Review of Lectures 10 to 17

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2020
https://myelms.umd.edu/courses/1291919

https://www.videoblocks.com/video/earth-sunset-spacewalk-view-from-space-station-r7dydlcsgjd23vml0

12 November 2020

Announcements: Class

Second Exam

Second exam which will be on-line, open book, open web, ***<u>that everyone will take during normal class hour on Tues, 17 Nov, from 2:02 to 3:17 pm.</u>***

However, please note that:

a) the exam will focus on a series of question that you can only answer properly in the limited time IF you are already familiar with the contents of each lecture;

b) there will be either minimal or no calculations on the exam, the vast majority of the exam will be qualitative rather than quantitative

c) if you have been doing all of the readings, answering the ATs based on a comprehensive understanding of the readings, and retaining knowledge from the readings and exams, as solidified by consistently high scores of the learning out come quizzes, then you'll be in great shape for the first exam. On the other hand, if you have been skimming the readings, doing the bare minimum to answer the ATs, and not completing the learning outcome quizzes, you will need to impart greater effort to prepare for the exam, in order to do well.

d) by “open web”, I mean you are allowed to search for information on the Web. **You absolutely, positively are not allowed to conduct any on-line chats, or solicit help from an on-line assistance program of any sort.**

Announcements: Outside of Class

Today, 12 Nov: AOSC Weekly Seminar (3:30 pm)

Dr. Dylan Jones, University of Toronto

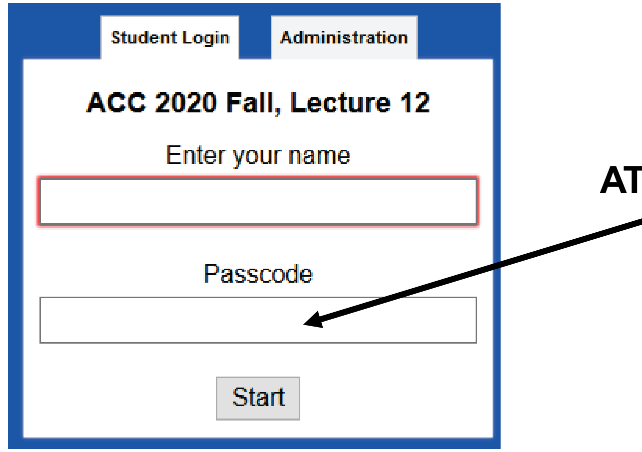
Summertime ozone in North America: Isolating weather-driven ozone pollution events and evaluating trends in precursor emissions

Air pollution regulations have led to dramatic reductions in emissions of air quality pollutants in North America, and thus improvements in air quality, during the past three decades. However, ozone pollution episodes remain an issue in some regions of North America. Furthermore, there are uncertainties in the trend in emissions of nitrogen oxides (NOx), a key ozone precursor. In this talk I will examine the link between summertime ozone pollution episodes and large-scale atmospheric circulation patterns and present an analysis isolating the weather-driven component of ozone pollution episodes. I will also review the discrepancies in recent trends of emissions of NOx in the United States and discuss the use of a deep learning model to evaluate the consistency of the reported trends in NOx emissions with observations of surface ozone.

https://aosc.umd.edu/seminars/department-seminar

Email Joseph Knisely at jknisely@umd.edu for Zoom connection info

Learning Outcome Quizzes



ATL2428 here

ACC 2020 Fall, Lecture 12 Results

Filter by name / partition by tag / group by name

Average Score
77%
60% to 100%

Average Time
0:08:57
0:00:55 to 0:28:25

Name▲	Score	Started On	Finished On	Time
	80% (4/5)	2020-10-27 10:11 PM	2020-10-27 10:13 PM	0:02:01
	80% (4/5)	2020-10-23 1:46 PM	2020-10-23 1:51 PM	0:05:20
	80% (4/5)	2020-10-26 7:13 PM	2020-10-26 7:16 PM	0:03:50
	60% (3/5)	2020-10-23 2:52 PM	2020-10-23 3:01 PM	0:09:17
	80% (4/5)	2020-11-11 12:03 PM	2020-11-11 12:18 PM	0:13:00
	60% (3/5)	2020-10-31 10:11 AM	2020-10-31 10:39 AM	0:28:22
	100% (5/5)	2020-10-31 10:40 AM	2020-10-31 10:41 AM	0:00:53

Importance of Radicals

- With a few exceptions, the only reactions between molecules that proceed at appreciable rates are those involving at least one radical

- Radicals require significant energy to form: a bond must be broken

- Radical formation is tied to absorption of photons that "photodissociate" a compound, leading to radical formation

Initiation

O_2 + photon $\rightarrow$ O + O

Propagation

$O + O_2 + M \rightarrow O_3 + M$

O_3 + photon $\rightarrow O(^1D) + O_2$

$O(^1D) + H_2O \rightarrow OH + OH$

$OH + O_3 \rightarrow HO_2 + O_2$

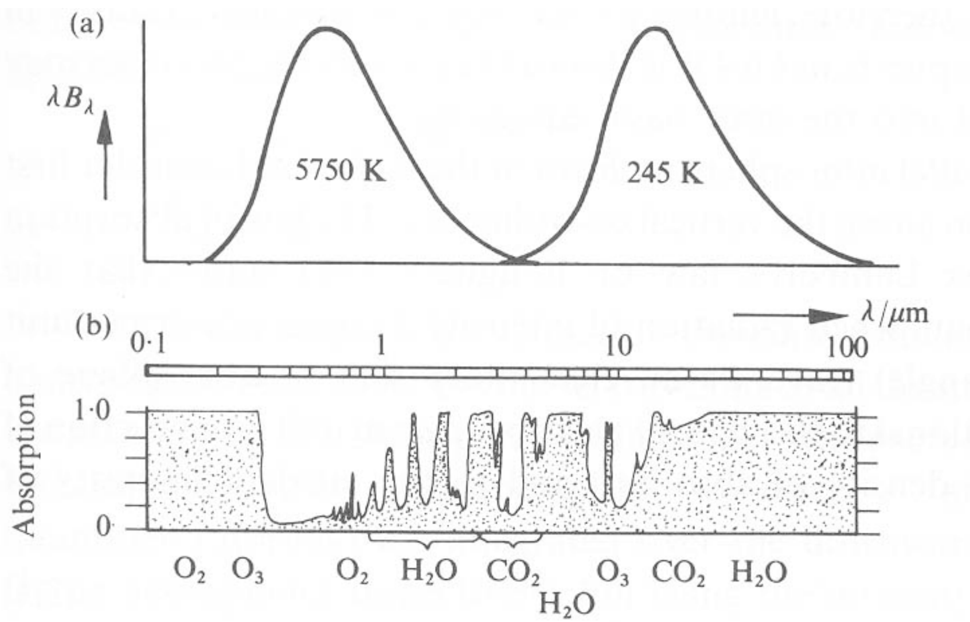
$HO_2 + O \rightarrow OH + O_2$

Termination

$OH + HO_2 \rightarrow H_2O + O_2$

Atmospheric Radiation

• Solar irradiance (downwelling) at top of atmosphere occurs at wavelengths between ~200 and 2000 nm (~5750 K "black body" temperature)



Panel (a) : Curves of black-body energy versus wavelength for 5750 K (Sun's approximate temperature) and for 245 K (Earth's mean temperature).

The curves are drawn with equal area since, integrated over the entire Earth at the top of the atmosphere, the solar (downwelling) and terrestrial (upwelling) fluxes must be equal.

Panel (b): absorption by atmospheric gases for a clear vertical column of the atmosphere (1.0 represents complete absorption).

From Houghton, *Physics of Atmospheres*, 1991

• Absorption and photodissociation in the UV occurs due to changes in the electronic state (orbital configuration) of molecules

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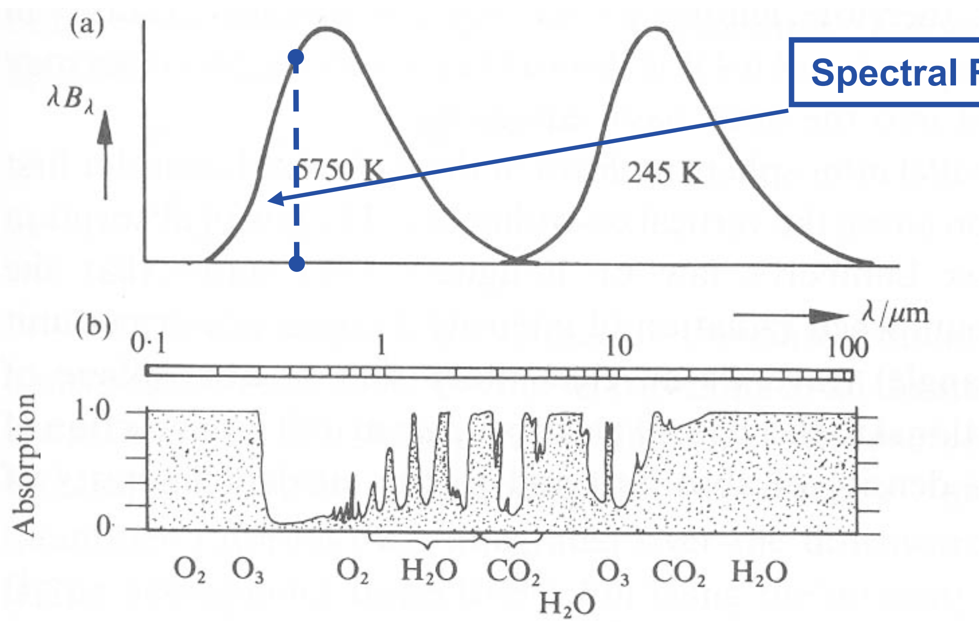

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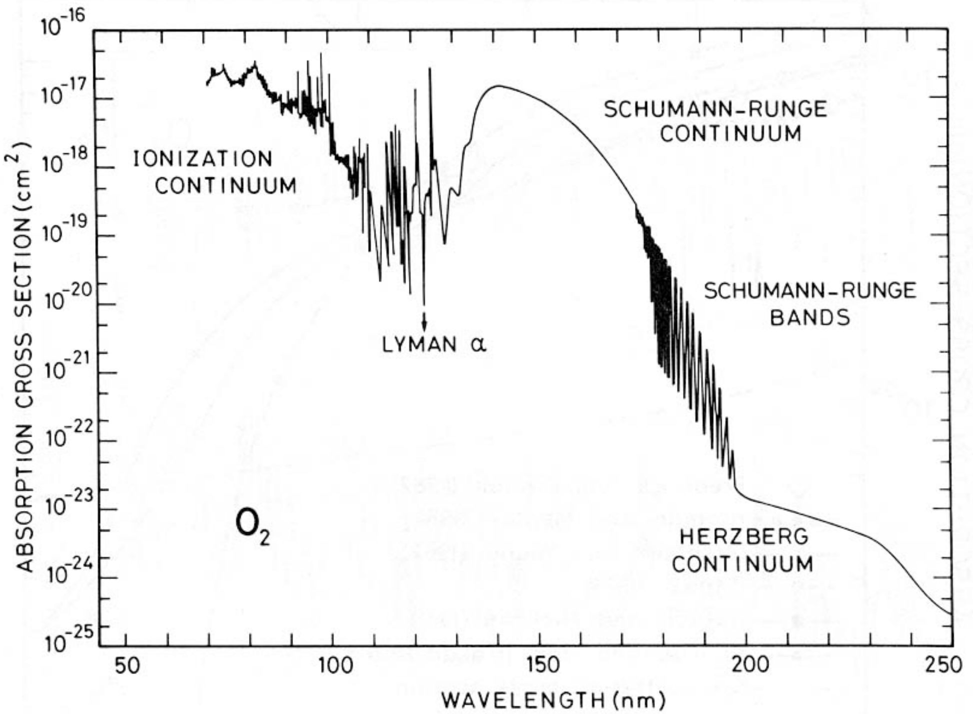
Absorption Cross Section of O_2



From Brasseur & Solomon, *Aeronomy of the Middle Atmosphere*, 1986

- O_2 can not dissociate longward of ~250 nm
- All of the absorption shown above is dissociative (e.g., leads to production of two O atoms)
- Structure in the O_2 cross section is related to whether the initial transition involves an unbound electronic state (smooth) or involves a specific vibrational level of an electronic state (banded, due to requirement of specific quanta of energy)

Optical Depth of O_2 Absorption

Recall the *Beer-Lambert Law*:

$$F(z,\lambda) = F_{TOA}(\lambda)\, e^{-\tau(z,\,\lambda)}$$ (TOA : Top of Atmosphere)

where:

$$\tau(z,\lambda) = m \int_z^\infty \sigma_\lambda\, [C]\, dz'$$ (τ: optical depth)

Also:

$$\int_0^\infty [O_2]\, dz' \approx 4 \times 10^{24} \text{ molecules/cm}^2$$

O_2 Optical Depth for $\theta = 0°$, $z = 0$ km			
	σ_{max} (cm^2)	τ (0 km)	$e^{-\tau\,(0\text{ km})}$
Schumann-Runge Continuum	10^{-17}	4×10^{7}	0.
Schumann-Runge Bands	10^{-20}	4×10^{4}	0.
	3×10^{-23}	120	7.6×10^{-53}
Herzberg Continuum	10^{-23}	40	4.2×10^{-18}

Optical Depth of O_3 Absorption

A typical mid-latitude column abundance for O_3 is 300 Dobson units (DU):

$$1 \text{ DU} = 2.687 \times 10^{16} \text{ molecules/cm}^2; \quad 300 \text{ DU} = 8 \times 10^{18} \text{ molecules/cm}^2$$

Aside:

$$\frac{\text{Column O}_3}{\text{Column Air}} = \frac{8\times10^{18}}{2\times10^{25}} = 0.4 \text{ parts per million } \Rightarrow \text{Ozone is a trace species!}$$

O_3 Optical Depth for $\theta = 0°$, $z = 0$ km				
	σ_{max} (cm^2)	τ (0 km)	$e^{-\tau\,(0\text{ km})}$	O_3 Column, $\tau = 1.0$
Hartley (~220 to 280 nm)	10^{-17}	80	1.8×10^{-35}	3.7 DU
Huggins (~310 to 330 nm)	10^{-19}	0.8	0.45	372 DU
Chappuis (~500 to 700 nm)	3×10^{-21}	0 .024	~1.0	12,400 DU

Solar Spectral Actinic Flux

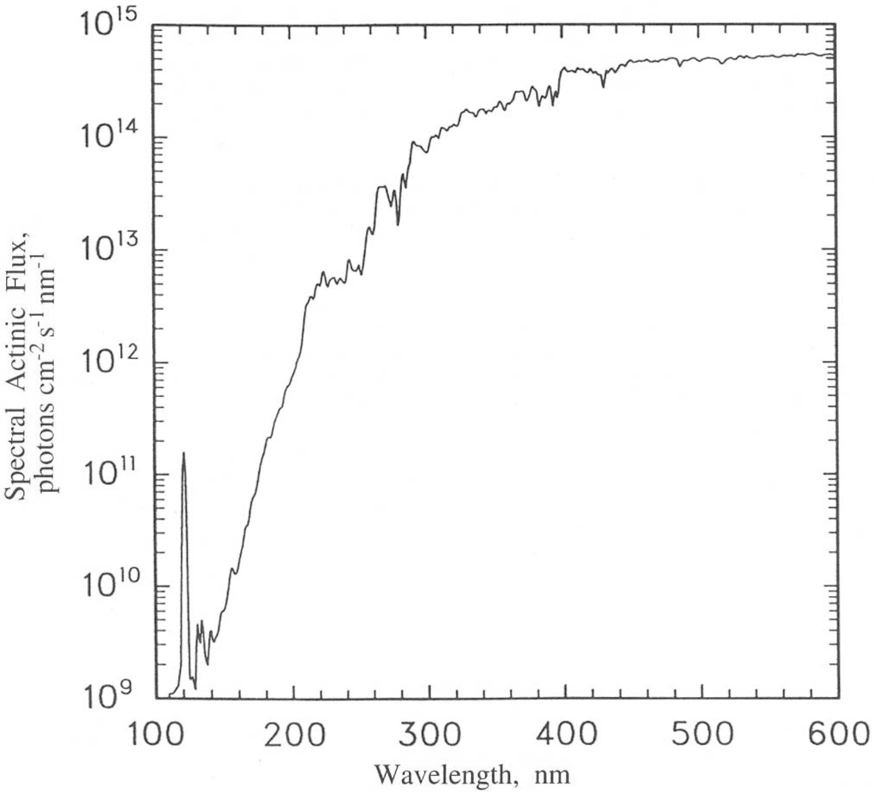
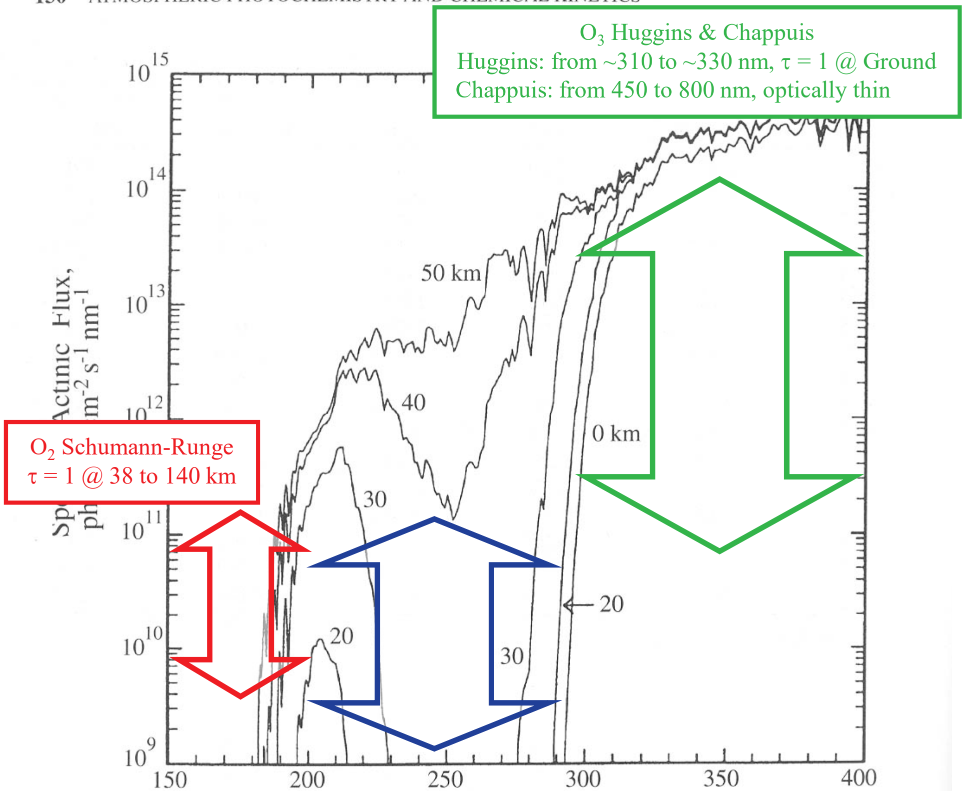


FIGURE 6. Solar spectral actinic flux (photons cm^{-2} s^{-1} nm^{-1}) at the top of Earth's atmosphere.



GURE 3.3 Solar s... various altitudes and at the Earth's surface (DeMo...

From DeMore et al., *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling*, Evaluation No. 11, 1994.

From Seinfeld and Pandis, *Atmospheric Chemistry and Physics*, 1998.

Photolysis Frequency

For a specific spectral interval, the photolysis frequency (***partial J value***) of a gas is given by the product of its absorption cross section and the solar irradiance:

$$J_{gas}(z,\lambda) = \text{Quantum\_Yield}(\lambda)\,\sigma_{gas}(\lambda,T)\,F(z,\lambda)$$

Units: $s^{-1}\,nm^{-1}$

The total ***photolysis frequency*** (***J value***) is found by integrating $J_{gas}(z,\lambda)$ over all wavelengths for which the gas photodissociates:

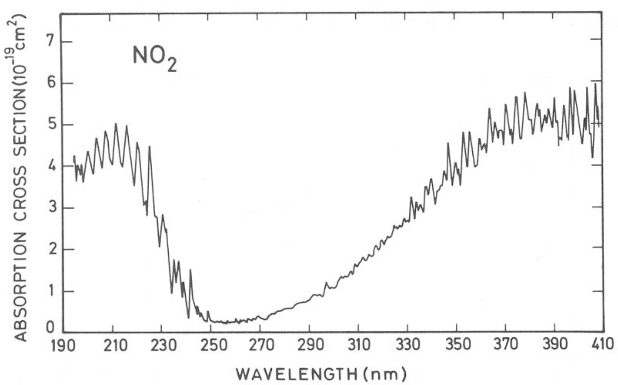
$$J_{gas}(z) = \int_{\lambda_{min}}^{\lambda_{max}} J_{gas}(z,\lambda)\,d\lambda$$

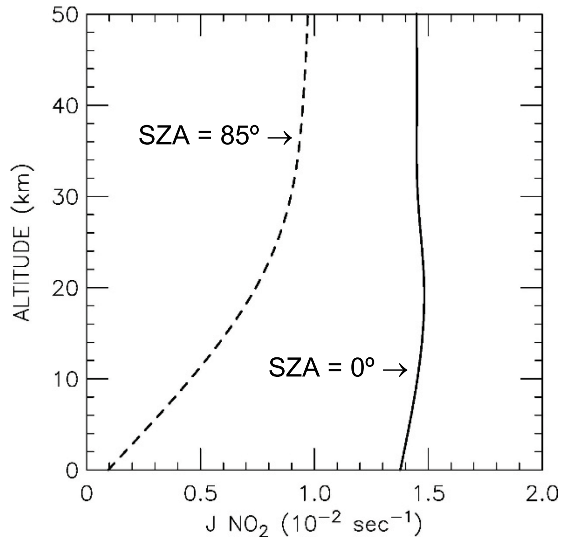
Units: s^{-1}

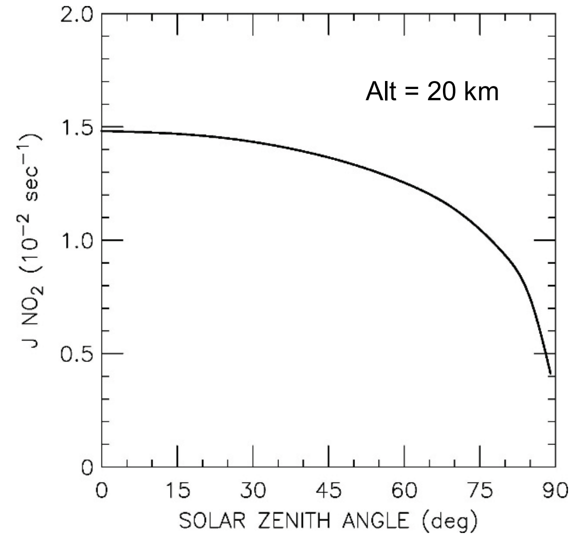
$$\text{Rate of Reaction} = \frac{dO_3}{dt} = J\,[O_3]; \quad \text{Units of } J \text{ are } s^{-1}$$

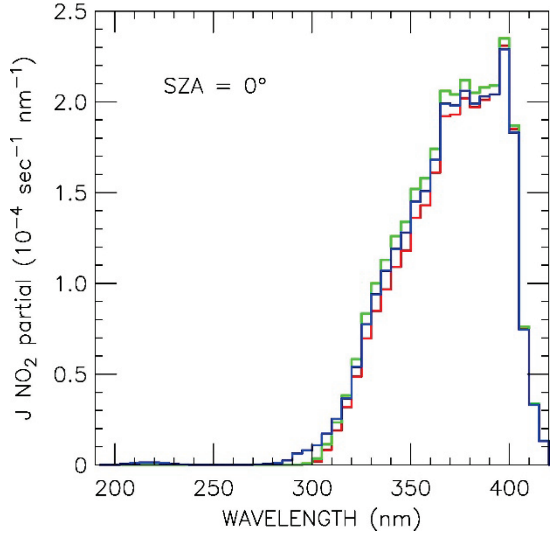
More precisely, calculations of photolysis frequencies consider the "spectral actinic flux", which represents the amount of available photons integrated over all angles, rather than "solar irradiance". These two quantities differ because of scattering of solar radiation by gases and aerosols, and reflection of radiation by clouds and the surface.

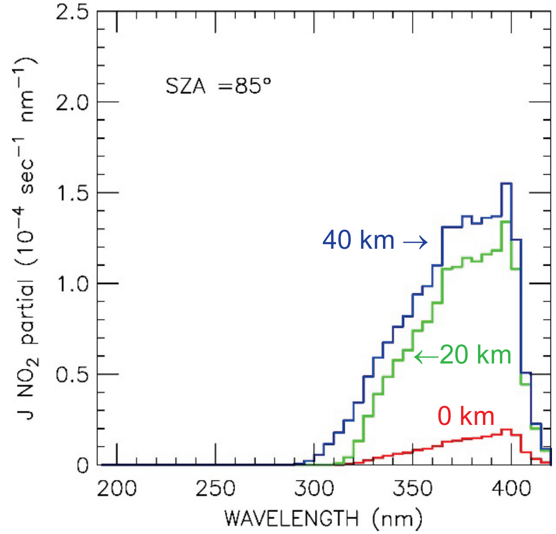
NO_2 Photolysis



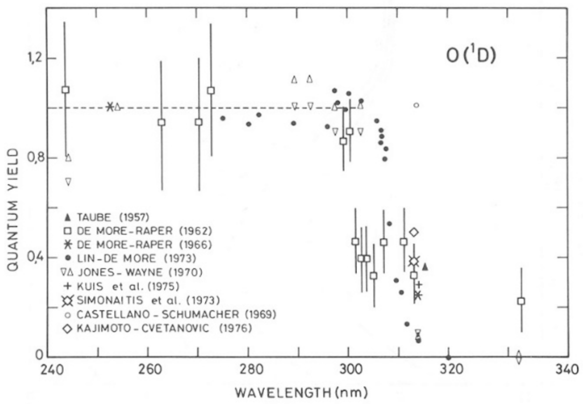


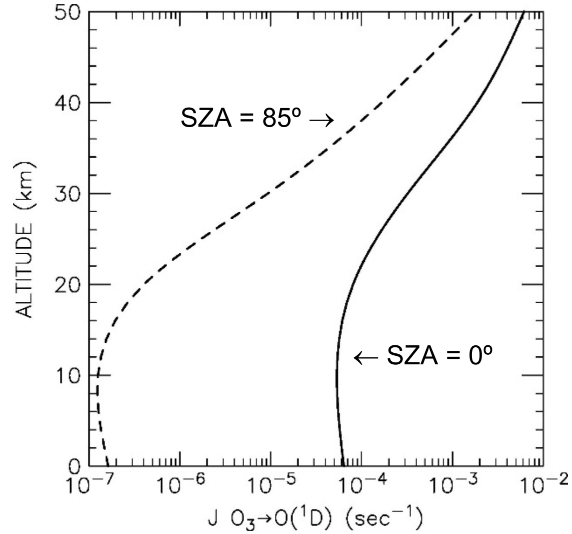


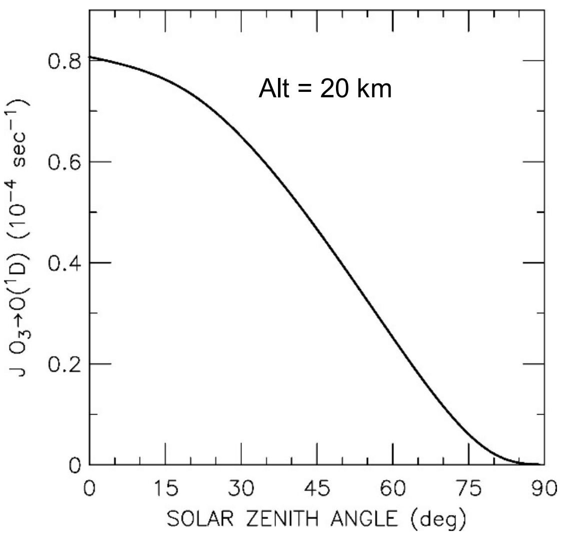


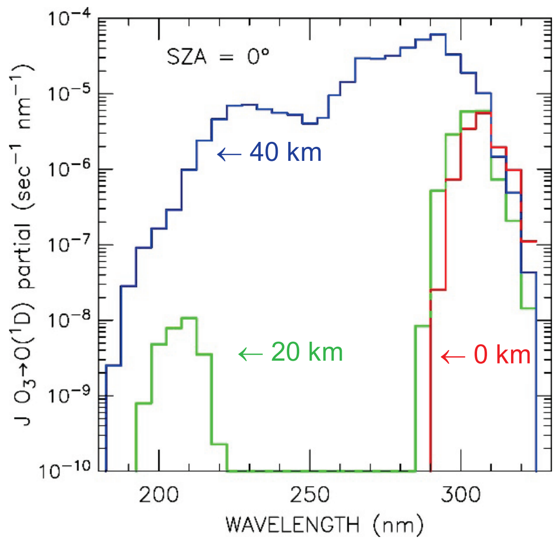


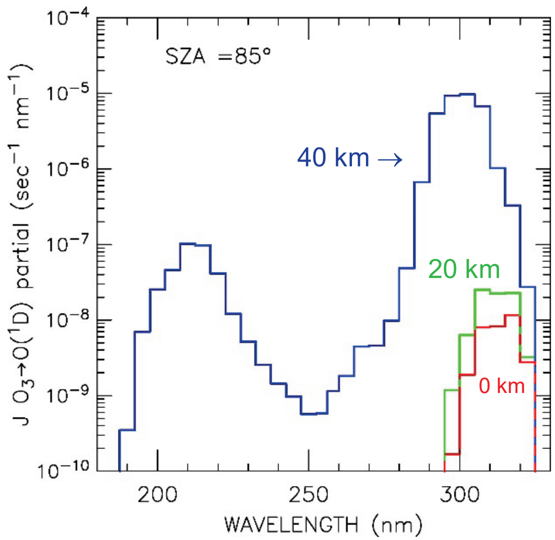
$O_3 \rightarrow O(^1D)$ Photolysis











Bimolecular Gas Phase Reactions

8.9 kcal/mole   **–17.8 kcal/mole**   **35.1 kcal/mole**   **–57.8 kcal/mole**

$$OH + CH_4 \rightarrow CH_3 + H_2O$$

ΔEnthalpy = –13.8 kcal/mole

Exothermic !

$$\text{Rate of Reaction} = \frac{dCH_4}{dt} = k\,[OH][CH_4]$$

E_A / R ⇒ Activation Energy / Gas Constant

Arrhenius Expression for rate constant:

$$k = 1.85 \times 10^{-12} \times e^{-1690/T} \;\text{cm}^3\;\text{sec}^{-1}$$

A factor

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Energy Term

R = 8.3143 × 10^7 erg / (K mole)
= 2.87 × 10^6 erg / (K gm) for air

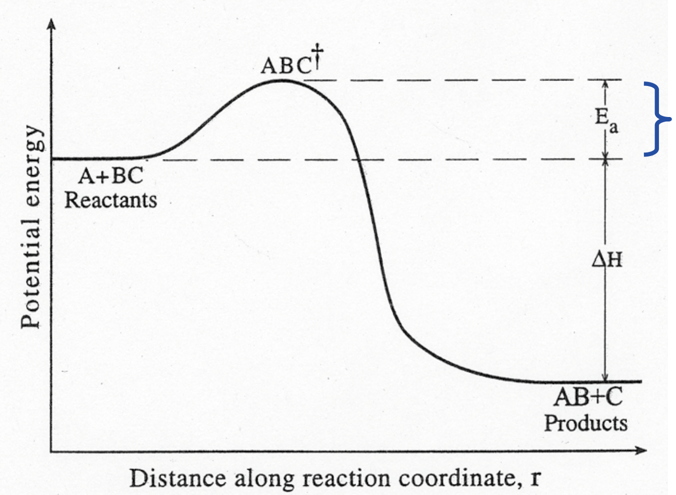

Figure 3.3 Barrier energies for the forward reaction (E_a) and the reverse reaction ($E_a + \Delta H$).

Yung and DeMore, *Photochemistry of Planetary Atmospheres*, Oxford, 1999.

Bimolecular Gas Phase Reactions

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$$k_c \; e^{\Delta S / R}$$

Entropy Term

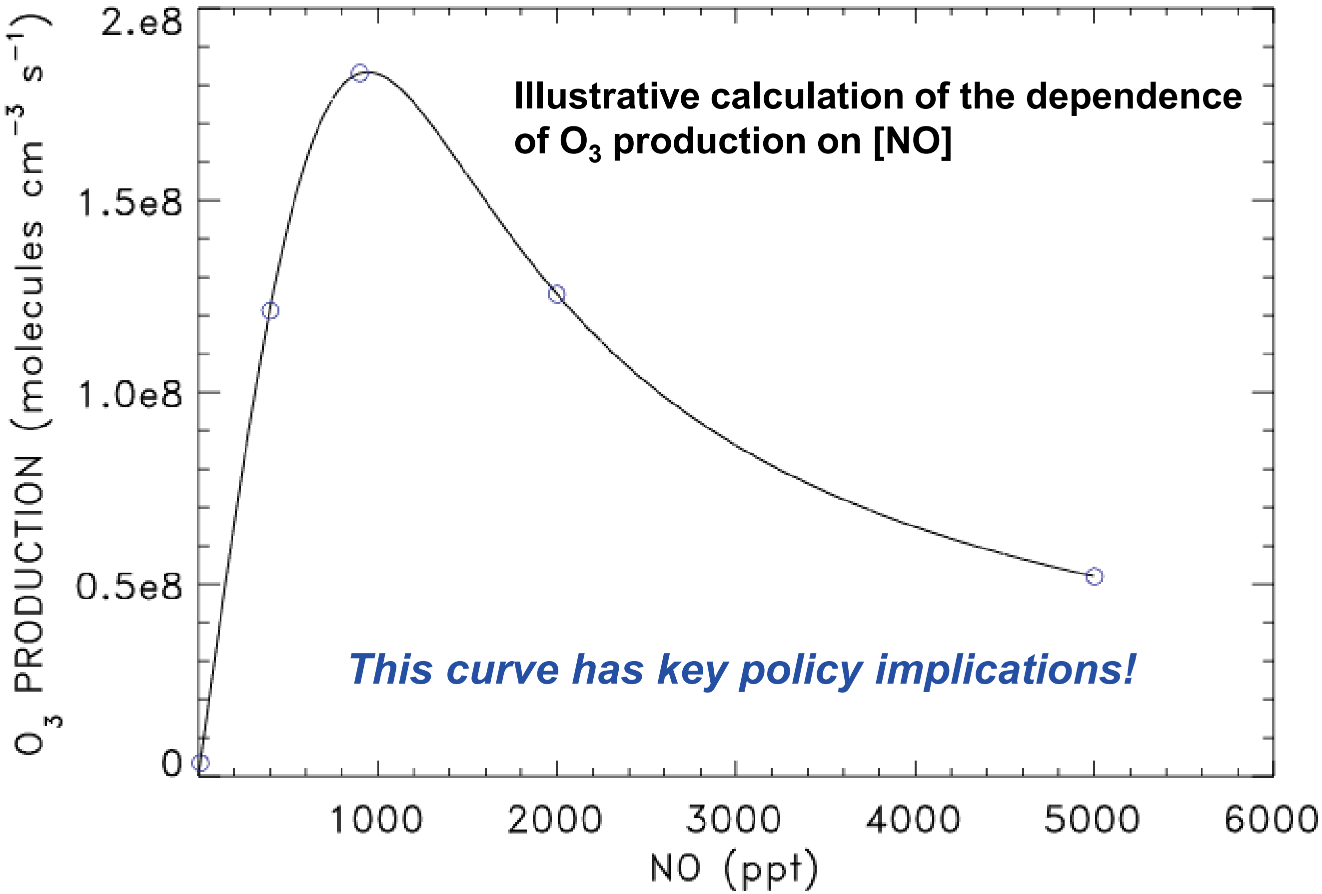
Tropospheric Ozone Production versus NO

Production of Tropospheric O_3 limited by: ____________ ?

As NO_x rises:

$[HO_2]$ falls faster than [NO] rises,

leading to a decrease in the value ______________



Tropospheric Ozone Production versus NO

Production of Tropospheric O_3 limited by: $k[HO_2][NO] + \Sigma\, k[RO_2][NO]$

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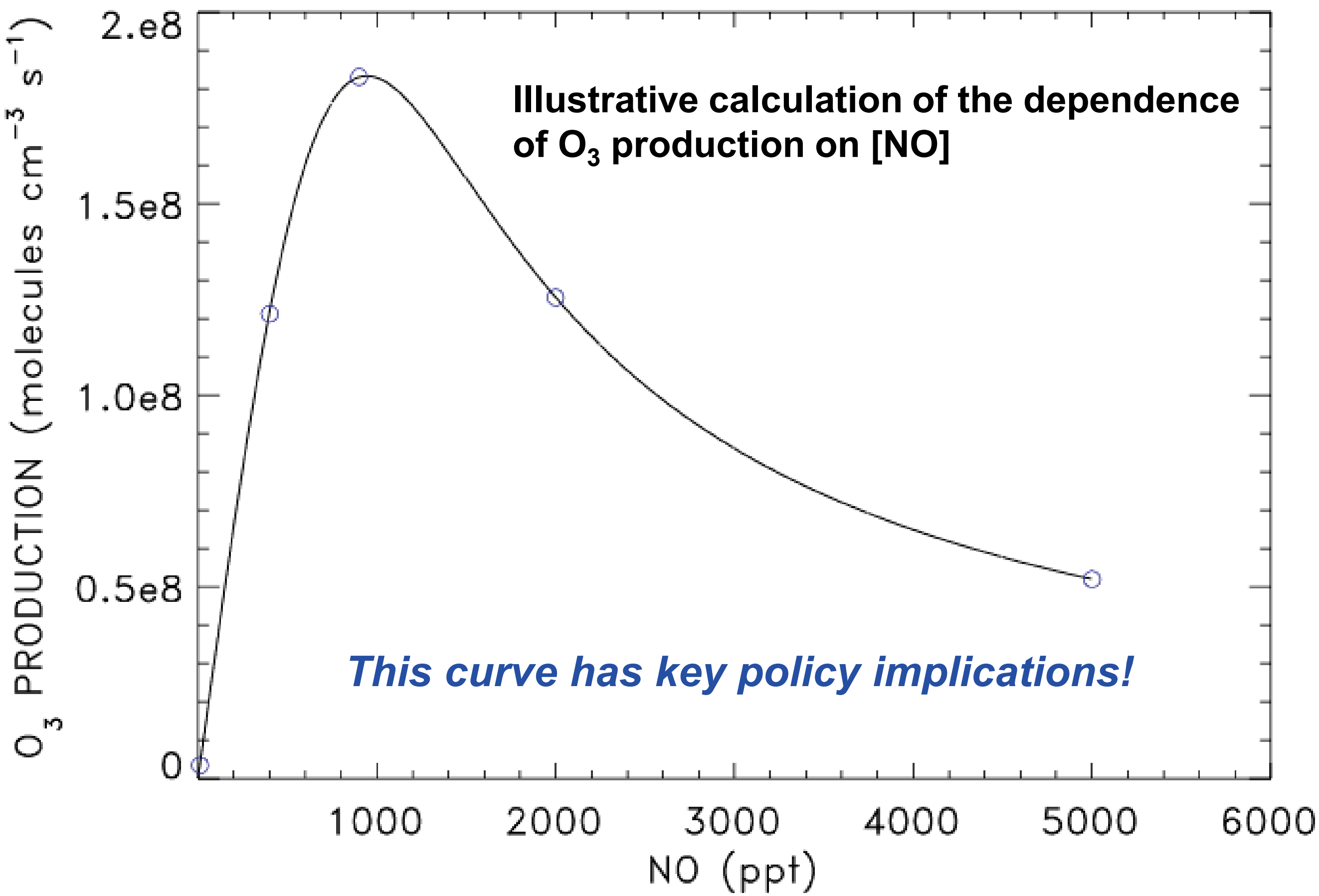

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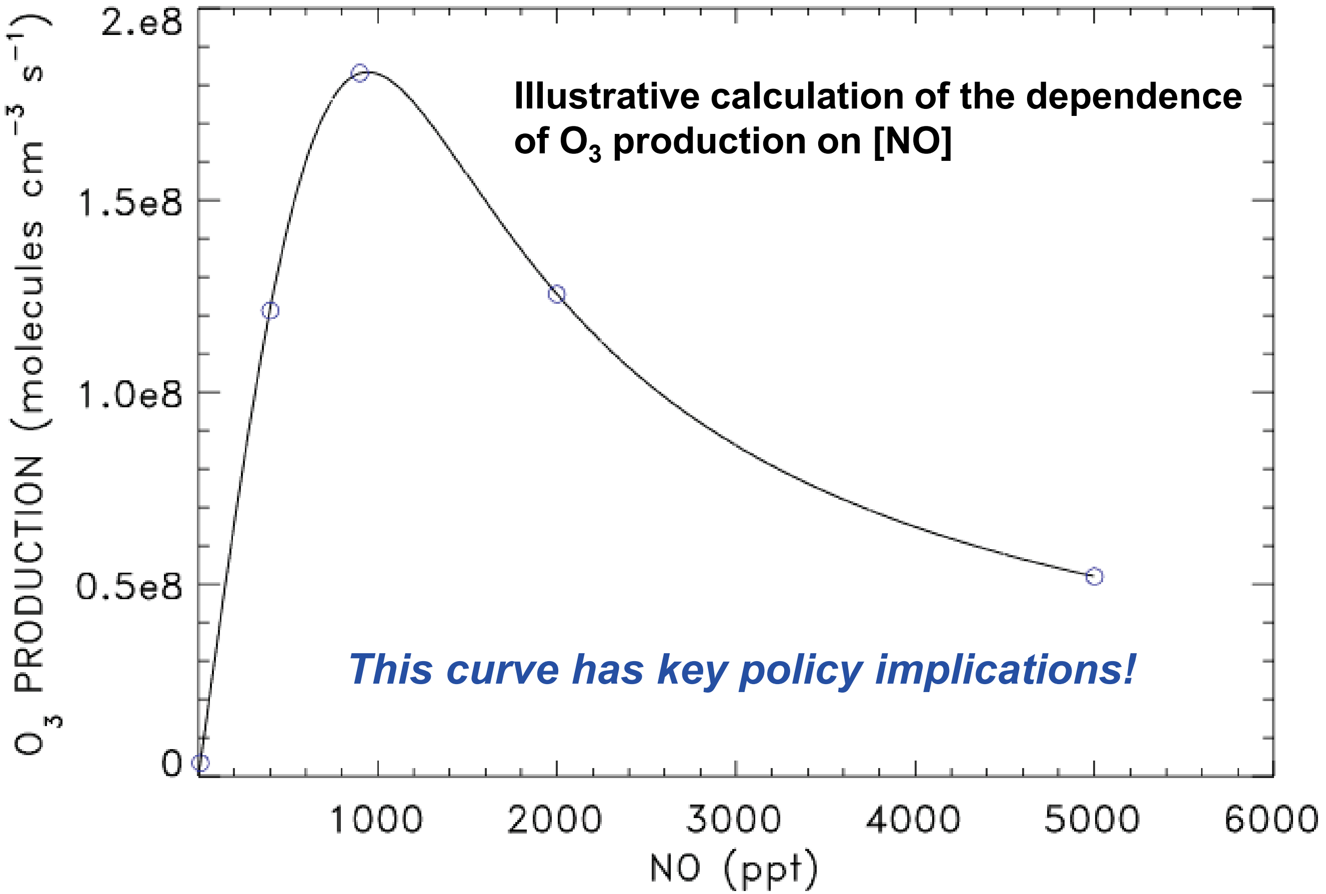
As NO_x rises:

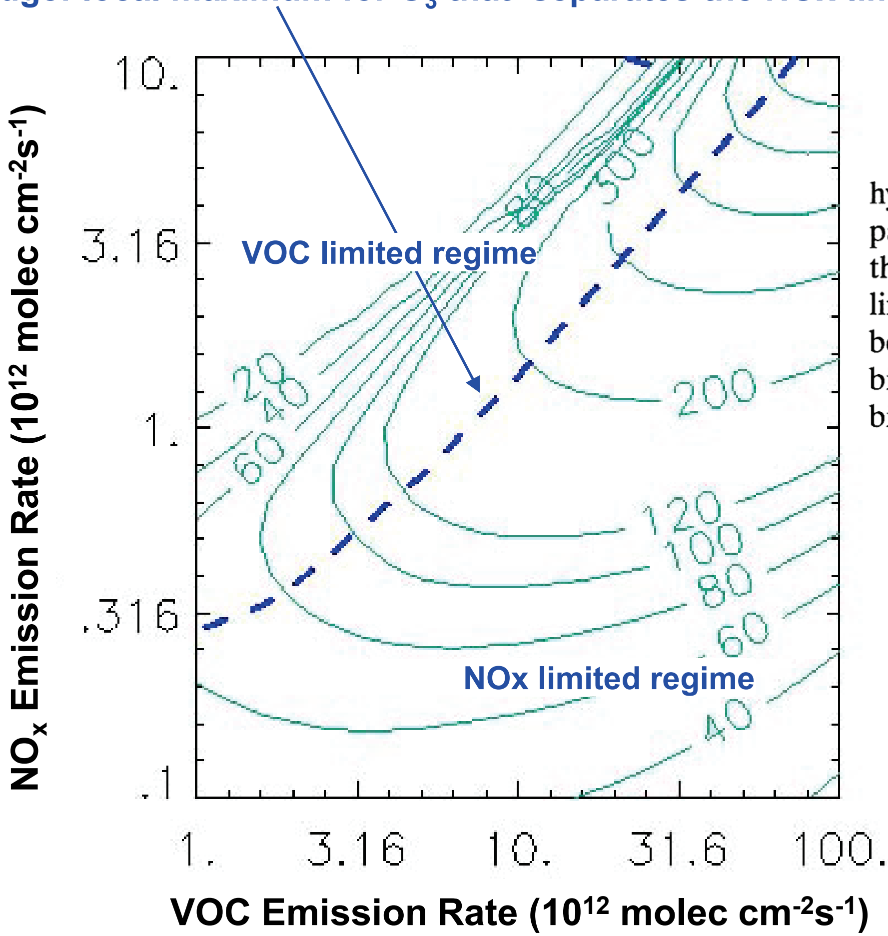
$[HO_2]$ falls faster than [NO] rises,

leading to a decrease in the value the production rate of O_3



Tropospheric Ozone Production versus NO_x and VOCs

Ridge: local maximum for O_3 that separates the NOx-limited regime from and VOC limited regime



An important discovery in the past decade is that the focus on hydrocarbon emission controls to combat O_3 pollution may have been partly misdirected. Measurements and model calculations now show that O_3 production over most of the United States is primarily NO_x limited, not hydrocarbon limited. The early models were in error in part because they underestimated emissions of hydrocarbons from automobiles, and in part because they did not account for natural emission of biogenic hydrocarbons from trees and crops.

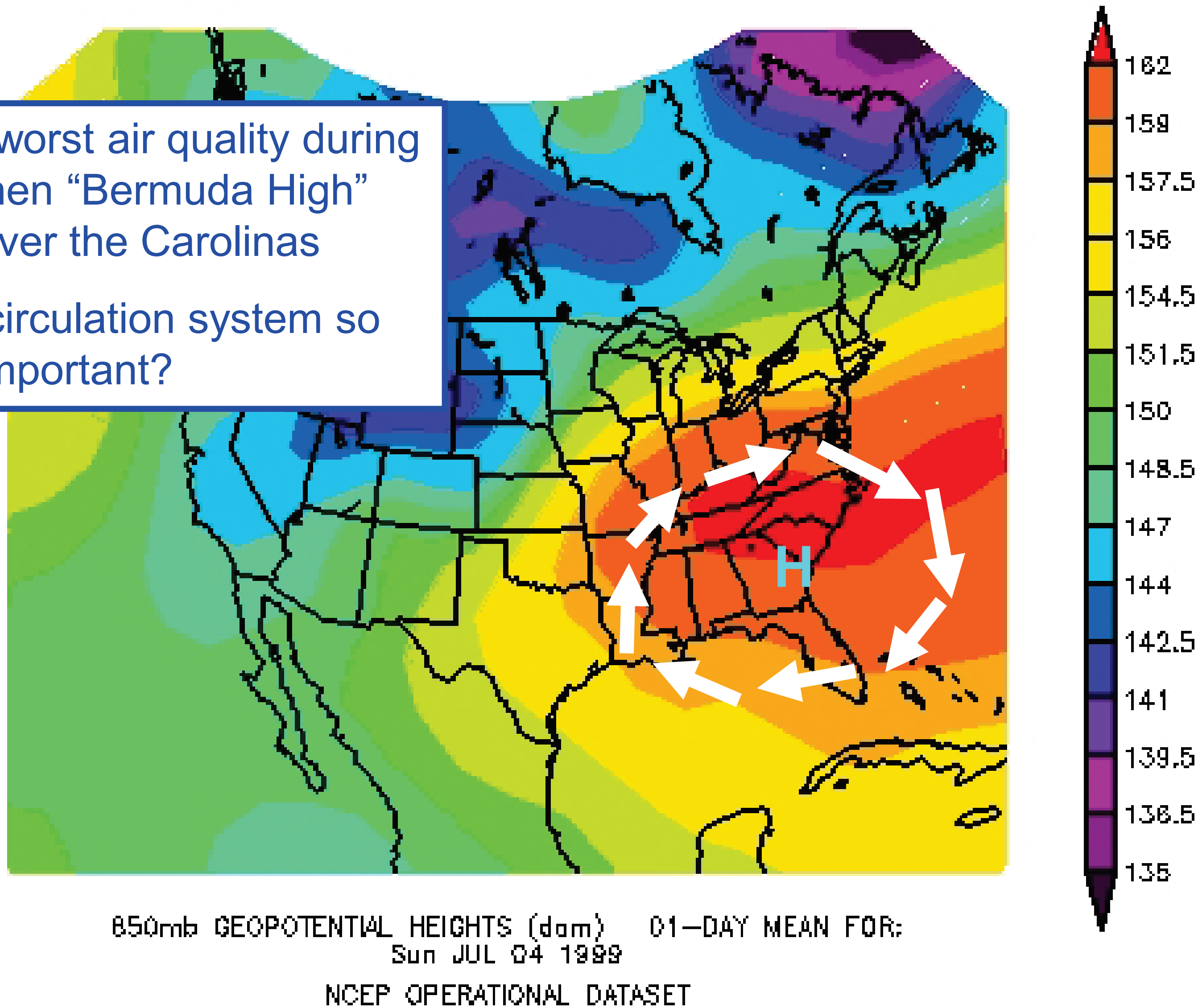
Jacob, Chapter 12, Introduction to Atmospheric Chemistry, 1999

Figure: http://www-personal.umich.edu/~sillman/ozone.htm

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

Maryland has worst air quality during summer, when "Bermuda High" sets up over the Carolinas

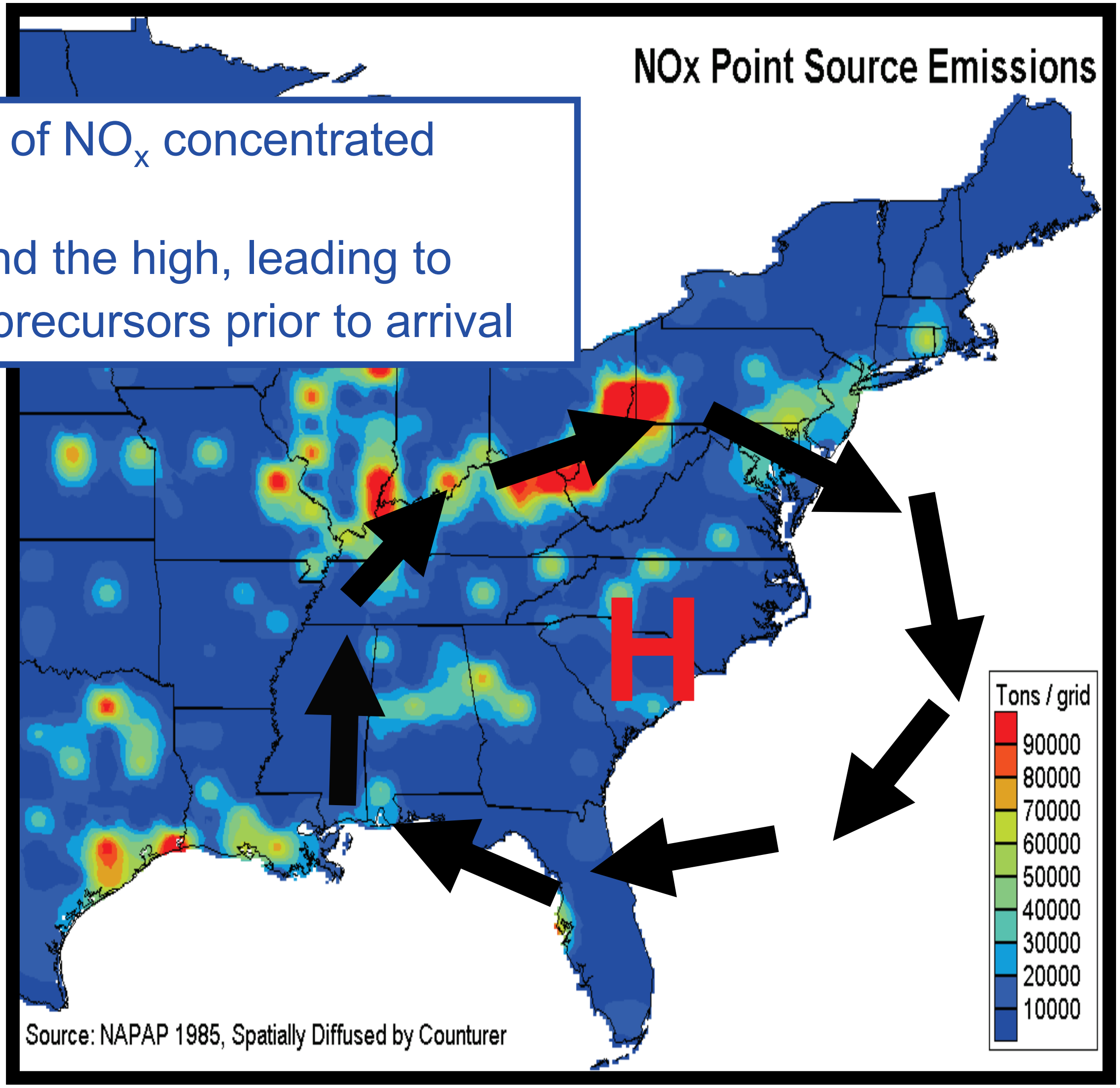
Why is this circulation system so important?



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

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



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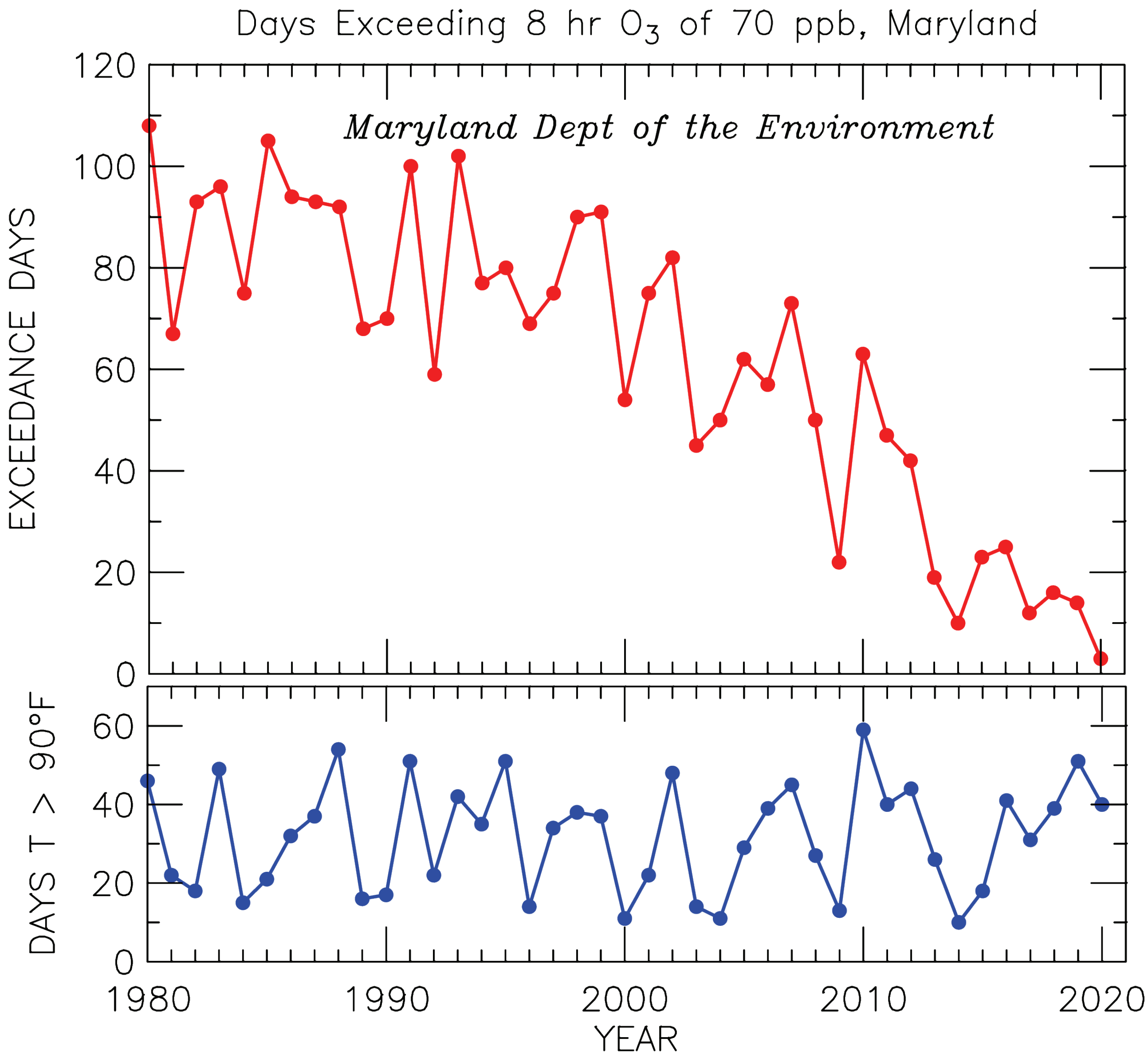
Significant Improvements in *Local* Air Quality since early 1980s



Number of days, each summer, for which T at BWI exceeded 90°F at some part of the day

http://www.mde.state.md.us/programs/Air/AirQualityMonitoring/Pages/SeasonalReports.aspx

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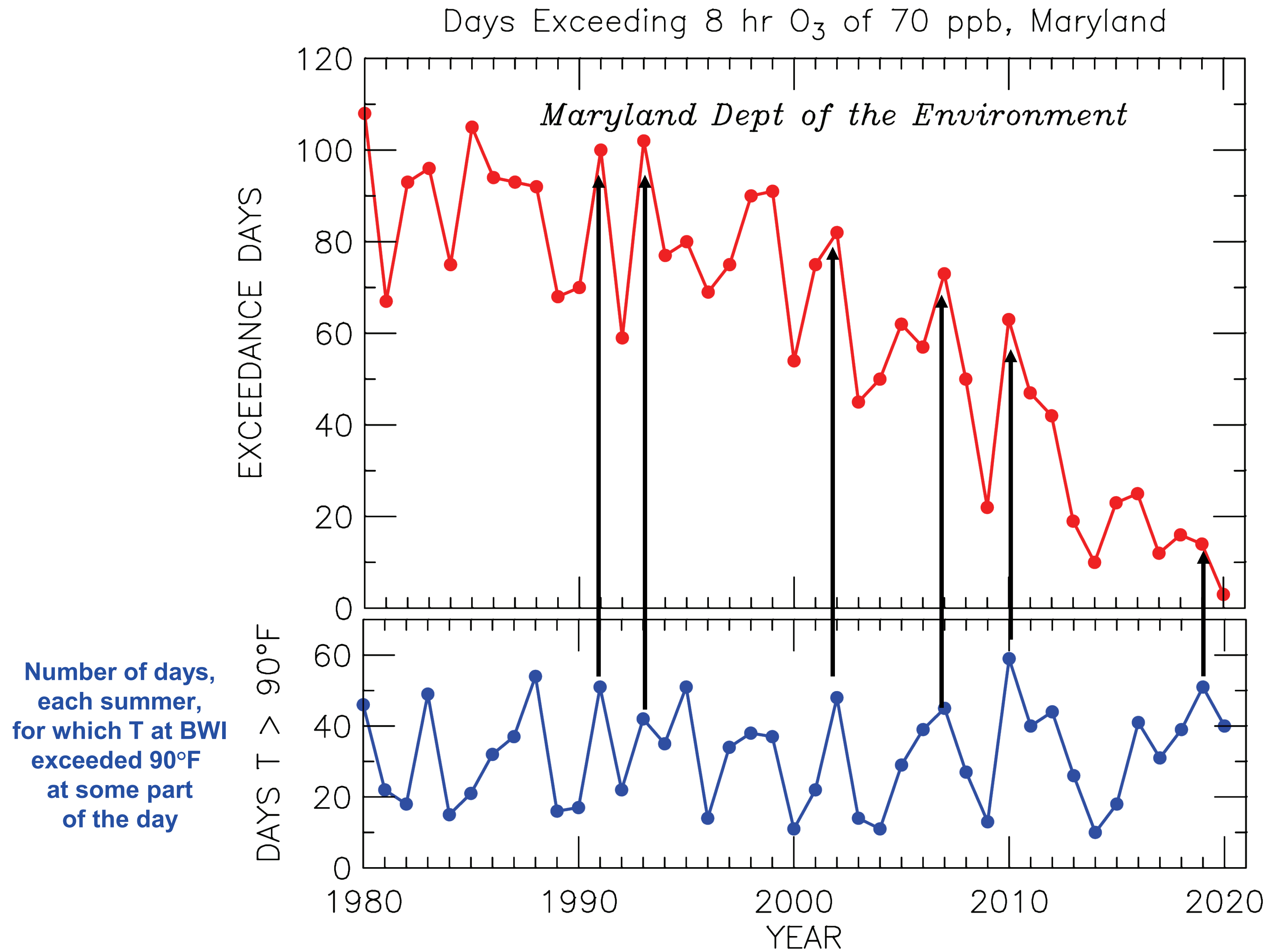

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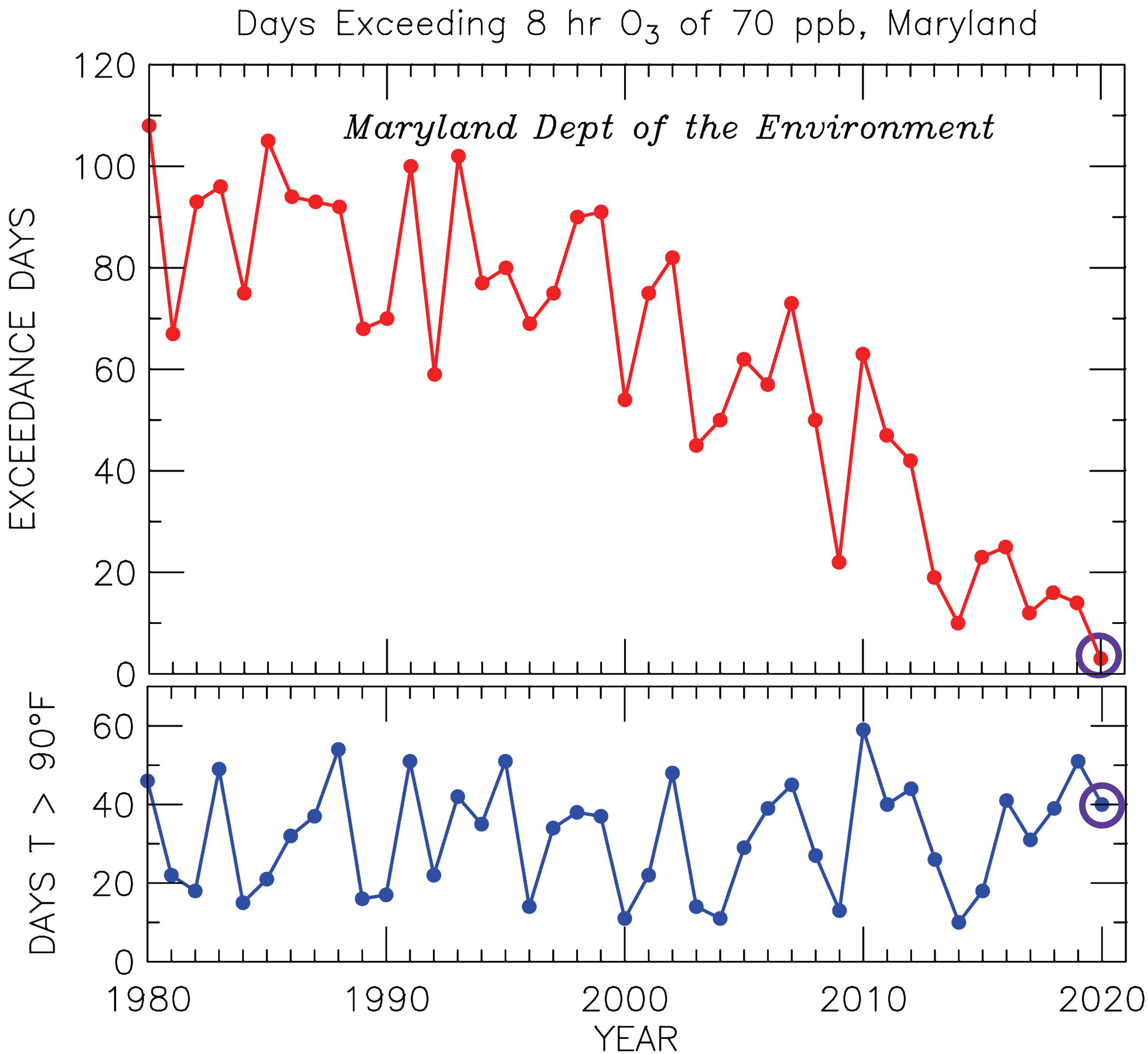


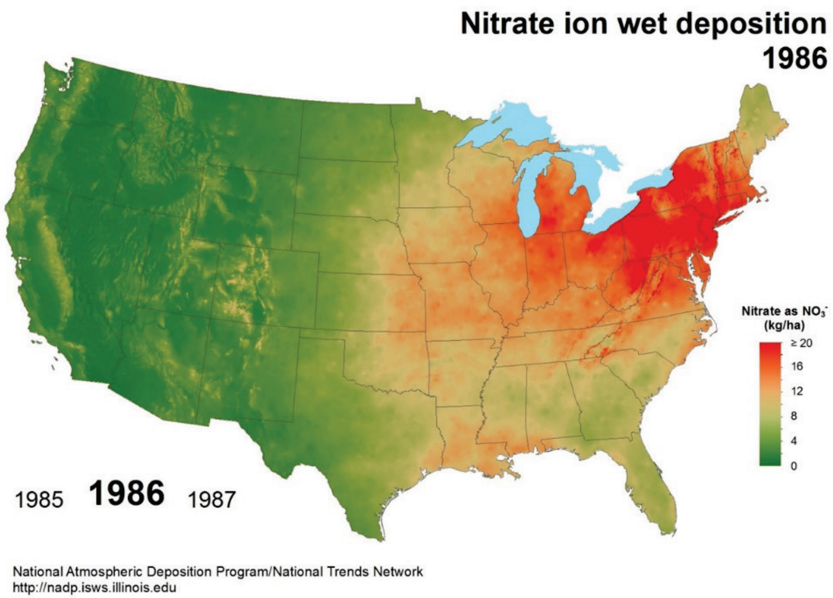
3 surface ozone exceedances in Maryland during 2020. Would have expected many more (i.e., 12 to 16) given relation between Exceedance Days & Days T > 90°F from prior recent years.

Number of days, each summer, for which T at BWI exceeded 90°F at some part of the day

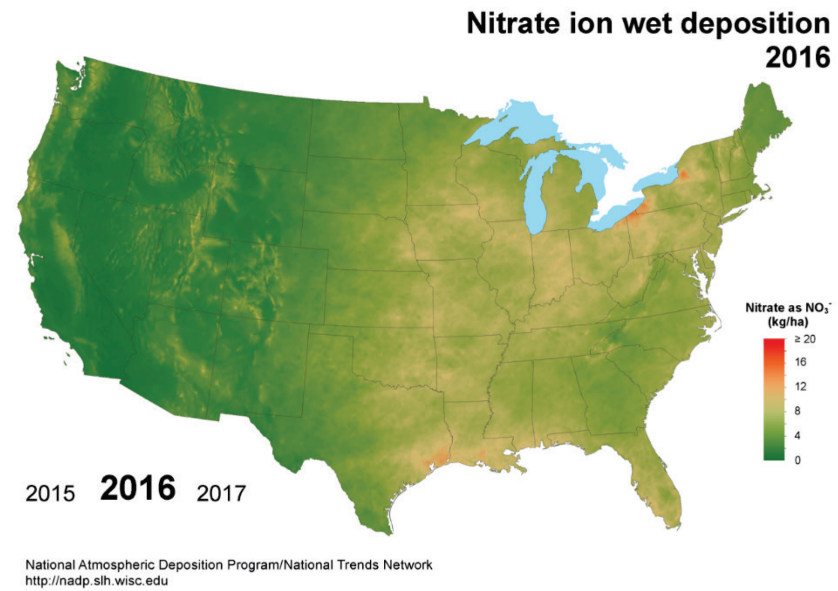
http://www.mde.state.md.us/programs/Air/AirQualityMonitoring/Pages/SeasonalReports.aspx

Nitrate Deposition (see Fig 6.12)

1986



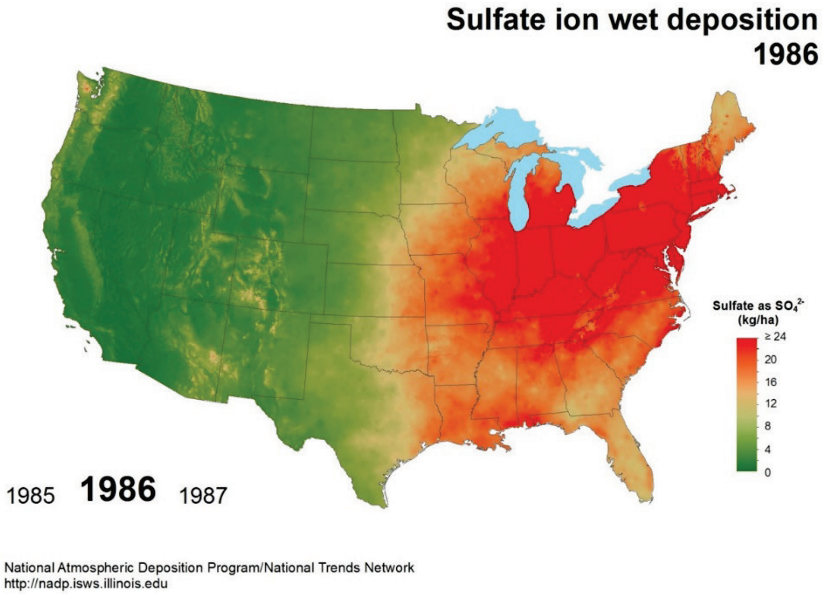
2016



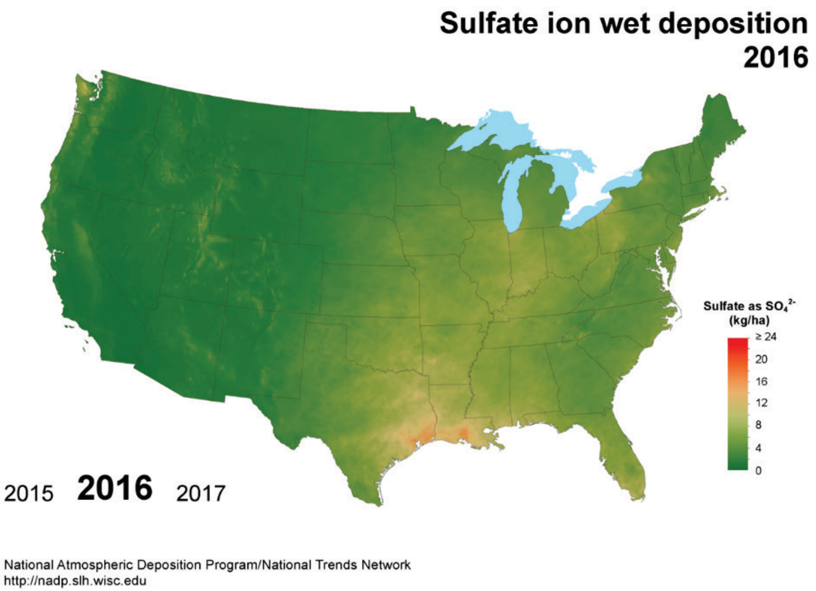
http://nadp.slh.wisc.edu/data/animaps.aspx

Sulfate Deposition (see Fig 6.12)

1986



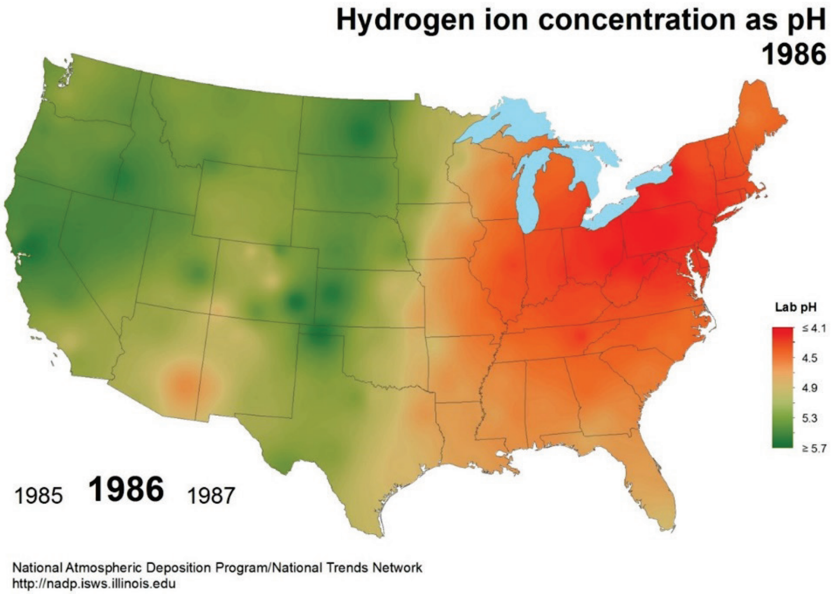
2016



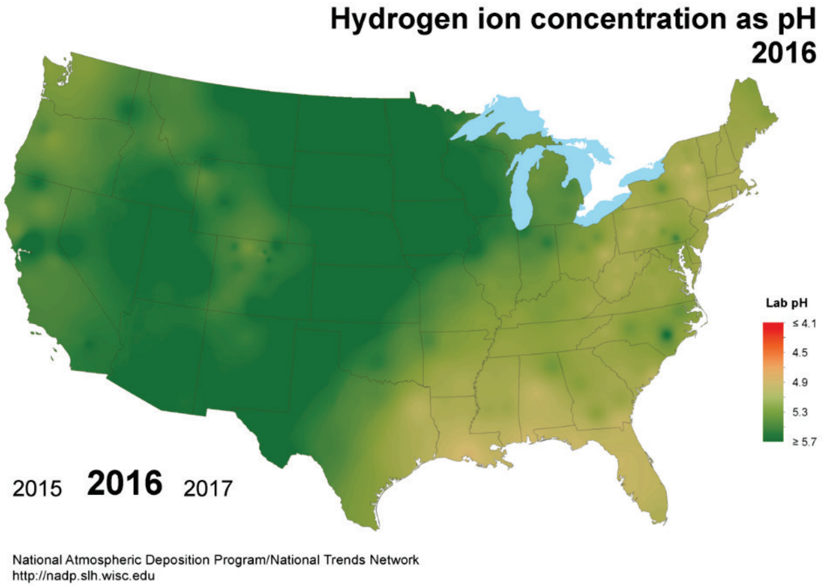
http://nadp.slh.wisc.edu/data/animaps.aspx

pH of rain samples (see Fig 6.11)

1986



2016



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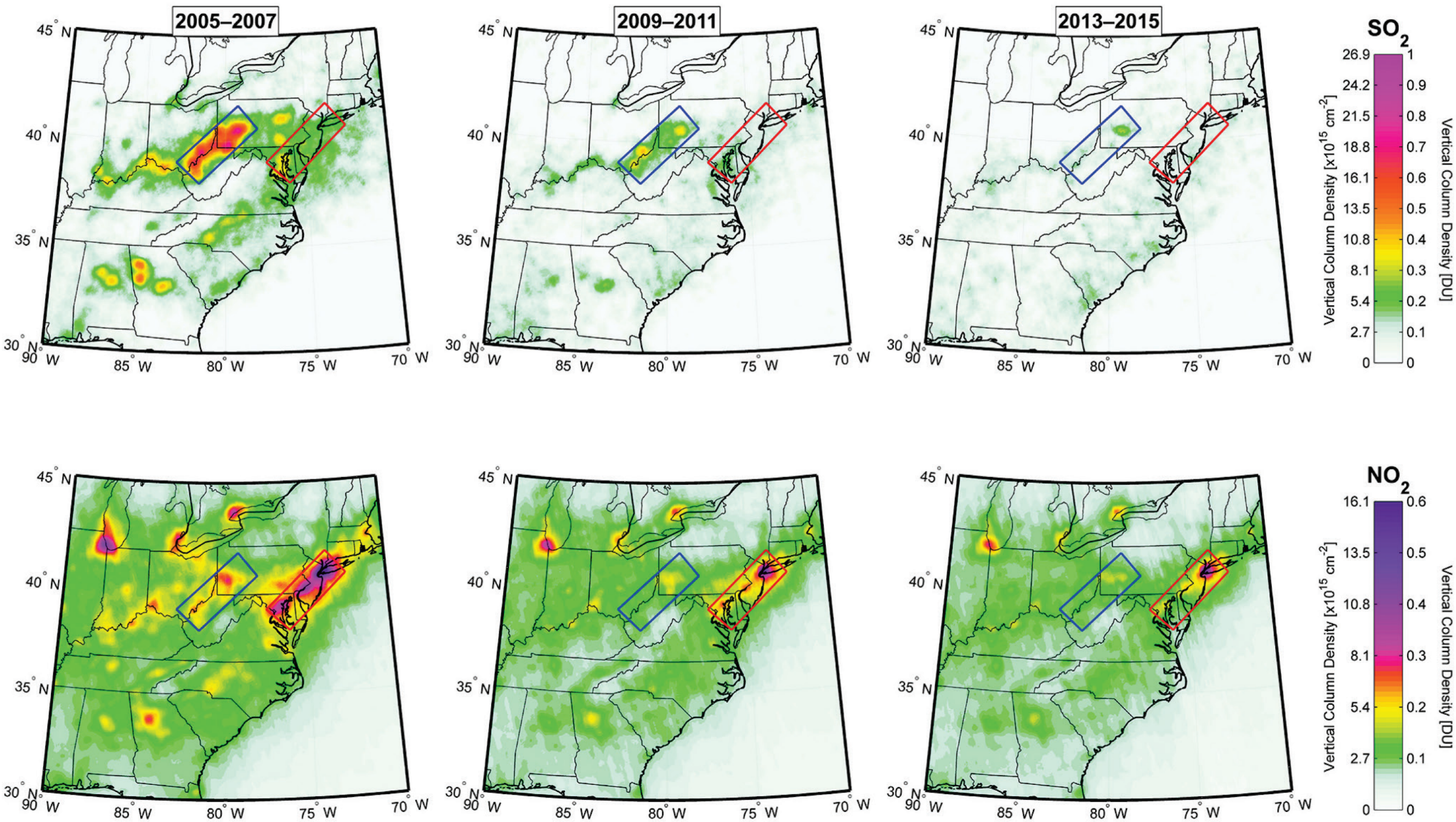
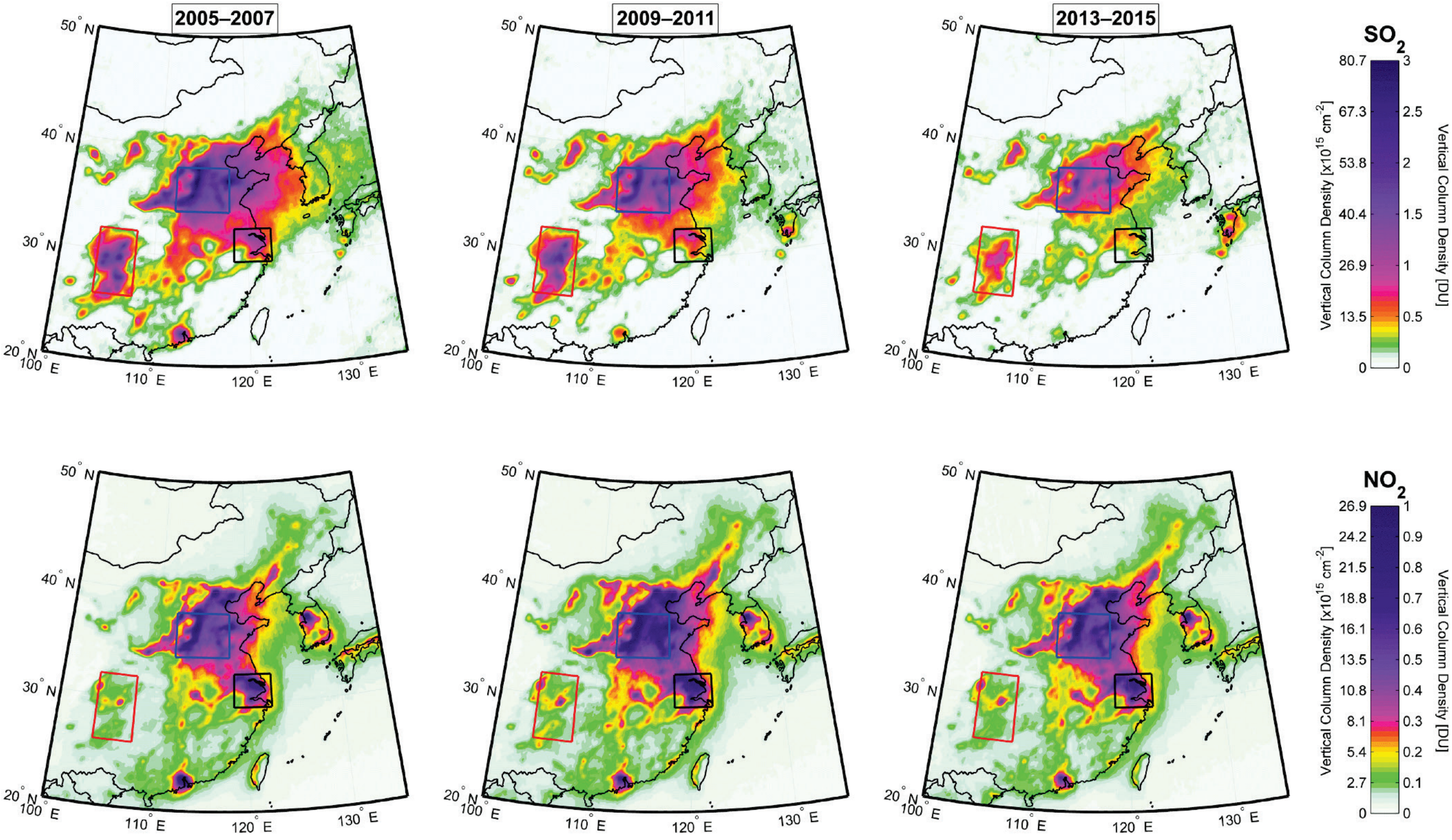
US Trends: NO_2 and SO_2



Krotkov *et al.*, *ACP*, 2016

China Trends: NO_2 and SO_2



Krotkov *et al.*, *ACP*, 2016

Stratospheric Ozone: Chapman Chemistry

- Production of O_3 initiated when O_2 is photodissociated by UV sunlight

- O_3 formed when resulting O atom reacts with O_2 :

$$h\nu + O_2 \rightarrow O + O \qquad (1)$$
$$O + O_2 + M \rightarrow O_3 + M \qquad (2)$$

- O_3 removed by photodissociation (UV sunlight) or by reaction with O :

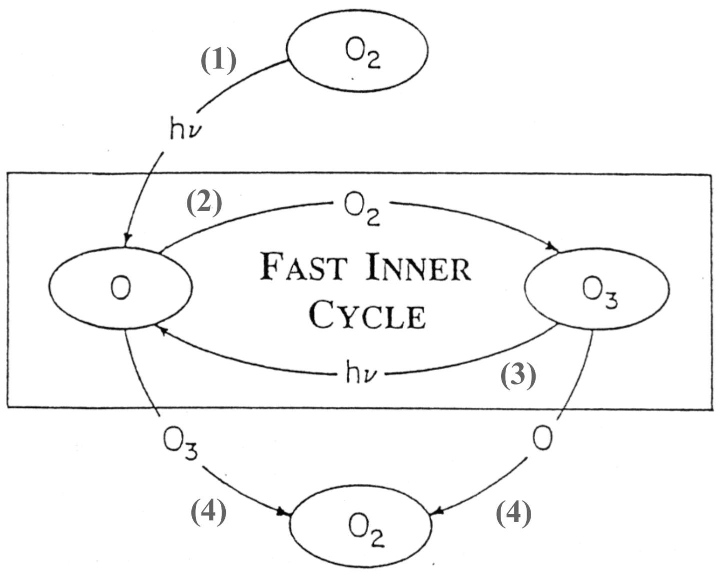
$$h\nu + O_3 \rightarrow O + O_2 \qquad (3)$$
$$O + O_3 \rightarrow O_2 + O_2 \qquad (4)$$

This reaction sequence was first worked out in the 1930s by Sidney Chapman, an English mathematician and geophysicist

Chapman Chemistry

• The cycling between O and O_2 (rxns 2 and 3) occurs *much* more rapidly than leakage into (rxn 1) or out of the system (rxn 4)

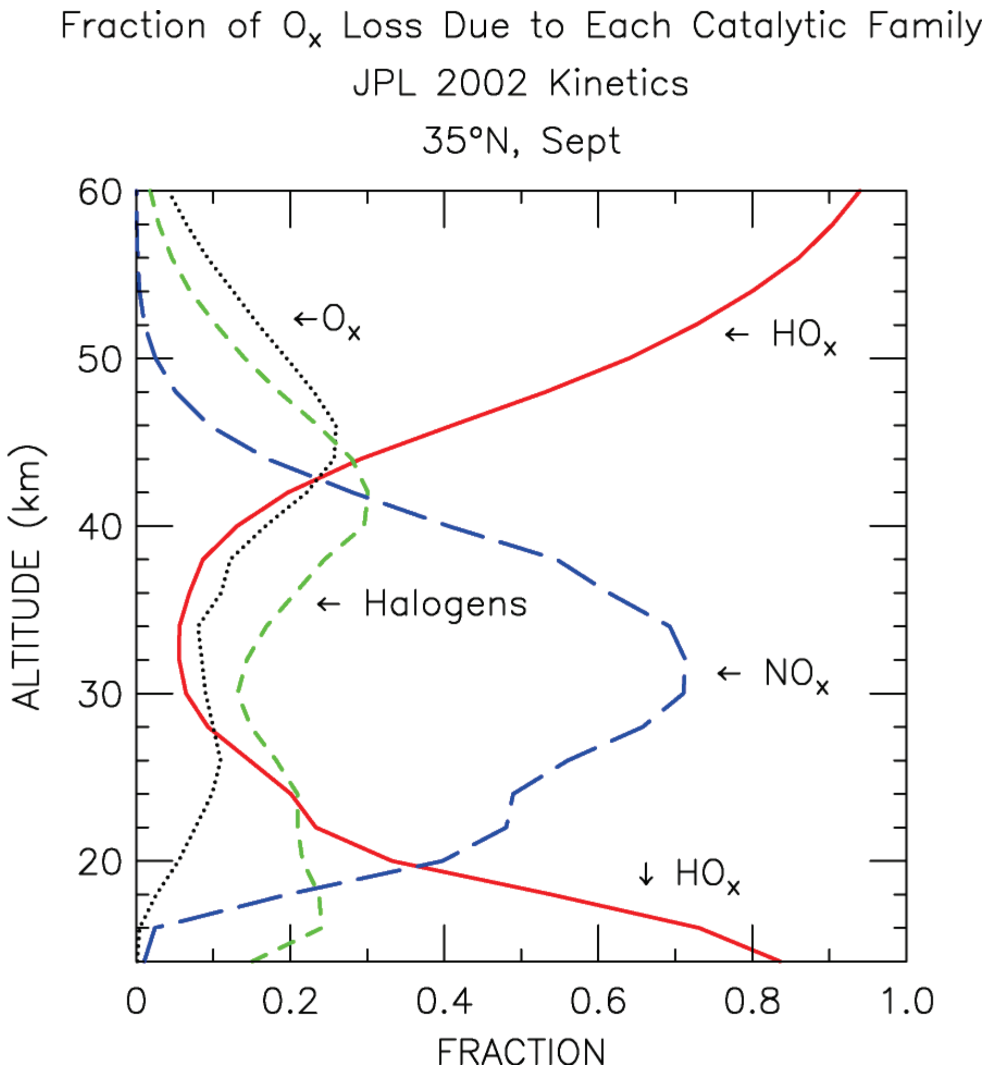
• The sum O + O_3 is commonly called *"odd oxygen"*



Rxn (1) produces two *odd oxygen* molecules
Rxn (4) consumes two *odd oxygen* molecules

and reactions 2 and 3 recycle *odd oxygen* molecules

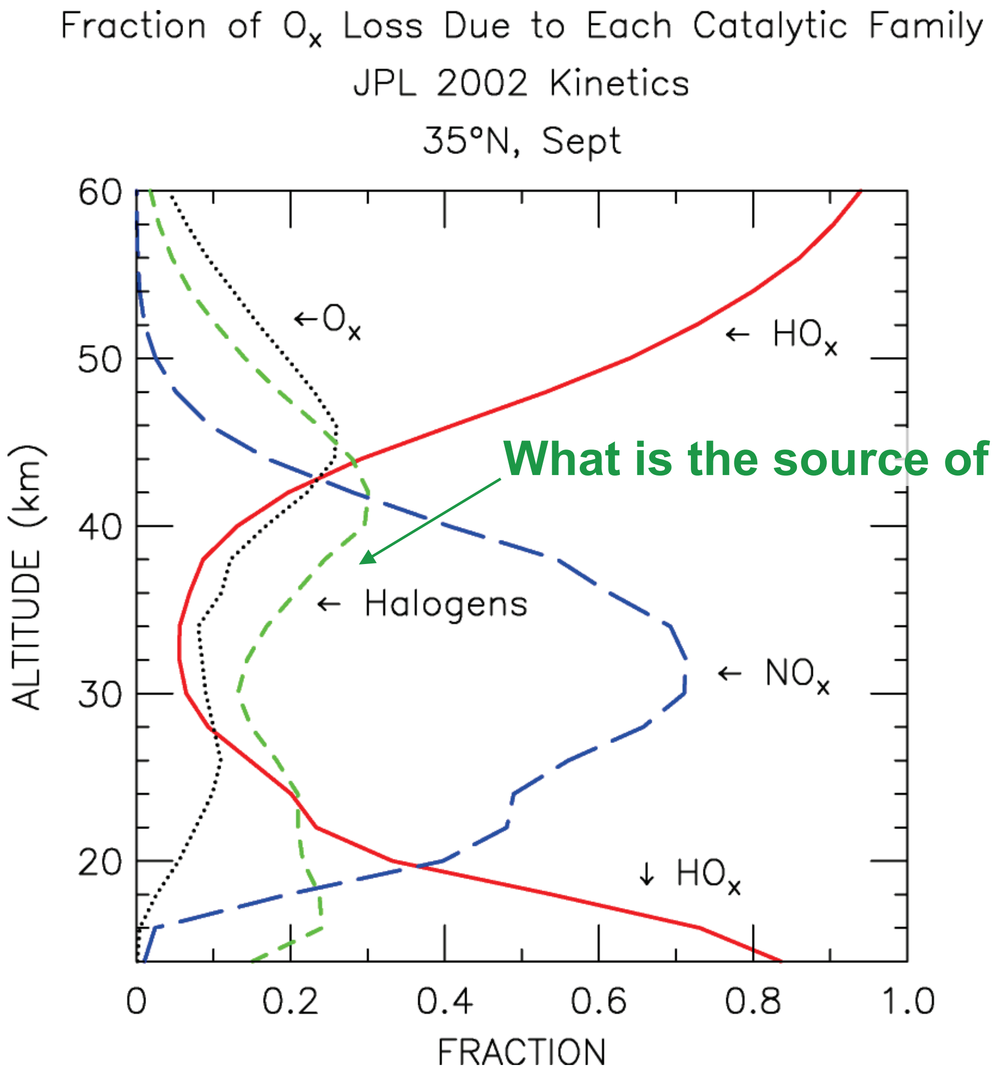
Stratospheric Photochemistry: Odd Oxygen Loss By Families



Calculated fraction of odd oxygen loss due to various families of radicals

After Osterman *et al*., *GRL*, 24, 1107, 1997;
Sen *et al*., *JGR*, 103, 3571. 1998;
Sen *et al*., *JGR*, 104, 26653, 1999.

Stratospheric Photochemistry: Odd Oxygen Loss By Families



What is the source of halogen radicals?

Calculated fraction of odd oxygen loss due to various families of radicals

After Osterman *et al*., *GRL*, 24, 1107, 1997;
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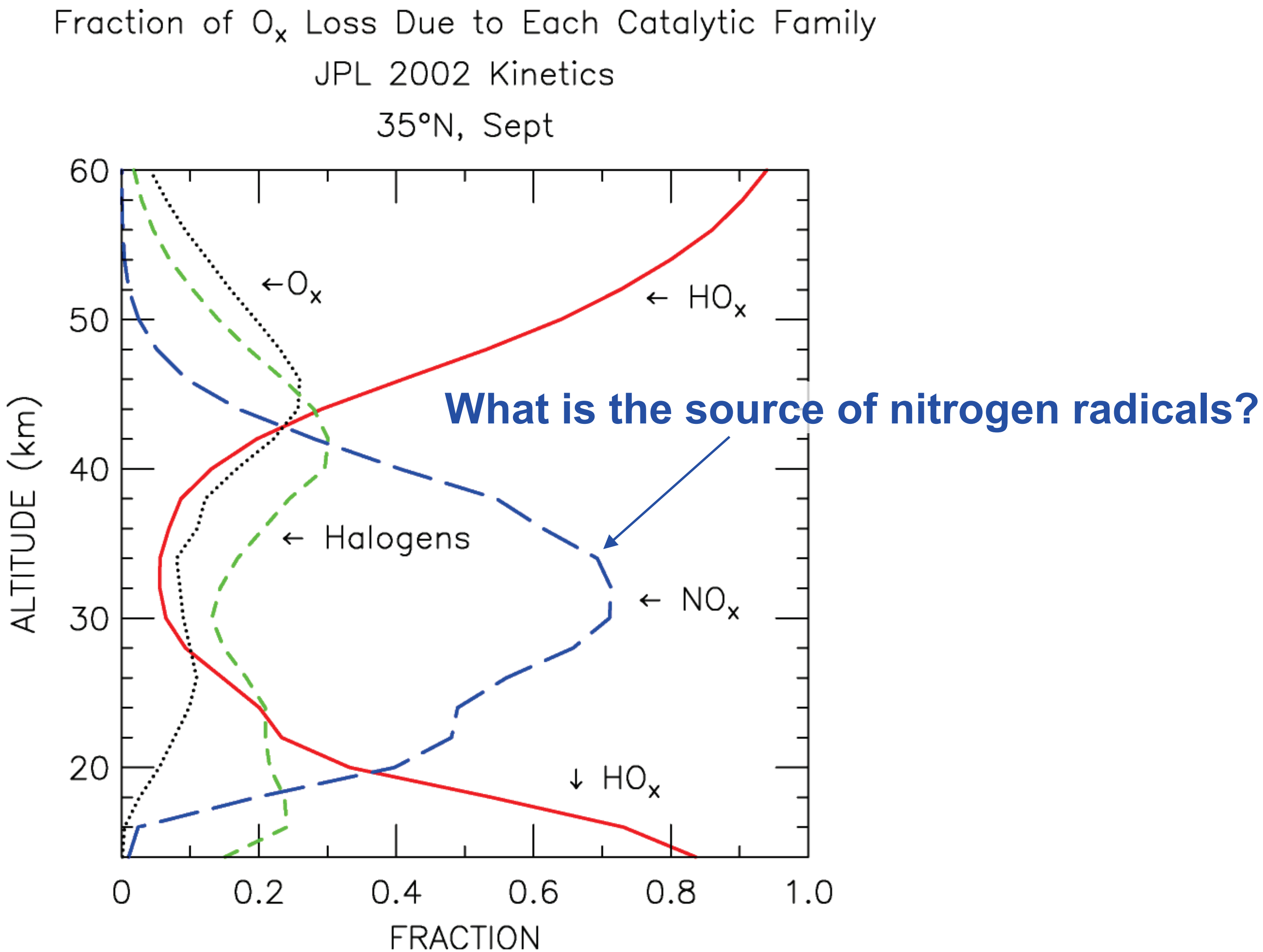

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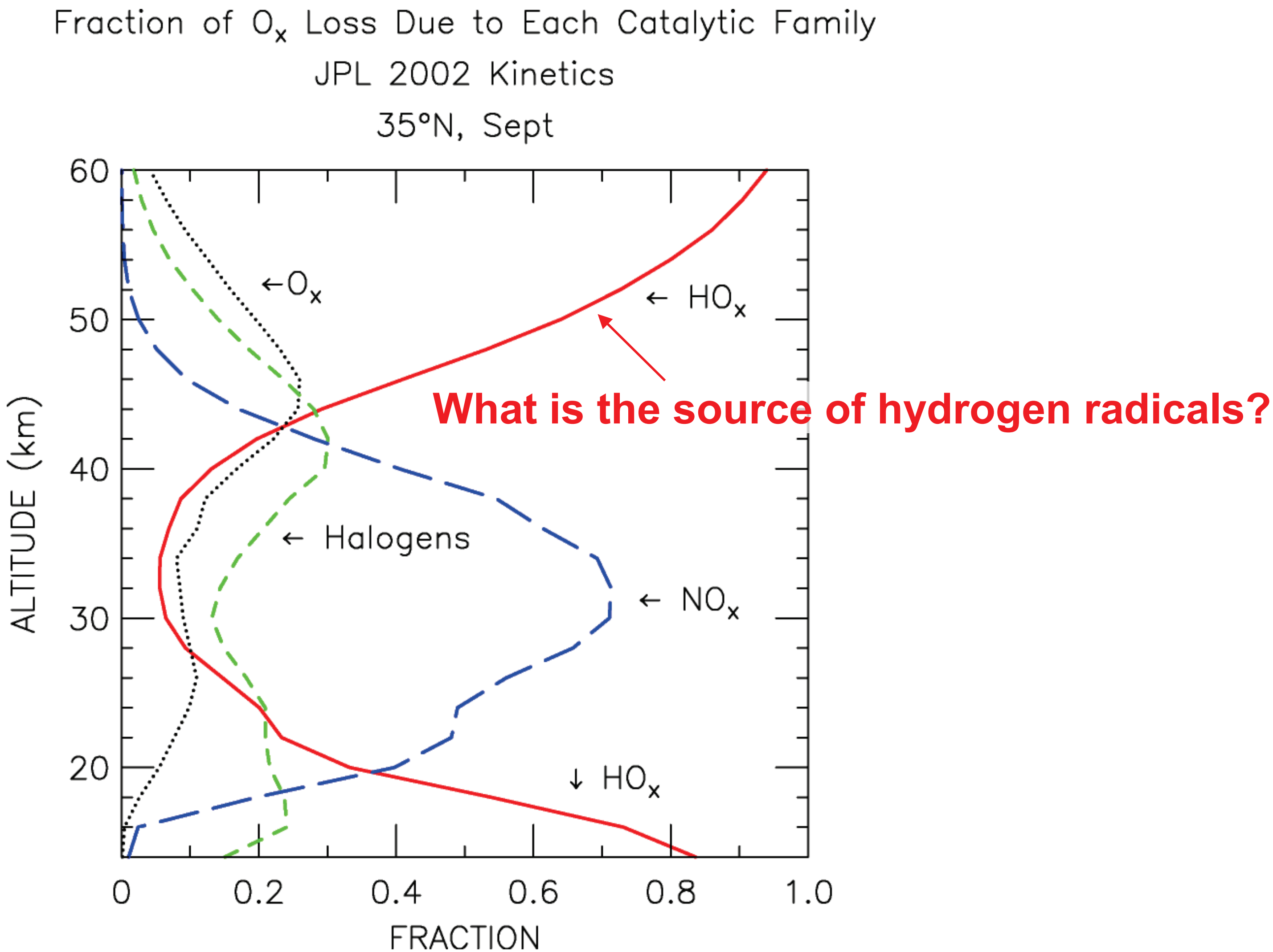
Stratospheric Photochemistry: Odd Oxygen Loss By Families



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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:

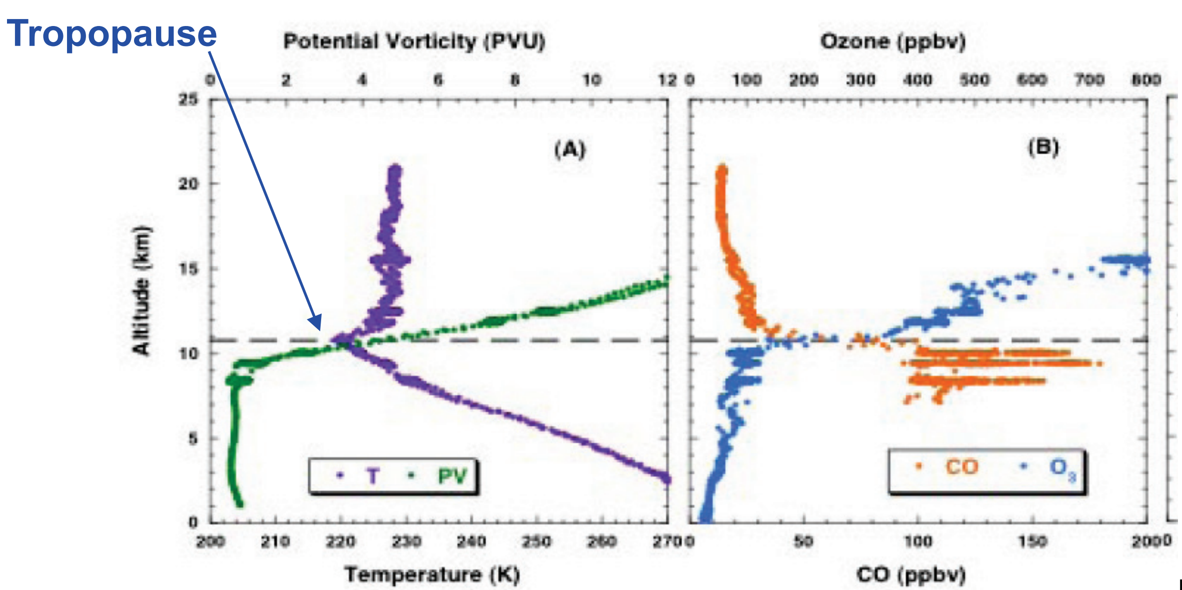
$$HO_2 + NO \rightarrow OH + NO_2$$

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$_3$

urtesy of Laura Pan, NCAR

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

Rate HO_2 Formation = k_{OH+O3}×[OH][O_3] + k_{OH+CO}×[OH][CO]

Rate HO_2 Loss = k_{HO2+O3}×[HO_2][O_3] + k_{HO2+NO}×[HO_2][NO]

Troposphere

HO_2 formation:

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

HO_2 loss:

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

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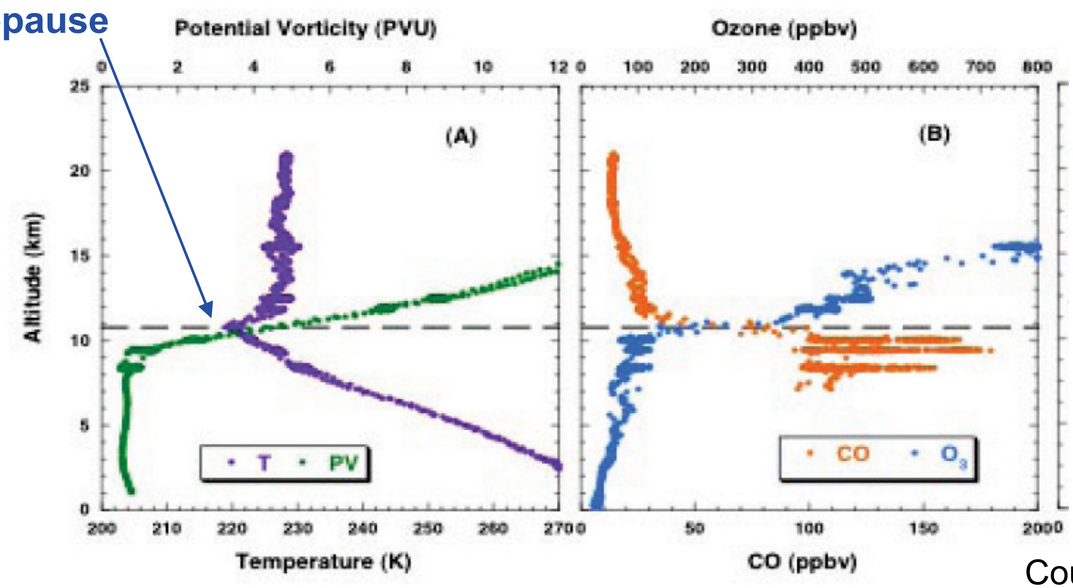
Tropopause

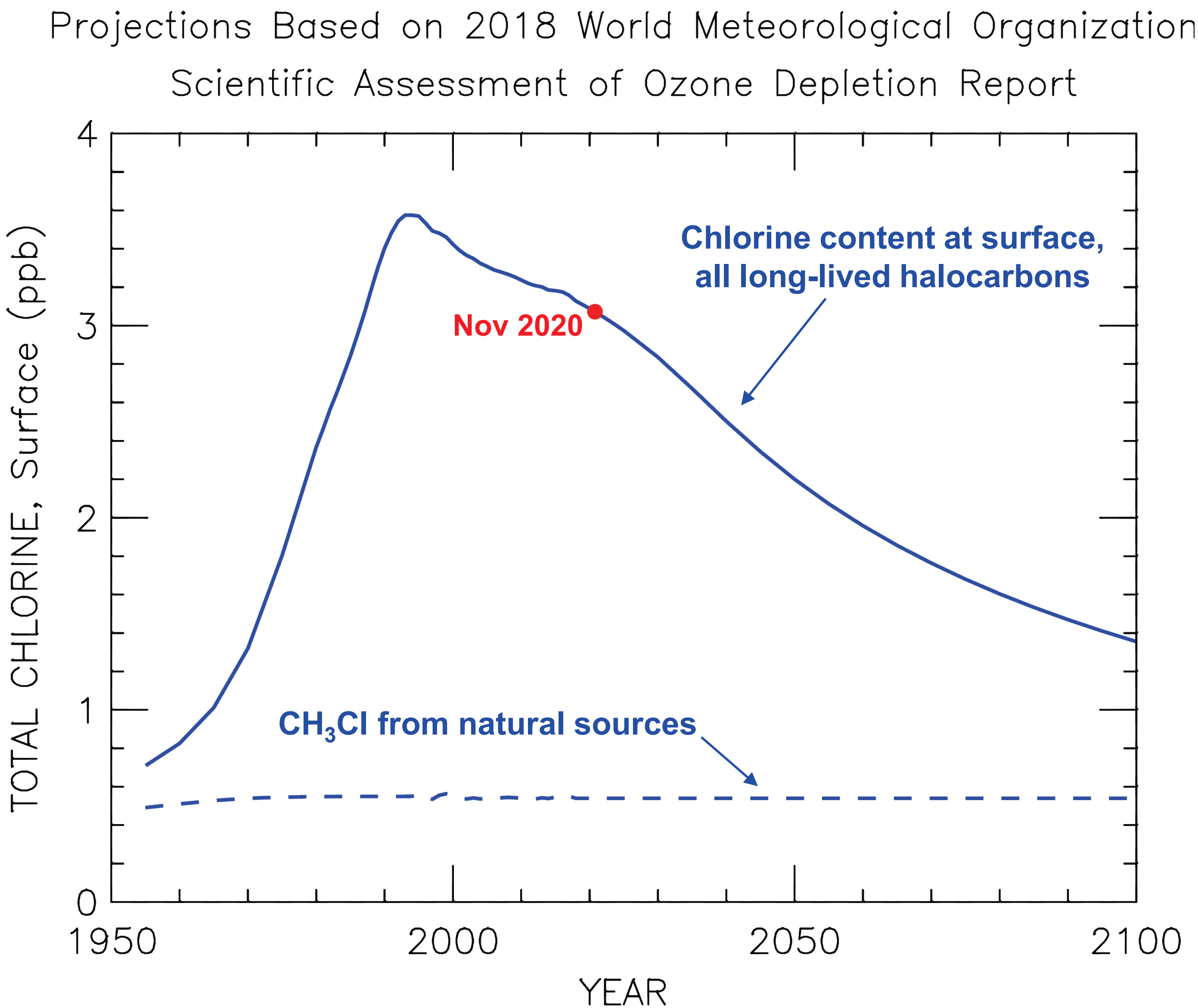


Above Tropopause:
Lots of O_3, little CO

Below Tropopause:
Lots of CO, little O_3

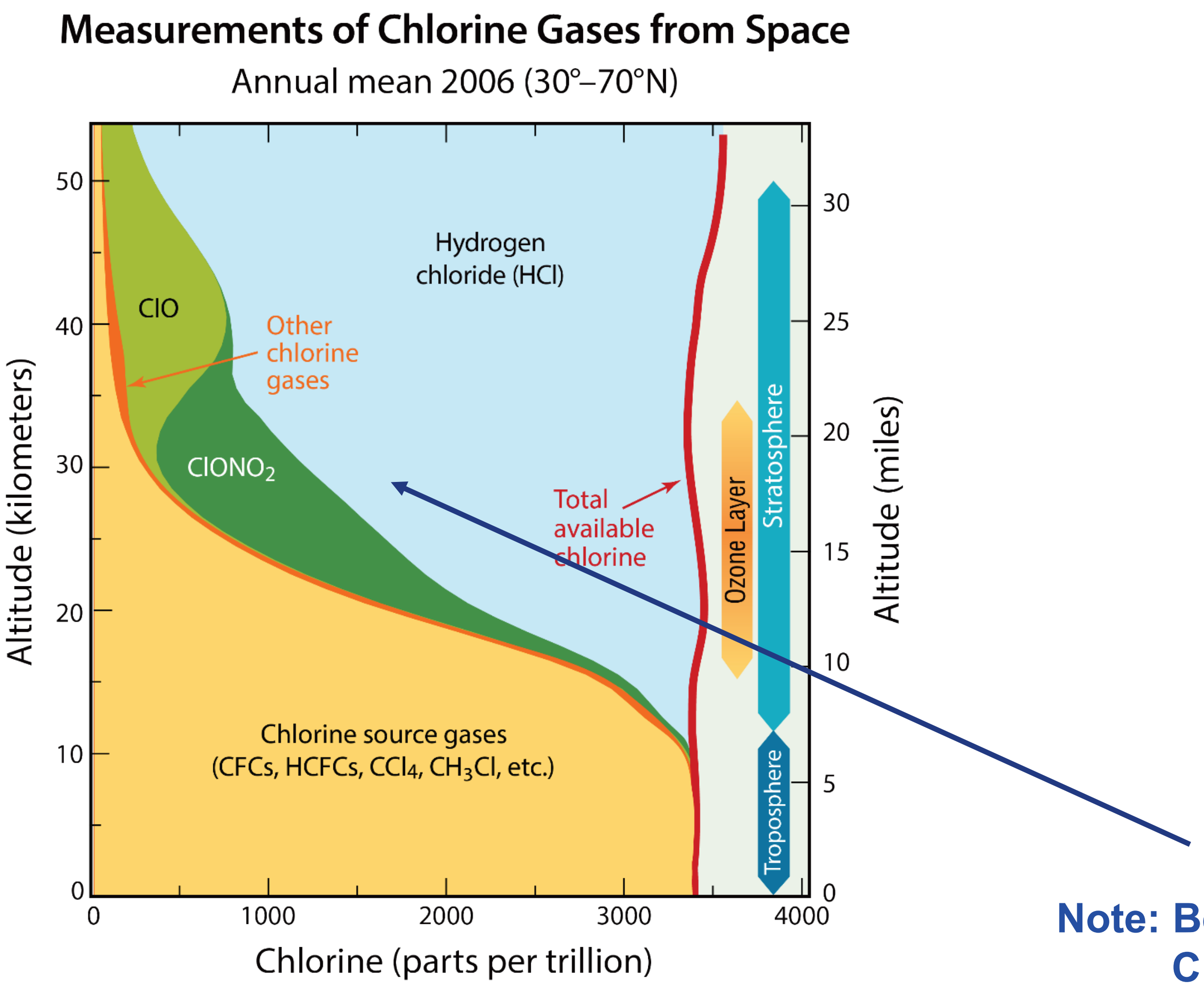
Courtesy of Laura Pan, NCAR

Montreal Protocol Has Banned Industrial Production of CFCs & Other ODS



2018 WMO Scientific Assessment of Ozone Depletion Report:
https://www.esrl.noaa.gov/csd/assessments/ozone/2018

Chlorine Abundance, Mid-Latitude Stratosphere



Note: Below ~30 km,
ClO << ClNO$_3$ and HCl

Fig Q7-2, *WMO/UNEP Twenty QAs Ozone*

Chlorine Source Gases

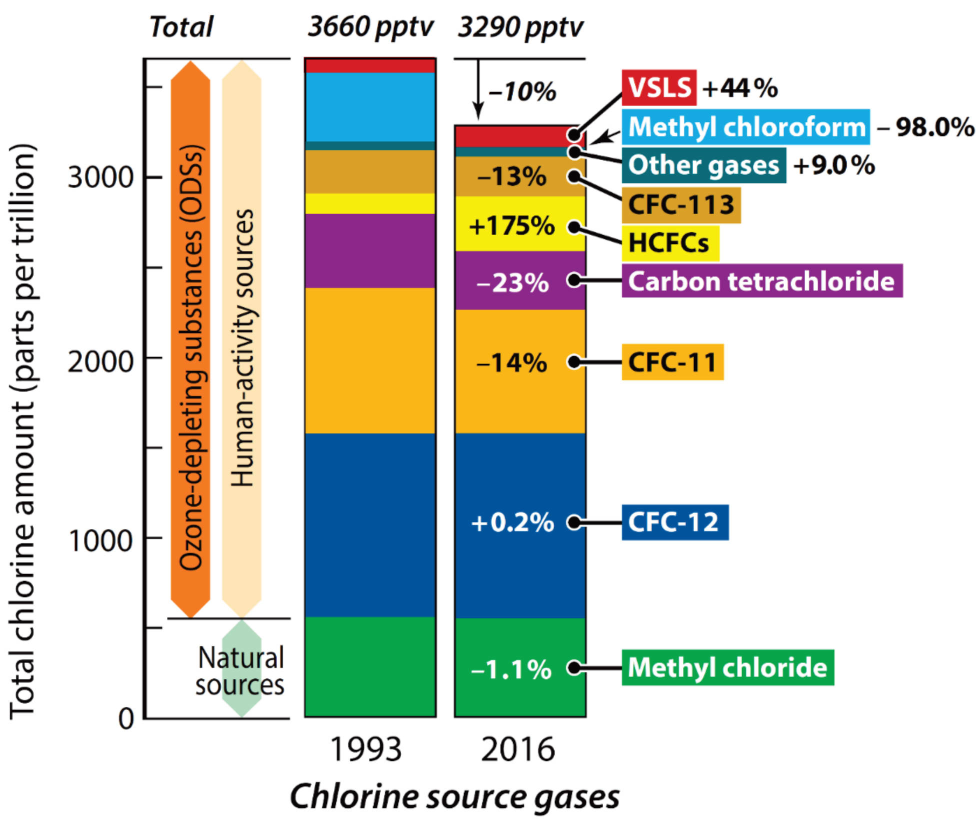


Fig Q6-1, *WMO/UNEP Twenty QAs Ozone*

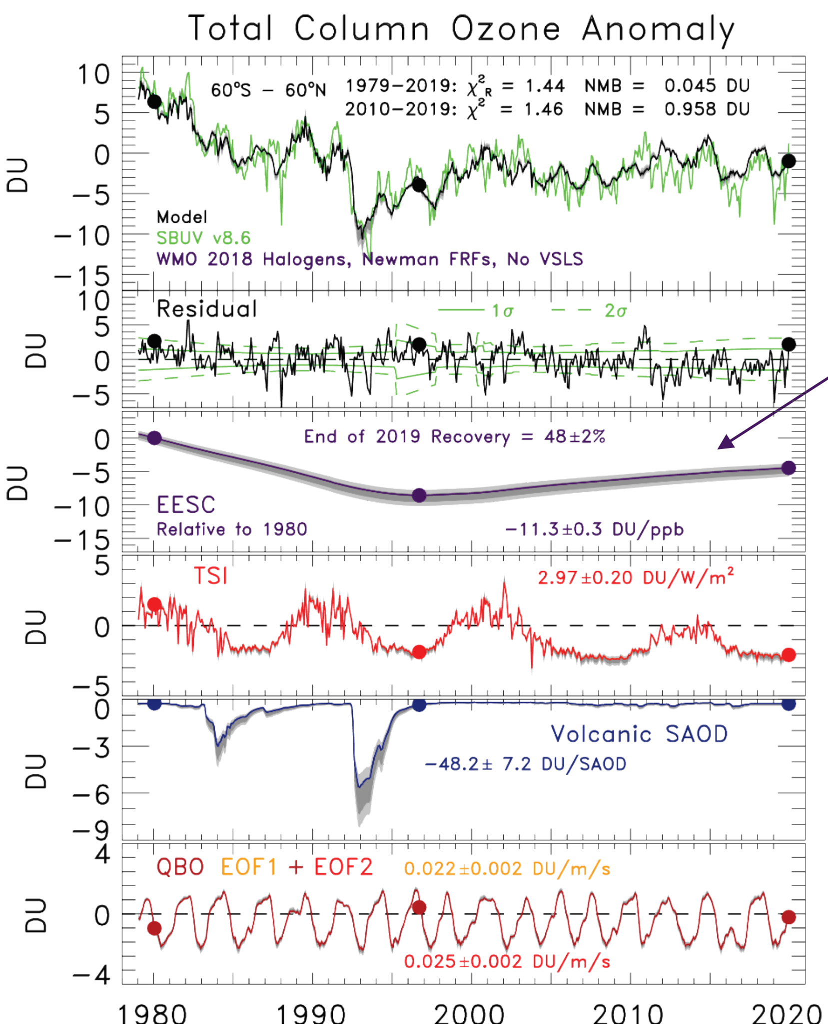
Time series of chlorine content of organic halocarbons that reach the stratosphere. Past values based on direct atmospheric observation. Future values based on projections that include the lifetime for removal of each halocarbon.

Table 6−4, WMO/UNEP 2018

Gas	Atmospheric Lifetime (years)	Ozone Depletion Potential (ODP)[b]
Halogen Source Gases		
Chlorine Gases		
CFC-11 (CCl_3F)	52	1
Carbon tetrachloride (CCl_4)	32	0.87
CFC-113 (CCl_2FCClF_2)	93	0.81
CFC-12 (CCl_2F_2)	102	0.73
Methyl chloroform (CH_3CCl_3)	5.0	0.14
HCFC-141b (CH_3CCl_2F)	9.4	0.102
HCFC-142b (CH_3CClF_2)	18	0.057
HCFC-22 (CHF_2Cl)	12	0.034
Methyl chloride (CH_3Cl)	0.9	0.015
Bromine Gases		
Halon-1301 ($CBrF_3$)	65	15.2
Halon-1211 ($CBrClF_2$)	16	6.9
Methyl bromide (CH_3Br)	0.8	0.57
Hydrofluorocarbons (HFCs)		
HFC-23 (CHF_3)	228	0
HFC-143a (CH_3CF_3)	51	0
HFC-125 (CHF_2CF_3)	30	0
HFC-134a (CH_2FCF_3)	14	0
HFC-32 (CH_2F_2)	5.4	0
HFC-152a (CH_3CHF_2)	1.6	0
HFO-1234yf ($CF_3CF{=}CH_2$)	0.03	0

Mid-Latitude Ozone Depletion

Total column ozone anomaly is deseasonalized, cosine latitude weighted average of total column ozone collected between 60°S and 60°N, relative to the mean total column abundance over the entire time period.



"Expected" recovery of near global ozone layer for end of 2019 relative to maximum depletion since 1980, driven by atmospheric halogens

Note:

a) this model predicts significant recovery of the global ozone layer should be underway

despite:

b) regular "ups" and "downs" of ozone caused by the 11-year solar cycle

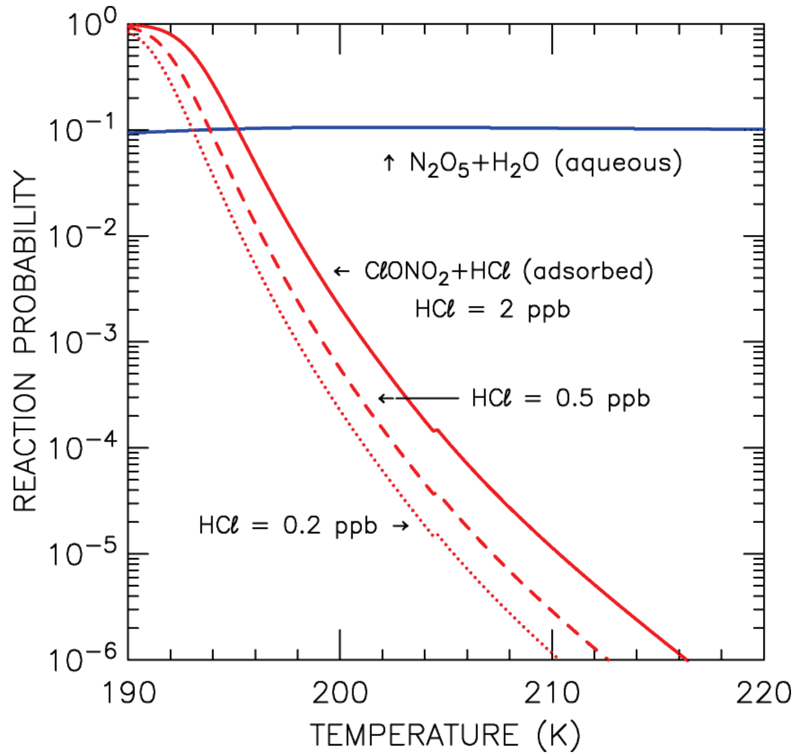
c) major ozone depletion after volcanic eruptions large enough to greatly enhance stratospheric aerosol optical depth (SAOD)

d) regulars "ups" and "downs" of ozone caused by the so-called quasi-biennial oscillation of the direction of the horizontal wind in the lower stratosphere

Salawitch *et al.*, In Prep, 2020

Heterogeneous Chemistry, Mid-Latitude vs Polar Regions

In all cases, γ must be measured in the laboratory



Reaction probabilities given for various surface types, with formulations of various degrees of complexity, in **Section 5** of the JPL Data Evaluation.

Atmospheric Chemistry and Physics by Seinfeld and Pandis provides extensive treatment of aqueous phase chemistry, properties of atmospheric aerosol, organic aerosols, etc.

Polar Ozone Loss

- Cold Temperatures → Polar Stratospheric Clouds (**PSCs**)
- Reactions on PSC surfaces lead to elevated **ClO**

$HCl + ClNO_3 \rightarrow Cl_2$ (gas) $+ HNO_3$ (solid)

$ClNO_3 + H_2O \rightarrow HOCl + HNO_3$

Cl_2 + SUNLIGHT + $O_3 \rightarrow ClO$

HOCl + SUNLIGHT + $O_3 \rightarrow ClO$

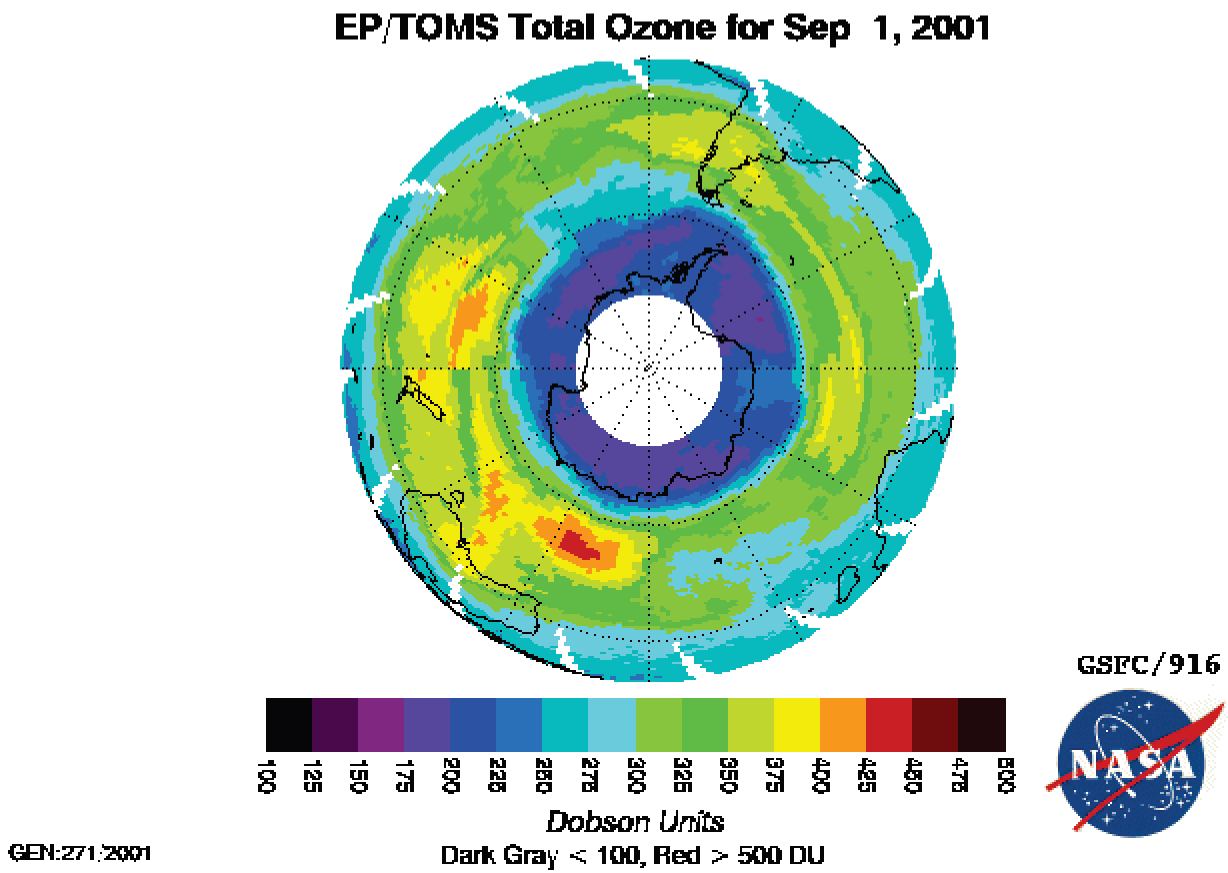
HNO_3 SEDIMENTS (PSCs fall due to gravity)

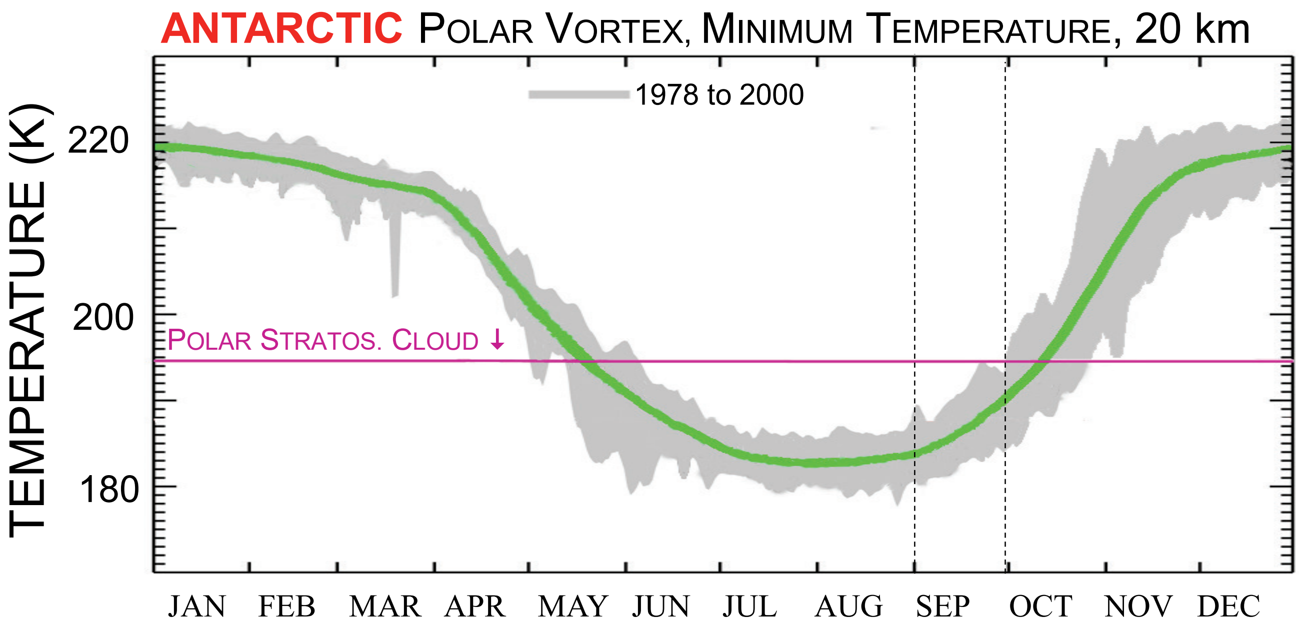
- Elevated **ClO** + Sunlight destroys O_3
- BrO : Reaction Partner For ClO ⇒ Additional O_3 Loss

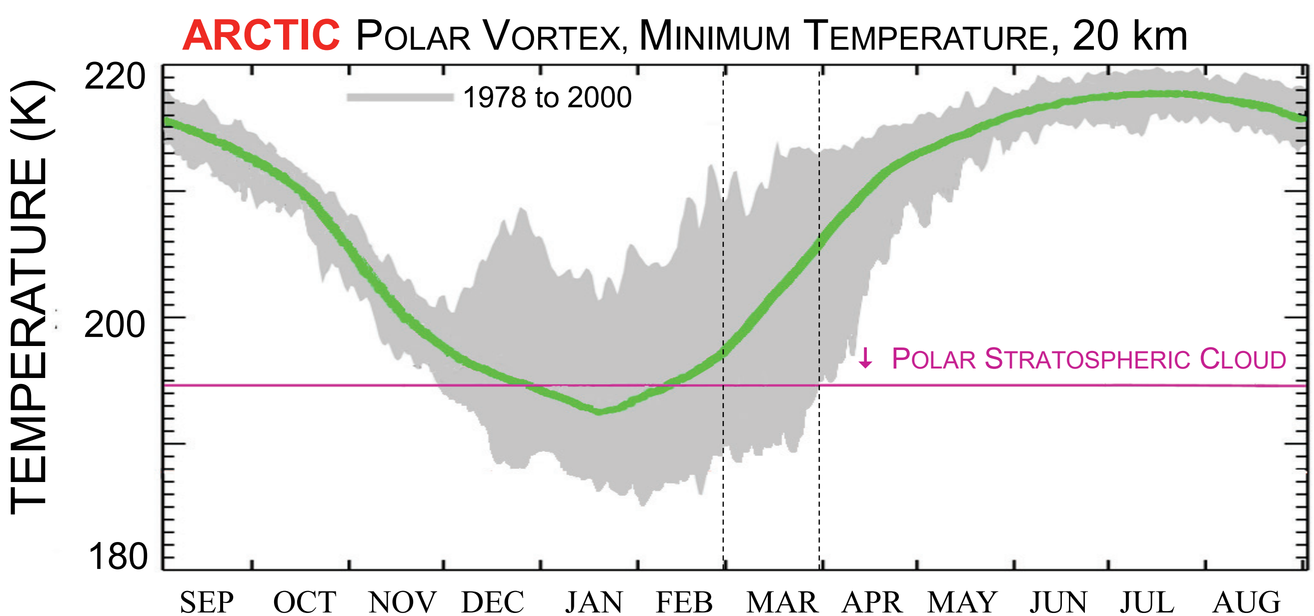
Polar Vortex Circulation

During winter:

- radiative cooling leads to cold air in polar stratosphere
- large scale low pressure region develops over pole
- strong “polar night jet” develops, isolating air at high latitudes from air at low latitudes
- T continues to fall in the “vortex like” circulation near the pole







Data Courtesy P. Newman,
NASA/GSFC

Minimum Temperature: NH and SH

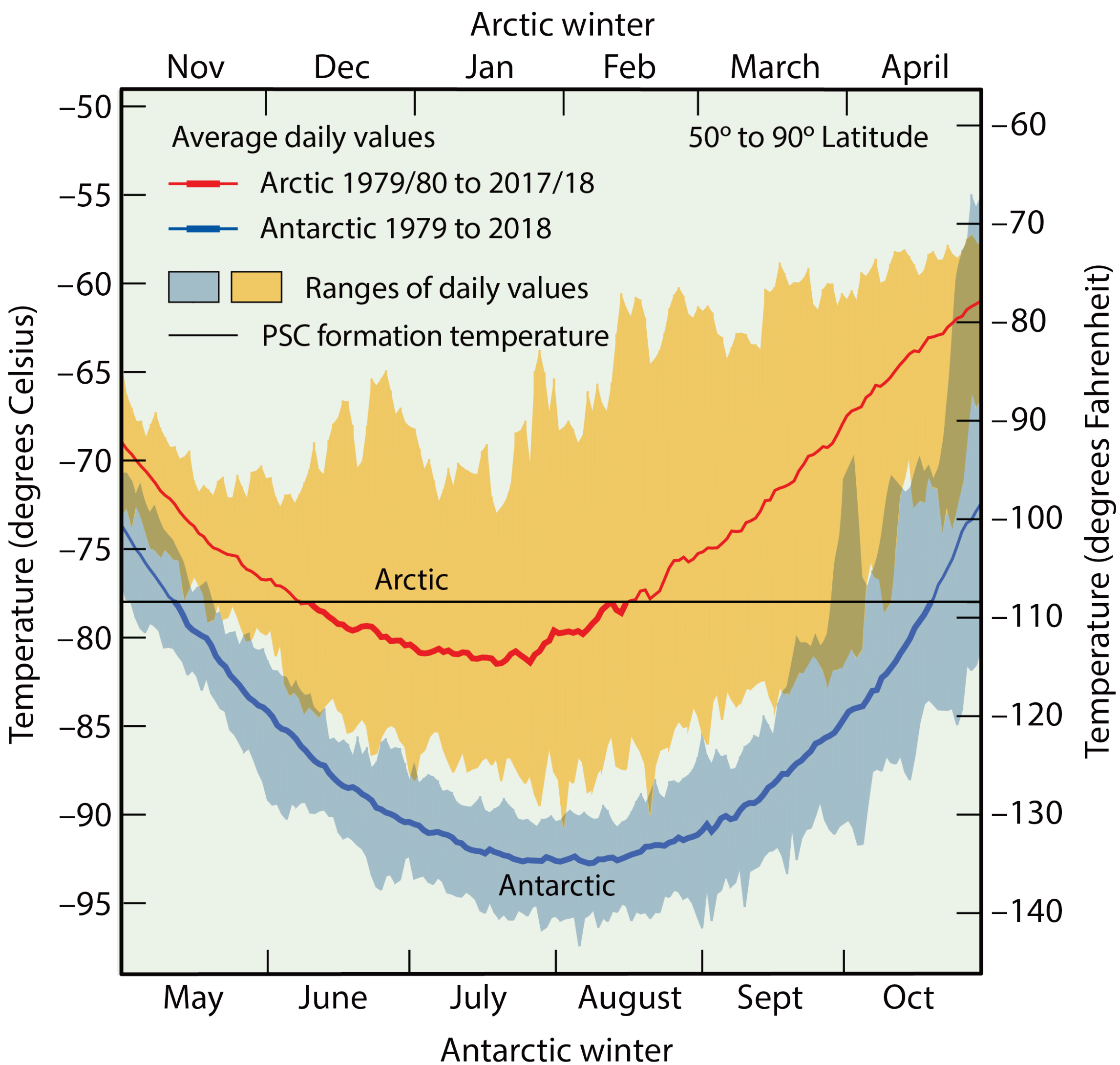


Fig Q9-1, *WMO/UNEP Twenty QAs Ozone*

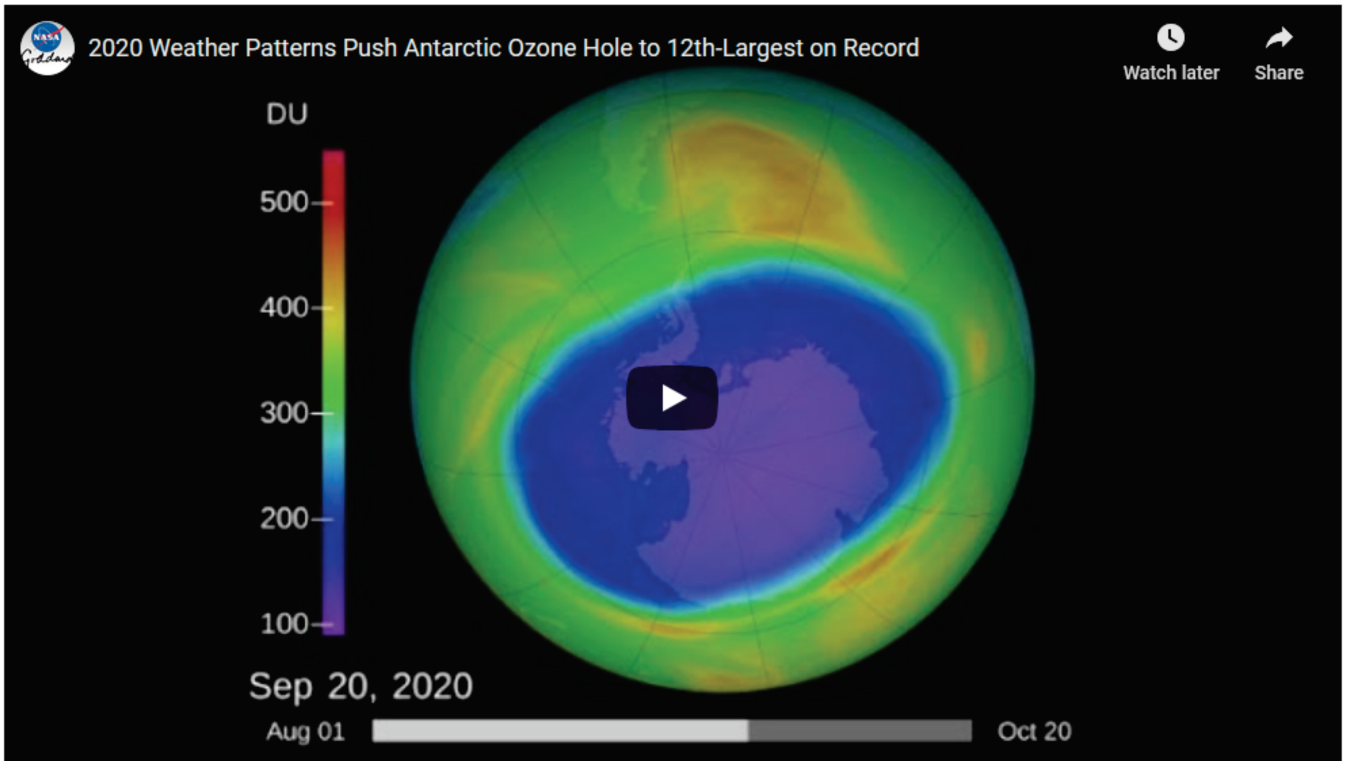
Antarctic Ozone, 2020

Oct. 30, 2020

Large, Deep Antarctic Ozone Hole Persisting into November

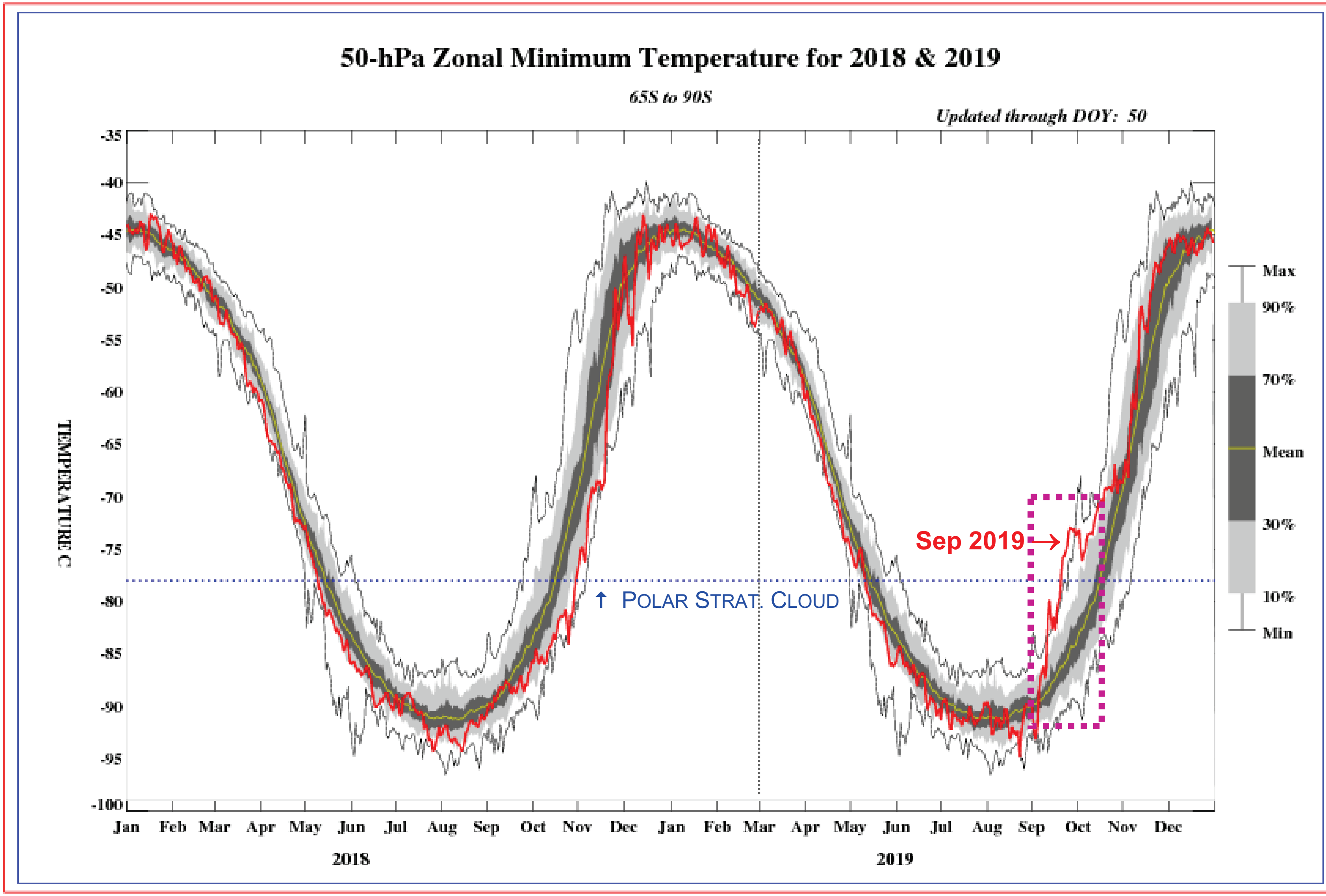
Persistent cold temperatures and strong circumpolar winds, also known as the polar vortex, supported the formation of a large and deep Antarctic ozone hole that should persist into November, NOAA and NASA scientists reported today.

The annual Antarctic ozone hole reached its peak size at about 9.6 million square miles (24.8 million square kilometers), roughly three times the area of the continental United States, on Sept. 20. Observations revealed the nearly complete elimination of ozone in a 4-mile-high column of the stratosphere over the South Pole.



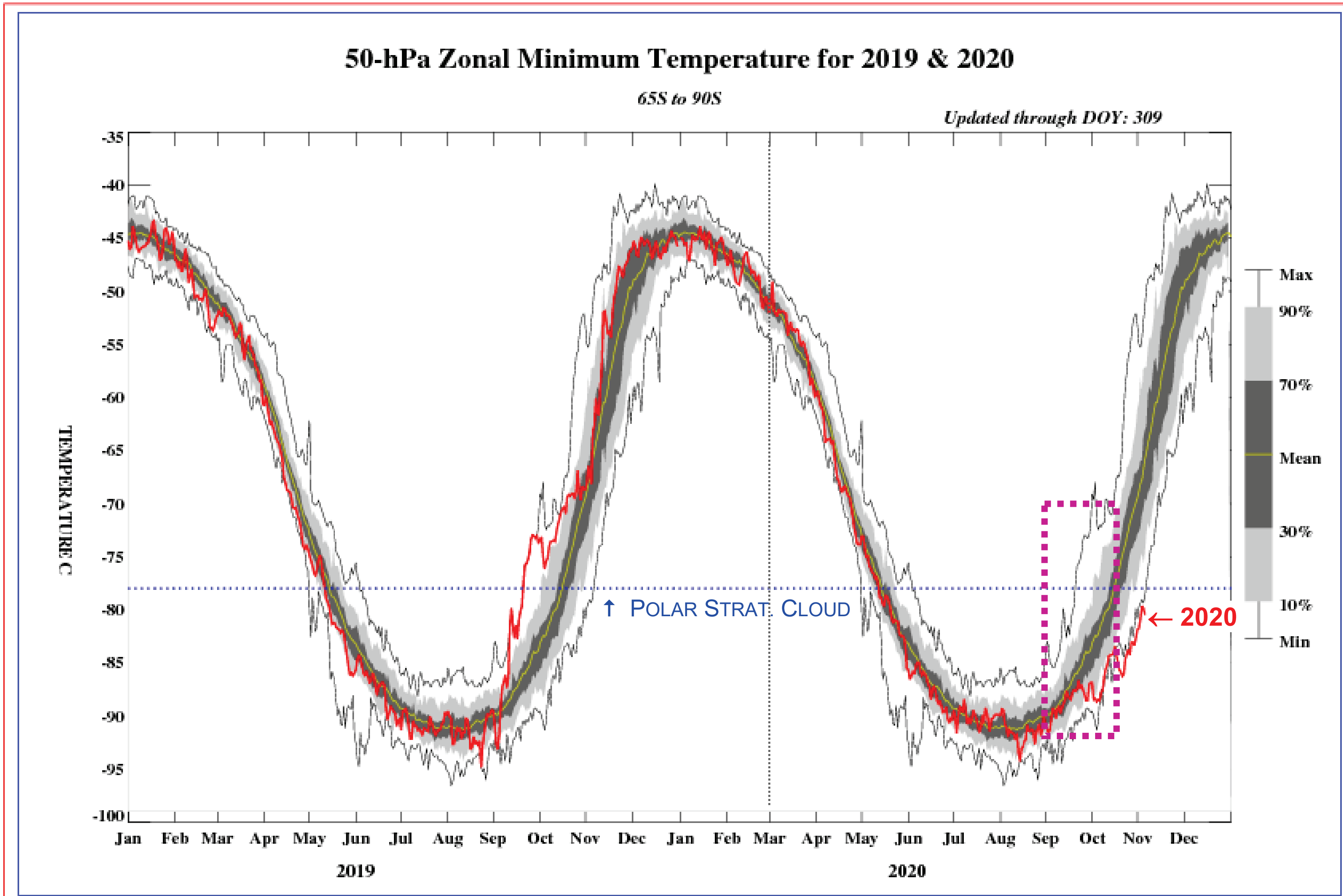
Please watch this 3 minute video: https://www.youtube.com/watch?v=4aq_F9Ma0DQ

Antarctic Vortex Minimum Temperature: 2018-2019



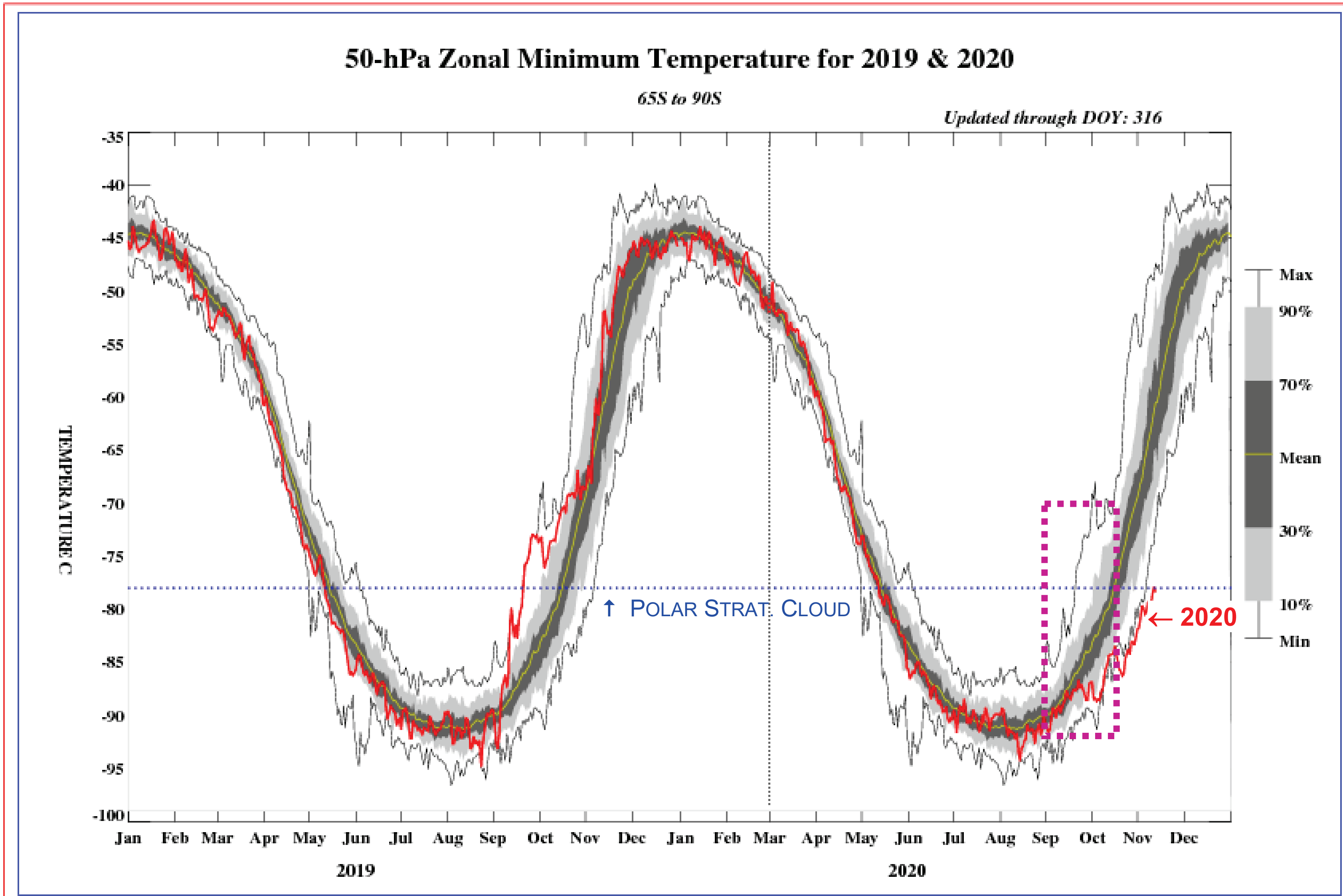
https://www.cpc.ncep.noaa.gov/products/stratosphere/temperature/archive/50mbshlo_2019.png

Antarctic Vortex Minimum Temperature: 2019-2020



https://www.cpc.ncep.noaa.gov/products/stratosphere/temperature/50mbshlo.png

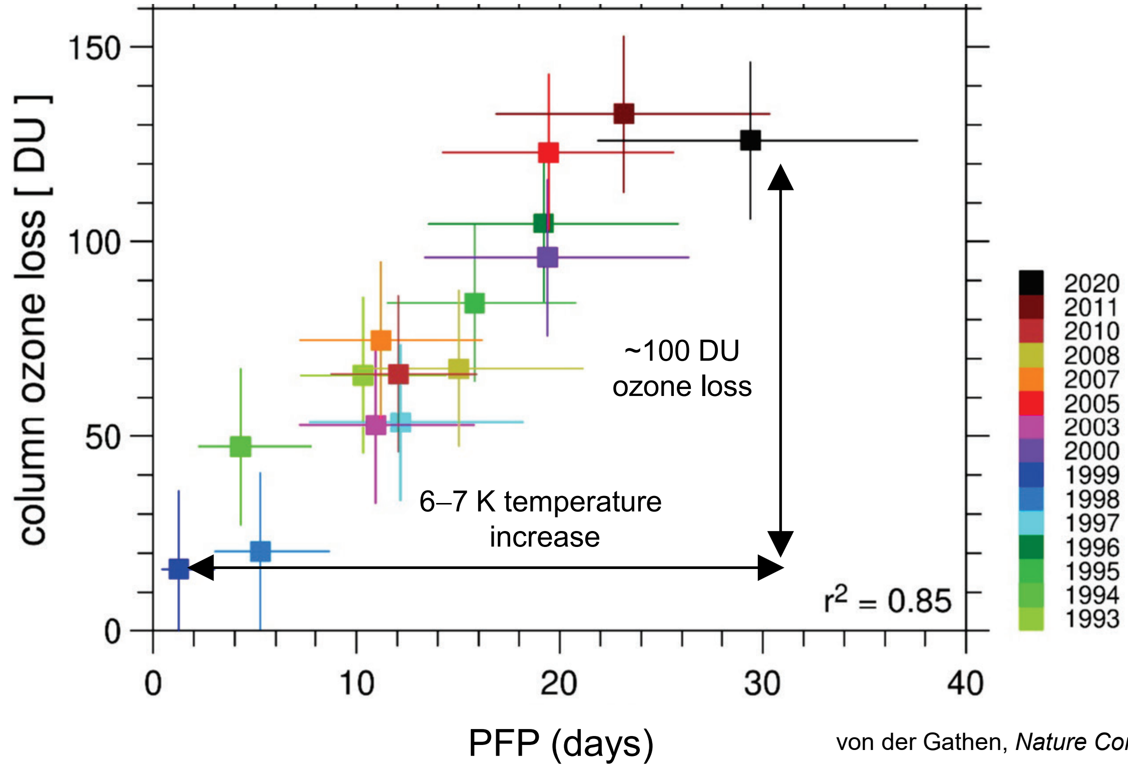
Antarctic Vortex Minimum Temperature: 2019-2020



https://www.cpc.ncep.noaa.gov/products/stratosphere/temperature/50mbshlo.png

Arctic Ozone Loss Varies as a function of PSC Formation Potential

Data:



von der Gathen, *Nature Communications*, submitted, 2020

- Surprisingly simple relationship between chemical loss of column ozone and volume of air exposed to PSC formation potential over winter, where

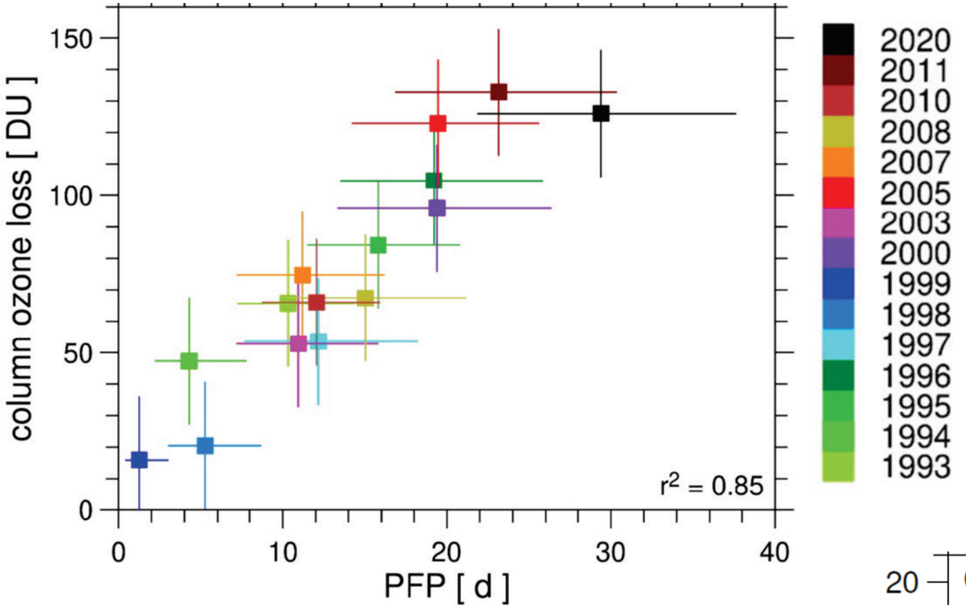
$$PFP = \int_{16\,Nov}^{17\,Apr} \frac{V_{PSC}(t)}{V_{VORTEX}(t)}\, dt$$

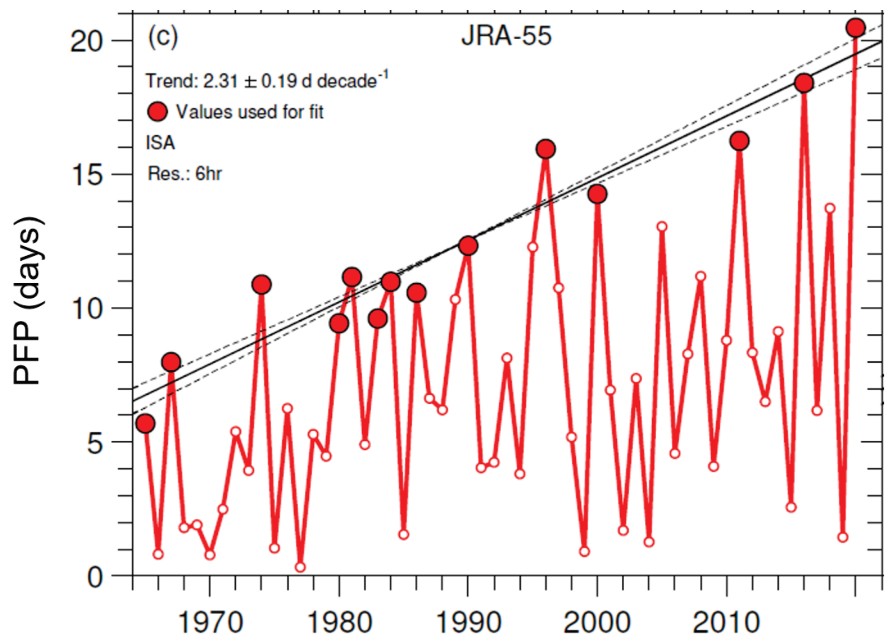
PFP is PSC Formation Potential

and V_{PSC} is the volume of the vortex where T is cold enough to allow for formation of PSCs, and V_{VORTEX} is the volume of the Arctic vortex

- Relation leads to estimate of ~15 DU additional loss of ozone per degree Kelvin cooling of *Arctic* stratosphere

Arctic Ozone 2020 in Context of Prior Years

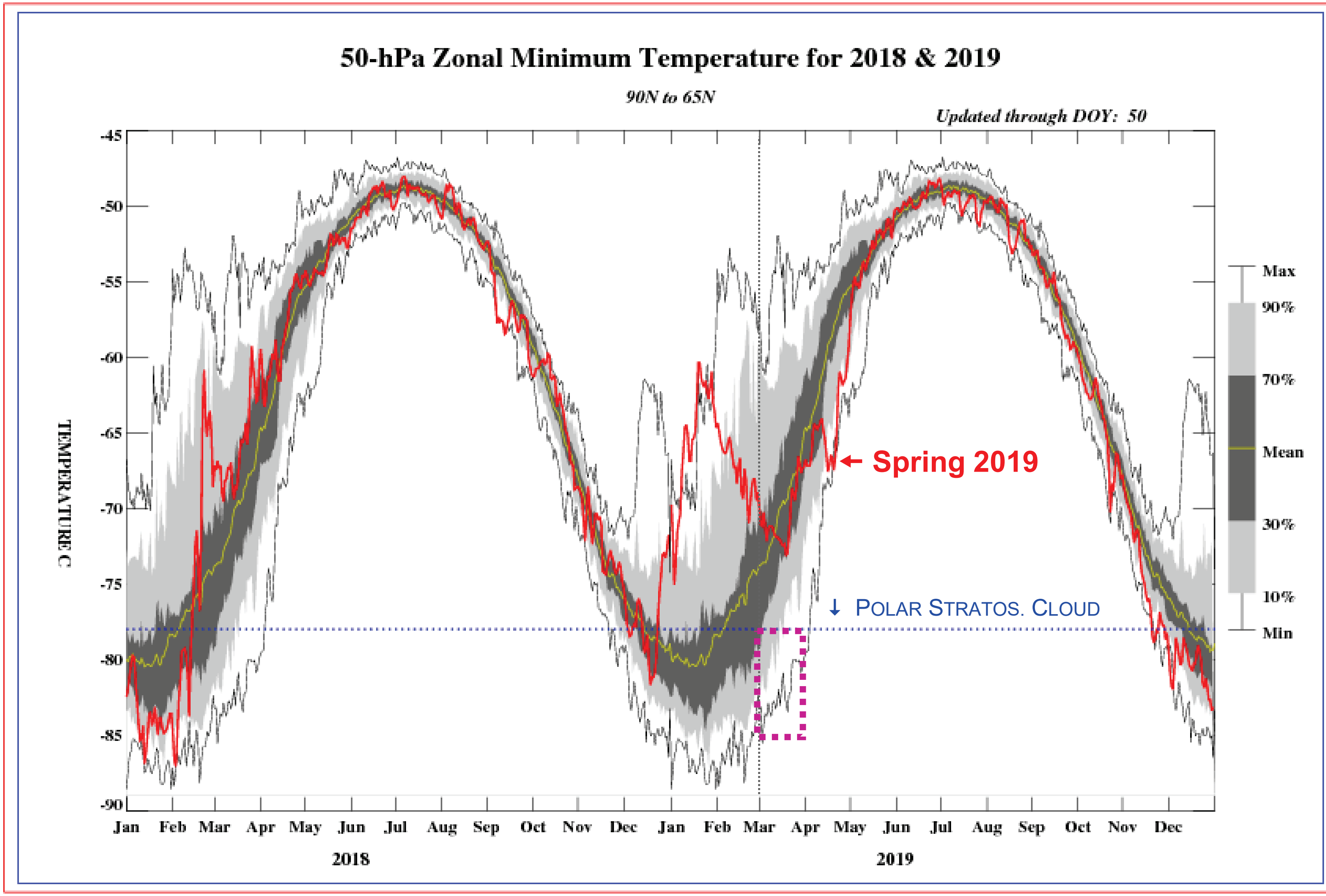




PFP: **P**olar Stratospheric Cloud **F**ormation **P**otential in the Arctic Vortex based on data from the Japanese 55 year re-analysis project

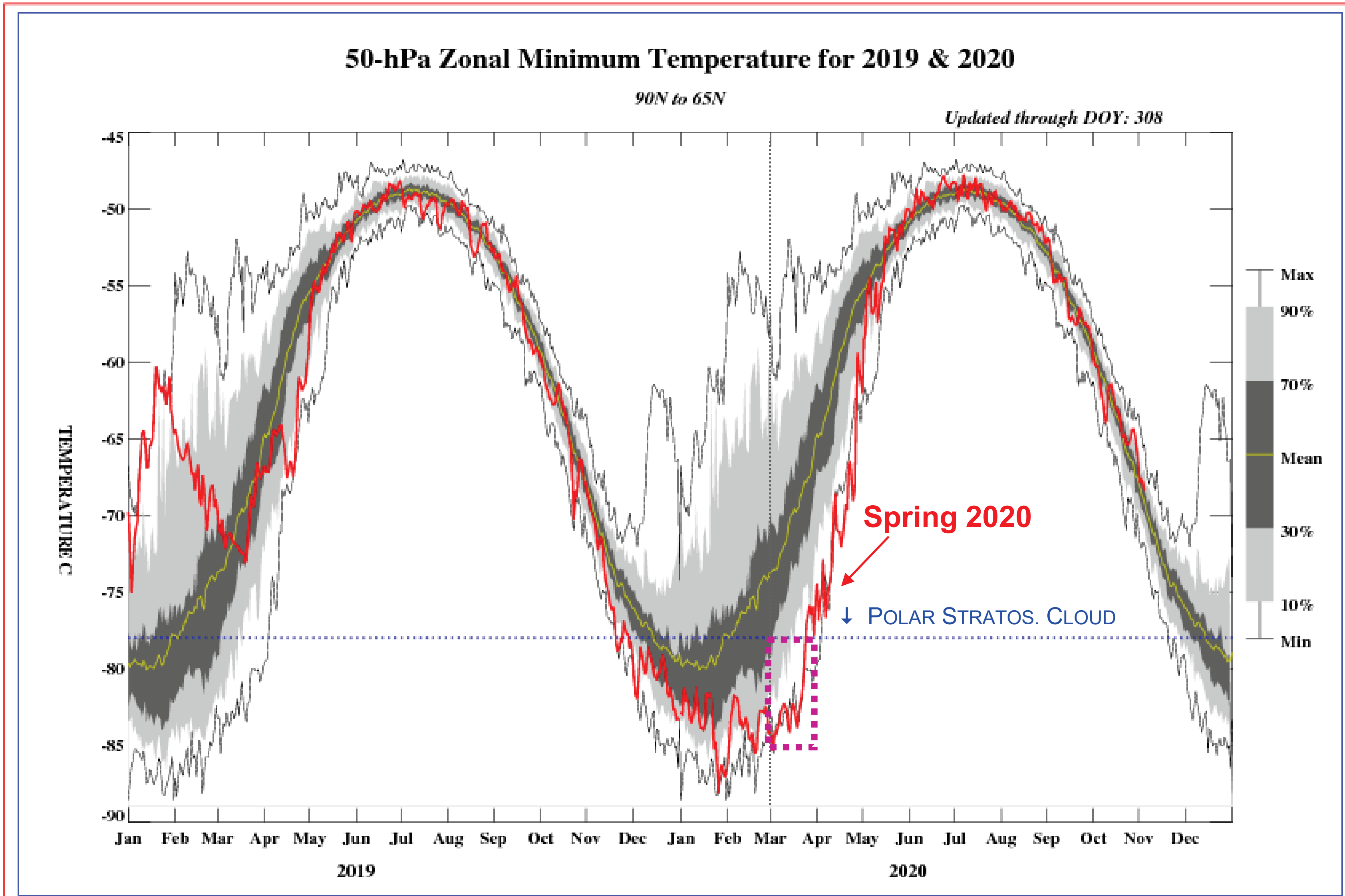
https://jra.kishou.go.jp/JRA-55/index_en.html

Arctic Temperature: Mar 2019



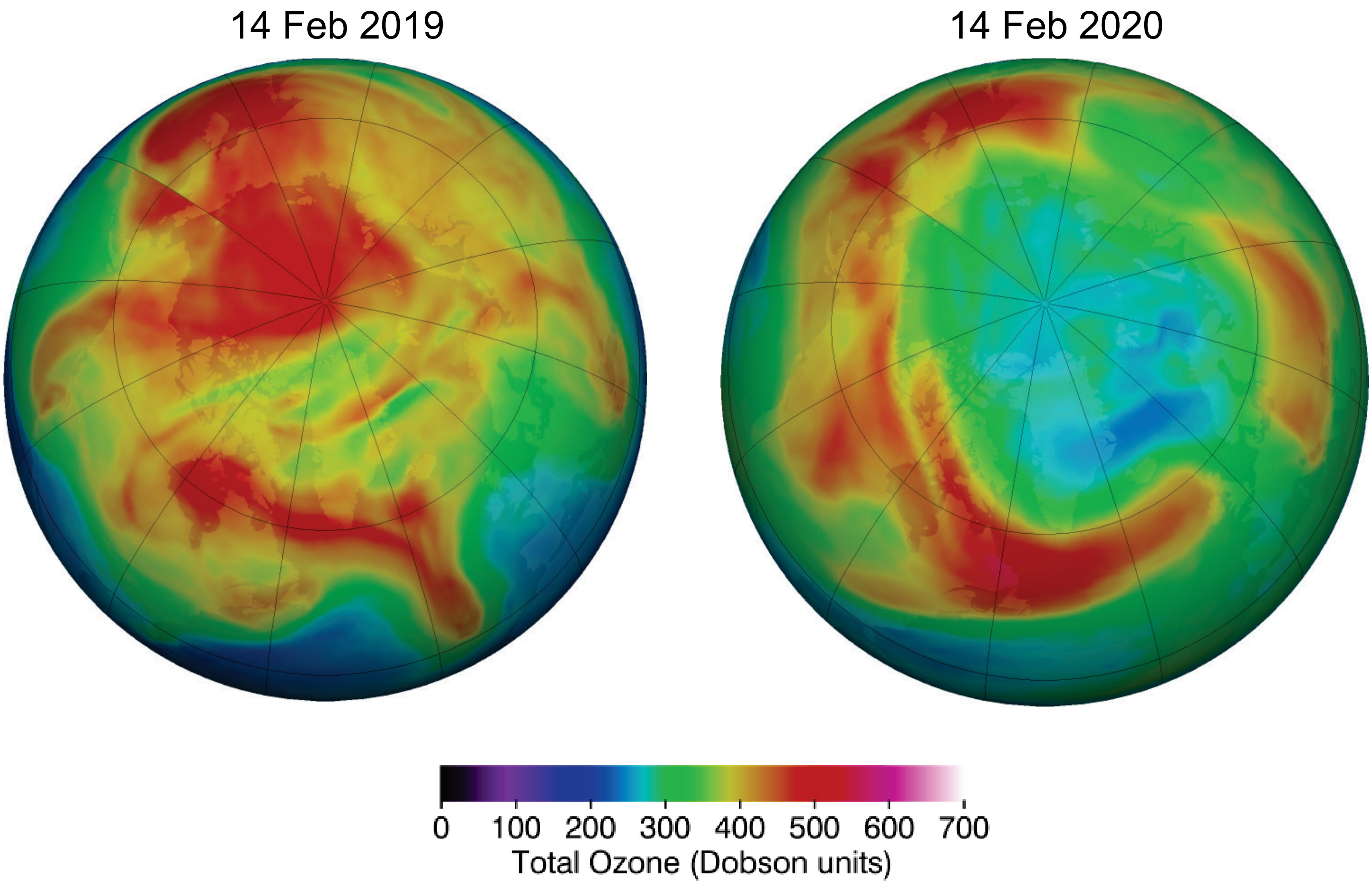
http://www.cpc.ncep.noaa.gov/products/stratosphere/temperature/50mbnhlo.png

Arctic Temperature: Mar 2020



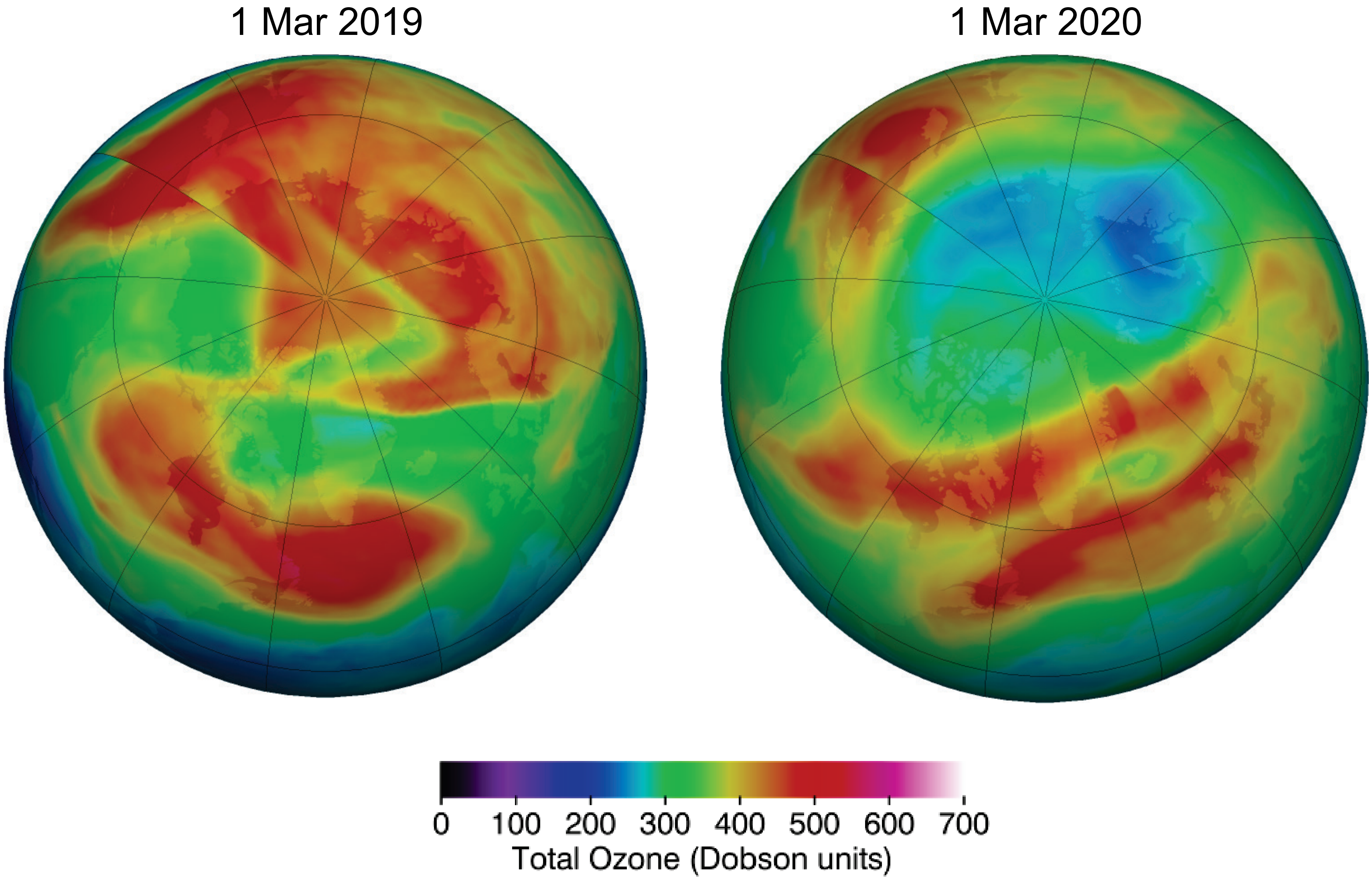
http://www.cpc.ncep.noaa.gov/products/stratosphere/temperature/50mbnhlo.png

Arctic Ozone: 2019 and 2020



https://ozonewatch.gsfc.nasa.gov/monthly/monthly_2019-04_NH.html

Arctic Ozone: 2019 and 2020



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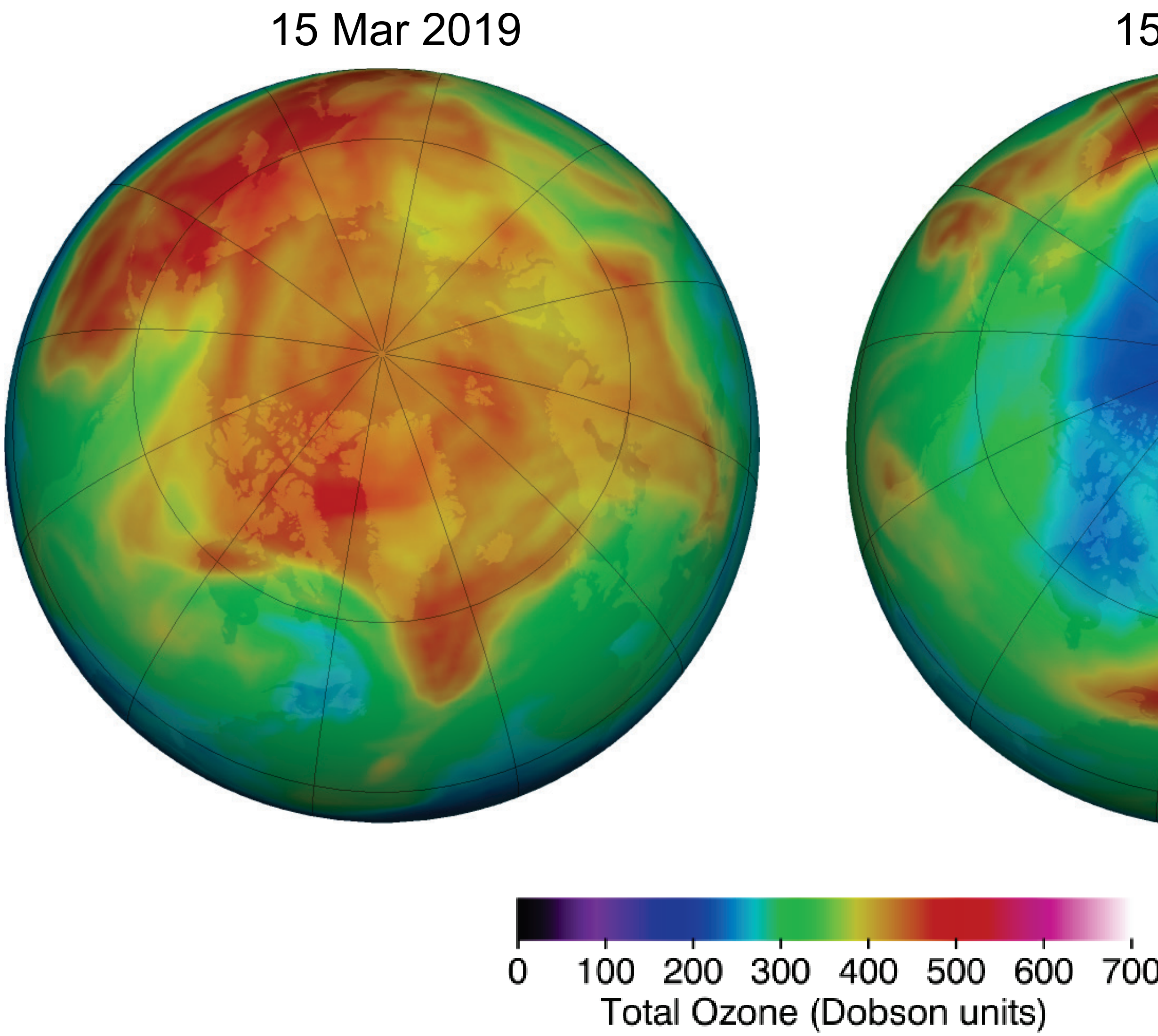
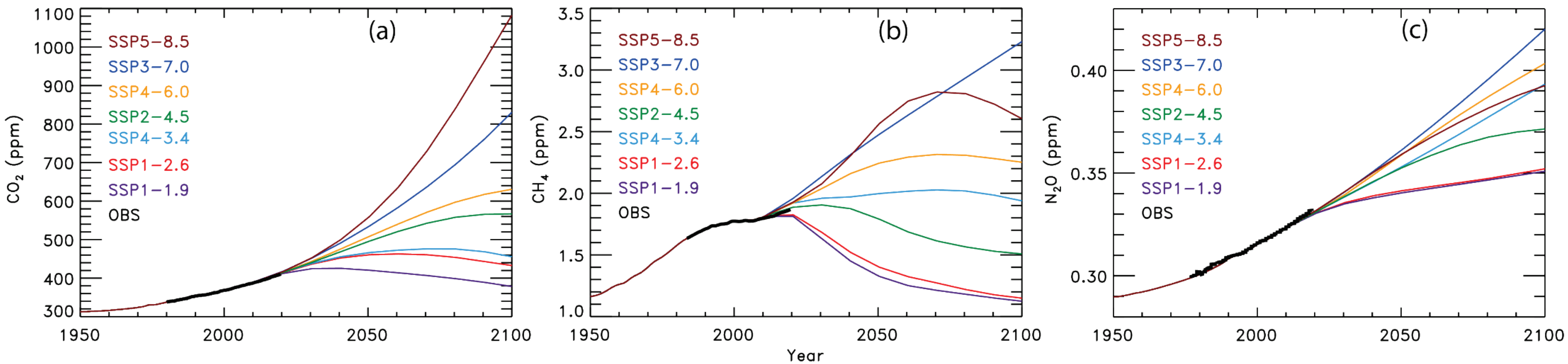
Arctic Ozone: 2019 and 2020



http://www.cpc.ncep.noaa.gov/products/stratosphere/temperature/50mbnhlo.png

SSP: Shared Socioeconomic Pathway Scenarios Will Drive Upcoming IPCC Report

Climate Model Input



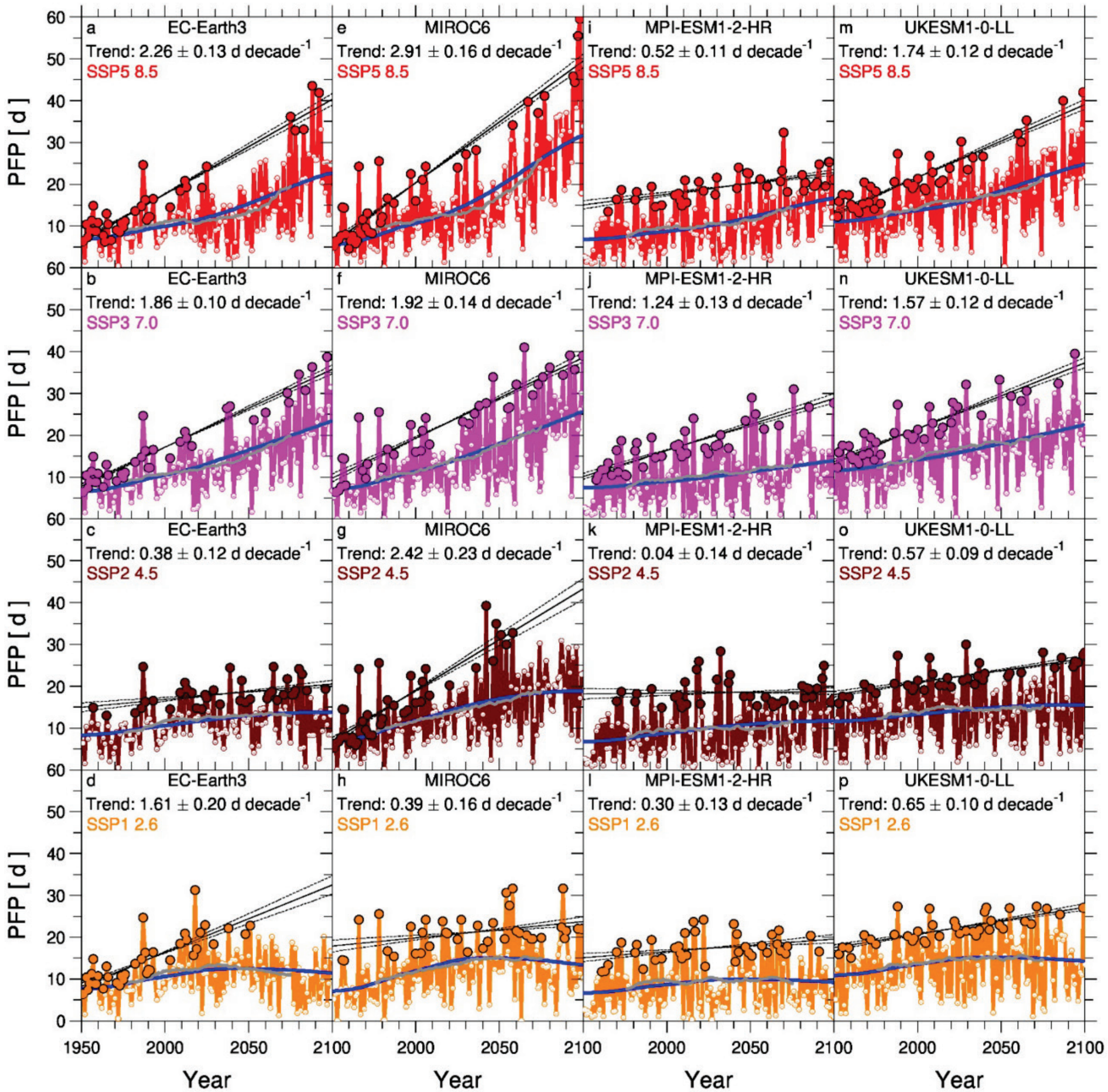
McBride et al., *Earth System Dynamics*, submitted, 2020

Number before dash represents base narrative and number after dash represents W m^{-2} RF of climate at end of century

Tendency for Colder Arctic Winters Getting Colder Drive by Rising GHGs

Climate Model Output

PFP is PSC Formation Potential



von der Gathen, *Nature Communications*, submitted, 2020

Future Ozone: ODSs, CO_2, CH_4 and N_2O

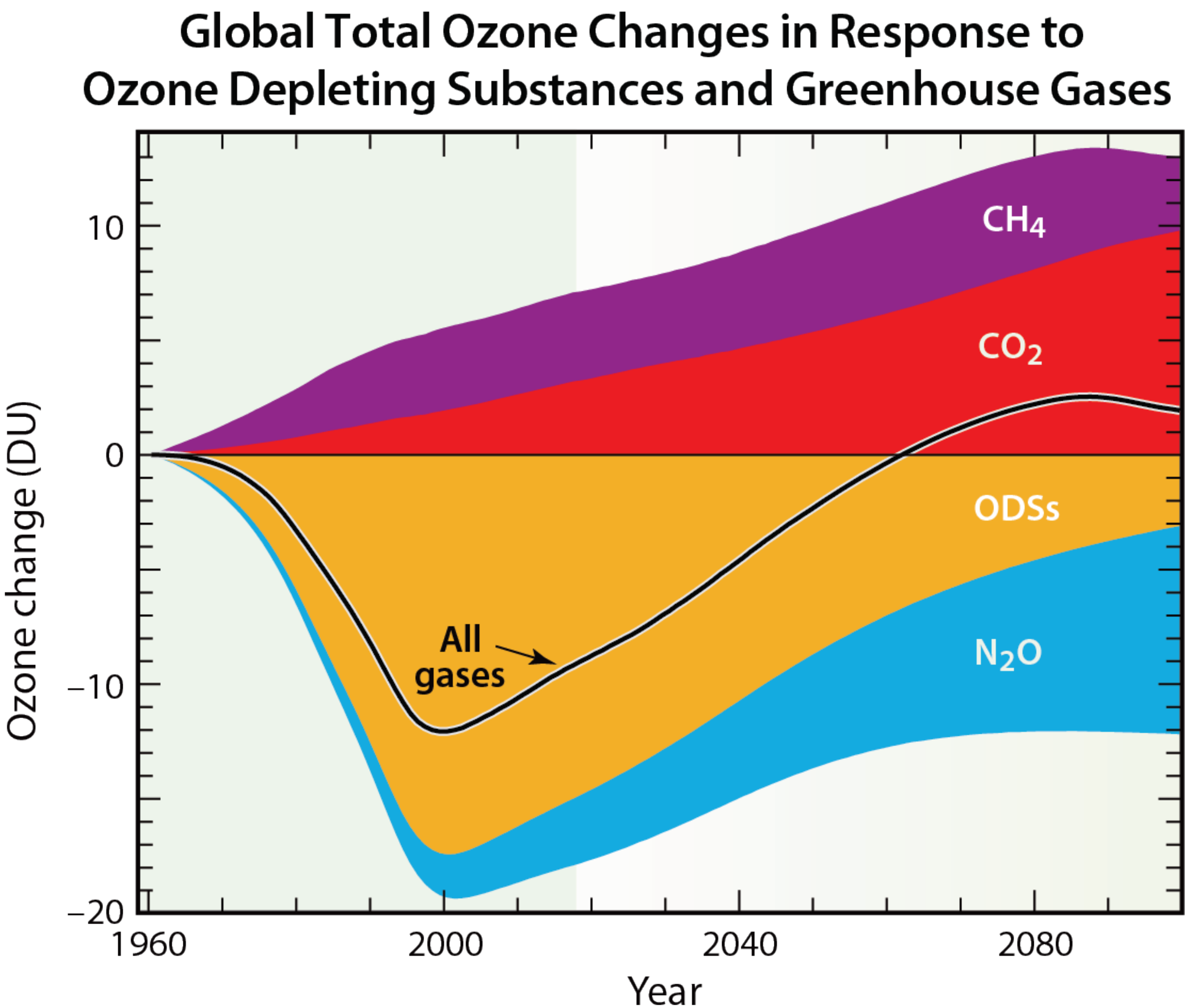
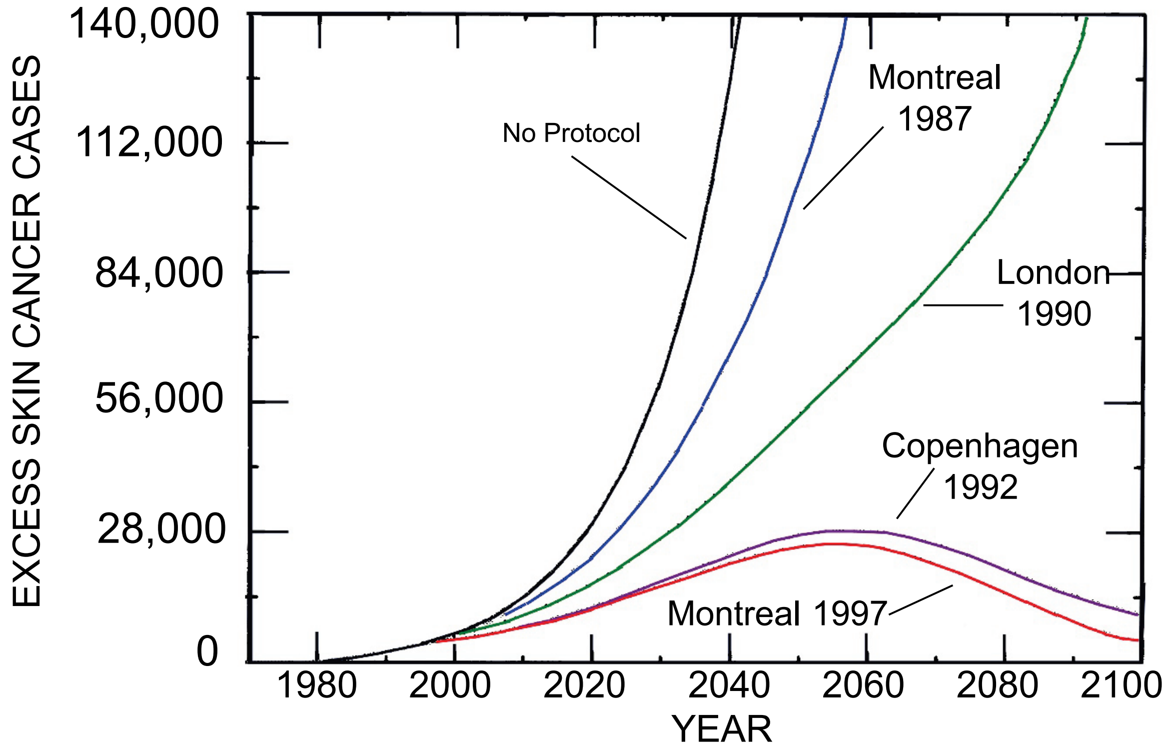


Fig Q20-3, 20 QAs, WMO (2019)

EXCESS SKIN CANCER CASES IN THE UNITED STATES, PER YEAR, DUE TO OZONE DEPLETION FOR VARIOUS CFC EMISSION SCENARIOS



Longstreth *et al.*, *J. of Photochemistry and Photobiology B*, 46, 20–39, 1998.

See also Slaper *et al.*, Estimates of ozone depletion and skin cancer incidence to examine the Vienna Convention achievements, *Nature*, *384*, 256–258, 1996, who state:

> The no-restrictions and Montreal Protocol scenarios produce a runaway increase in skin cancer incidence, up to a quadrupling and doubling, respectively, by year 2100.

Announcements: Class

Second Exam

Second exam which will be on-line, open book, open web, ***that everyone will take during normal class hour on Tues, 17 Nov, from 2:02 to 3:17 pm.***

However, please note that:

a) the exam will focus on a series of question that you can only answer properly in the limited time IF you are already familiar with the contents of each lecture;

b) there will be either minimal or no calculations on the exam, the vast majority of the exam will be qualitative rather than quantitative

c) if you have been doing all of the readings, answering the ATs based on a comprehensive understanding of the readings, and retaining knowledge from the readings and exams, as solidified by consistently high scores of the learning out come quizzes, then you'll be in great shape for the first exam. On the other hand, if you have been skimming the readings, doing the bare minimum to answer the ATs, and not completing the learning outcome quizzes, you will need to impart greater effort to prepare for the exam, in order to do well.

d) by "open web", I mean you are allowed to search for information on the Web. **You absolutely, positively are not allowed to conduct any on-line chats, or solicit help from an on-line assistance program of any sort.**