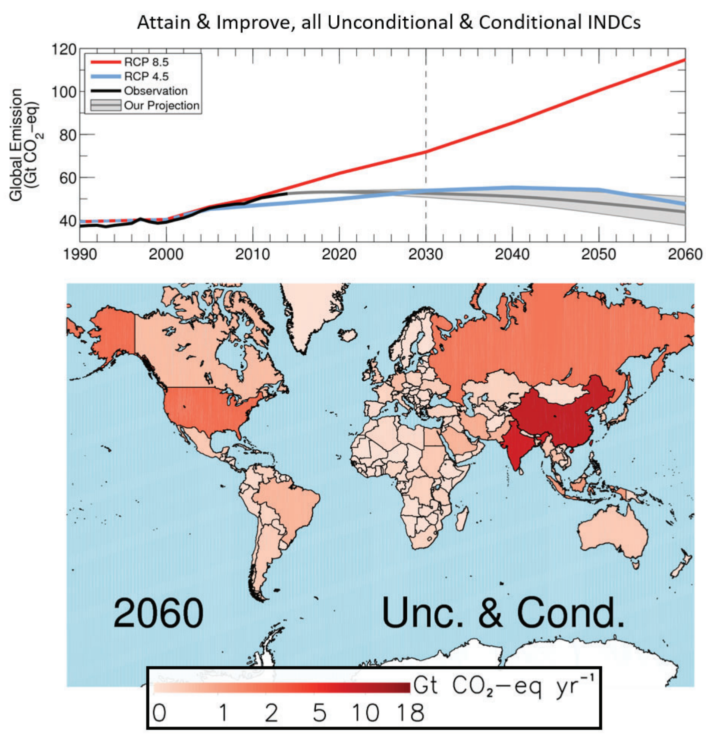


Fig. 3.11 & 3.13

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

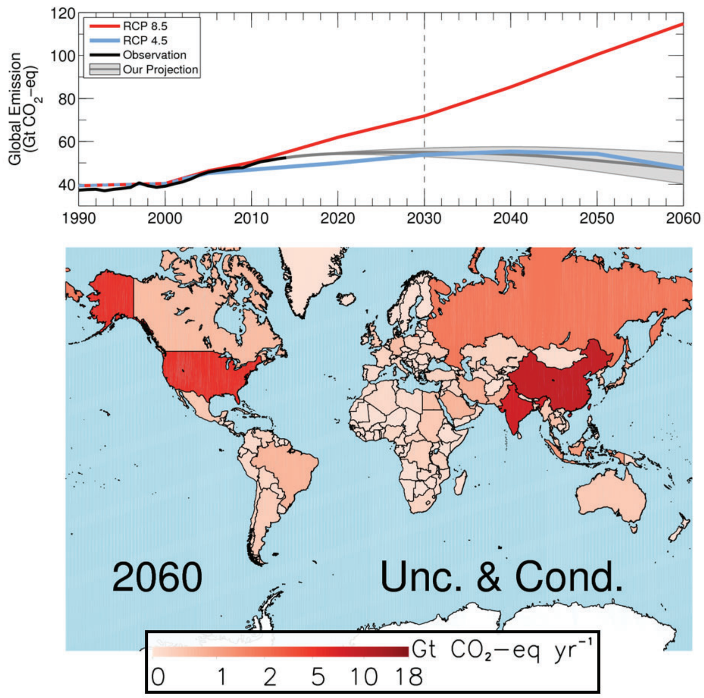
INDC: Intended Nationally Determined Contribution (to reduce emission of GHGs)

Unconditional: We promise, no matter what, to follow our INDC and keep ***improving the carbon efficiency of our economy***

Conditional: GHG reductions contingent on financial and/or technology transfer

Attain & Improve, all Unconditional & Conditional INDCs

Except US BAU



New Work

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

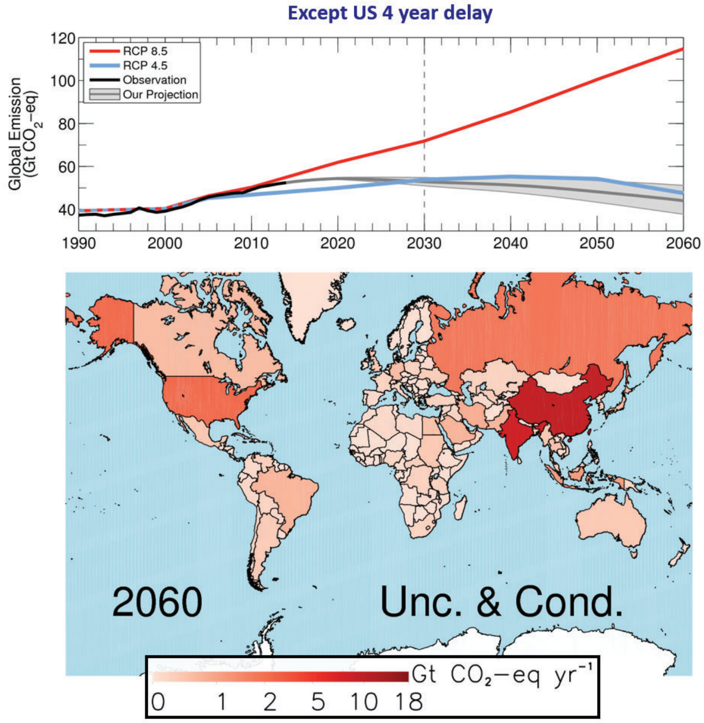
INDC: Intended Nationally Determined Contribution (to reduce emission of GHGs)

Unconditional: We promise, no matter what, to follow our INDC and keep ***improving the carbon efficiency of our economy***

Conditional: GHG reductions contingent on financial and/or technology transfer

Attain & Improve, all Unconditional & Conditional INDCs

Except US 4 year delay



New Work

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

INDC: Intended Nationally Determined Contribution (to reduce emission of GHGs)

Unconditional: We promise, no matter what, to follow our INDC and keep ***improving the carbon efficiency of our economy***

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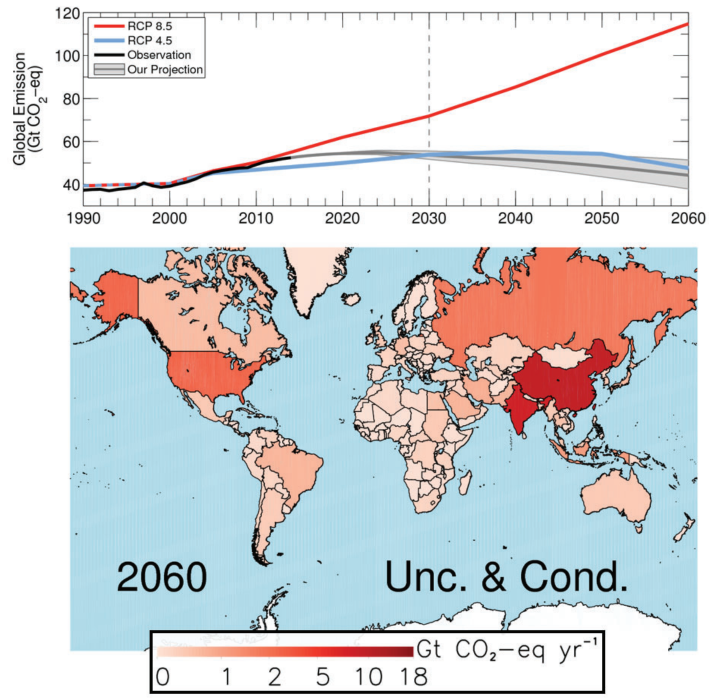
Attain & Improve, all Unconditional & Conditional INDCs

Except US 8 year delay



New Work

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

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Pacala and Socolow: CO_2 Stabilization Wedges

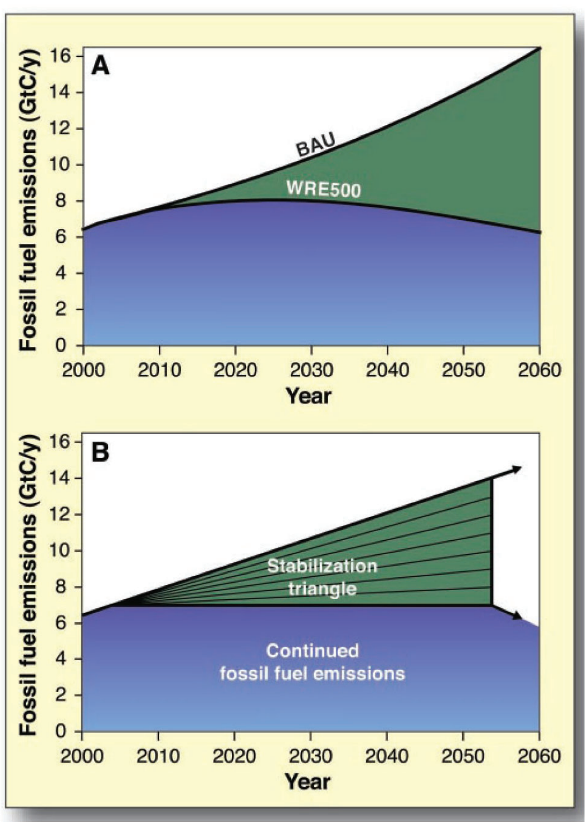

Fig. 1. (**A**) The top curve is a representative BAU emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization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

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

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)