Final Review

AOSC / CHEM 433 & AOSC 633

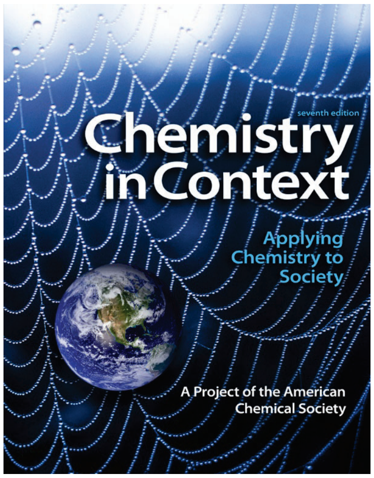
Ross Salawitch & Walt Tribett

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

Lecture 24

14 May 2019

Course Logistics



Chemistry in Context : Applying Chemistry to Society, 7/e

American Chemical Society (ACS)
Catherine H. Middlecamp, University of Wisconsin--Madison
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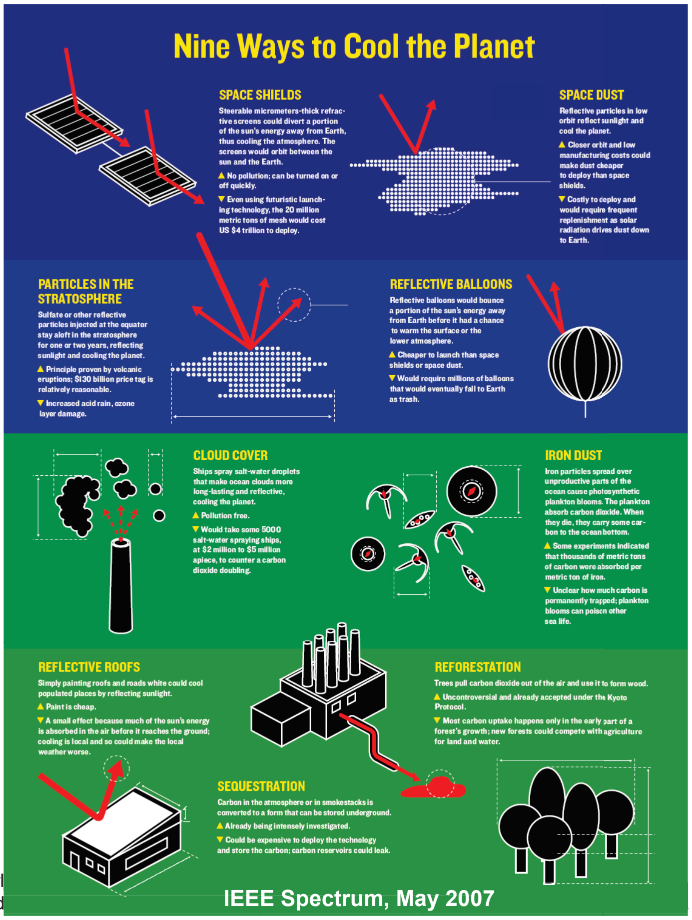
The author team truly benefitted from the expertise of a wider community. We extend our thanks to the following individuals for the technical expertise they provided to us in preparing the manuscript:

Mark E. Anderson, University of Wisconsin–Madison
David Argentar, Sun Edge, LLC
Marion O'Leary, Carnegie Institution for Science
Ross Salawitch, University of Maryland
Kenneth A. Walz, Madison Area Technical College

If you've rented, ***please bring with you to final exam, on Mon 20 May, 10:30 am*** (this room)

Of the “nine ways to cool the planet” discussed in the IEEE article, which of these seems most appealing to you? Briefly state why.

9 ideas:



Nine Ways to Cool the Planet

SPACE SHIELDS

Steerable micrometers-thick refractive screens could divert a portion of the sun’s energy away from Earth, thus cooling the atmosphere. The screens would orbit between the sun and the Earth.

▲ No pollution; can be turned on or off quickly.

▼ Even using futuristic launching technology, the 20 million metric tons of mesh would cost US $4 trillion to deploy.

SPACE DUST

Reflective particles in low orbit reflect sunlight and cool the planet.

▲ Closer orbit and low manufacturing costs could make dust cheaper to deploy than space shields.

▼ Costly to deploy and would require frequent replenishment as solar radiation drives dust down to Earth.

PARTICLES IN THE STRATOSPHERE

Sulfate or other reflective particles injected at the equator stay aloft in the stratosphere for one or two years, reflecting sunlight and cooling the planet.

▲ Principle proven by volcanic eruptions; $130 billion price tag is relatively reasonable.

▼ Increased acid rain, ozone layer damage.

REFLECTIVE BALLOONS

Reflective balloons would bounce a portion of the sun’s energy away from Earth before it had a chance to warm the surface or the lower atmosphere.

▲ Cheaper to launch than space shields or space dust.

▼ Would require millions of balloons that would eventually fall to Earth as trash.

CLOUD COVER

Ships spray salt-water droplets that make ocean clouds more long-lasting and reflective, cooling the planet.

▲ Pollution free.

▼ Would take some 5000 salt-water spraying ships, at $2 million to $5 million apiece, to counter a carbon dioxide doubling.

IRON DUST

Iron particles spread over unproductive parts of the ocean cause photosynthetic plankton blooms. The plankton absorb carbon dioxide. When they die, they carry some carbon to the ocean bottom.

▲ Some experiments indicated that thousands of metric tons of carbon were absorbed per metric ton of iron.

▼ Unclear how much carbon is permanently trapped; plankton blooms can poison other sea life.

REFLECTIVE ROOFS

Simply painting roofs and roads white could cool populated places by reflecting sunlight.

▲ Paint is cheap.

▼ A small effect because much of the sun’s energy is absorbed in the air before it reaches the ground; cooling is local and so could make the local weather worse.

REFORESTATION

Trees pull carbon dioxide out of the air and use it to form wood.

▲ Uncontroversial and already accepted under the Kyoto Protocol.

▼ Most carbon uptake happens only in the early part of a forest’s growth; new forests could compete with agriculture for land and water.

SEQUESTRATION

Carbon in the atmosphere or in smokestacks is converted to a form that can be stored underground.

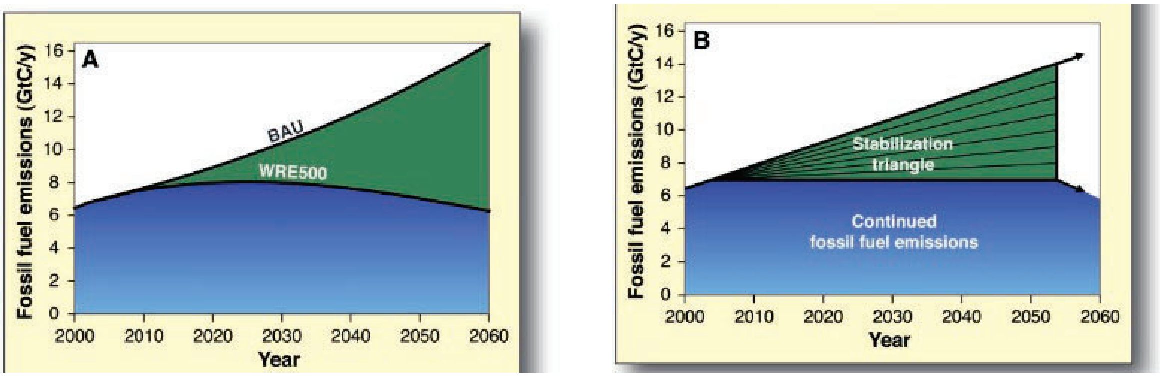
▲ Already being intensely investigated.

▼ Could be expensive to deploy the technology and store the carbon; carbon reservoirs could leak.

IEEE Spectrum, May 2007

Pacala and Socolow: CO_2 Stabilization Wedges

Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century. A portfolio of technologies now exists to meet the world’s energy needs over the next 50 years and limit atmospheric CO_2 to a trajectory that avoids a doubling of the preindustrial concentration. Every element in this portfolio has passed beyond the laboratory bench and demonstration project; many are already implemented somewhere at full industrial scale. Although no element is a credible candidate for doing the entire job (or even half the job) by itself, the portfolio as a whole is large enough that not every element has to be used.



Pacala and Socolow, Science, 2004 (Aux reading, Lecture 18)

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)

Final Exam

- Monday, 20 May, 10:30 am to 12:30 pm
- This room
- Format similar to prior exams

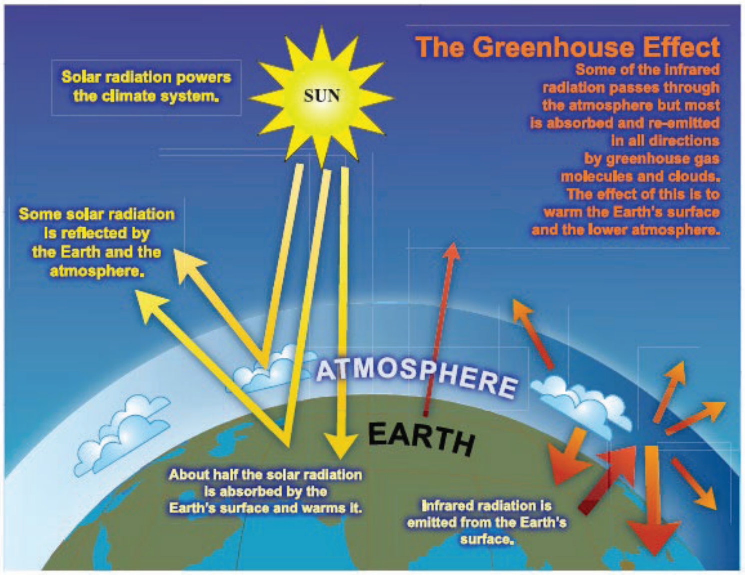
- “Virtual conversation”
- Closed book, no notes, no calculator
- Backbone of course remains the lectures

- ***Entire course*** will be covered on the final exam

- Please ask if you think a question requires clarification

- **If you have an exam either right before or right after this exam, please let me and Walt know ASAP**

Greenhouse Effect



FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

What is the most important greenhouse gas (GHG) ?

Question 1.3, IPCC, 2007

Radiative Forcing of Climate, 1750 to 2011

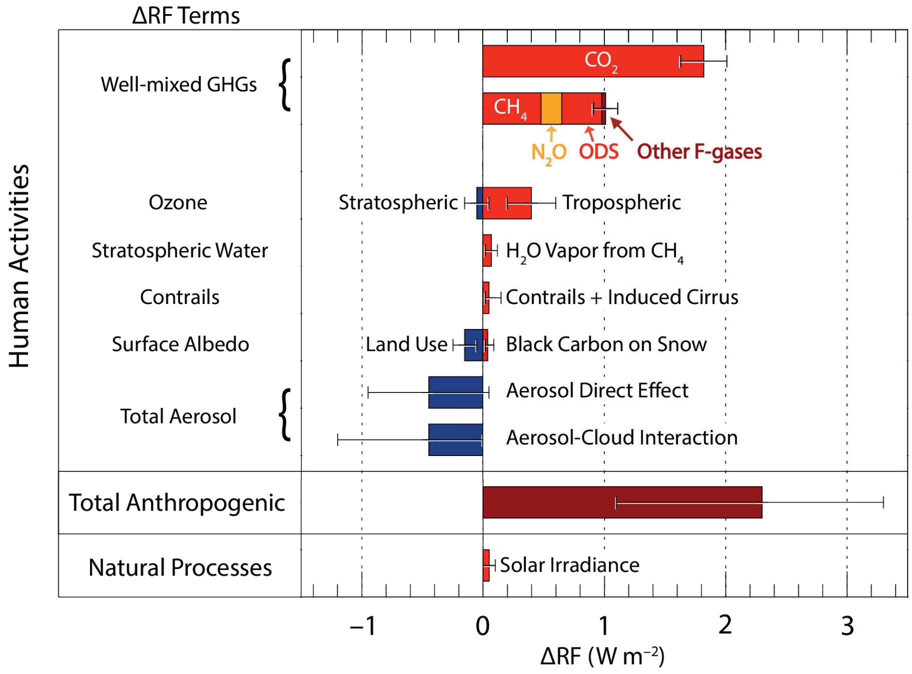
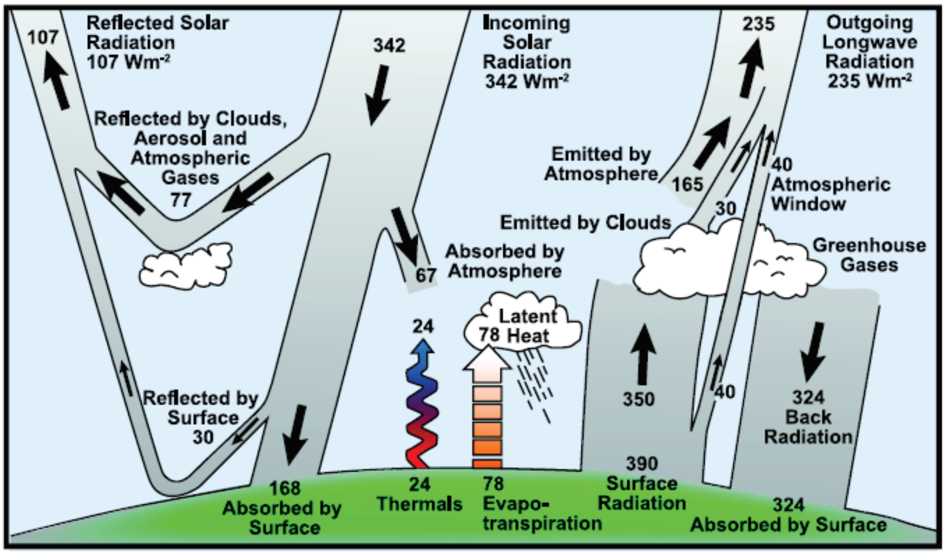


Figure 1.4, Paris Beacon of Hope

Radiative Forcing



FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

Question 1.1, IPCC, 2007

Radiative Forcing of Climate **is** ***Change in Energy***
reaching the lower atmosphere (surface to tropopause) as GHGs rise.
"Back Radiation" is most important term.

GWP – Global Warming Potential

$$\mathrm{GWP}\,(\mathrm{CH_4}) = \frac{\displaystyle\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CH4}} \times [\mathrm{CH_4}(t)]\; dt}{\displaystyle\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CO2}} \times [\mathrm{CO_2}(t)\; dt]}$$

where:

a_{CH4} = Radiative Efficiency (W m^{-2} ppb^{-1}) due to an increase in CH_4

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

CH_4 (t) = time-dependent response to an instantaneous release of a pulse of CH_4

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

GWP – Global Warming Potential

SAR: Second Assessment Report (issued in 1995)

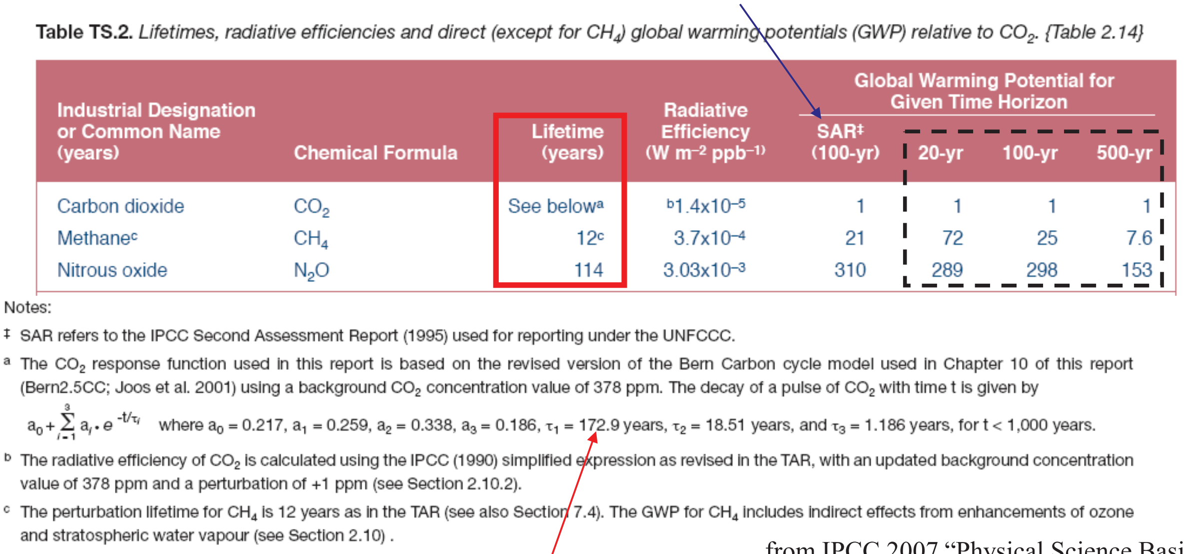


Table TS.2. *Lifetimes, radiative efficiencies and direct (except for CH_4) global warming potentials (GWP) relative to CO_2. {Table 2.14}*

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

Notes:

‡ SAR refers to the IPCC Second Assessment Report (1995) used for reporting under the UNFCCC.

[a] The CO_2 response function used in this report is based on the revised version of the Bern Carbon cycle model used in Chapter 10 of this report (Bern2.5CC; Joos et al. 2001) using a background CO_2 concentration value of 378 ppm. The decay of a pulse of CO_2 with time t is given by

$a_0 + \sum_{i=1}^{3} a_i \cdot e^{-t/\tau_i}$ where $a_0 = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, and $\tau_3 = 1.186$ years, for $t < 1{,}000$ years.

[b] The radiative efficiency of CO_2 is calculated using the IPCC (1990) simplified expression as revised in the TAR, with an updated background concentration value of 378 ppm and a perturbation of +1 ppm (see Section 2.10.2).

[c] The perturbation lifetime for CH_4 is 12 years as in the TAR (see also Section 7.4). The GWP for CH_4 includes indirect effects from enhancements of ozone and stratospheric water vapour (see Section 2.10) .

from IPCC 2007 “Physical Science Basis”

Time constant of 172.9 years dominates

GWP – Global Warming Potential

Table 1-1, Paris Beacon of Hope

$$\mathrm{GWP}\,(\mathrm{CH_4}) = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CH4}} \times [\mathrm{CH_4}(t)]\,dt}{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CO2}} \times [\mathrm{CO_2}(t)\,dt]}$$

$$\mathrm{GWP}\,(\mathrm{N_2O}) = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{N2O}} \times [\mathrm{N_2O}(t)]\,dt}{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CO2}} \times [\mathrm{CO_2}(t)\,dt]}$$

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					

CO_2 – equivalent emissions = Emissions of CO_2 +
Emissions of CH_4 × GWP of CH_4 +
Emissions of N_2O × GWP of N_2O +
etc.

Commonly, GWPs on 100 year time horizon are used although entities such as the Sierra Club prefer the 20 year time horizon

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Connection Between GHG Abundance and Surface T

How much does ΔF change when CO_2 changes?

$$\Delta \mathrm{F} \;\approx\; 5.35\ \mathrm{W/m^2}\ \ln\left(\frac{\mathrm{CO_2}^{\,Final}}{\mathrm{CO_2}^{\,Initial}}\right)$$

Changes in ΔF can be caused by changes in chemical composition (GHGs), aerosol loading, as well as surface albedo, H_2O, & cloud feedback

$$\Delta \mathrm{T} = \lambda_{\mathrm{BB}}(1+f)\;(\Delta \mathrm{F}_{\mathrm{CO2}} + \Delta \mathrm{F}_{\mathrm{CH4+N2O}} + \Delta \mathrm{F}_{\mathrm{ALBEDO}} + \Delta \mathrm{F}_{\mathrm{AEROSOLS}})$$

where $\lambda_{\mathrm{BB}} = 0.3\ \mathrm{K}\ /\ \mathrm{W\ m^{-2}}$,

and $f =$ represents total feedbacks due to surface albedo, H_2O, & clouds

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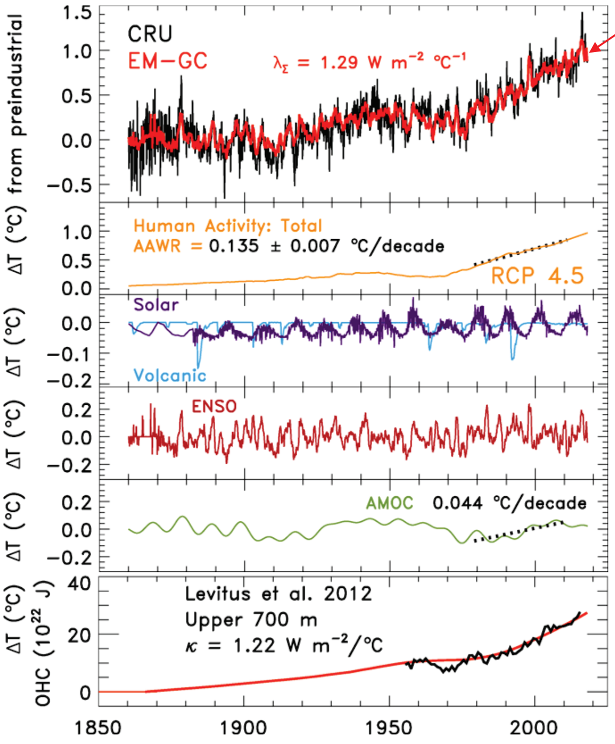
where $\lambda_{BB} = 0.3\ \mathrm{K\ /\ W\ m^{-2}}$,

and $f =$ represents total feedbacks due to surface albedo, H_2O, & clouds

Climate models that consider water vapor & lapse rate (LR) feedback find:

$$feedback_{\mathrm{H2O\ \&\ LR}} = 0.45$$

Are humans responsible?



$$\Delta T_{MDL\,i} = (1+\gamma)\left(\frac{GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i}{\lambda_p}\right) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - \left(\frac{Q_{OCEAN_i}}{\lambda_p}\right)$$

where:

i denotes month

$\lambda_p = 3.2\ \mathrm{W\ m^{-2}\ °C^{-1}}$

$1+\gamma = \{1 - \lambda_\Sigma/\lambda_p\}^{-1}$

GHG RF = RF due to all anthropogenic GHGs

LUC RF = RF due to Land Use Change

Aerosol RF = RF due to Tropospheric Aerosols

SOD = Stratospheric Optical Depth

TSI = Total Solar Irradiance

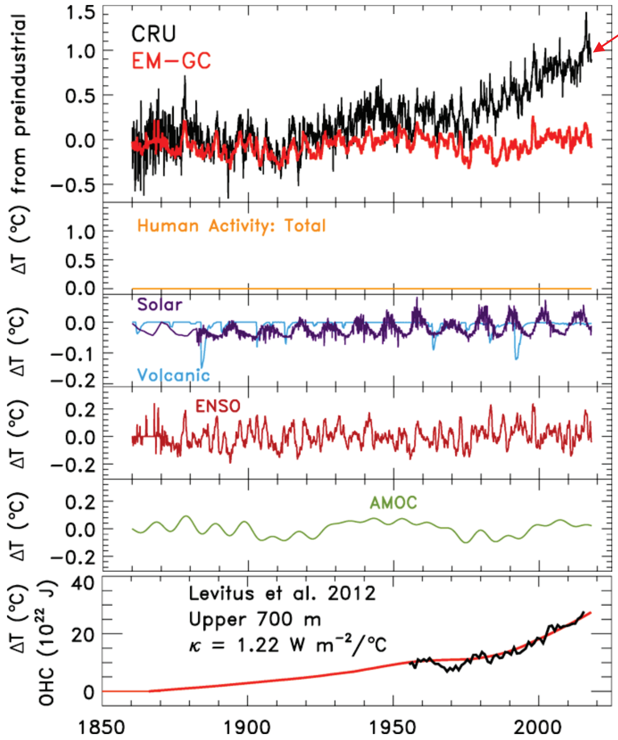
ENSO = El Niño Southern Oscillation

AMOC = Atlantic Meridional Overturning Circulation

Q_{OCEAN} = Ocean heat export = $\kappa(1+\gamma)\{\Delta T_{MDL\,i} - \Delta T_{OCEAN\ SURFACE\ i}\}$

Canty *et al.*, *ACP*, 2013
https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
updated by Austin Hope & Laura McBride

Are humans responsible?



$$\Delta T_{MDL\ i} = (1+\gamma)\left(\frac{GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i}{\lambda_p}\right) +$$
$$C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} +$$
$$C_4 \times AMOC_i - \left(\frac{Q_{OCEAN_i}}{\lambda_p}\right)$$

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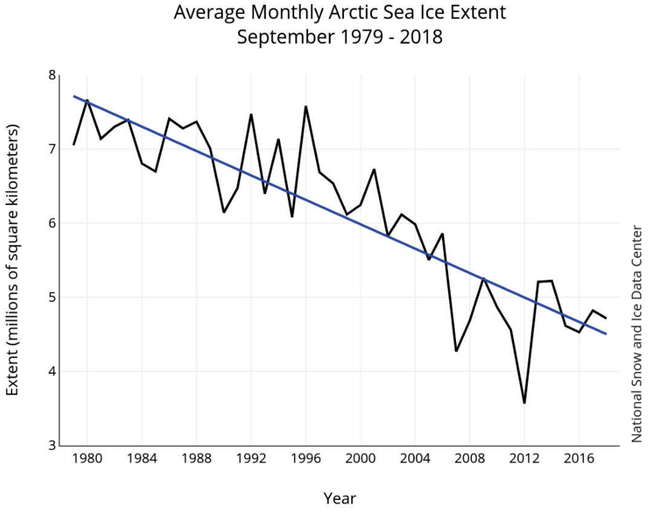
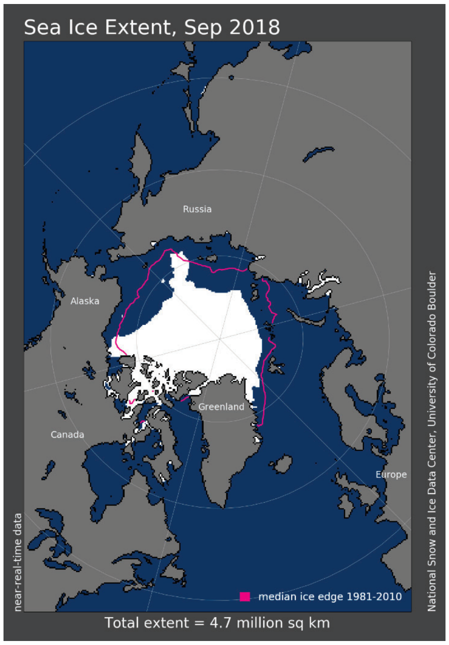
Canty *et al.*, *ACP*, 2013
https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
updated by Austin Hope & Laura McBride

Arctic Sea Ice: Canary of Climate Chnage





https://nsidc.org/arcticseaicenews/2018/10/september-extent-ties-for-sixth-lowest/

Arctic Sea Ice: Canary of Climate Chnage

- In 2004, 25% of monitored polar bears made a long-distance swim
- In 2012, 69% of monitored polar bears made a long-distance swim
- During long swims, adult bears will lose significant body weight and cubs will die

Source: https://www.washingtonpost.com/news/speaking-of-science/wp/2016/04/21/melting-arctic-ice-is-forcing-polar-bears-to-swim-for-more-than-a-week-without-rest

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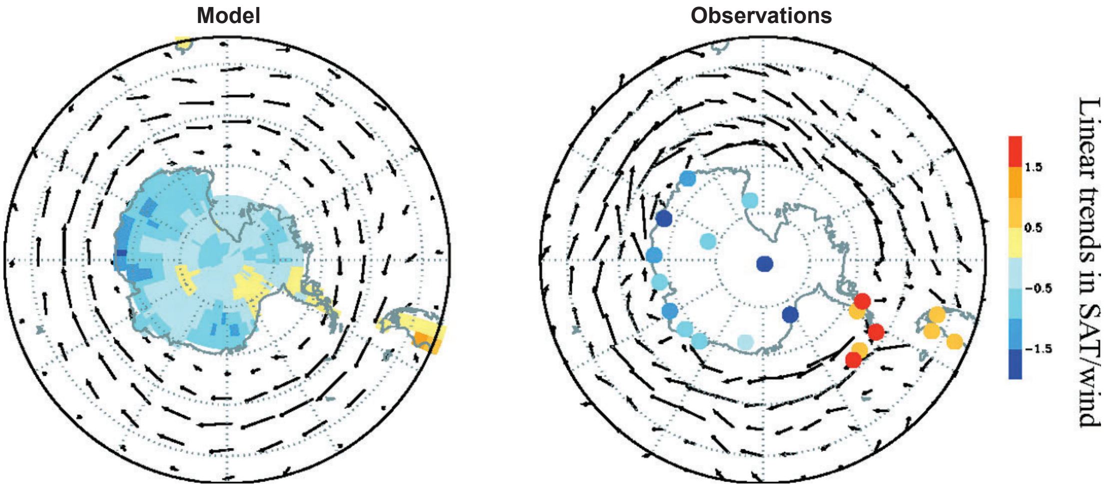
The Ozone Hole may have shielded the Antarctic from warming



Simulated and observed changes in surface temperature (K) and winds from 1969 to 2000, averaged over December to May.

Gillett and Thompson, *Science*, 2003

Ozone Depletion Potential and Halocarbons

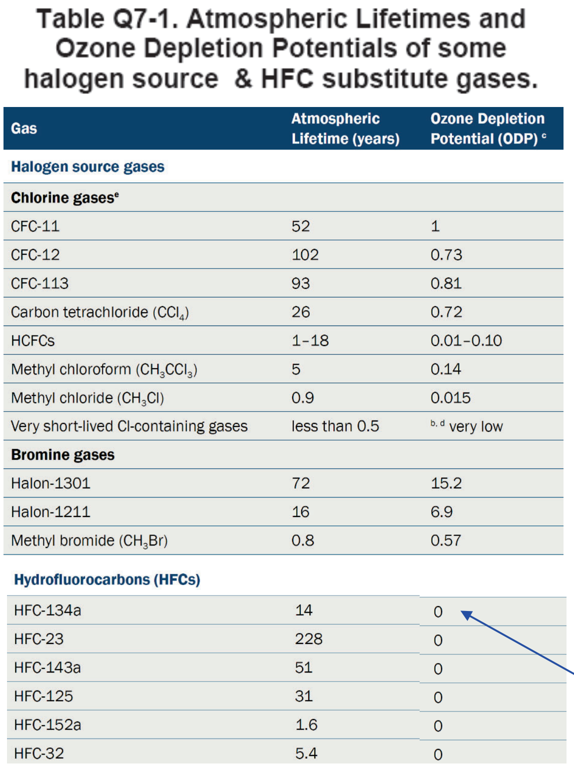


Table Q7-1. Atmospheric Lifetimes and Ozone Depletion Potentials of some halogen source & HFC substitute gases.

Gas	Atmospheric Lifetime (years)	Ozone Depletion Potential (ODP) [c]
Halogen source gases		
Chlorine gases[a]		
CFC-11	52	1
CFC-12	102	0.73
CFC-113	93	0.81
Carbon tetrachloride (CCl_4)	26	0.72
HCFCs	1–18	0.01–0.10
Methyl chloroform (CH_3CCl_3)	5	0.14
Methyl chloride (CH_3Cl)	0.9	0.015
Very short-lived Cl-containing gases	less than 0.5	[b, d] very low
Bromine gases		
Halon-1301	72	15.2
Halon-1211	16	6.9
Methyl bromide (CH_3Br)	0.8	0.57
Hydrofluorocarbons (HFCs)		
HFC-134a	14	0
HFC-23	228	0
HFC-143a	51	0
HFC-125	31	0
HFC-152a	1.6	0
HFC-32	5.4	0

continuous

$$\text{ODP (species "}i\text{")} = \frac{\text{global loss of } O_3 \text{ due to unit mass emission of "}i\text{"}}{\text{global loss of } O_3 \text{ due to unit mass emission of CFC-11}}$$

$$\approx \frac{(\alpha\, n_{\mathrm{Br}} + n_{\mathrm{Cl}})}{3}\,\frac{\tau_i}{\tau_{\text{CFC-11}}}\,\frac{MW_{\text{CFC-11}}}{MW_i}$$

continuous

where :

τ is the global atmospheric lifetime

MW is the molecular weight

n is the number of chlorine or bromine atoms

α is the effectiveness of ozone loss by bromine relative to ozone loss by chlorine

$$\boxed{\alpha = 60}$$

Bromine molecules are about 60 times more damaging to the ozone layer than chlorine molecules

HFCs (anthropogenic halocarbons containing only fluorine, carbon, and hydrogen) and thus pose no threat to the ozone layer

Heterogeneous Chemistry, Mid-Latitude vs Polar Regions

a) What type of aerosol particles are present in the mid-latitude stratosphere (i.e., what is the chemical composition of these aerosols?)

b) What heterogeneous chemical reaction occurs on the aerosol particles present in the mid-latitude stratosphere and how is the abundance of ClO affected by this reaction?

c) What type of particles are present in the polar stratosphere during winter (i.e., what are these particles called and what is the chemical composition of a "common type" of these particles?)

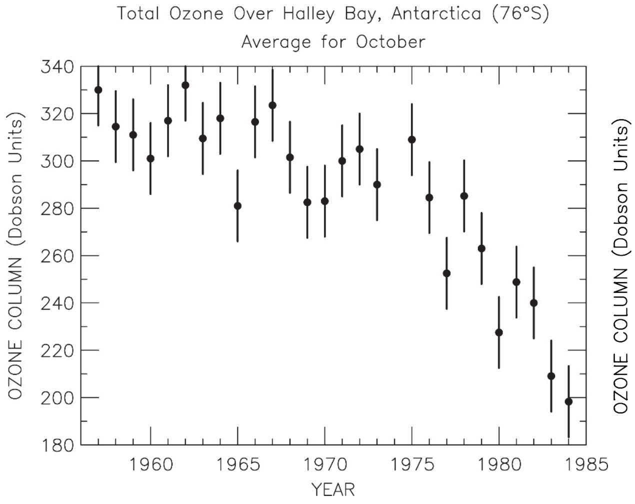
d) What is the effect of these particles on the chemical composition of the polar stratosphere? Scientists have shown that chemical reactions occurring on the surface of these particles convert species such as and (that do not deplete ozone) and that, while reactive, do not not cause harm to the ozone layer during the darkness of winter.

e) Following the return of sunlight, significant levels of what radical compound builds up inside the Antarctic stratosphere, leading to rapid loss of ozone? Hint: we're looking for a monoxide

f) Why does the ozone hole occur only over Antarctica?

Earth’s Atmosphere – Effect of Humans

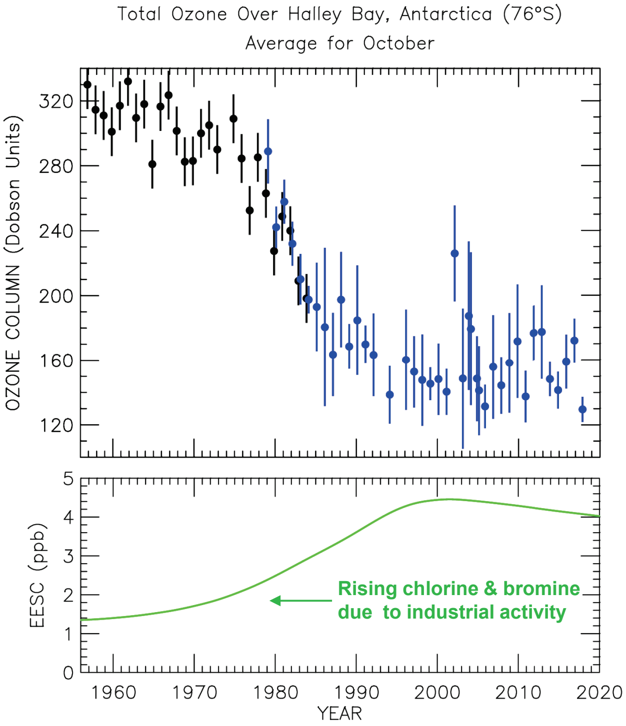
Stratospheric Ozone – shields surface from solar UV radiation



After Farman *et al*., Large losses of total ozone in Antarctica reveal Seasonal ClOx/NOx interaction, Nature, 315, 207, 1985.

EESC = Total Chlorine + 60 × Total Bromine
(actually, scientists use multipliers of 65 for polar regions and 60 for extra-polar regions … don’t ask)

Update



Rising chlorine & bromine due to industrial activity

Climate and Chemistry Coupling

Scientists have long known that rising GHGs leads to cooling of the stratosphere, due to direct radiative effects

The stratosphere has been cooling past several decades in a manner broadly consistent with theory:

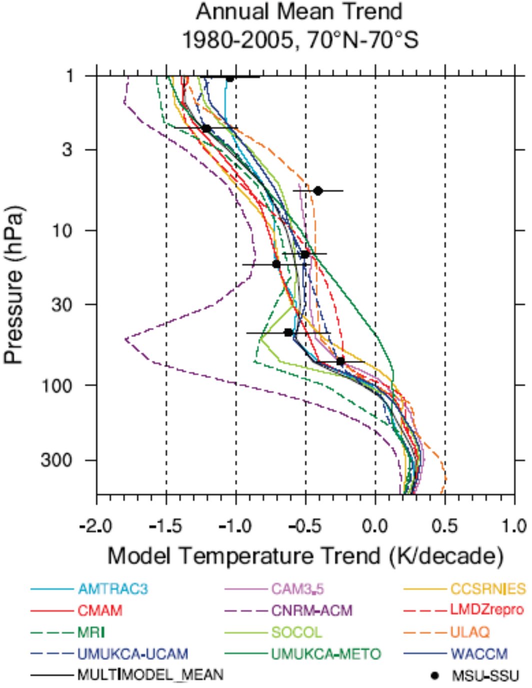
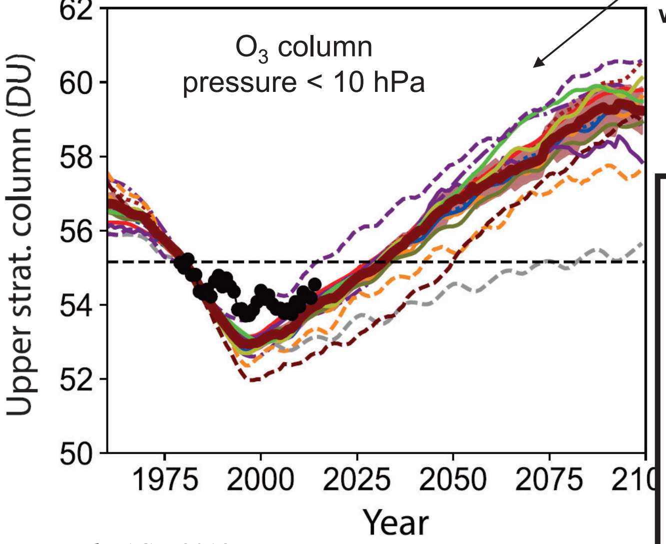


Figure 4−11, WMO/UNEP (2011)

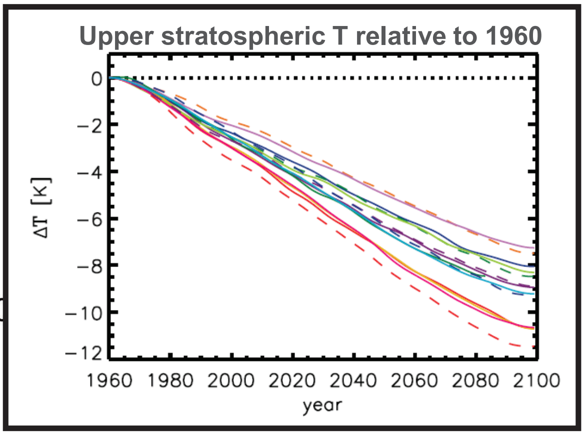
Future Trends, Upper Stratospheric Ozone



Dhomse *et al.*, *ACP*, 2018

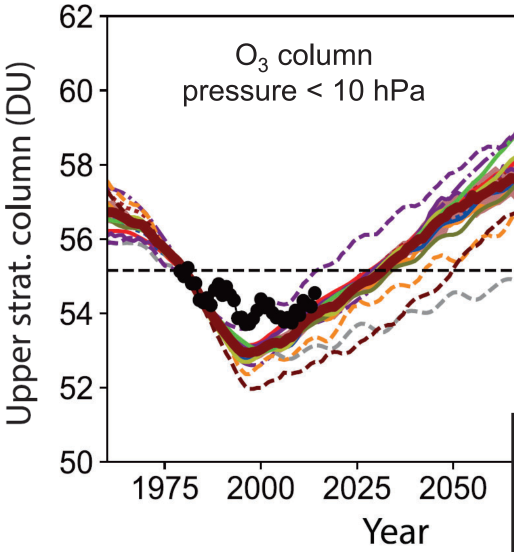
14 coupled chemistry climate models (CCMs) predict upper stratospheric ozone in 2100 will exceed upper stratospheric ozone in 1960

Due to stratospheric cooling !



Oman *et al.*, *JGR*, 2010

Future Trends, Upper Stratospheric Ozone



Dhomse *et al.*, *ACP*, 2018

14 coupled chemistry climate models (CCMs) predict upper stratospheric ozone in 2100 will exceed upper stratospheric ozone in 1960

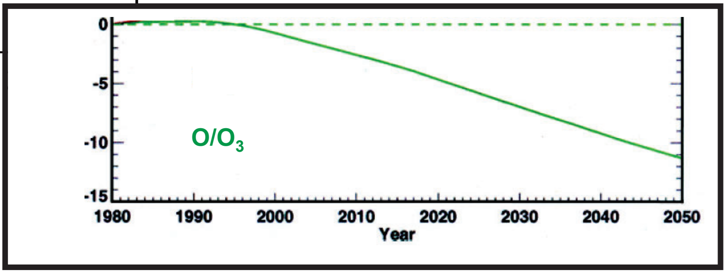
Due to stratospheric cooling !

Why this response of ozone to lower T ?

Gas phase rate constants are sensitive to temperature

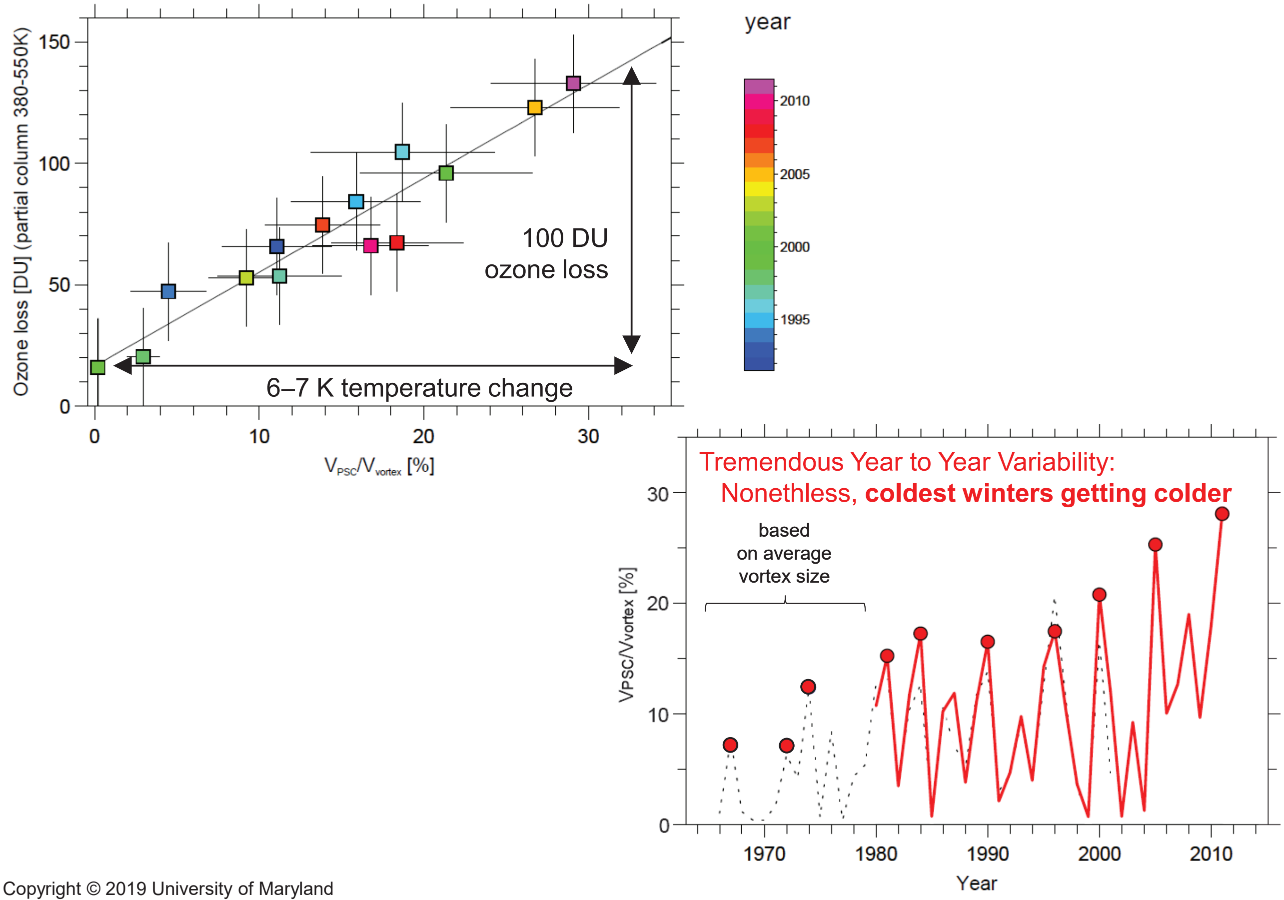
In particular, $O + O_2 + M \rightarrow O_3 + M$ speeds up as T drops

This cooling will alter the partitioning of O and O_3



Rosenfield *et al.*, *JGR*, 2002

Arctic Ozone 2011 in Context of Prior Years



Tremendous Year to Year Variability:
Nonethless, **coldest winters getting colder**

One Atmosphere – One Photochemistry

Stratosphere

HO_2 formation:

$$OH + O_3 \rightarrow HO_2 + O_2$$

HO_2 loss:

$$HO_2 + O_3 \rightarrow OH + 2\ O_2$$

Net: $$O_3 + O_3 \rightarrow 3\ O_2$$

Troposphere

HO_2 formation:

$$OH + CO \xrightarrow{O_2} HO_2 + CO_2$$

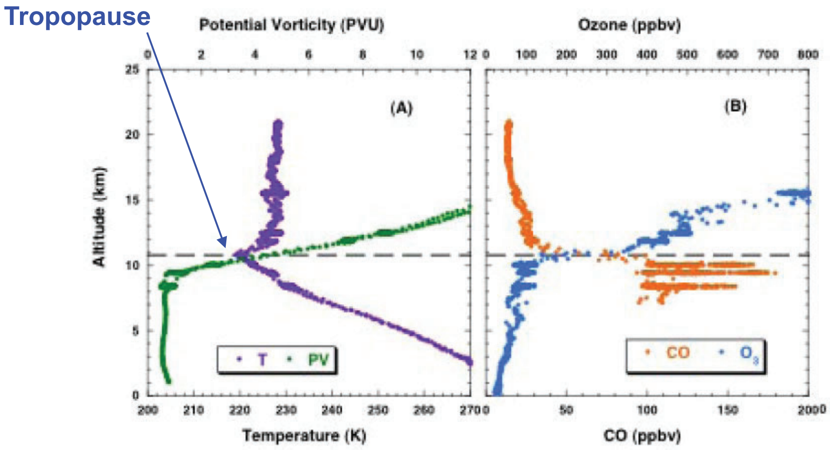
HO_2 loss:

$$HO_2 + NO \rightarrow OH + NO_2$$

Followed by:

$$NO_2 + h\nu \rightarrow NO + O$$
$$O + O_2 + M \rightarrow O_3 + M$$

Net: $$CO + 2\ O_2 \rightarrow CO_2 + O_3$$



Above Tropopause:
Lots of O_3, little CO
Below Tropopause:
Lots of CO, little O_3

Laura Pan, NCAR: http://surf.arc.nasa.gov/archive/lpan.pdf

Tropospheric Ozone Production

$$
\begin{aligned}
CO + OH &\rightarrow CO_2 + H \\
H + O_2 + M &\rightarrow HO_2 + M \\
HO_2 + NO &\rightarrow OH + NO_2 \\
NO_2 + h\nu &\rightarrow NO + O \\
O + O_2 + M &\rightarrow O_3 + M
\end{aligned}
$$

$$\text{Net:} \quad CO + 2\,O_2 \rightarrow CO_2 + O_3$$

“Chain Mechanism” for production of ozone

Initiation: O_3 photolysis giving $O(^1D)$, followed by $H_2O+O(^1D) \rightarrow 2OH$
as well as emission of CO & NO_x from combustion of fossil fuels

Termination: $HO_2 + HO_2 \rightarrow H_2O_2 + O_2$ or $OH + NO_2 + M \rightarrow HNO_3 + M$

Propagation: $HO_2 + NO$

Ozone Production “limited” by $k[HO_2][NO]$ (propagation term)

High NO_x ($NO+NO_2$) forces termination via production of HNO_3.

In this case, as NO_x rises, OH and HO_2 (HO_x) fall

⇨ what happens to O_3 production ?

Tropospheric Ozone Production

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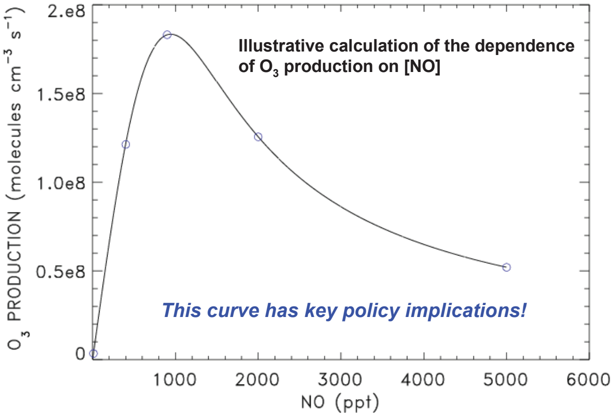
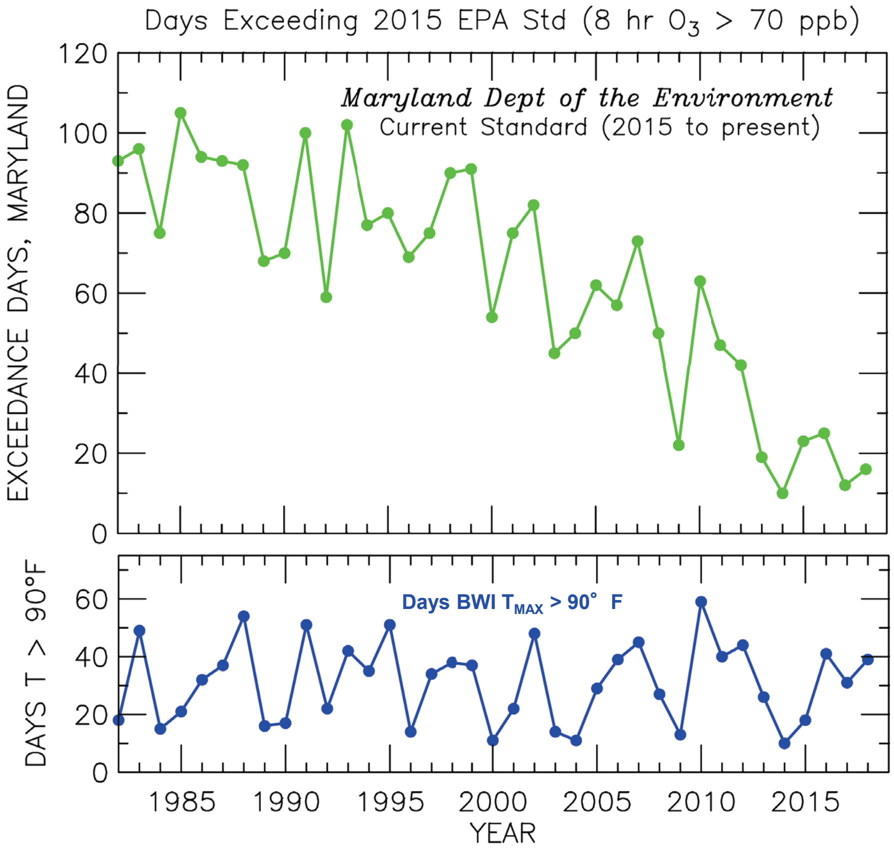


Illustrative calculation of the dependence of O_3 production on [NO]

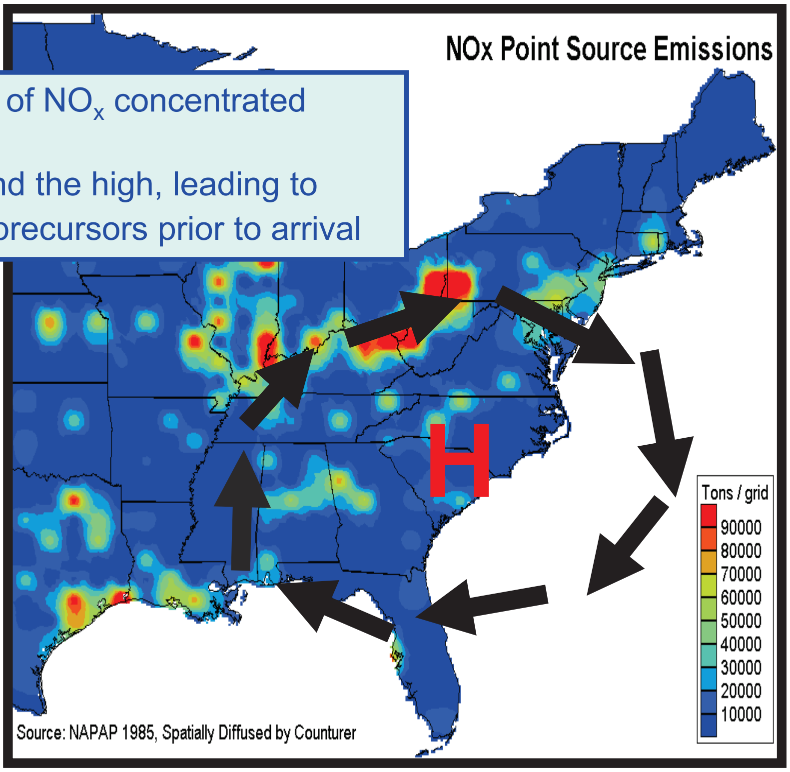
This curve has key policy implications!

Dramatic Improvements Local Air Quality, Past 4 Decades



Day-to-day meteorology (weather!) affects severity and duration of pollution episodes

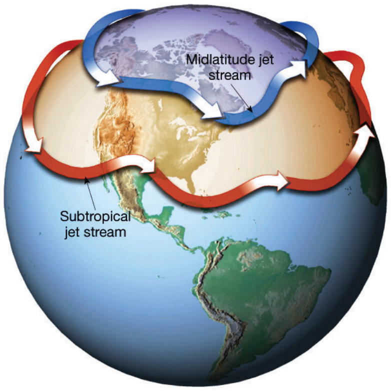
- Large power plant emissions of NO_x concentrated along the Ohio River valley
- Air circulates clockwise around the high, leading to significant build up of ozone precursors prior to arrival



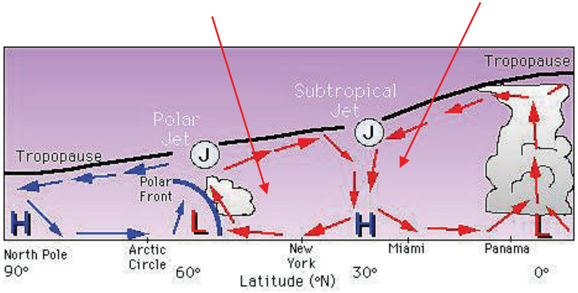
Source: NAPAP 1985, Spatially Diffused by Counturer

http://www.mde.state.md.us/assets/document/BJH%20-%20Basics%20on%20Ozone%20Transport.ppt

Subtropical Jet



http://www.ux1.eiu.edu/~cfjps/1400/FIG07_014A.jpg



http://www.fas.org/irp/imint/docs/rst/Sect14/jet_stream.jpg

Subtropical Jet: where poleward descending branch of the Hadley Circulation meets the equatorward descending of the Ferrel Cell

Area of high pressure, fair weather, low rainfall: conductive to high ozone

Poleward expansion of the sub-tropical jet:

- Number of days Subtropical Jet within 150 miles of Baltimore has increased by ~50% between 1979 and 2003 due to “frontal movement”
- Driving force: weakening of the equator to pole temperature gradient, caused by more rapid warming at high latitudes compared to tropics

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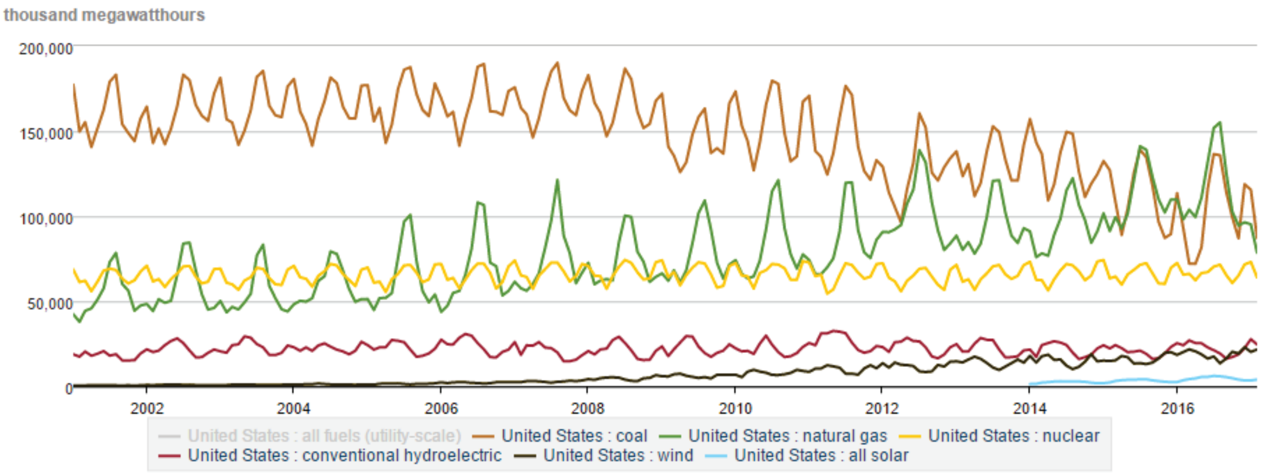
Our Favorite Air Pollutants ☺

Species	Source	Consequence
CO_2		
CH_4		
N_2O		
NO_x		
SO_2		
Soot		
CFCs		
Halons		
CH_3Br		
HFCs		

Final Statements

We're on the path to more use of renewables:

United States electricity
Net generation for all sectors, monthly



Source: U.S. Energy Information Administration

but how do we extend the transition away from fossil fuels to more sectors, and move more quickly?

Final Statements

It is difficult for people living now, who have become accustomed to the steady exponential growth in the consumption of energy from fossil fuels, to realize how transitory the fossil fuel epoch will eventually prove to be when it is viewed over a longer span of human history

M. King Hubbert, Scientific American, 1971
as quoted in foreword of
***When Oil Peaked* by Kenneth S. Deffeyes**

In many ways, fossil fuels should be considered as a gift from nature, which have allowed mankind to reach unprecedented levels of development. They served us well, but now – due to their finite nature – must be replaced by more sustainable sources of energy.

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.