Final Review

AOSC 433/633 & CHEM 433

Ross Salawitch

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

11 May 2017

Final Exam

– Wednesday, 17 May, 10:30 am to 12:30 pm
– This room
– Format similar to prior exams

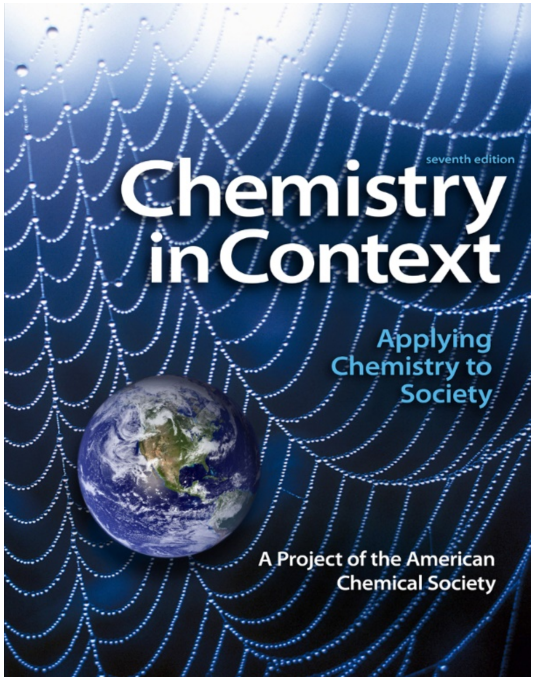
– “Virtual conversation”
– Closed book, no notes, no calculator
– Backbone of course remains the lectures

– ***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 know ASAP**

Course Logistics



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

American Chemical Society (ACS)
Catherine H. Middlecamp, University of Wisconsin--Madison
Steven W. Keller, University of Missouri--Columbia
Karen L. Anderson, Madison Area Technical College
Anne K. Bentley, Lewis & Clark College
Michael C. Cann, University of Scranton
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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 Wed 17 May, 10:30 am*** (this room)
- Thurs lecture will be class review

Class Material in the News

Saturday April 29, 2017

Scientists discover oil sands pollution significantly under-reported

A scarecrow lies in a tailings pond in front of the Suncor oil sands extraction facility near the town of Fort McMurray in Alberta. (Mark Ralston/AFP /Getty Images)

In Canada, when it comes to figuring out how much pollution the oil sands emit, the government relies on industry to report their own numbers. That's how policies get made and regulations are formed, but it turns out the oil sands companies have been significantly underestimating the level of a certain type of pollution they emit.

Back in 2013, researchers gathered their own data by flying above and around four different oil sands facilities at different altitudes. Dr. Shao-Meng Li, a senior research scientist for Environment and Climate Change Canada and lead author of the study, says he found the oil sands producers were emitting two to four-and-a-half times more volatile organic compounds than they had reported. Those are gaseous organic compounds that can be toxic for human and environmental health.

http://www.cbc.ca/radio/quirks/plastic-eating-worms-dolphin-sex-and-nuclear-fusion-1.4086846/scientists-discover-oil-sands-pollution-significantly-under-reported-1.4086942

Class Material in the News

WE'RE DONE

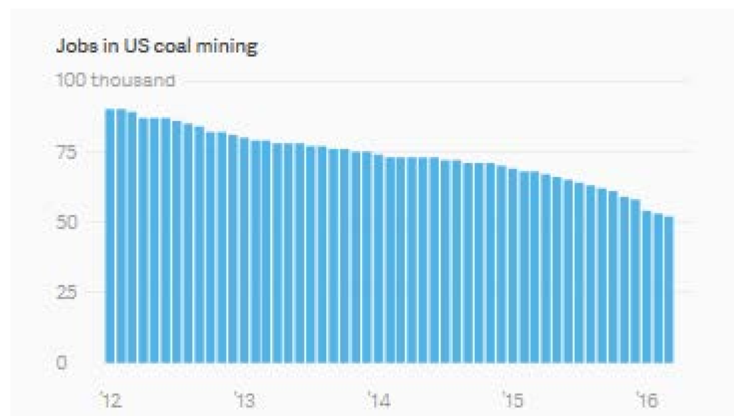
West Virginia's biggest utility just told the governor burning more coal is "not going to happen"

West Virginia is coal country. And so, given Trump's promise to "put our [coal] miners back to work," it's no surprise that the state's Democratic governor Jim Justice wants his state's biggest utility to burn more of it.

But Chris Beam, president of Appalachian Power, the state's largest utility, has some bad news.

Beam told the governor—a farmer and coal mogul himself—that all new power generation would likely come from wind, solar, and natural gas. "The governor asked me, 'I'd like you to burn more coal,'" Beam said according to the West Virginia Gazette-Mail. "Well, we don't have any more coal plants. We're not going to build any more coal plants. That's not going to happen."

This isn't an issue of pollution controls, however; Customers and economics are driving today's energy agenda. Beam says the debate over climate change, and the role of coal in it, is essentially over. Appalachian Power's parent company AEP believes the regulation of carbon dioxide is inevitable. In the coming decades, renewable energy and natural gas are poised to dominate the fuel mix. "We're past that argument as a company," Beam said.



https://qz.com/970595/w-virginias-biggest-utility-appalachian-power-just-told-the-states-governor-jim-justice-that-burning-more-coal-is-not-going-happen-because-customers-dont-want-it/?utm_source=fark&utm_medium=website&utm_content=link&ICID=ref_fark

Class Material in the News

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Iceland begins radical 'Thor' experiment to produce geothermal energy from magma

- **$100m project could produce 10 times more energy than conventional well**
- **Would enable Iceland to export more energy**
- **Could revive a plan to build a power cable from Iceland to Britain**

By MARK PRIGG and AFP AND REUTERS REPORTERS
PUBLISHED: 12:57 EDT, 5 May 2017 | **UPDATED:** 13:27 EDT, 5 May 2017

Engineer Albert Albertsson says Iceland's geothermal well could generate five to 10 times more power than a conventional well

If successful, the experimental project could produce up to 10 times more energy than an existing conventional gas or oil well, by generating electricity from the heat stored inside the earth: in this case, volcanic areas.

Launched in August last year, the drilling was completed on January 25, reaching a record-breaking depth of 4,659 metres (nearly 3 miles).

At this depth, engineers hope to access hot liquids under extreme pressure and at temperatures of 427 degrees C (800 F), creating steam that turns a turbine to generate clean electricity.

'We expect to get five to 10 times more power from the well than a conventional well today,' said Albert Albertsson, an engineer at the Icelandic energy company HS Orka, involved in the drilling project.

To supply electricity and hot water to a city like Reykjavik with 212,000 inhabitants, 'we would need 30-35 conventional high temperature wells' compared to only three or five supercritical wells, says Albertsson.

http://www.dailymail.co.uk/sciencetech/article-4477944/Iceland-begins-Thor-magma-energy-experiment.html

Make America's Buildings Great Again

- Step 1: Take stock of what we already have
- Step 2: Make America's Buildings Great Again!
- Step 3: Replace fossil fuel power plants with renewable resources

Tyler Boyle

America's Energy Plan

Goals of Energy Plan:

1. Improve air quality by decreasing emissions
2. Increase energy independence
3. Reduce impact on climate change

Efficiency	Small Scale Renewable Energies
Increase tax incentives for energy audits and improvements.	Require that new constructions in cities implement relevant renewable energy systems
Require that all buildings built using any federal funds are LEED certified.	Provide incentives for installation on existing buildings.
Perform energy audits and improvements on all federal buildings.	Implement net metering laws across the country.

Hannah Russell

America’s Energy Plan

Large Scale
Strictly regulate emissions on existing coal power plants and put tight restrictions on proposed building of new ones.
Tighten regulations on drilling for natural gas and provide tax incentives for procurement by natural means.
Perform regional analysis for implementation of renewable technologies.
Expand offshore wind and eliminate offshore drilling.
Incentivize multi-use lands: grazing land with turbines, with ranchers/farmers receiving credits for some of the electricity generated.
Fund research into renewable energies and climate science.

The answer to creating an economy based on renewable energy is not going to come from one technology alone, it must be a combination of increasing the efficiency of the way we currently use power and implementing renewable energy solutions on both the small and large scale.

Hannah Russell

Sustainable Energy Plan

- Tesla's gigafactory
  - 100 needed worldwide to remove fossil fuels from energy equation
  - My plan: 5 gigafactories must be constructed and operational by the year 2035
  - decrease the cost of lithium ion batteries for cars and powerwall generators (via mass production)
  - Powerwall provides backup power during utility outages – charges via solar power

- Collectively, automobiles on the road must have an average gas mileage of 65mpg by the year 2080
  - 75% of cars sold must be hydrogen-powered or electric by 2050 and 100% by 2070
  - Hydrogen production must be done using water electrolysis (cleanest source – only produces hydrogen and oxygen), powered by renewable sources (excluding nuclear, as hydrogen is explosive)

Justin Hicks

JUST TRANSITION

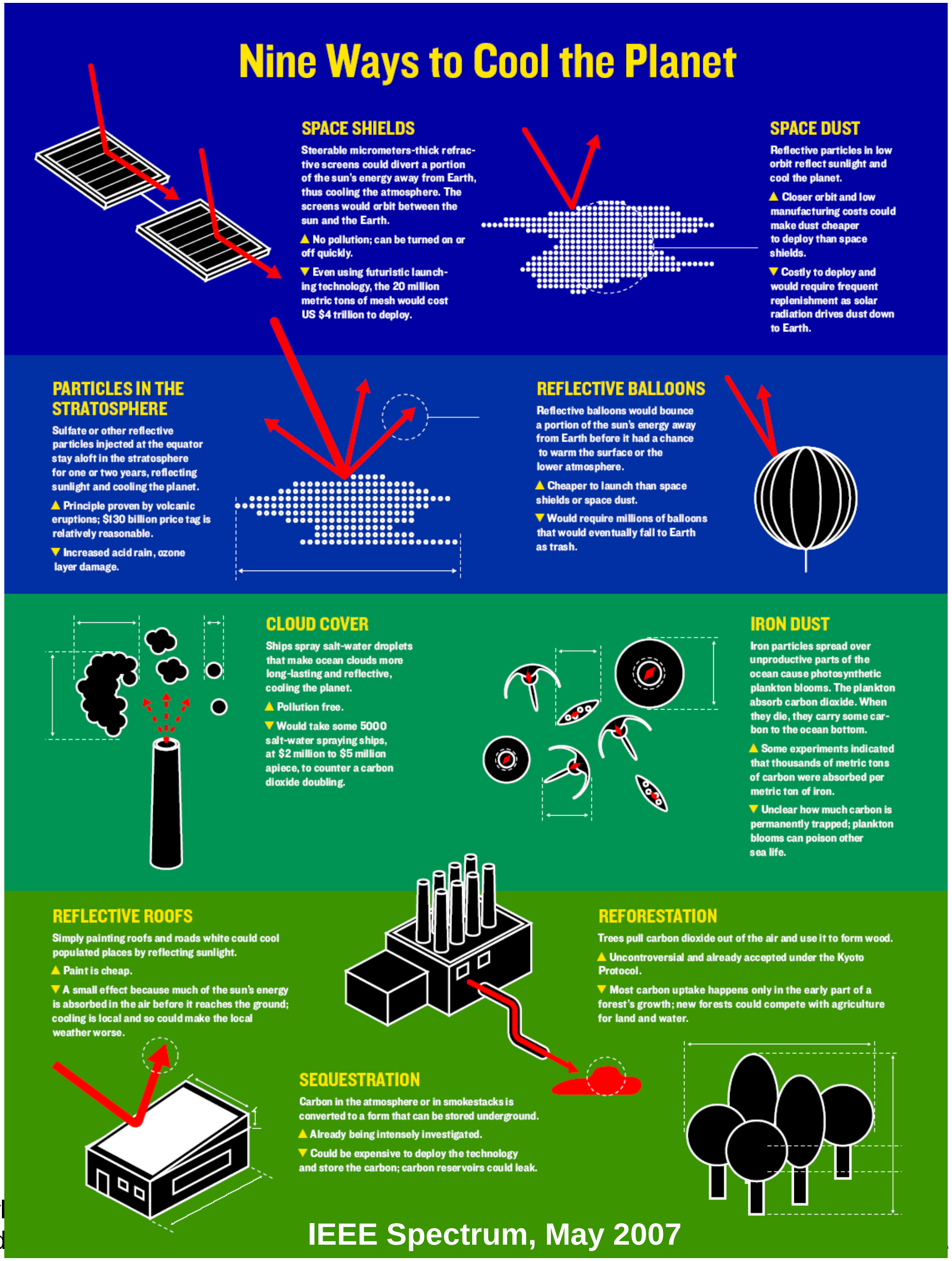
Good Jobs and Healthy Communities

A transition in our energy system has the potential to eliminate jobs in the fossil fuel industry, but creates even more good-paying jobs; to reduce job loss, we will:

- Expand the "Just Transition" framework described in the Paris Climate Agreement
    - Workers in today's energy sector will receive education and training required to carry out the tasks that come with sustainable energy; their pensions and health care benefits are preserved

Justin Hicks

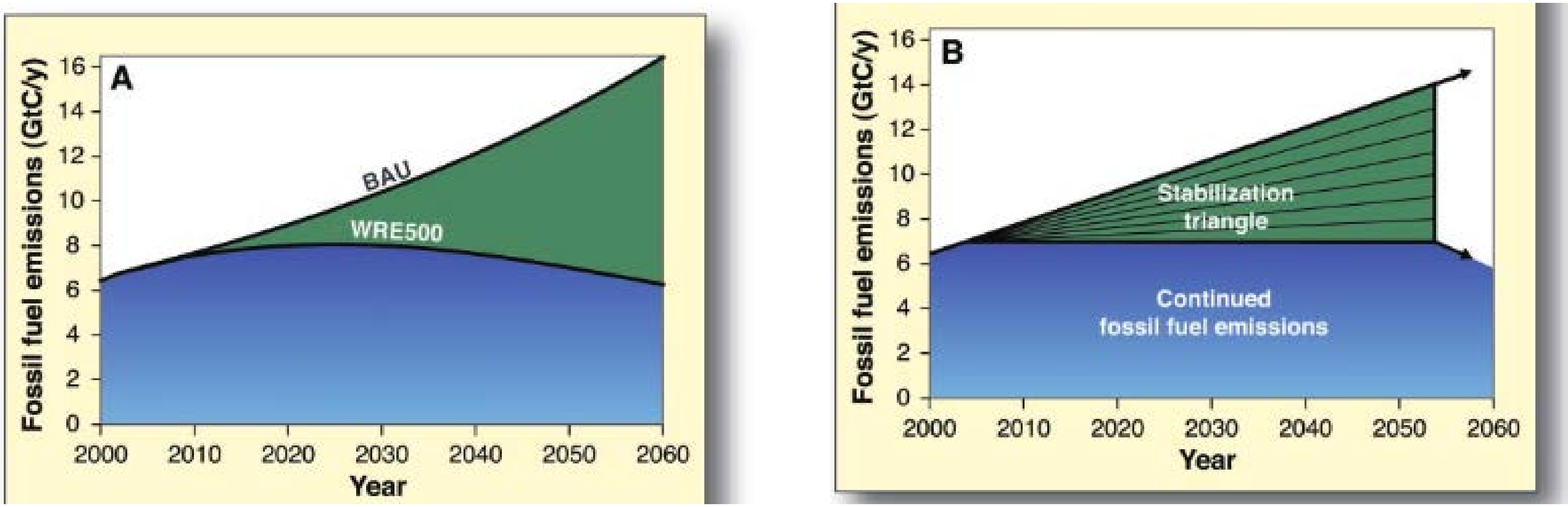
Of the "nine ways to cool the planet" discussed in the IEEE article, which of these seems most appealing to you? Briefly state why.



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)

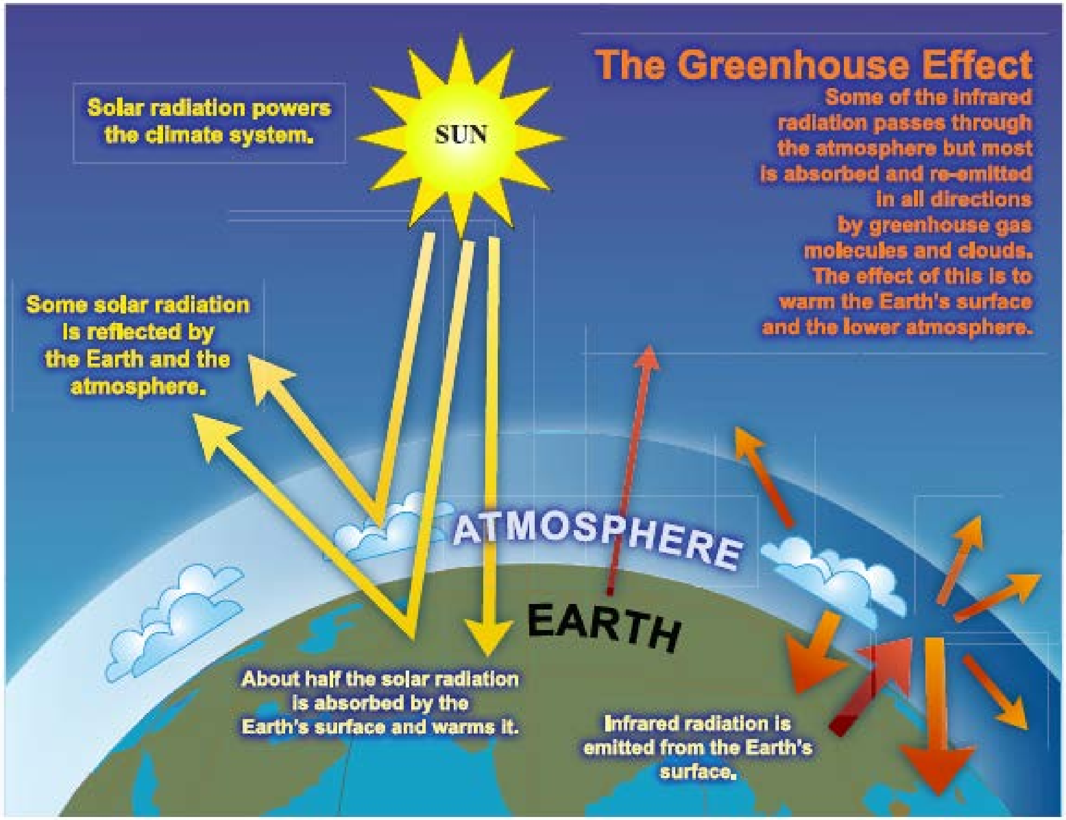
Pacala and Socolow: CO_2 Stabilization Wedges

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)

Greenhouse Effect



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

What is the "most important" GHG?

Radiative Forcing

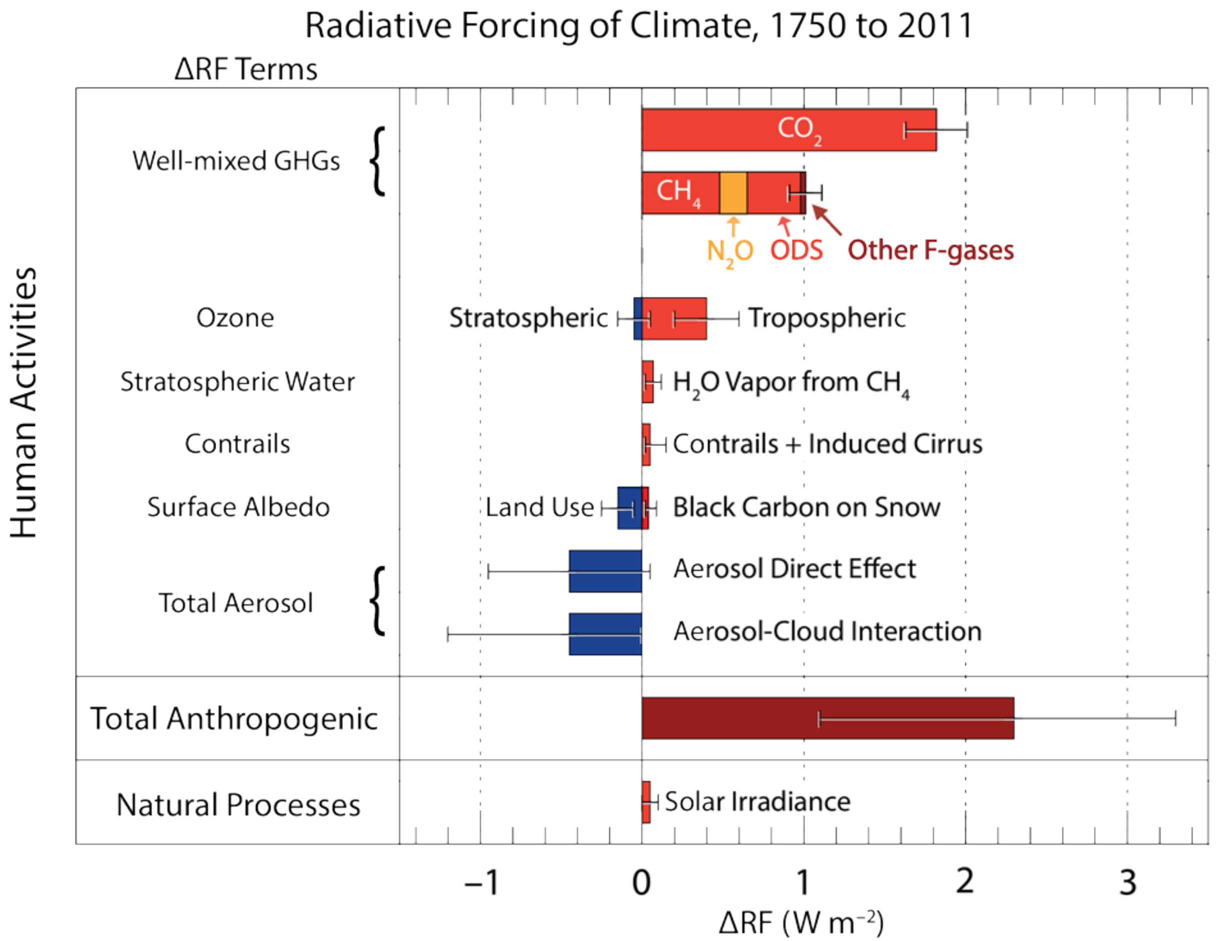
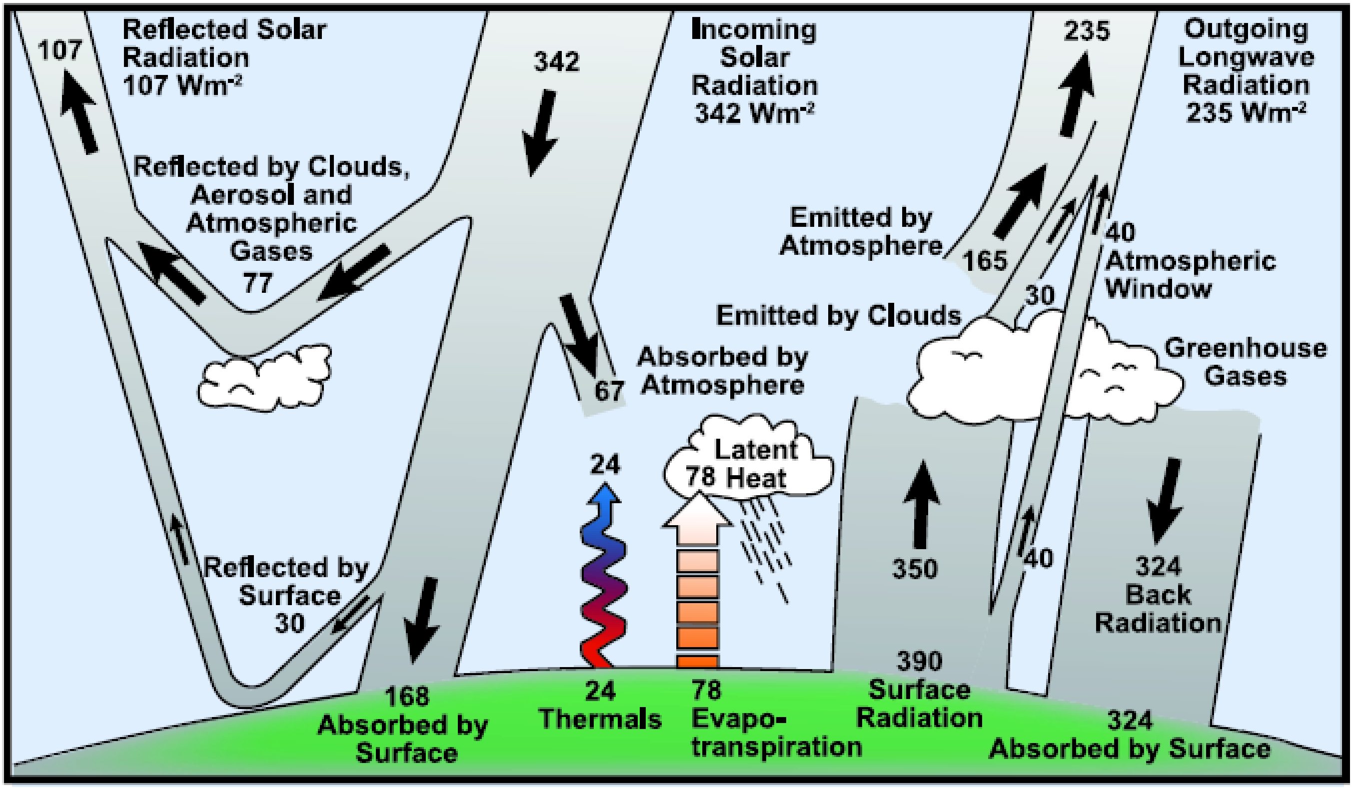


Figure 1.4
Paris Climate Agreement: Beacon of Hope

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.

Connection Between GHG Abundance and Surface T

How much does ΔF change when CO_2 changes?

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

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

$$\Delta T = \frac{1 + feedbacks}{\lambda_P}\,(\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS})$$

where

$$\lambda_P = 3.2\ \mathrm{W\ m^{-2}\ {}^\circ C^{-1}}$$

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

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

GWP – Global Warming Potential

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

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) .

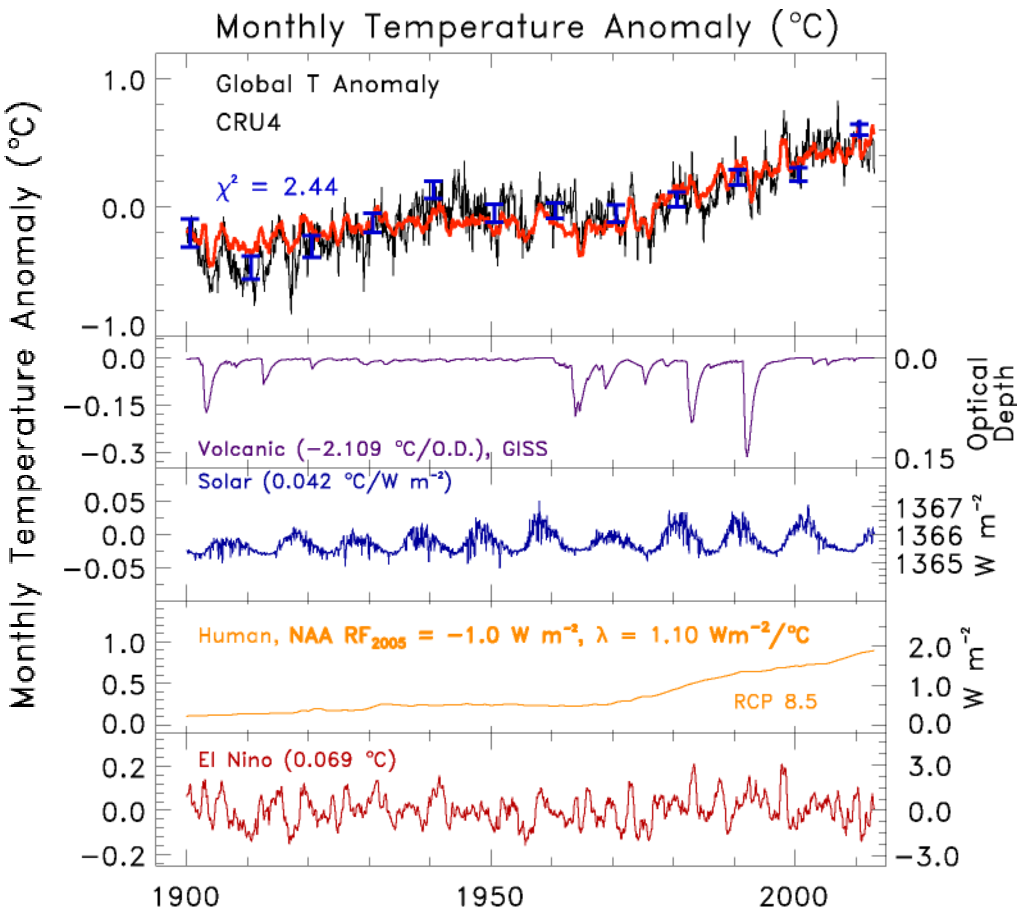
from IPCC 2007 "Physical Science Basis"

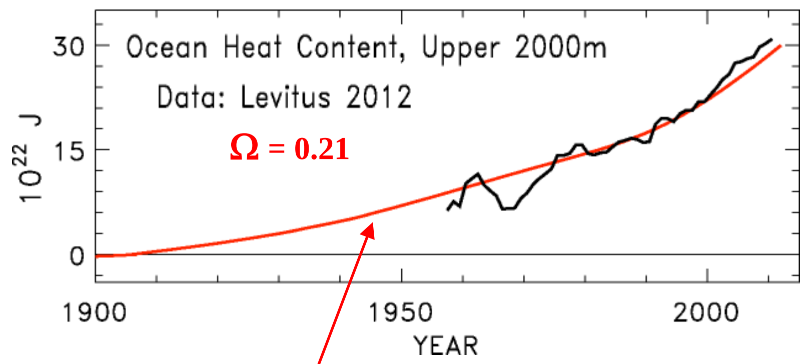
Time constant of 172.9 years dominates

GWP – Global Warming Potential

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 Climate Agreement: Beacon of Hope





$$\Delta T_{MDL\ i} = (1+\gamma)\ (GHG\ RF_{\ i}\ + NAA\ RF_{\ i}\ )\ /\ \lambda_{BB}$$
$$+\ C_o + C_1 \times SOD_{\ i-6} + C_2 \times TSI_{\ i-1} + C_3 \times ENSO_{\ i-2}$$
$$-\ Q_{OCEAN\ i}\ \ /\ \lambda_{BB}$$

where

$\lambda_{BB} = 3.21\ W\ m^{-2} / °C$

$1+\gamma\ = \{\ 1 - \Sigma(\text{Feedback Parameters}) / \lambda_{BB}\}^{-1}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

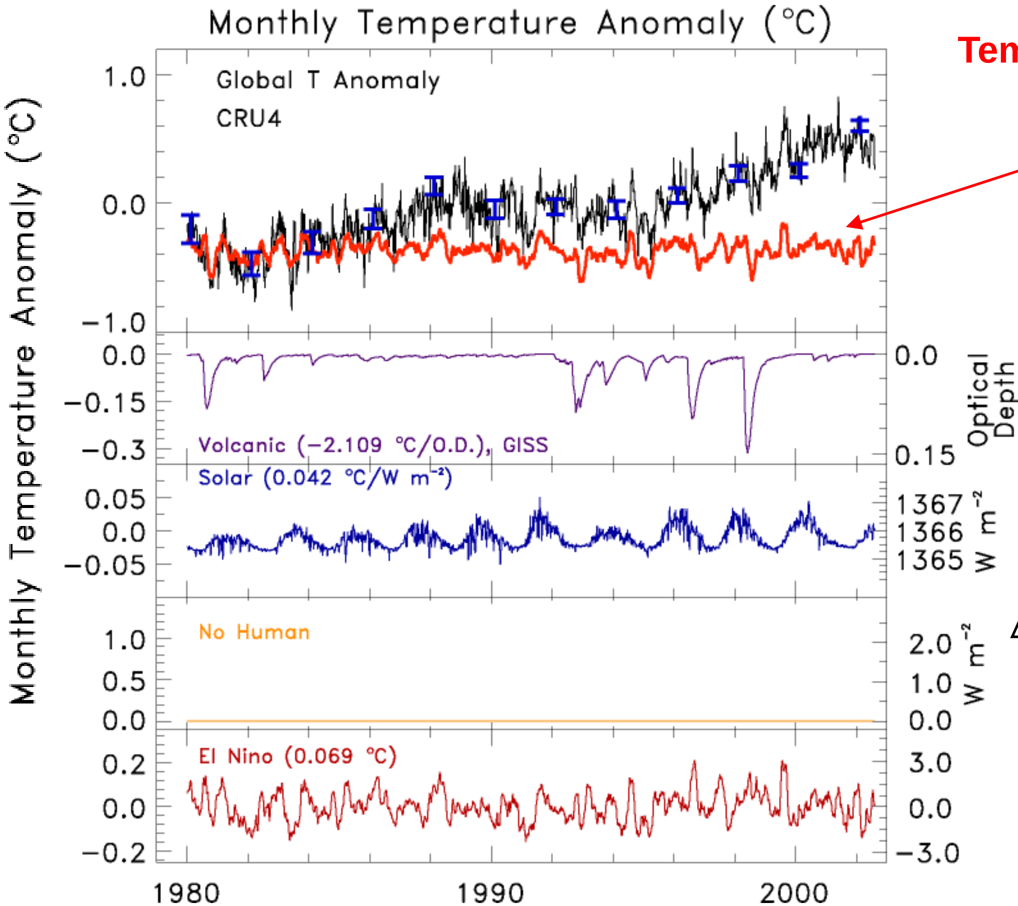
TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

Q_{OCEAN} = **Export of heat, atmos. to ocean**

$= \Omega\ (1+\gamma)\ \{(GHG\ RF_{\ i-72}\ ) +$

$(NAA\ RF_{\ i-72})\}$



Temperature nearly flat without human influence, i.e., if volcanoes, solar, & ENSO are sole drivers of global climate

$\Delta T_{MDL\,i}$ = ~~$(1+\gamma)\,(GHG\ RF_i + NAA\ RF_i) / \lambda_{BB}$~~
$+ C_o + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2}$
~~$- Q_{OCEAN\,i} / \lambda_{BB}$~~

Global warming is caused by CO_2, the greatest waste product of modern society, and we should reduce our collective dependence on fossil fuels sooner rather than later

where

λ_{BB} = 3.21 W m^{-2} / °C

$1+\gamma = \{ 1 - \Sigma(\text{Feedback Parameters}) / \lambda_{BB} \}^{-1}$

~~NAA RF = net RF due to anthropogenic aerosols~~

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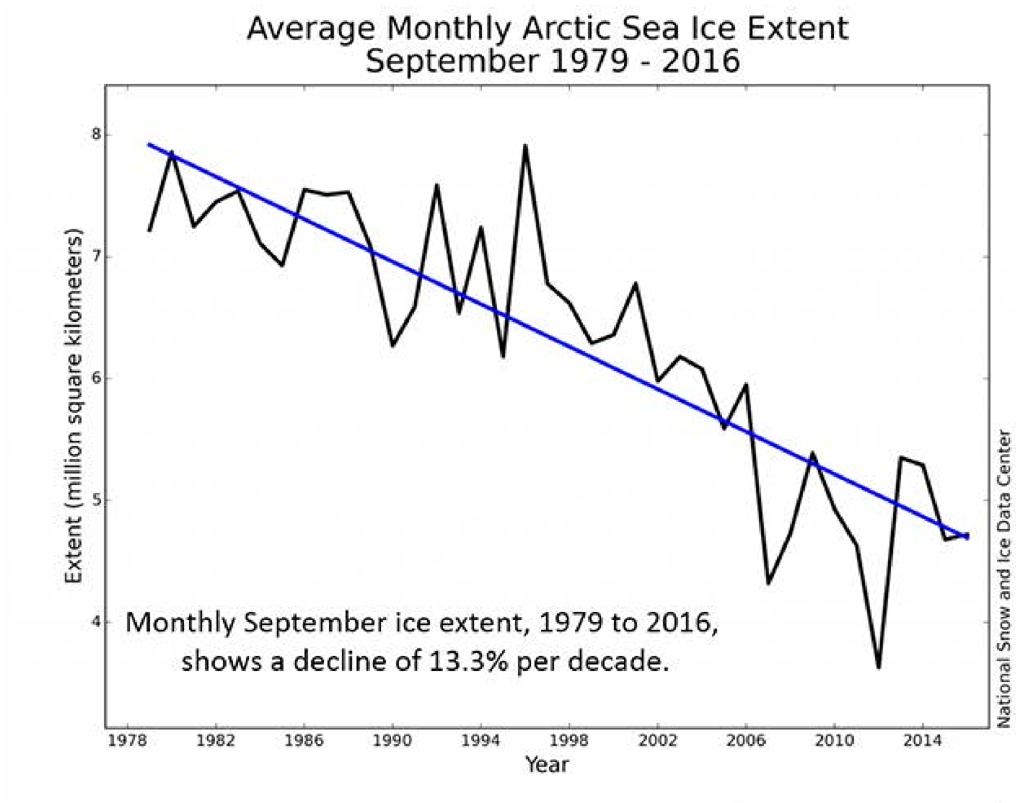
TSI = Total solar irradiance

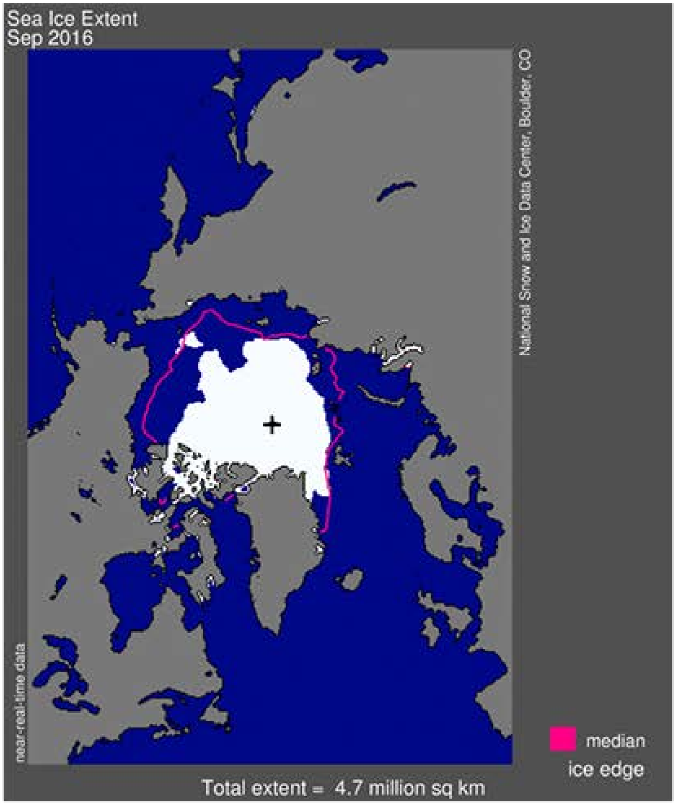
ENSO = Multivariate El Niño South. Osc Index

~~Q_{OCEAN} = Export of heat from atmosphere to ocean~~

Arctic Sea Ice: Canary of Climate Chnage

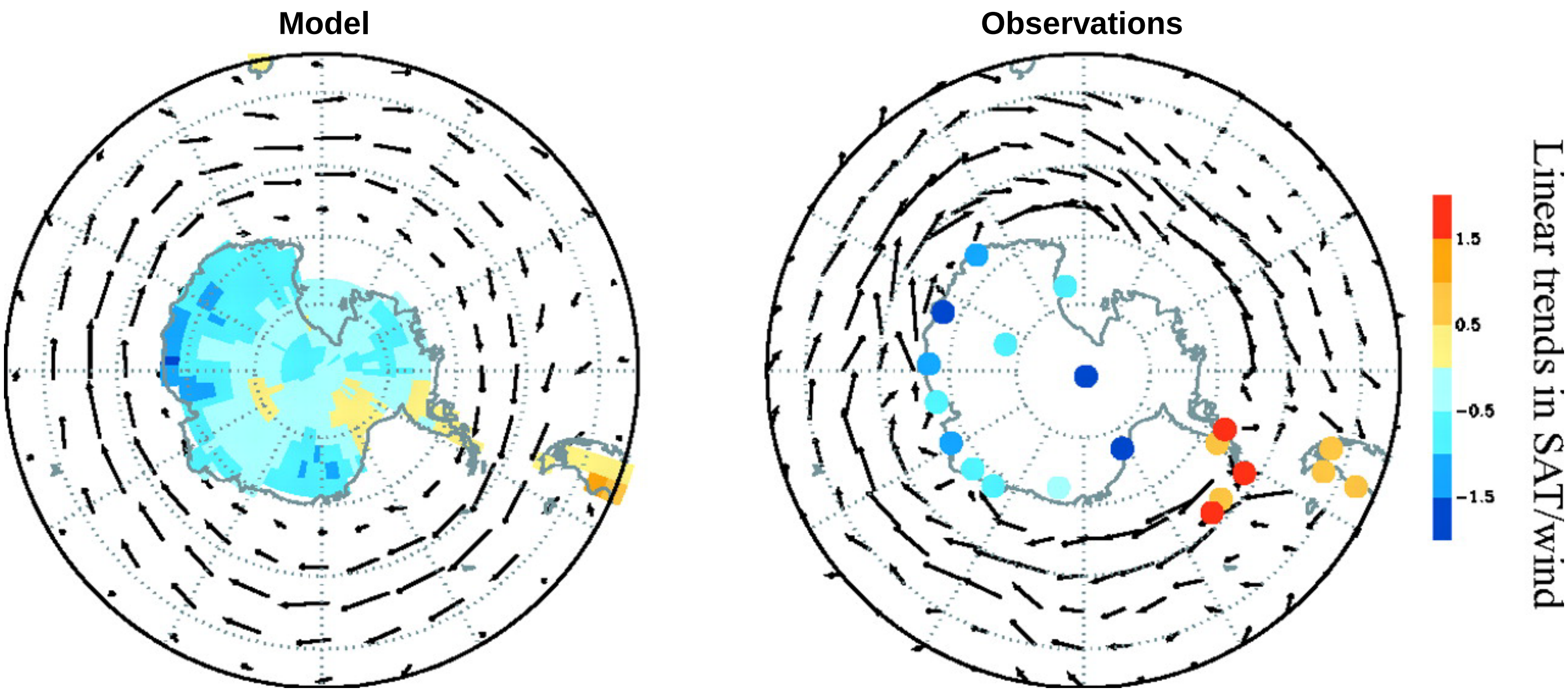


Source: http://nsidc.org/arcticseaicenews



Arctic sea ice extent for Sep 2016 was 4.72 million square kilometers (1.82 million square miles). Magenta line shows the 1981 to 2010 median extent of sea ice; black cross indicates North Pole.

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 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		
CFC-11	45	1
CFC-12	100	0.82
CFC-113	85	0.85
Carbon tetrachloride (CCl_4)	26	0.82
HCFCs	1–17	0.01–0.12
Methyl chloroform (CH_3CCl_3)	5	0.16
Methyl chloride (CH_3Cl)	1	0.02
Bromine gases		
Halon-1301	65	15.9
Halon-1211	16	7.9
Methyl bromide (CH_3Br)	0.8	0.66
Hydrofluorocarbons (HFCs)		
HFC-134a	13.4	0
HFC-23	222	0

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

$$\approx (\alpha\, n_{\mathrm{Br}} + n_{\mathrm{Cl}}) \frac{\tau_i}{\tau_{\mathrm{CFC\text{-}11}}} \frac{MW_{\mathrm{CFC\text{-}11}}}{MW_i} \frac{1}{3}$$

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

α = 60

Halons (anthropogenic halocarbons containing bromine) much worse for ozone than CFCs (anthropogenic halocarbons containing chlorine)

Heterogeneous Chemistry, Mid-Latitude vs Polar Regions

a) What type of aerosol particles are present in the mid-latitude stratosphere?

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

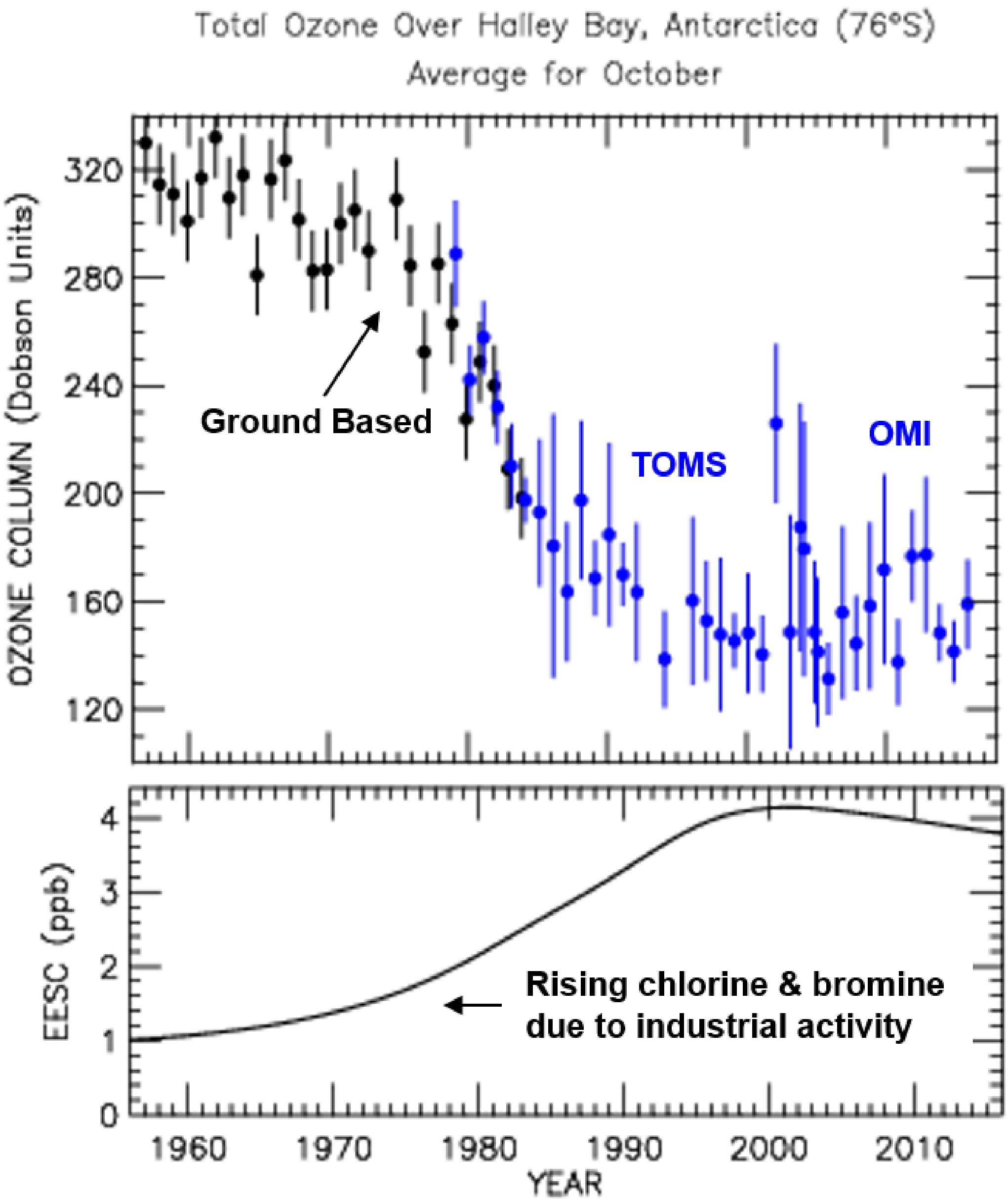
c) What type of particles are present in the polar stratosphere during winter?

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 depleted ozone) and that do not cause harm to the ozone layer in the dark 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?

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

Polar Ozone Loss: Antarctica



Much of this "leveling off" is indeed due to the "leveling off" of halogens

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:

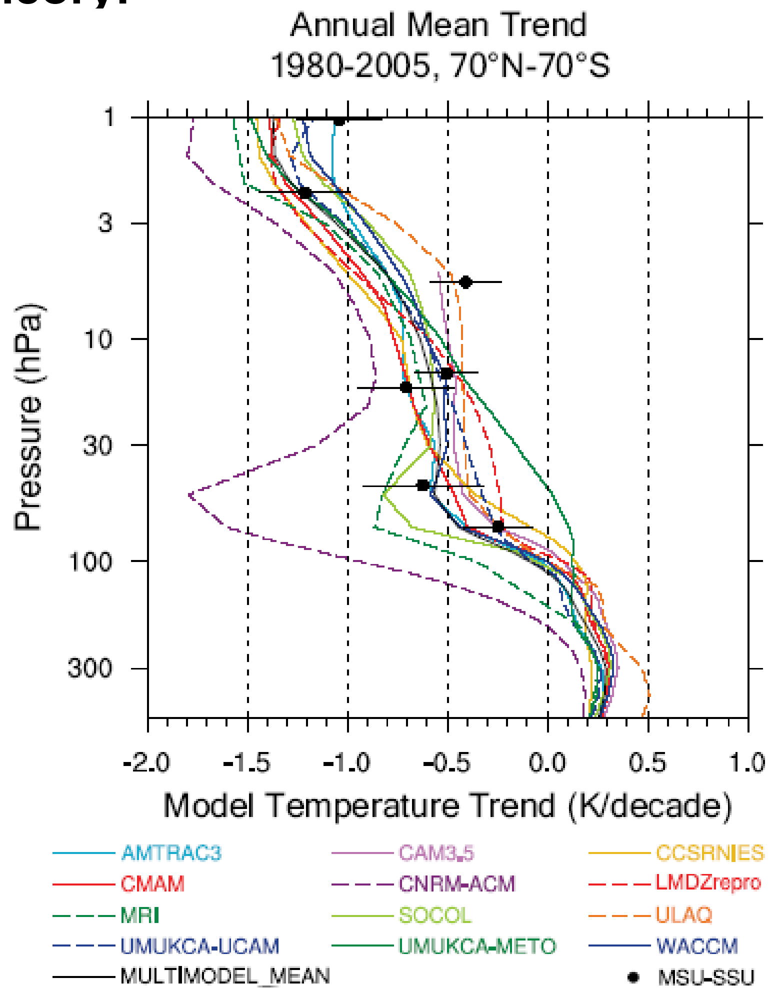
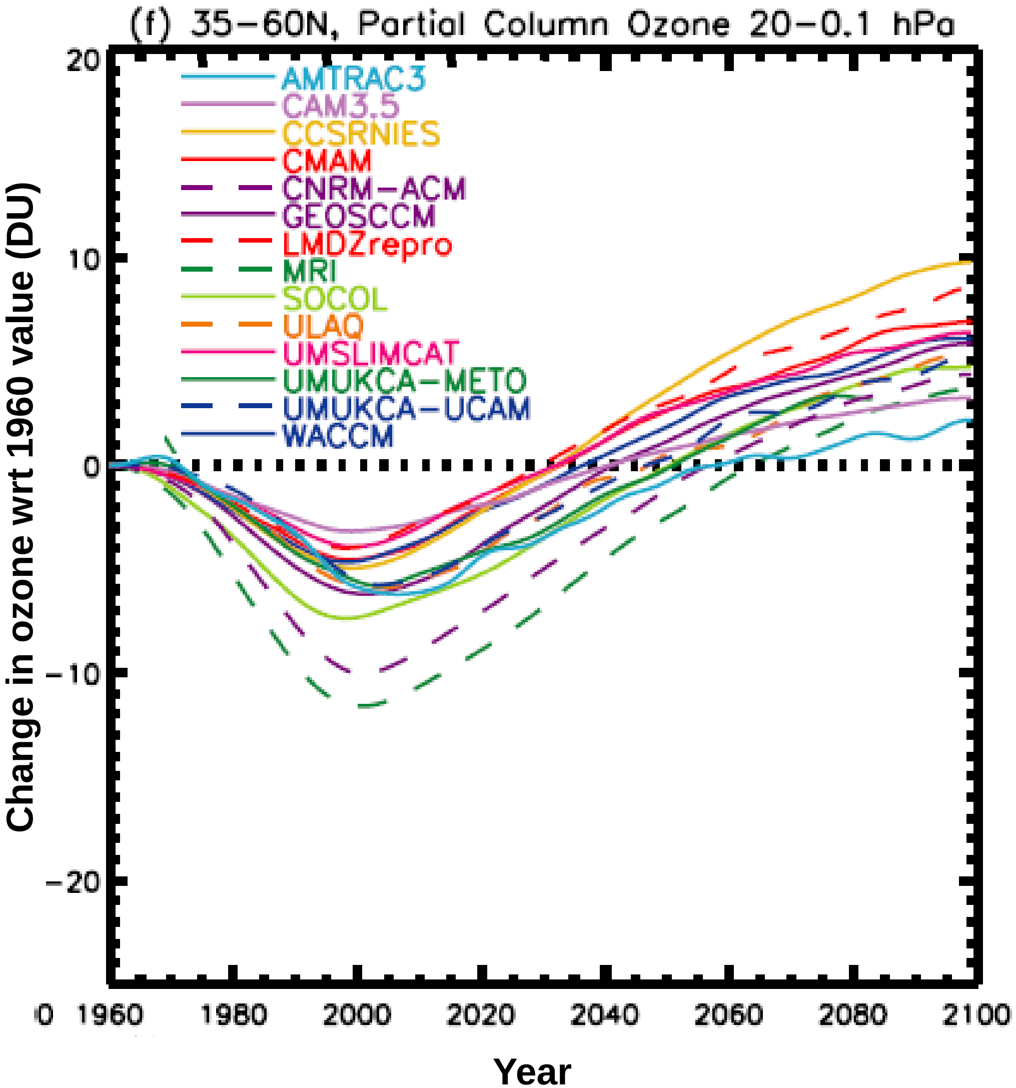


Figure 4−11, WMO/UNEP (2011)

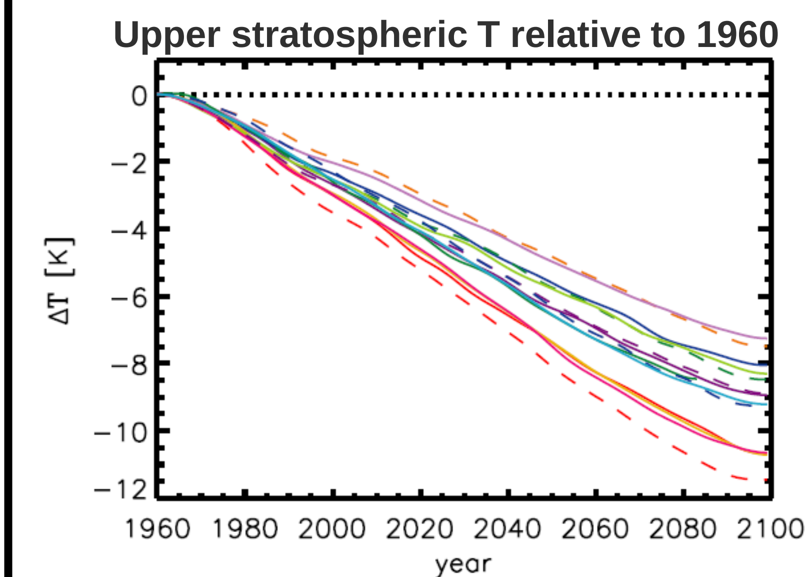
Future Trends, Upper Stratospheric Ozone



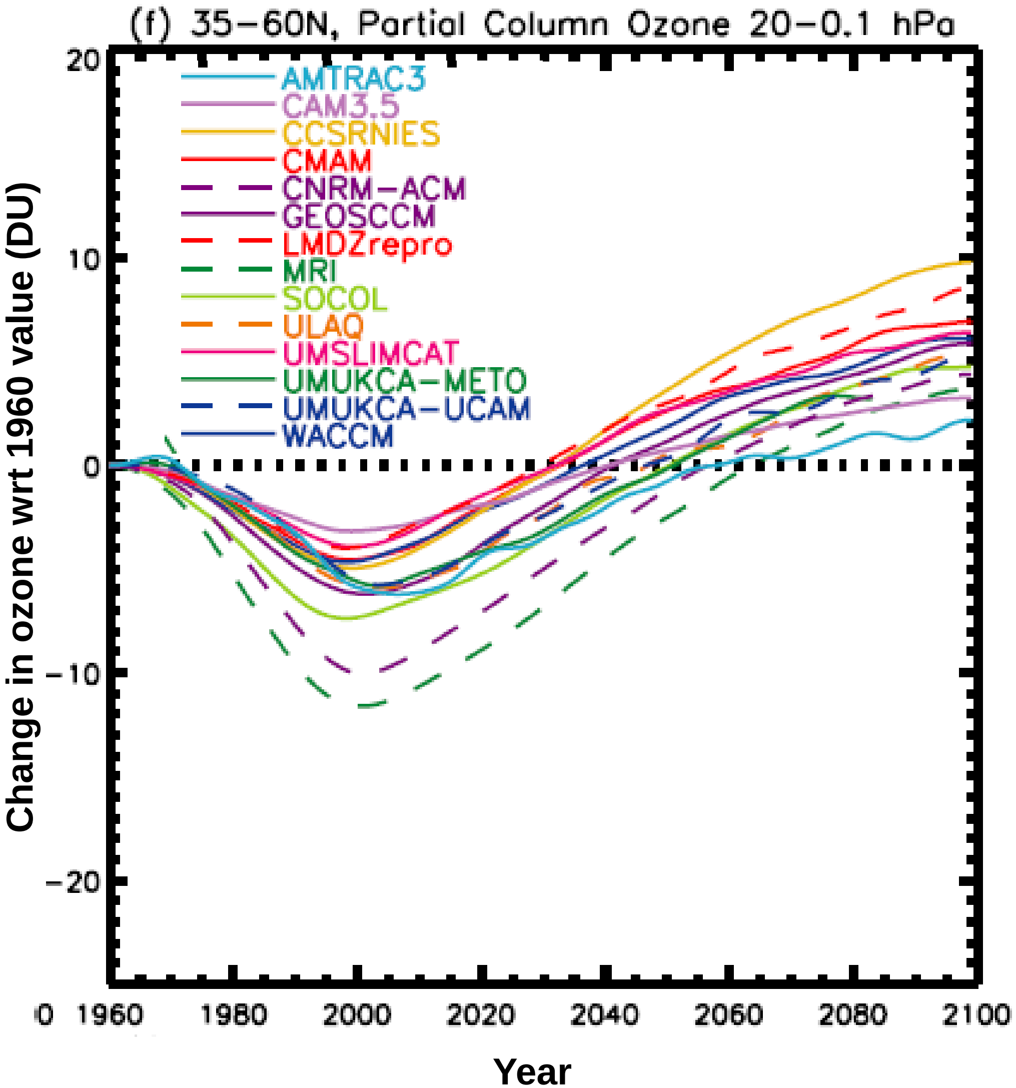
Oman *et al*., *JGR*, 2010

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

Due to stratospheric cooling !



Future Trends, Upper Stratospheric Ozone

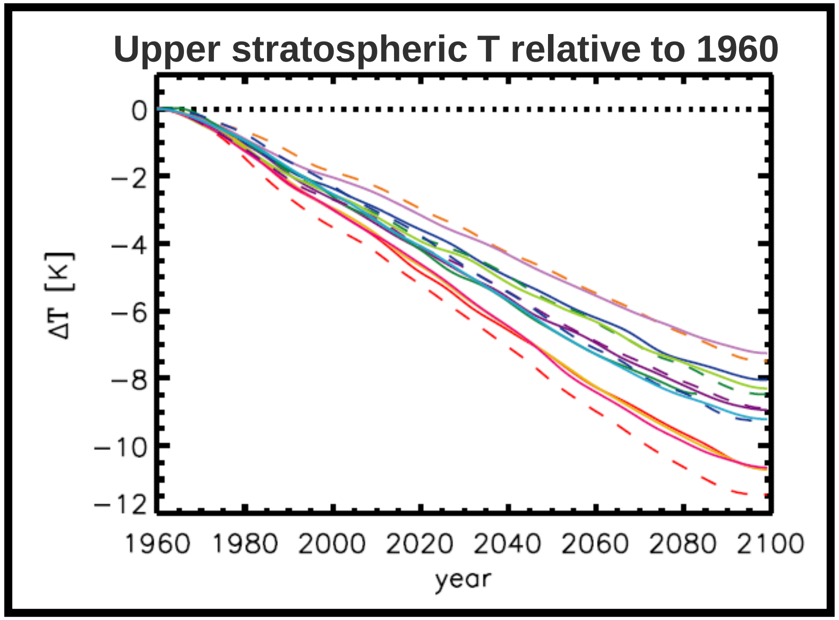


Oman *et al.*, *JGR*, 2010

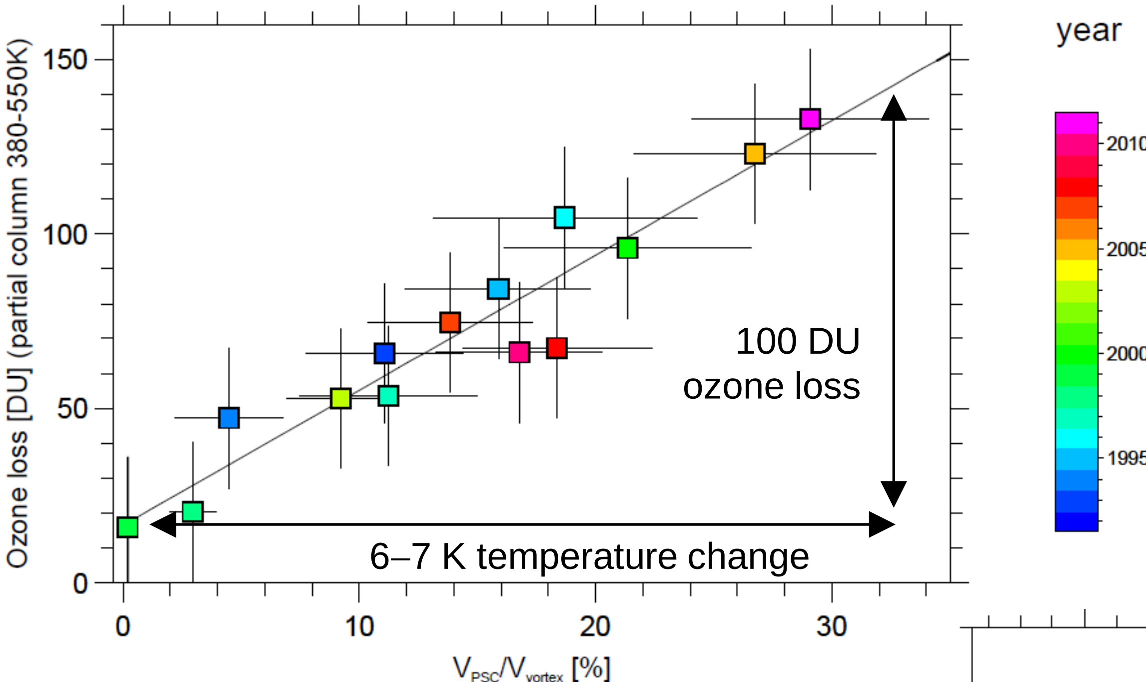
14 coupled chemistry climate models (CCMs) predict upper stratospheric ozone in 2100 will exceed upper stratospheric ozone in 1960

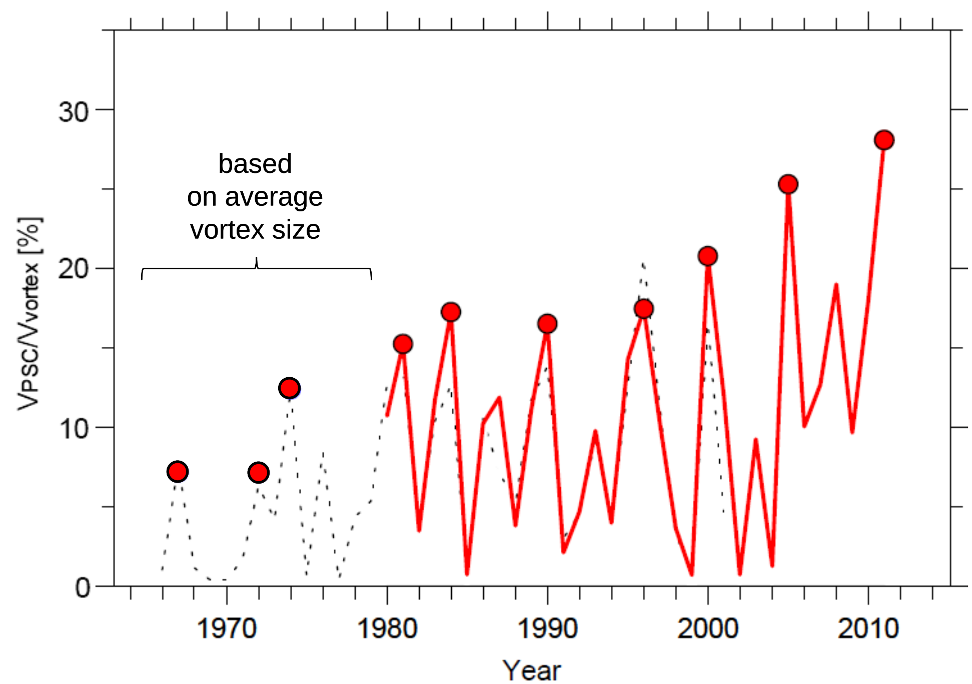
Due to stratospheric cooling !

Why this response of ozone to lower T ?



Arctic Ozone 2011 in Context of Prior Years





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:

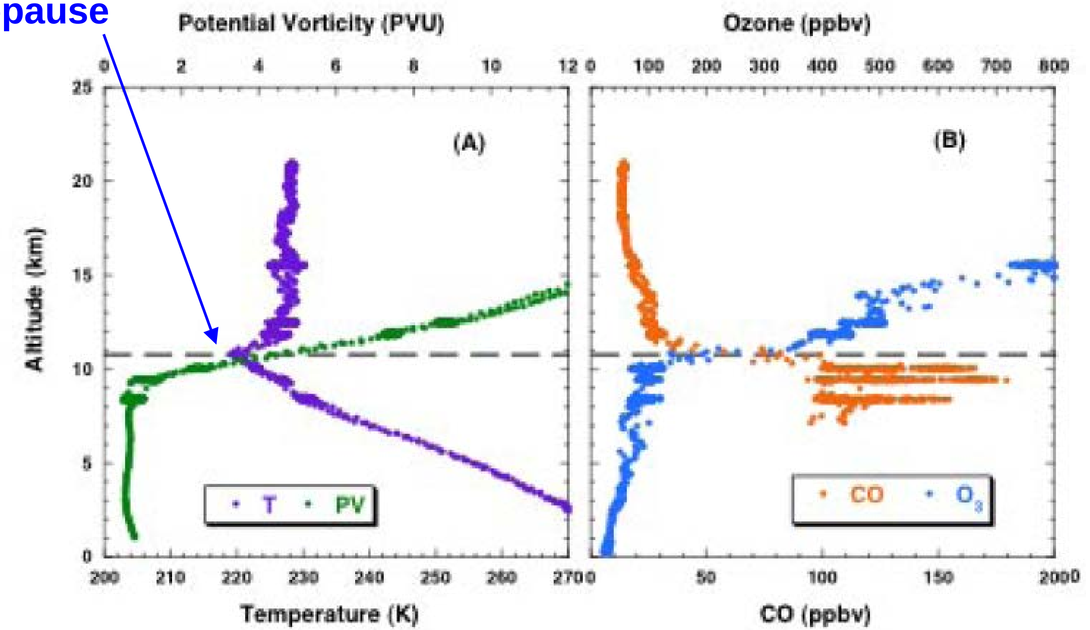
$$HO_2 + NO \rightarrow OH + NO_2$$

Followed by:

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

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

Tropopause



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

$$CO + OH \rightarrow CO_2 + H$$
$$H + O_2 + M \rightarrow HO_2 + M$$
$$HO_2 + NO \rightarrow OH + NO_2$$
$$NO_2 + h\nu \rightarrow NO + O$$
$$O + O_2 + M \rightarrow O_3 + M$$

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

"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: $HO_2 + NO$

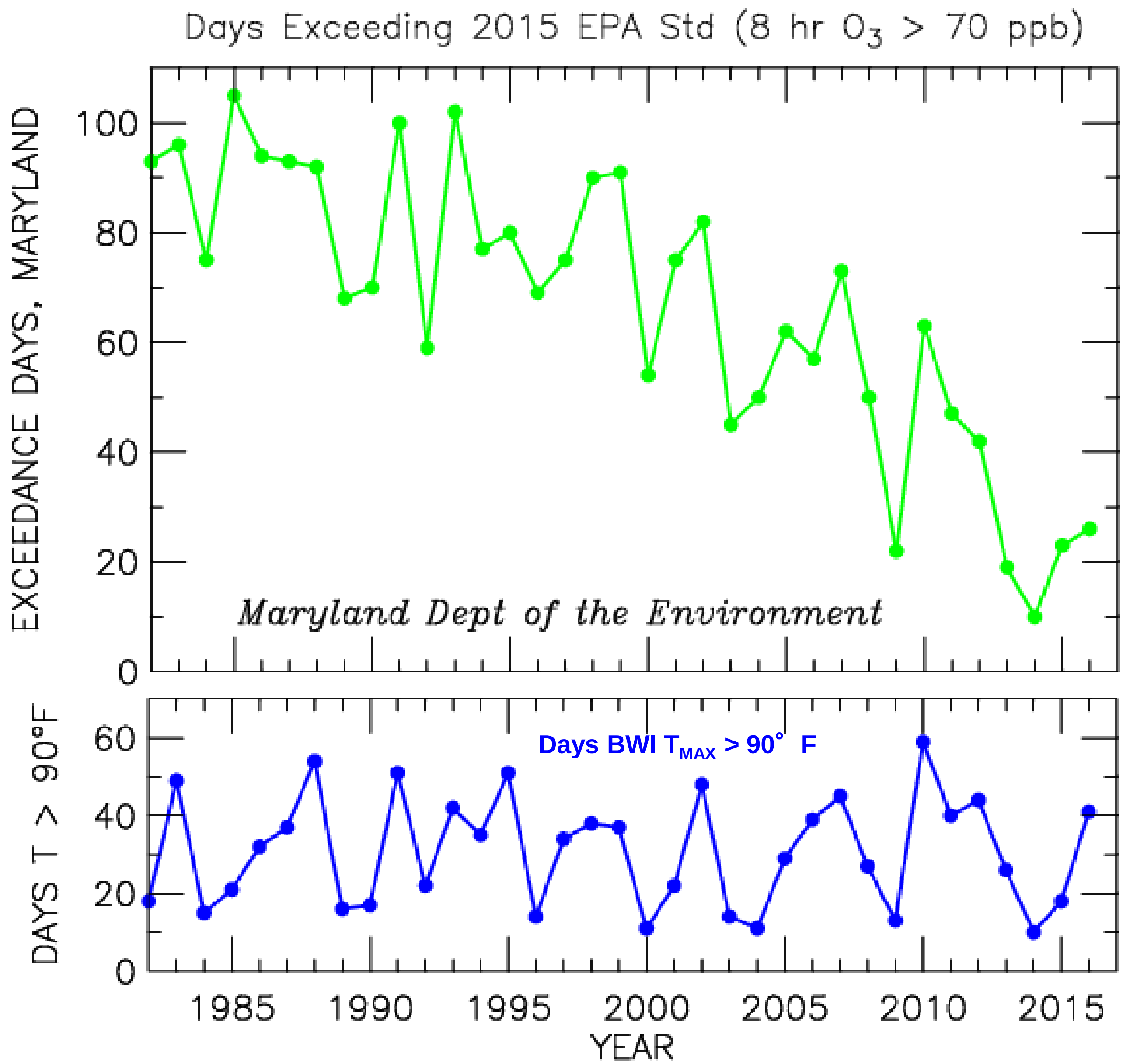
Ozone Production "limited" by $k[HO_2][NO]$ (propagation term)

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

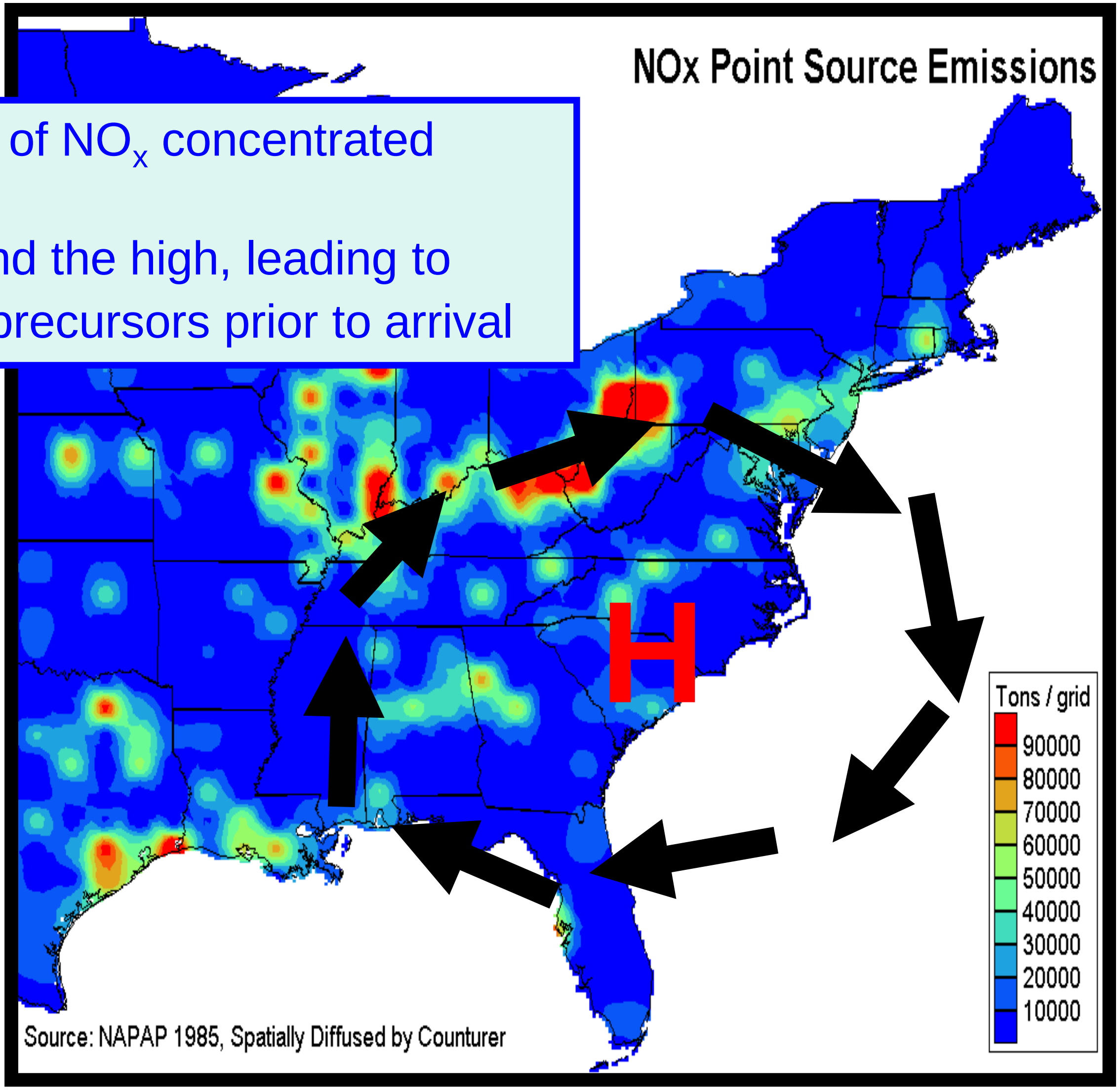
⇨ what happens to O_3 production ?

Dramatic Improvements Local Air Quality, Past 4 Decades



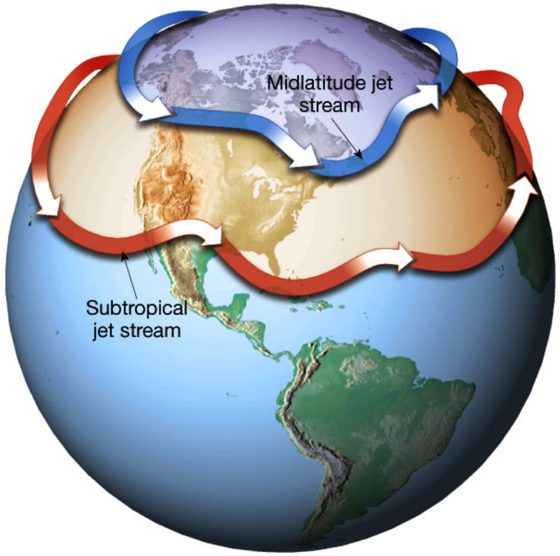
Day-to-day meteorology (weather!) affects severity and duration of pollution episodes

- 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

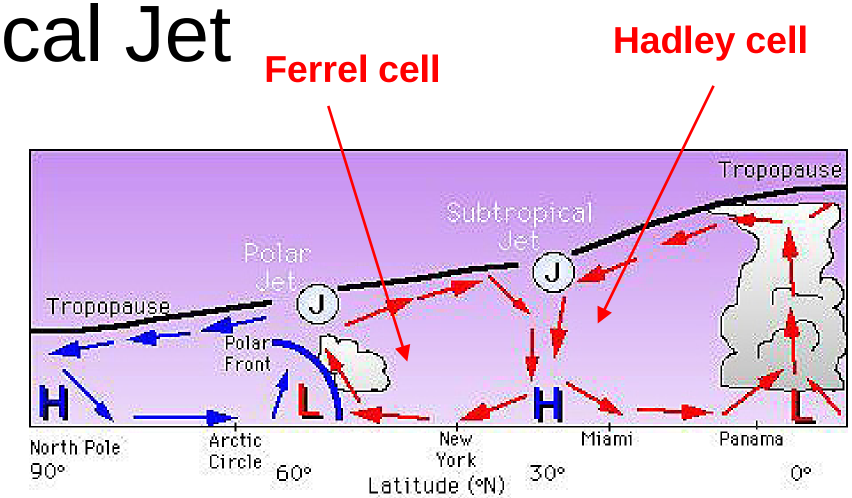


http://www.mde.state.md.us/assets/document/BJH%20-%20Basics%20on%20Ozone%20Transport.ppt

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:

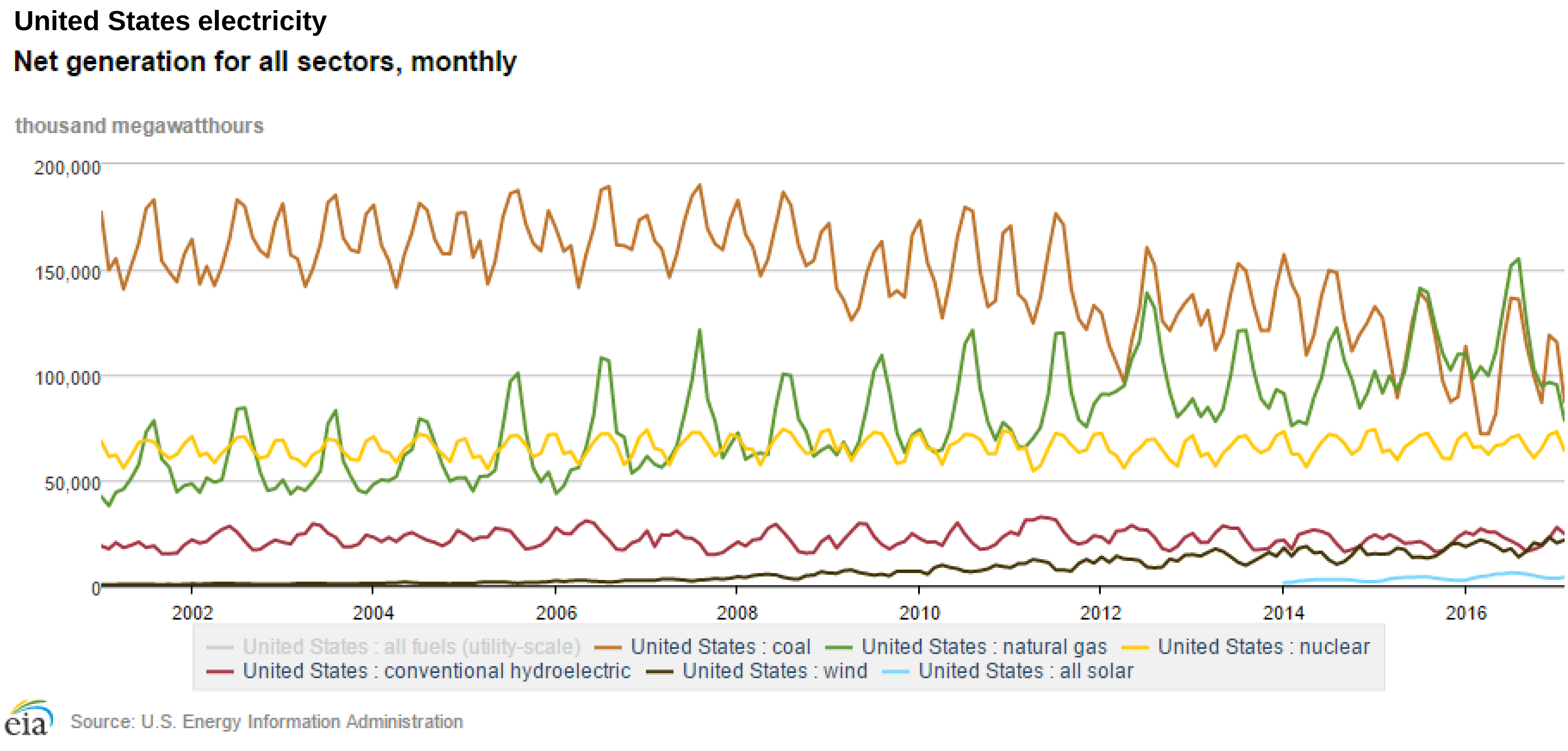
- Number of days Subtropical Jet within 150 miles of Baltimore has increased by ~50% between 1979 and 2003 due to "frontal movement"
- Driving force: weakening of the equator to pole temperature gradient, caused by more rapid warming at high latitudes compared to tropics

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:



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.