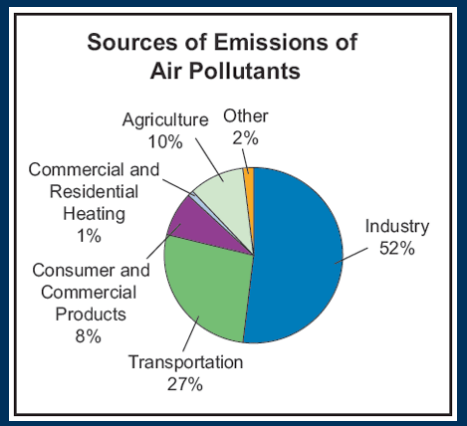
GGS 319
Part 1: Air Pollution Fundamentals

- ✓ The atmosphere and its components
- ✓ ***How air pollutants are categorized***
- ✓ ***The source/cycle of air pollutants***
- ✓ How pollution affects health and welfare
- ✓ Clean air acts
- ✓ Air quality management & standards







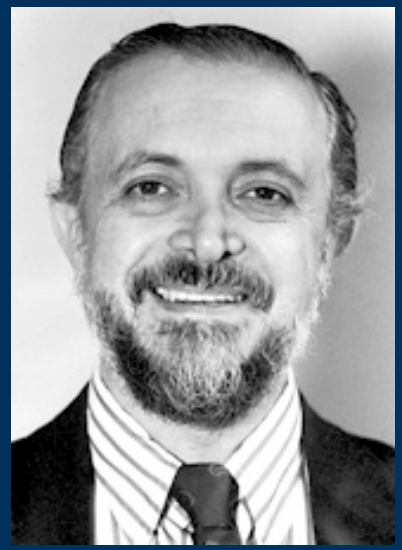
History

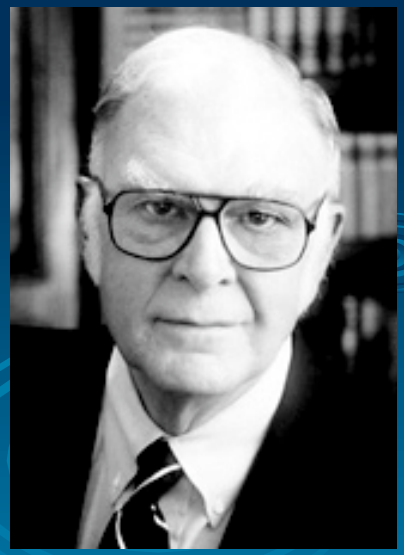
- A theory for the origin of this ozone layer was proposed in 1930 by a British scientist Sydney Chapman
- The Chapman mechanism lays the foundation for current understanding of stratospheric ozone



History

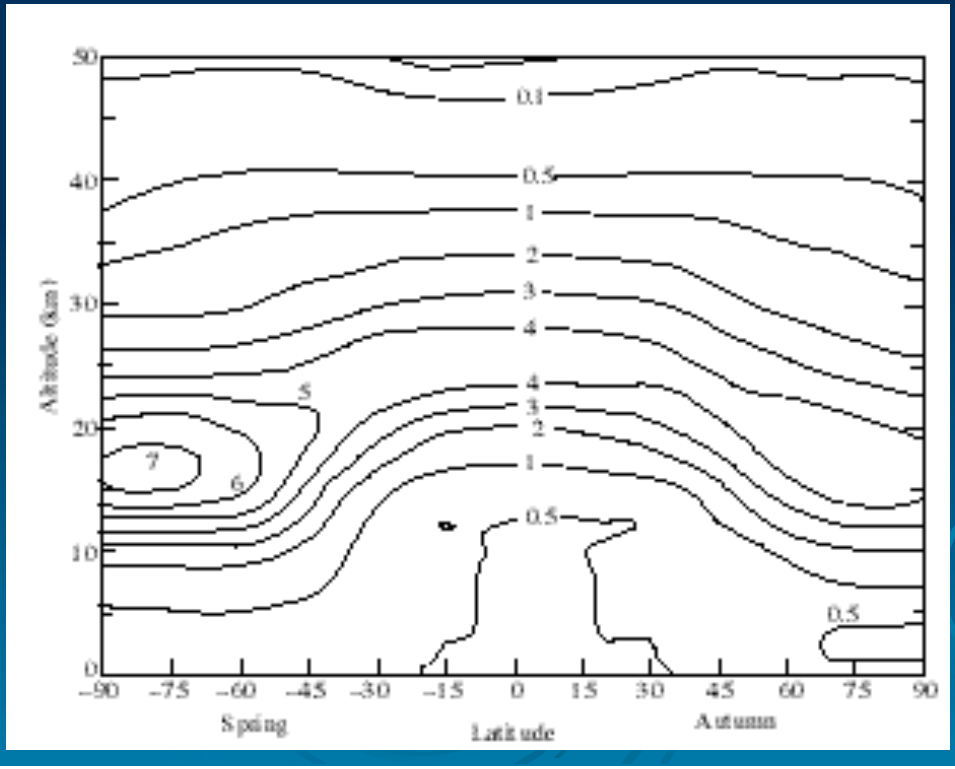
- 1974: Molina & Rowland (1974) Nature 249, 810-812
  - Paper calls attention to dangers of CFC's in ozone breakdown
- 1978: U.S. bans CFCs as propellants
- 1987: Montreal Protocol calls for decrease in CFC to 50% of 1986 levels by 1999
- 1990: London Amendments call for complete CFC phase out by 2000
- 1992: Copenhagen Amendments accelerate phase out to 1996
- 1995: Molina & Rowland win Nobel Prize in Chemistry





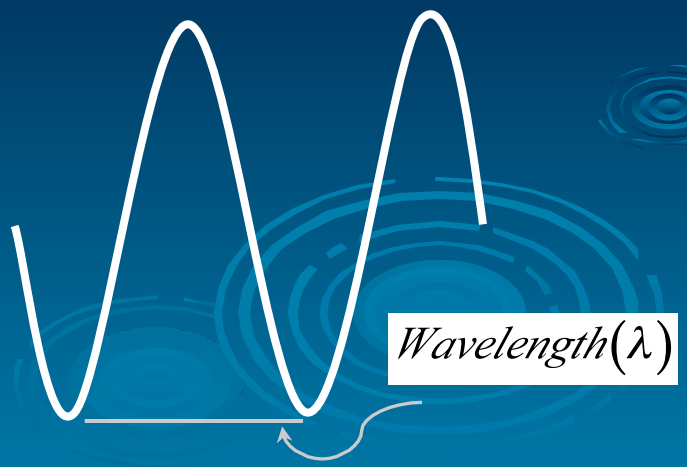
Ozone Distribution in the Atmosphere

- Ozone is a triatomic form of oxygen (O3) found in Earth's upper and lower atmosphere.
- The stratospheric ozone layer, centered at about 20 km above the surface of the Earth
- The natural ozone layer: vertical and latitudinal distribution of ozone number of density (1012 molecules cm^{-3})



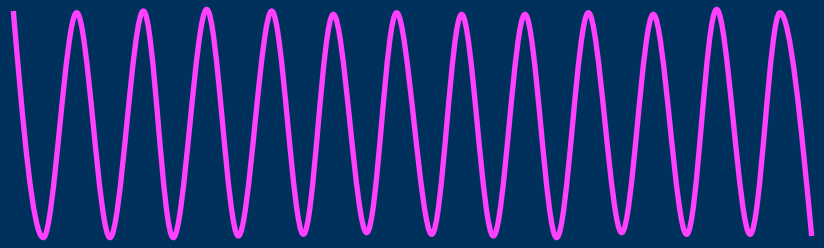
Electromagnetic Radiation

- Solar Radiation
  - Important to understand radiation, in order to understand climate controls
- The Electromagnetic Spectrum
  - All radiant energy occurs in the form of electromagnetic radiation
  - The energy exists in particle units called photons, which travel at all times at the speed of light (300,000 km/s in a vacuum)
  - Photons have no mass, are bundles of energy
- Photons as Waves
  - Photons vibrate as waves, and have a wavelength and a frequency
    - Wavelength
      - Distance crest to crest
      - Expressed in distance (e.g. nm)
    - Frequency
      - No. of waves that pass a point in a unit of time (e.g. 1 sec.)
      - Expressed in Hertz (waves/sec)

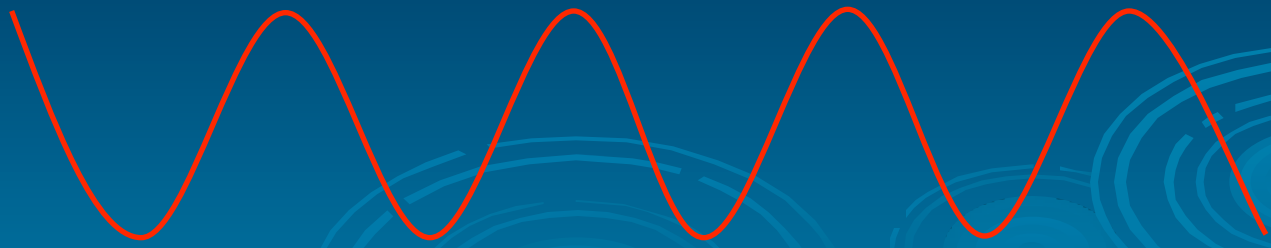


Photon Energy

- High Energy photons
  - Have short wavelengths and high frequencies

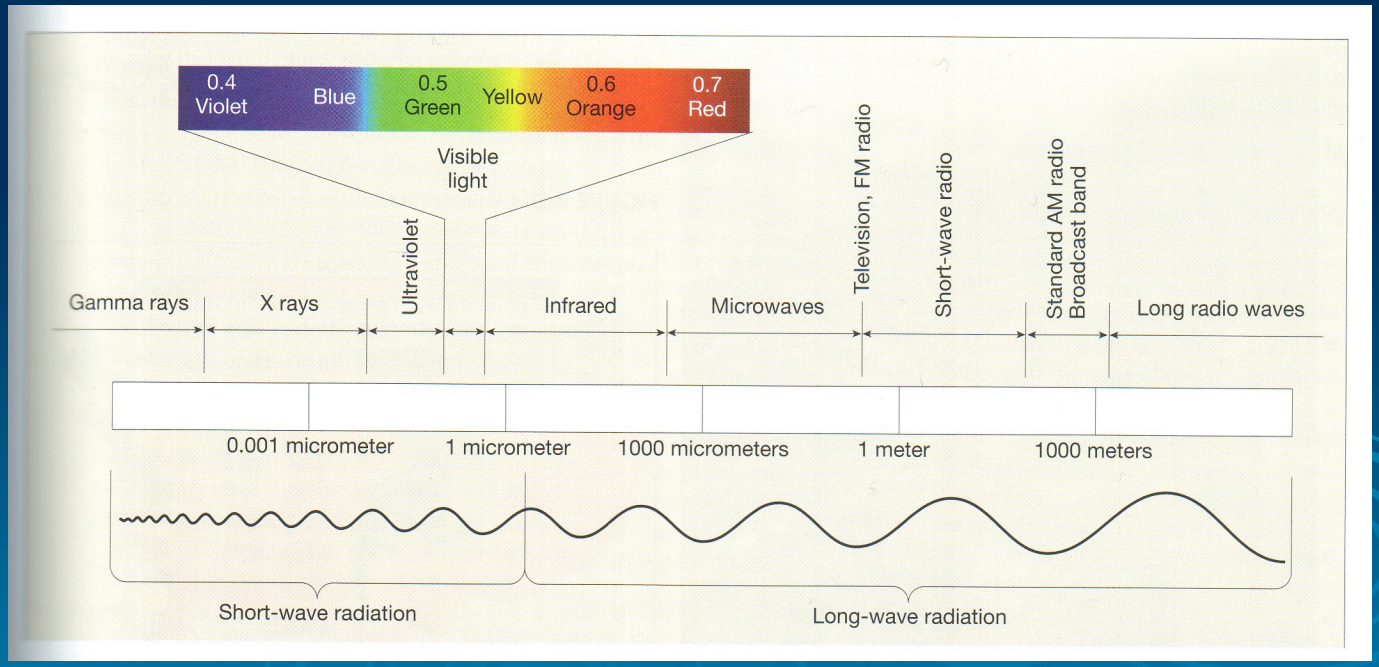


- Lower Energy photons
  - Have long wavelengths and low frequencies



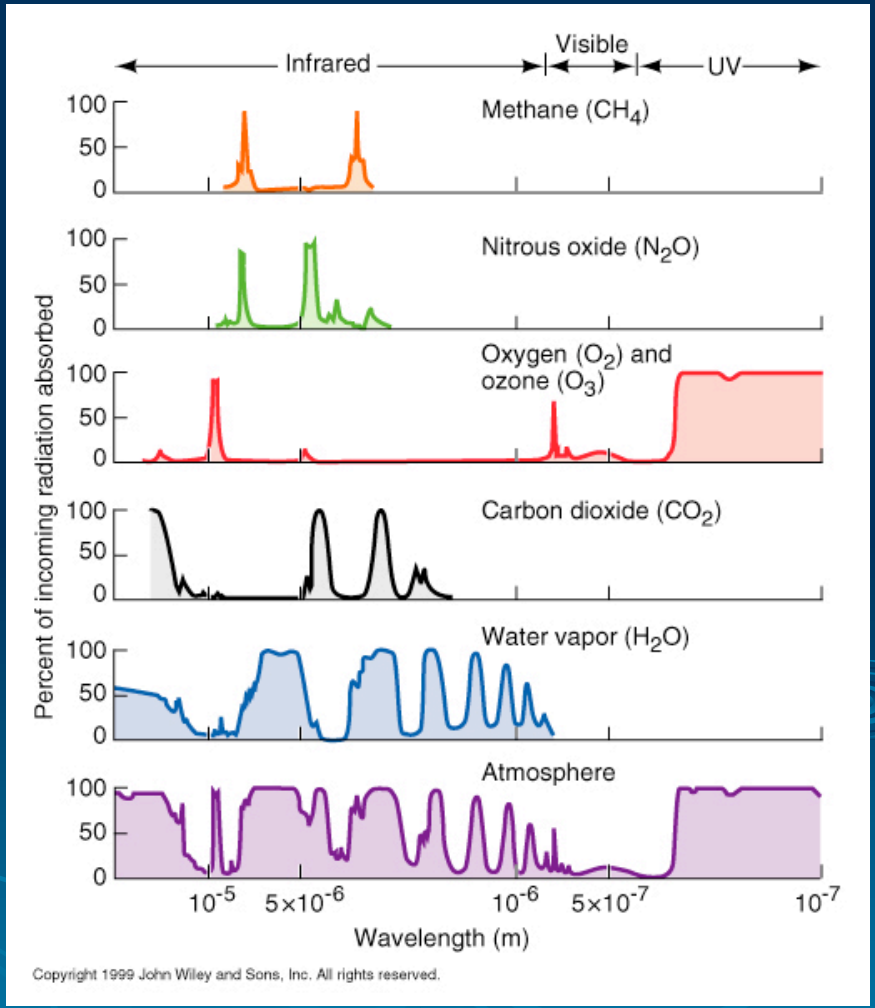
The Chapman Mechanism
(Ozone Formation in the Stratosphere)

- Chapman proposed that the ozone layer originates from the photolysis of atmospheric O_2
- The bond energy of the O_2 molecule corresponds to the energy of a 240 nm UV photon



The Chapman Mechanism
(Ozone Formation in the Atmosphere)

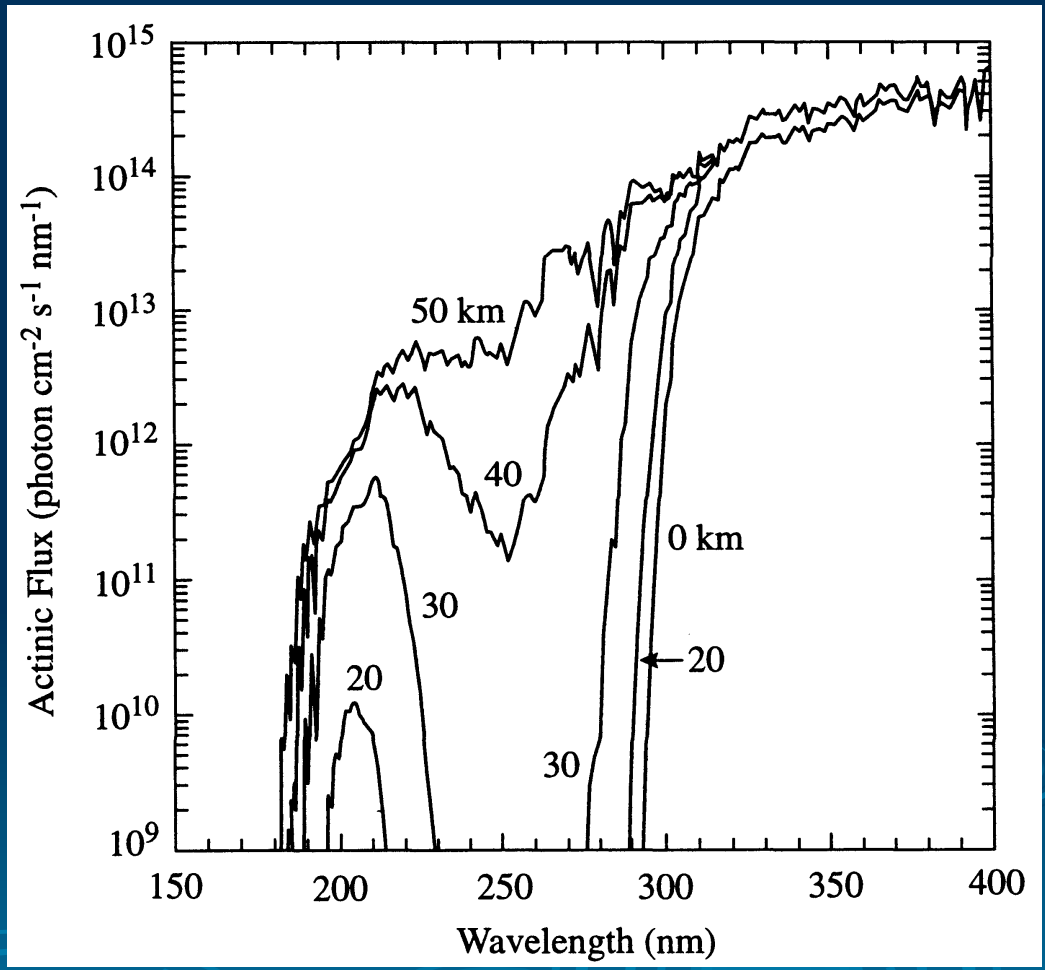
- Only photons of wavelengths less than 240 nm can photolyze the O_2 molecule
- Such high energy photons are present in the solar spectrum at high altitude



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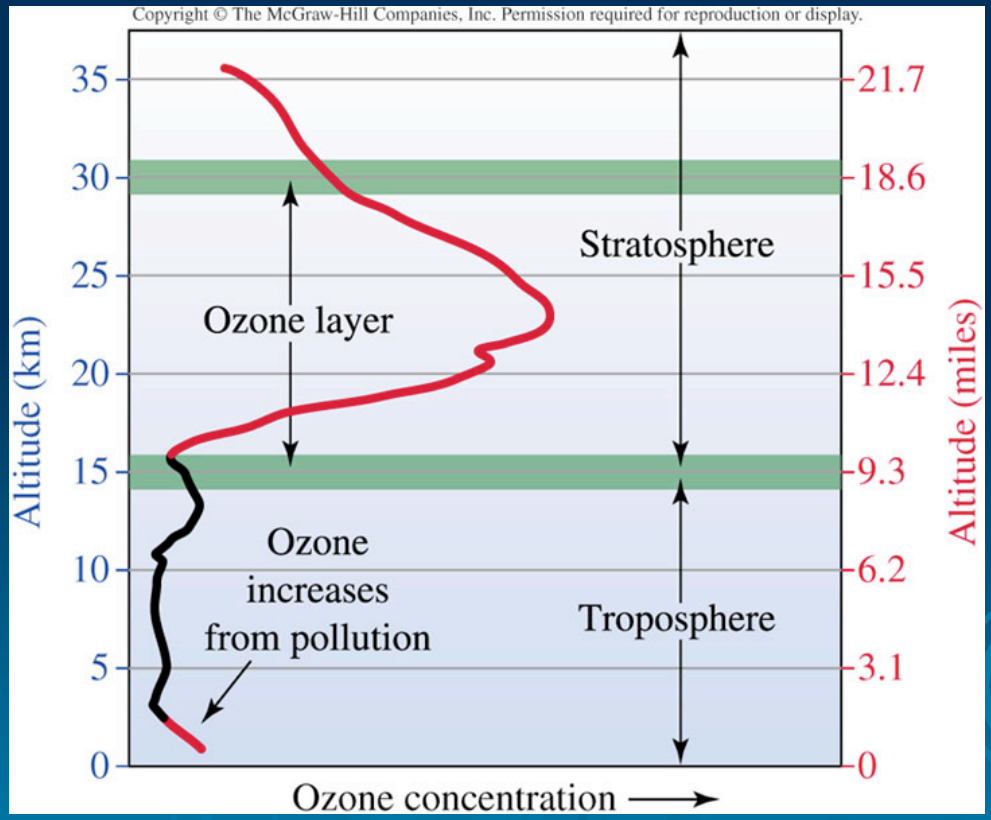
Attenuation of Solar Flux in the Stratosphere

- ✓ The presence of a high-altitude ozone layer in the atmosphere was first determined in the 1920s from observations of solar UV spectrum
- ✓ Ground-level sunlight is limited to wavelength above 290 nm
- ✓ Stratosphere filters out light between 180 and 290 nm
- ✓ 50 km-level light is limited to wavelength above 180 nm
- ✓ There is a "spectral window" centered at 205 nm where uv light penetrates more deeply into the stratosphere.

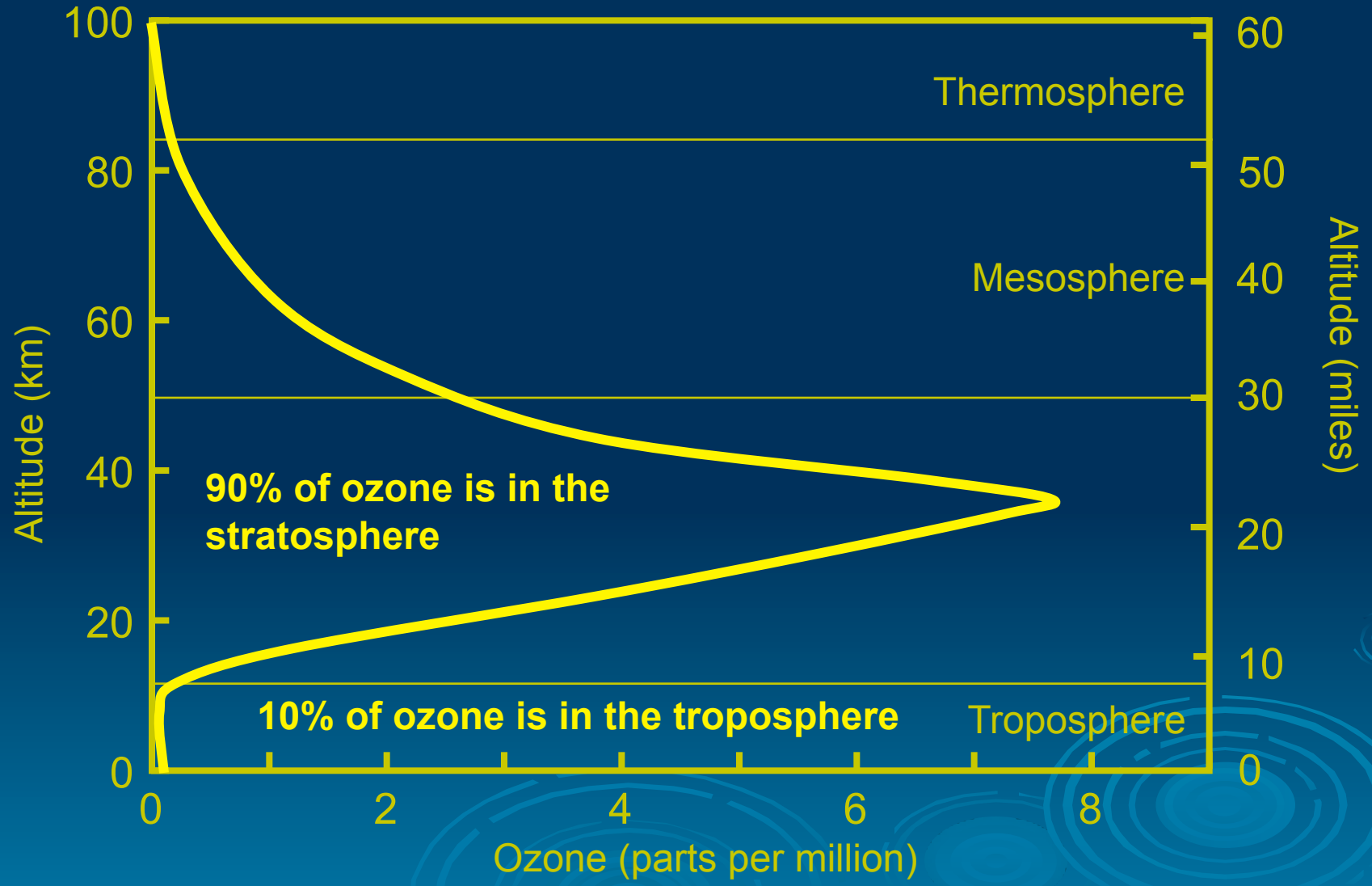


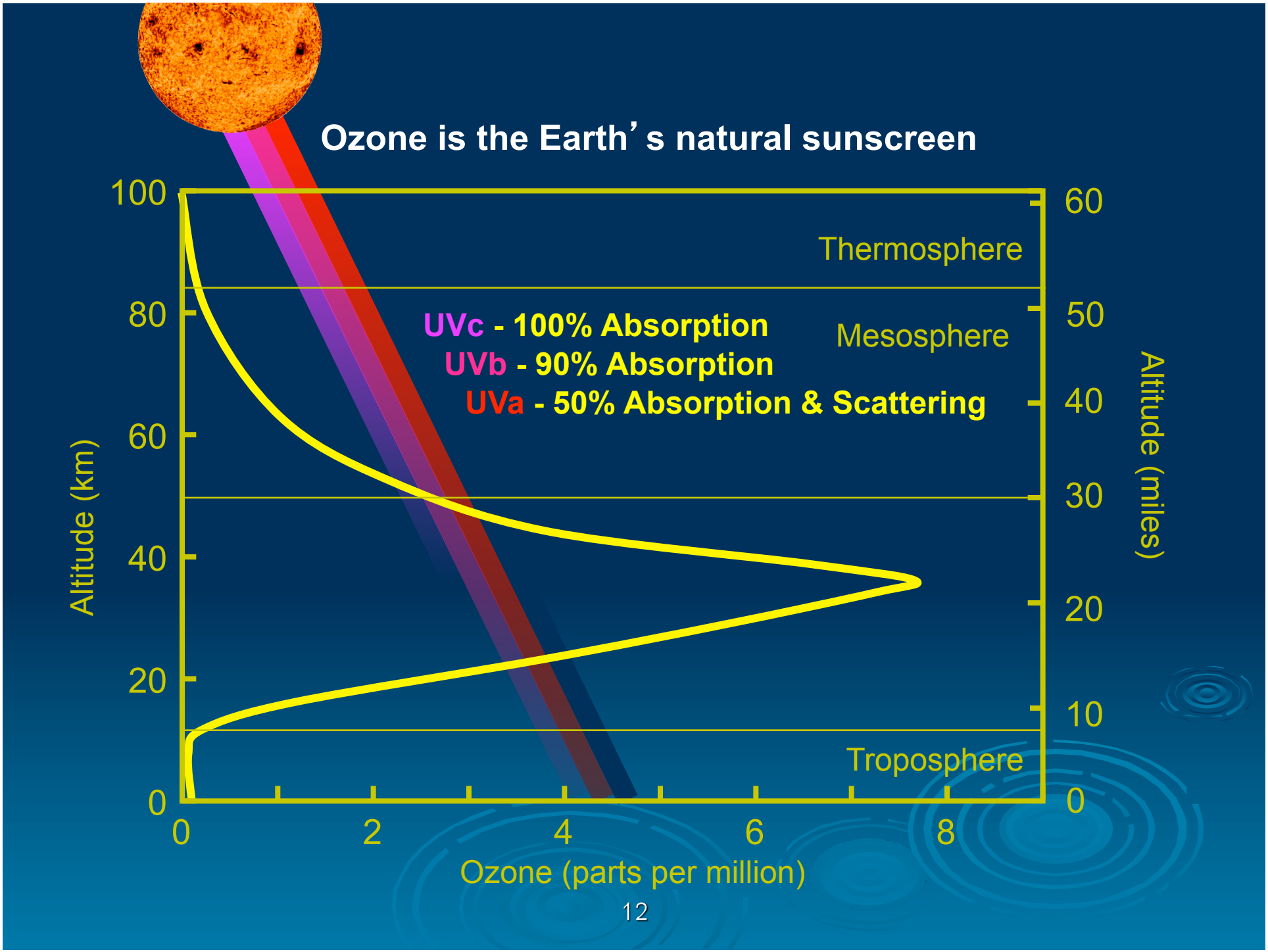
Ozone Distribution in the Atmosphere

- ✓ 16 – 35 km (above background level)
- ✓ Maximum concentration is at about 23 km (up to 10^{13} molecules/mL)
- ✓ Stratosphere contains about 90% of all atmospheric ozone
- ✓ Troposphere contains about 10% of all atmospheric ozone



Ozone Distribution in the Atmosphere

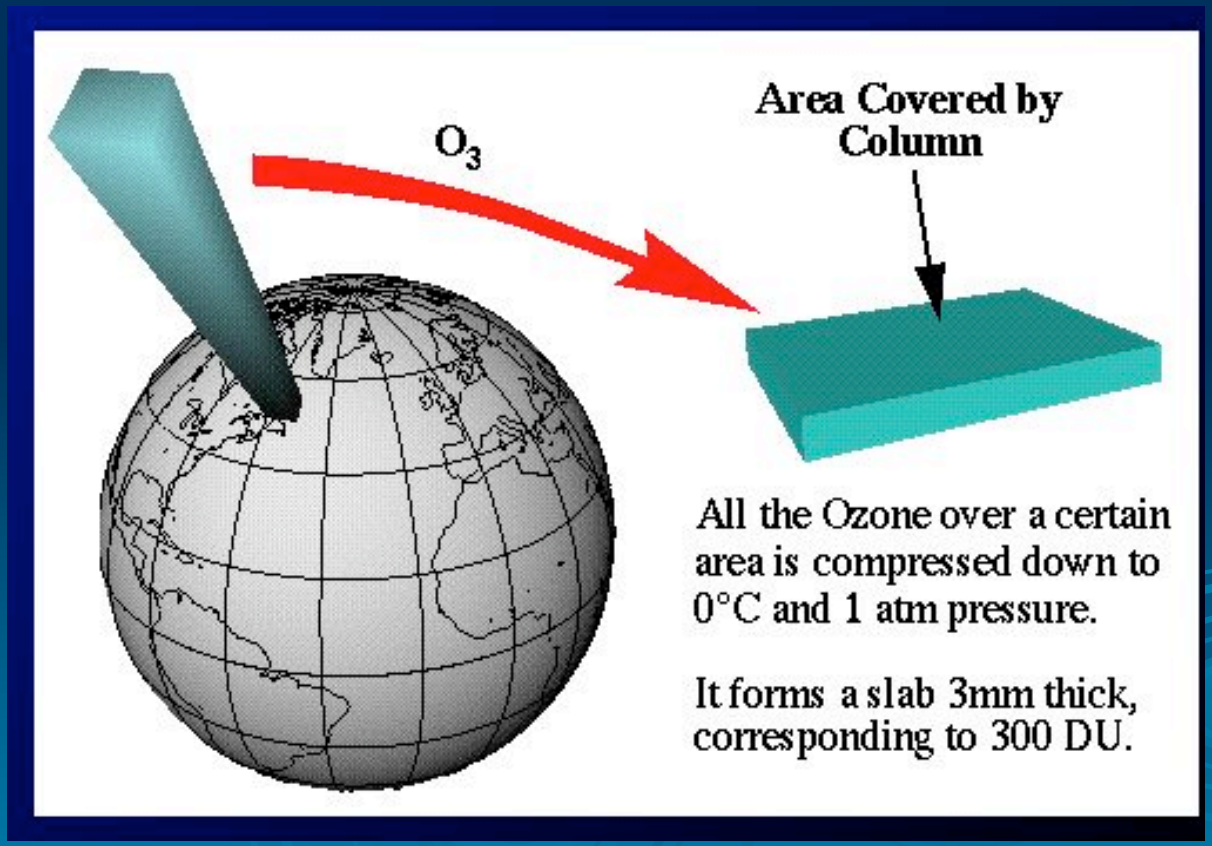



Ozone is the Earth's natural sunscreen
100
80
60
40
20
0
Altitude (km)
60
50
40
30
20
10
0
Altitude (miles)
Thermosphere
Mesosphere
Troposphere
UVc - 100% Absorption
UVb - 90% Absorption
UVa - 50% Absorption & Scattering
0
2
4
6
8
Ozone (parts per million)

	UVa	UVb	UVc
Wavelength (nm)	315-400	280-315	100-280
Absorption by ozone	It gets through the ozone layer	Mostly absorbed by the ozone layer	All absorbed by ozone
Amount reaching the Earth's surface	>98%	<2%	negligible

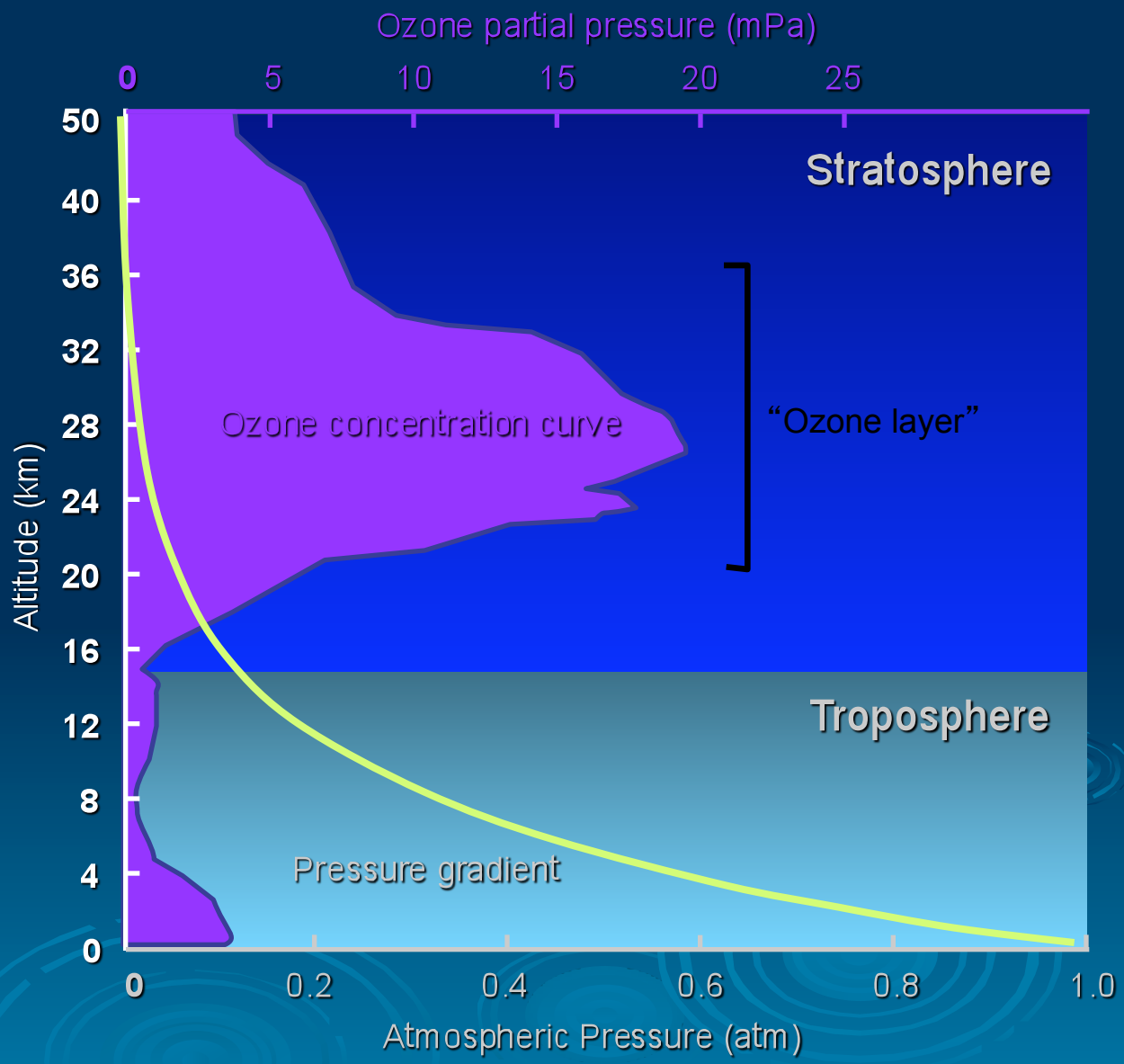
Ozone Distribution in the Atmosphere

- Conventionally, the relative abundance of ozone in the stratosphere is measured using “Dobson Unit” , DU
- Total column ozone: ~300 DU (1 DU = 3 mm thick layer at 1 atm)

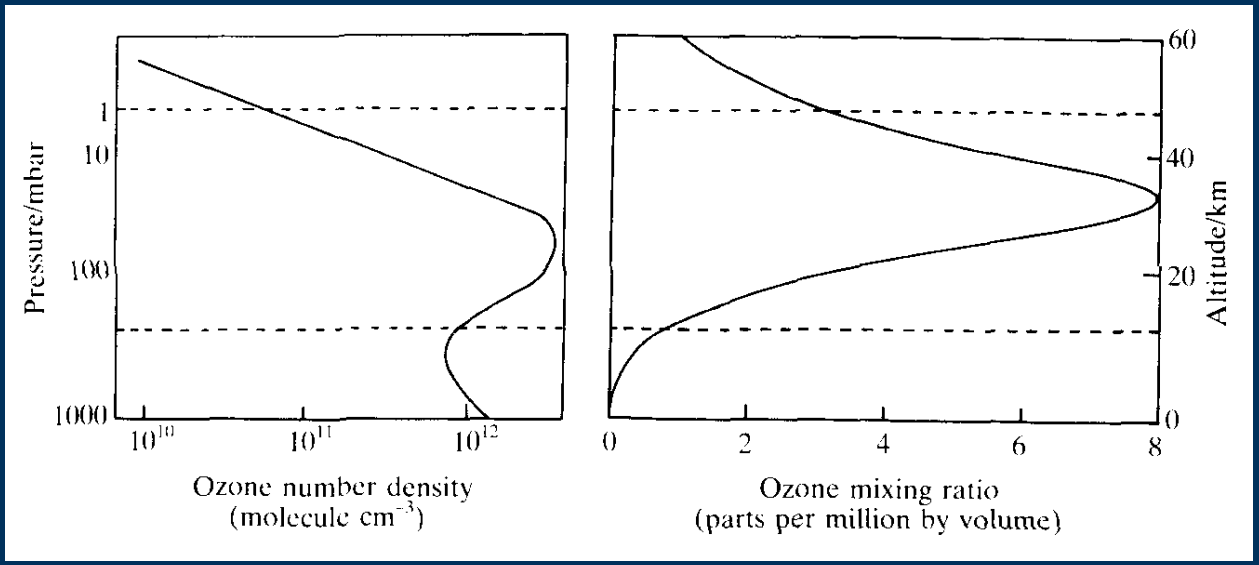


Ozone Distribution in the Atmosphere

- Total column ozone: ~300 DU (1 DU = 0.3 cm or 3 mm thick layer at 1 atm)
- Maximum of absolute conc about 23 km (up to 10^{13} molecules/mL)



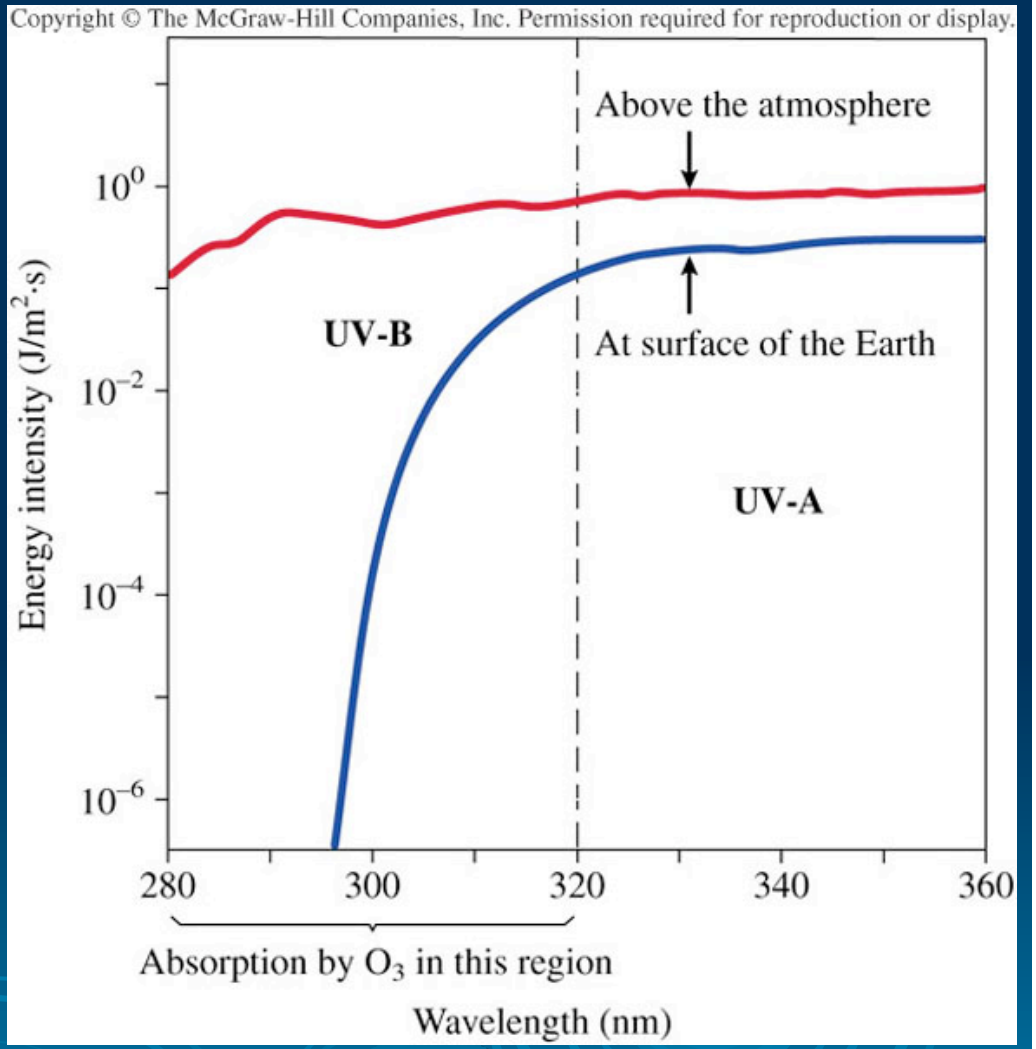
Structure of the Ozone Layer



- ✓ Observations:
  - ✓ O_3 is ***NOT*** the most concentrated gas in the ozone layer (not even close!)
  - ✓ maximum concentration is in the middle stratosphere.
- ✓ **Big question**: why does the ozone layer exist in the stratosphere? What processes are responsible for its formation and maintenance?

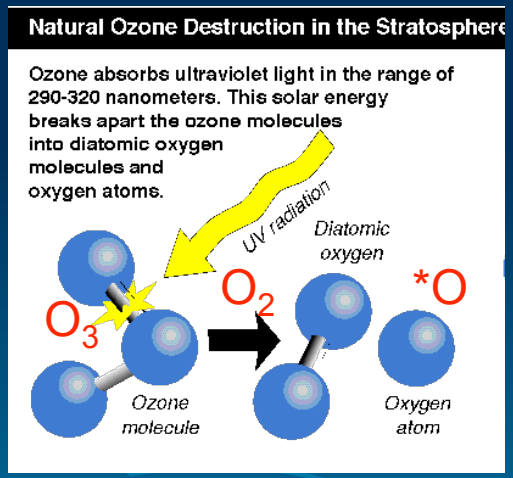
Ozone Layer: Function

- Question
  - What does the ozone layer do for us?
  - Ozone is the only major atmospheric constituent that absorbs significantly between 180 and 290 nm.
  - Without it life would have remained underwater
  - The ozone layer is a consequence of *oxygen-only chemistry*. It formed once photosynthetic marine organisms (cyanobacteria) began "polluting" the atmosphere with oxygen.



The Chapman Mechanism
(Ozone Destruction in the Stratosphere)

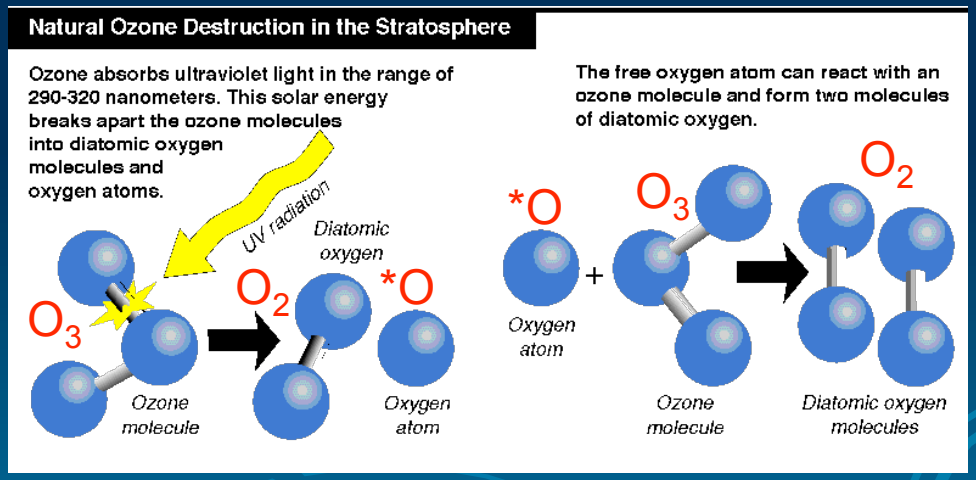
- UV radiation can also destroy ozone molecules…
- Ozone molecules go on to photolze
- The bonds in the O_3 molecule are weaker than those in the O_2 molecule
- Therefore, photolysis is achieved with lower-energy (i.e., <320 nm) photons



R3 $O_3 + UV \rightarrow O_2 + O \qquad \lambda < 320$

The Chapman Mechanism
(Ozone Destruction in the Stratosphere)

- Note that this is not a terminal sink for O_3 since the O atom product may recombine with O_2 to regenerate O_3
- For O_3 to actually be lost the O atom must undergo another reaction (R4)

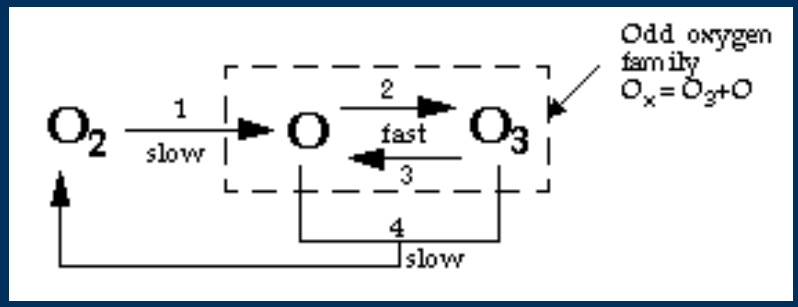


$$O_3 + UV \rightarrow O_2 + O \qquad \lambda < 320\,nm$$

R4 $$O + O_3 \rightarrow 2O_2$$

The Chapman Mechanism

- *The Chapman cycle*



  - Four chemical reactions (R)
  - *R1-Initiation (slow & rate constant)* $O_2 + UV \rightarrow 2O \quad (\lambda < 240\,nm)$
  - *R2-Formation (fast & generates heat)* $O + O_2 + M \rightarrow O_3 + M$
  - *R3-Deactivation (fast)* $O_3 + UV \rightarrow O_2 + O \quad \lambda < 320\,nm$

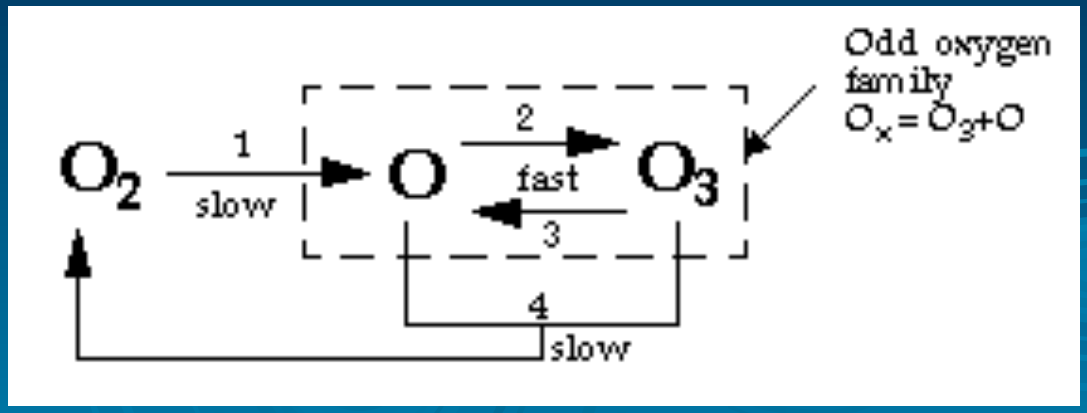
Rapid cycle between O & O_3

Slower cycle between O_2 and (O & O_3)

  - *R4-Termination (slow & rate constant)* $O + O_3 \rightarrow 2O_2$

The Chapman Mechanism

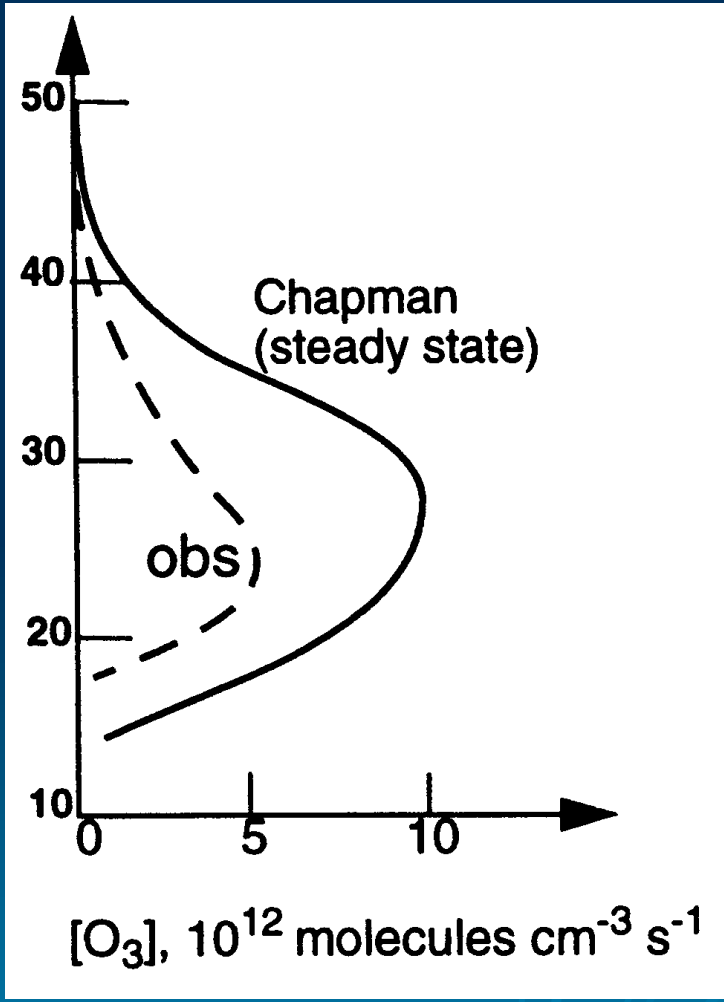
- *The Chapman cycle*
  - Oxygen atom O is unstable and shortest lived
  - Oxygen molecule O_2 is stable
  - O_3 is unstable
  - The concentration of O_3 is controlled by slower R1 & R4 rather than by fast R2 & R3
  - The effective lifetime of O_3 against chemical loss is defined by the O_x (odd oxygen family)



Evaluation of Chapman's Model

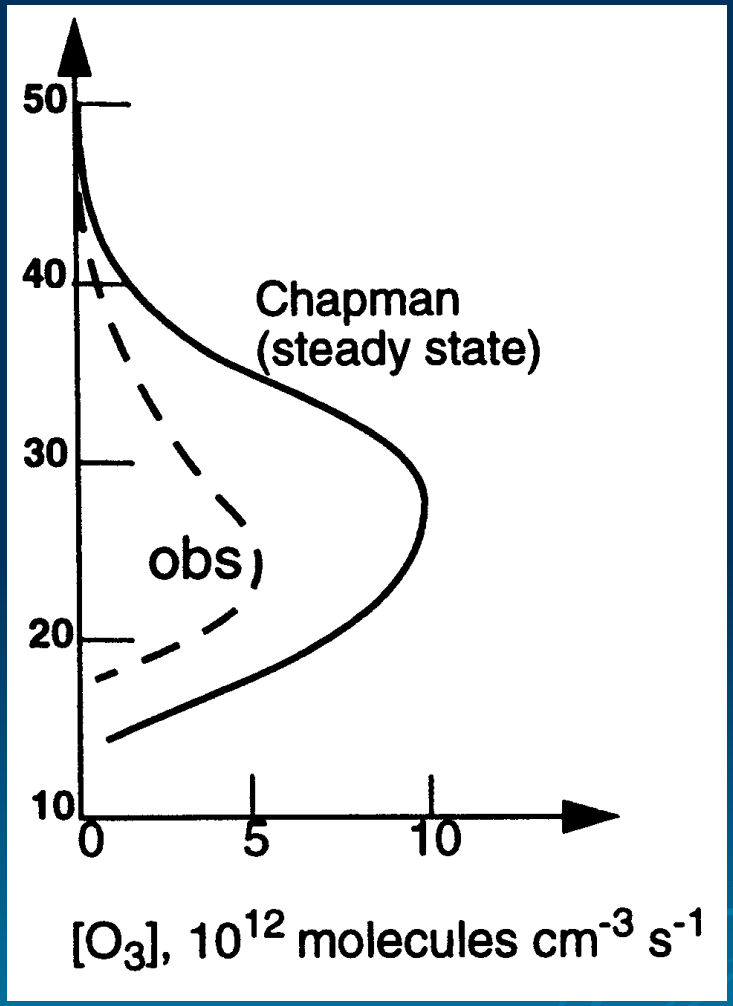
- How to evaluate Chapman's Theory?
- Qualitative agreement:
  - Predicts stratosphere as a source of ozone
  - Predicts thermal inversion in the stratosphere
- Quantitative agreement?
  - Check by comparing measured ozone levels with those predicted by Chapman's model

Evaluation of Chapman's Model



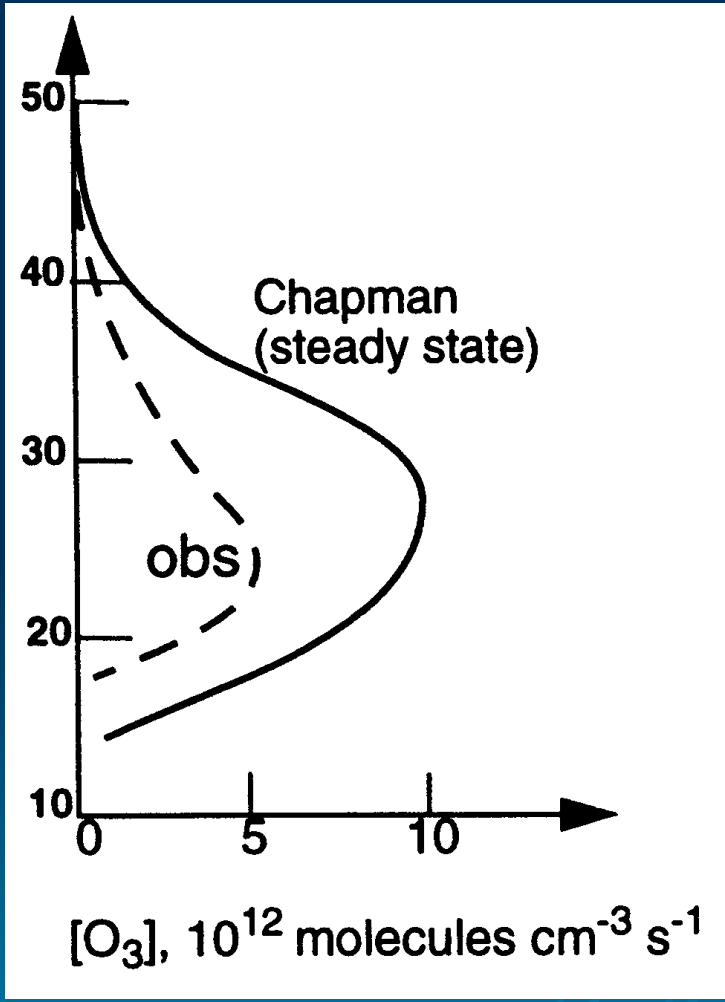
- ✓ Chemists looked at the Chapman's processes
- ✓ Qualitative agreement: presence of an ozone layer at the right height; predicts thermal inversion. But it predicts O_3 much higher (by a factor of 2 or more) than what is actually observed..
- ✓ This was not evident until the 1950s
- ✓ What is wrong?

Evaluation of Chapman's Model



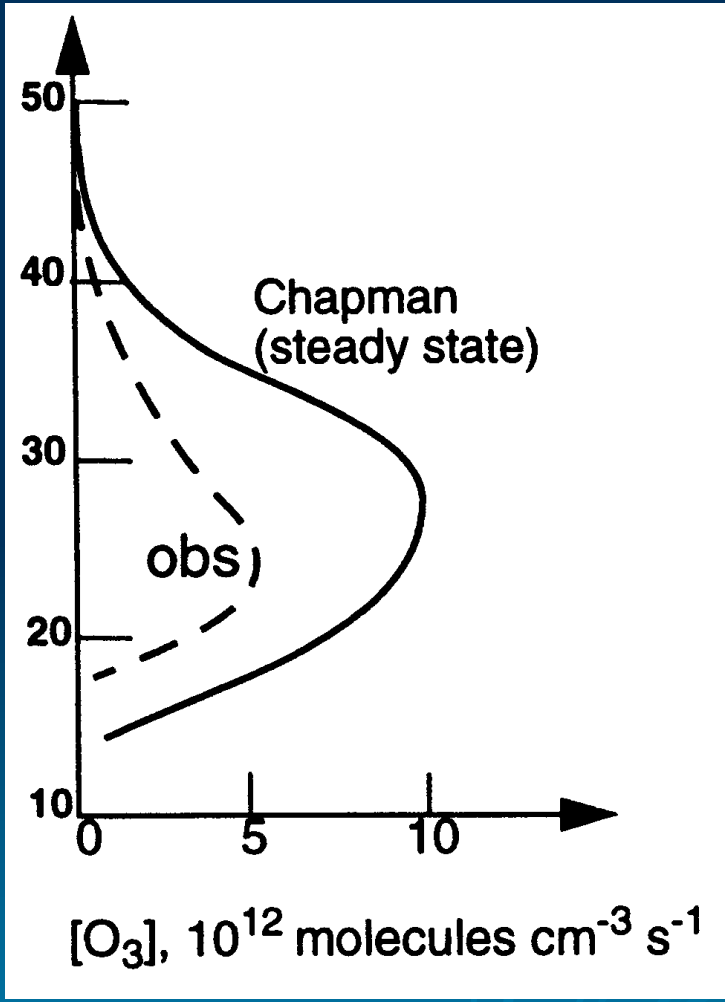
- Why does the maximum of O_3 occur at 20-30 km?
  - Production of O_3 depends on the UV light intensity and the amount of O_2 molecules
  - Above the stratosphere there is plenty of uv light but fewer O_2 molecules (air is thinner)
  - While below the stratosphere there is plenty of O_2 molecules but not much uv light
  - Thus it makes sense (qualitatively) that ozone is created in the stratosphere

Evaluation of Chapman's Model



- According to Chapman, main source of heat is the association reaction between atomic O and O_2.
- The rate of this reaction is proportional to the product of O and O_2 concentrations, which is at a maximum at the top of the stratosphere.

Problem with Chapman's Model



- Suggests that there is another O_3 destruction process at work…
  - Either there is an extra ***source*** of O_x or
  - There are other ***sinks***: pathways that destroy ozone

Missing Element
Catalytic O_3 Destruction!

- O_3 is **unstable**, but **degrades slowly** on its own
- **CATALYSTS** can greatly accelerate the process
  - *Catalyst* = chemical species that *helps a reaction* along, but is *not used up* in the reaction
  - "*chain carrier* X", X is the "*divorce lawyer*"

$$X + O_3 + UV \rightarrow XO + O_2$$
$$XO + O \rightarrow X + O_2$$

$$Net\ effect \rightarrow O_3 + UV \rightarrow O + O_2$$

  - One molecule of X will continue to act as a catalyst in this reaction again and again, destroying O_3 molecules until X itself is removed or destroyed
  - **X is a missing element!**
  - **WHAT IS X?**

Missing Element
Catalytic O_3 Destruction!

- Four main "families" of chemicals responsible for catalyzing ozone destruction:
  - Hydrogen Oxides: HO_x
    $OH + HO_2$
  - Nitrogen Oxides: NO_x
    $NO + NO_2$
  - Chlorine: ClO_x
    $Cl + ClO$
  - Bromine: BrO_x
    $Br + BrO$

So X = NO, OH, Cl or Br

Sources of Catalysts

- Stratospheric HO_x
  - Source: tropospheric CH_4, H_2, H_2O
  - Much is natural, however…
  - 150% increase in tropospheric CH_4 since 1850 (agricultural activities; landfills; other sources)
- Stratospheric NO_x
  - Source: tropospheric N_2O
  - Natural sources (mostly)
  - 10% increase since 1850 (ie, due to anthropogenic activities…mostly fertilizer application)
- Stratospheric Cl and Br
  - Almost entirely due to human activity
  - Sources: tropospheric CFCs, HCFCs

Catalytic Loss Cycles

- **Hydrogen Oxide Radicals (HOx)**
  - Water vapor mixing ratios in the stratosphere are relatively uniform, in the range of 3-5 ppm
  - In the stratosphere, water vapor is oxidized by **O**

R5 $H_2O + O \rightarrow 2OH$ Initiation step

  - OH can react with O3

R6 $OH + O_3 \rightarrow HO_2 + O_2$

R7 $HO_2 + O_3 \rightarrow OH + 2O_2$

Propagation steps

$Net \quad 2O_3 \rightarrow 3O_2$

  - Here the ensemble of **OH** and **HO_2** are referred as the **HOx** chemical family

Catalytic Loss Cycles

- **Hydrogen Oxide Radicals (HOx)**
  - The sequence of reactions consumes **O_3** while conserving **HOx**
  - Termination of the catalytic cycle requires loss of HOx by a reaction

R8 $OH + HO_2 \rightarrow H_2O + O_2$ Termination step

  - The HOx-catalyzed mechanism represents the dominant sink of **O_3** in the lowest part of the stratosphere
  - Responsible for up to **1/2** of all **O_3** destruction in lower stratosphere
  - So, the HOx-catalyzed mechanism is a significant **O_3** sink, but not sufficient to reconcile the chemical budget of **O_3**

Catalytic Loss Cycles

- **Nitrogen Oxide Radicals (NO_x)**
  - The next breakthrough in our understanding of stratospheric **O_3** came about in the late 1960s when the US and other countries considered the laugh of a supersonic aircraft fleet flying in the stratosphere
  - Scientists called to assess the effects of such a fleet on the **O_3** layer
  - An important component of aircraft exhaust is nitric oxide (**NO**)
  - In the stratosphere NO reacts rapidly with **O_3** to produce **NO_2**, which then photolyzes

R9 $NO + O_3 \rightarrow NO_2 + O_2$

R10 $NO_2 + UV \rightarrow NO + O$

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

Catalytic Loss Cycles

- **Nitrogen Oxide Radicals (NO_x)**
  - This cycling between NO and NO_2 takes place on a time scale of about one minute during daytime
  - It has no effect on **O_3** (a null cycle!)
  - It causes, however, rapid exchange between NO and NO_2
  - We refer NO and NO_2 as a new chemical family NOx
  - Further investigation of NOx shows that a fraction of the NO_2 reacts with oxygen

R11 $$NO_2 + O \rightarrow NO + O_2$$

Catalytic Loss Cycles

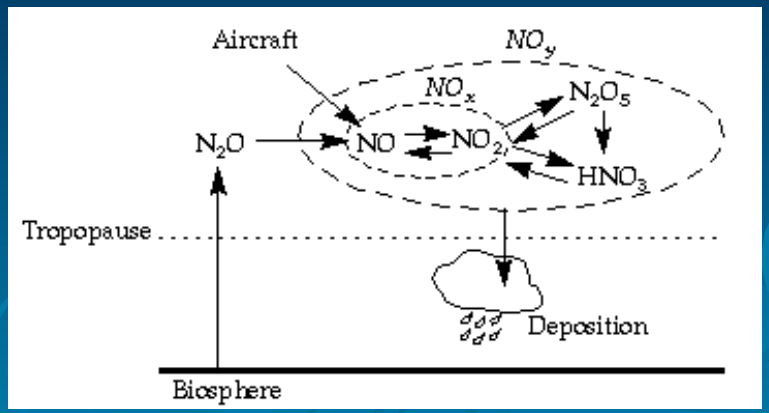
- **Nitrogen Oxide Radicals (No_x)**
  - The sequence of reactions R9 and R11 represents a catalytic cycle for **O_3** with a net effect identical to R4

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$

$$Net \quad O_3 + O \rightarrow 2O_2$$

Catalytic Loss Cycles

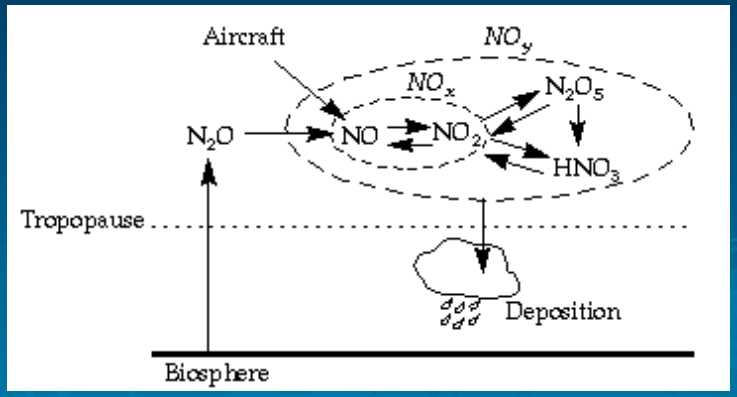
- **Nitrogen Oxide Radicals (NO_x)**
  - In addition, NO_2 reactions with other X molecules (OH, Cl), can store them and then release them later
  - Complex results
    - Above 25 km NO accounts for >50% of O_3 destruction
    - Below 25 km NO net effect is to slow O_3 destruction
  - This means an aircraft fleet in the stratosphere would represent a serious threat to the O3 layer
  - This led to scrapping of the supersonic aircraft plan in the US (the Europeans still built the Concorde)



Catalytic Loss Cycles

- **Nitrogen Oxide Radicals (NO_x)**
  - Further work in the early 1970s showed that N_2O (a low-yield product of nitrification and denitrification processes in the biosphere) provides such a source for NOx
  - N_2O is very stable molecule which has no significant sinks in the troposphere
  - It is therefore transported to the stratosphere where it encounters high concentrations of O

$$N_2O + O \rightarrow 2NO$$



Catalytic Loss Cycles

- **Nitrogen Oxide Radicals (NO_x)**
  - Ice core data show that atmospheric concentrations of N_2O have risen from 285 ppbv in the 18th century to 310 ppbv today
  - Present day observations indicate a growth rate of 0.3% per year
  - There is much interest in understanding this rise because of the importance of N_2O not only as a sink for stratospheric O_3 but also as a greenhouse gas

Catalytic Loss Cycles

- **Global budget of N2O**
  - Biogenic sources in the tropical continents cultivated areas, and oceans provide the dominant sources of N_2O
  - This increase of N_2O over the past century is thought to be due principally to increasing use of fertilizer for agriculture

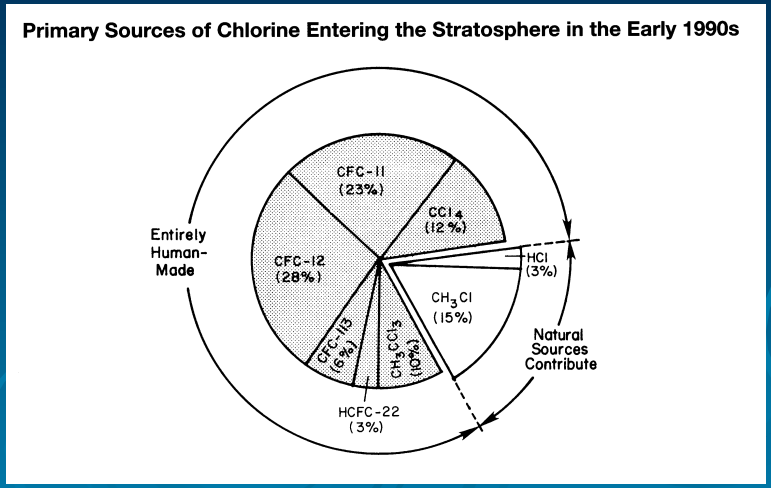
	Rate (Tg N yr-1) best estimate and range of uncertainty
NATURAL SOURCES	9 (6-12)
Oceans	3 (1-5)
Tropical soils	4 (3-6)
Temperature soils	2 (0.6-4)
ANTHROPOGENIC SOURCES	6 (4-8)
Cultivated soils	4 (2-5)
Biomass burning	0.5 (0.2-1.0)
Chemical industry	1.3 (0.7-1.8)
Livestock	0.4 (0.2-0.5)
SINK	12 (9-16)
ATMOSPHERIC INCERASE	3

Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - In 1974, Mario Molina and Sherwood Rowland pointed out the potential for O_3 loss associated with rising atmospheric concentrations of chlorofluorocarbons (CFCs)
  - CFCs are not found in the nature
  - They were first manufactured for industrial purposes in the 1930s and their use increased rapidly
  - During 1970s and 1980s, CFCs concentration rose by 2-4% per year
  - CFC molecules are inert in the troposphere, they are therefore transported to the stratosphere, where they photolyze to release Cl atoms

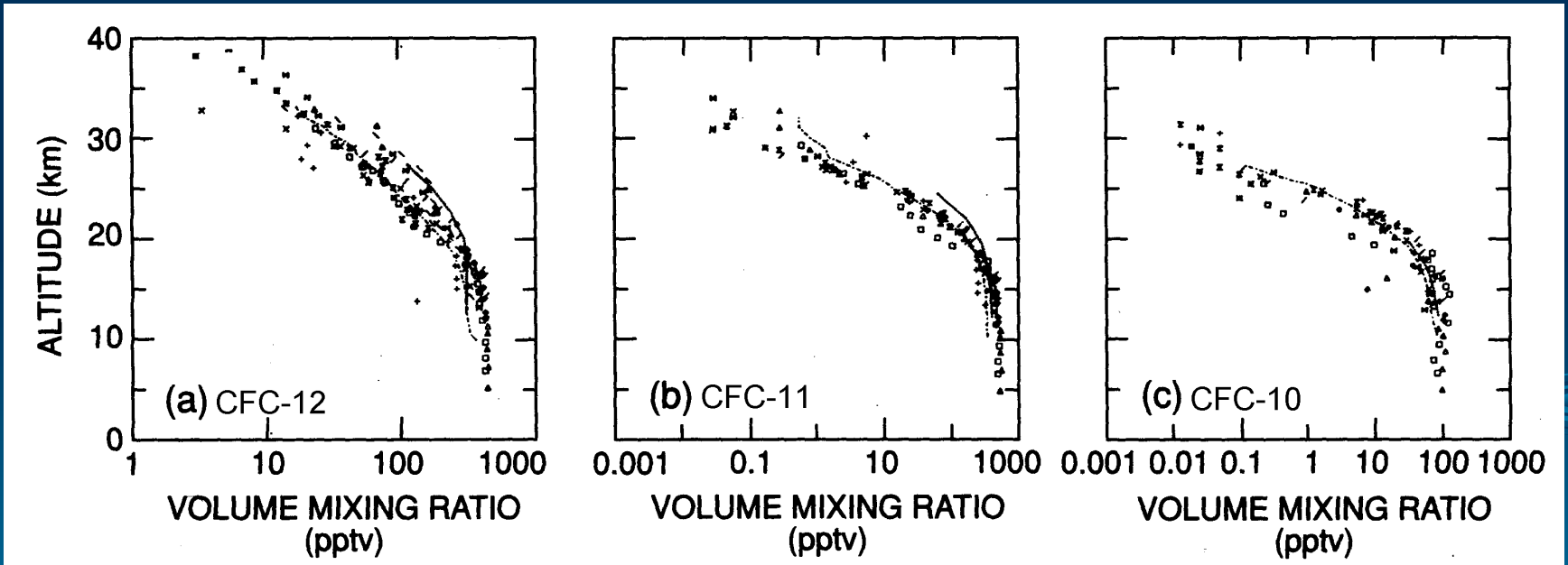
Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - CFCs were manufactured by DuPont for use as refrigerents. Hailed as the perfect chemical due to their nontoxic and unreactive nature, they were also used widely as solvents and as blowing agents
  - CFCs are small molecules that contain chlorine, fluorine and carbon atoms (usually 1-2 carbon atoms)
  - CFCs are sometimes called ***Freons*** (that was their trade name for DuPont)
  - CFCs are referred to by a number
  - The most common CFCs are: CFC-11, CFC-12, CFC-113



Catalytic Loss Cycles

✓ Vertical concentration profiles of “hard CFCs” consistent with long tropospheric lifetimes (long enough to be completely mixed) followed by destruction in the stratosphere by UV lights.



Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - For example, in the case of CF_2Cl_2 (known by the trade name CFC-12)

$$CF_2CI_2 + UV \rightarrow CF_2CI + CI$$

  - Cl atoms then trigger a catalytic loss mechanism for O_3, similar to NOx catalyzed mechanism

$$CI + O_3 \rightarrow CIO + O_2$$
$$CIO + O \rightarrow CI + O_2$$

$$net \quad O_3 + O \rightarrow 2O_2$$

Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - The catalytic cycle is terminated by conversion of ClOx to non-radical reservoirs, HCl and $ClNO_3$

$$Cl + CH_4 \rightarrow HCl + CH_3$$
$$ClO + NO_2 + M \rightarrow ClNO_3 + M$$

  - The lifetime of HCl is typically a few weeks and the lifetime of $ClNO_3$ is of the order of a day
  - Eventually these reservoirs return ClOx

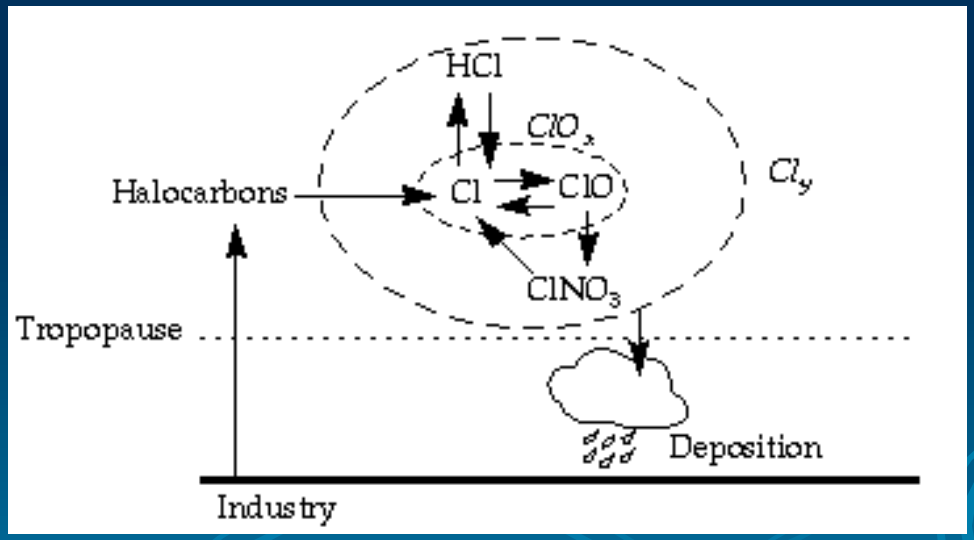
$$HCl + OH \rightarrow Cl + H_2O$$
$$ClNO_3 + UV \rightarrow Cl + NO_3$$

Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - *Very efficient carrier molecules* -- primary cause of ozone depletion in the stratosphere
  - *Naturally low abundance*
  - *Anthropogenic Source*: *production of CFCs* (hydrocarbons having at least one hydrogen replaced by a halogen)
  - *Uses*: refrigerants, aerosol spray propellant, solvents, fire retardants

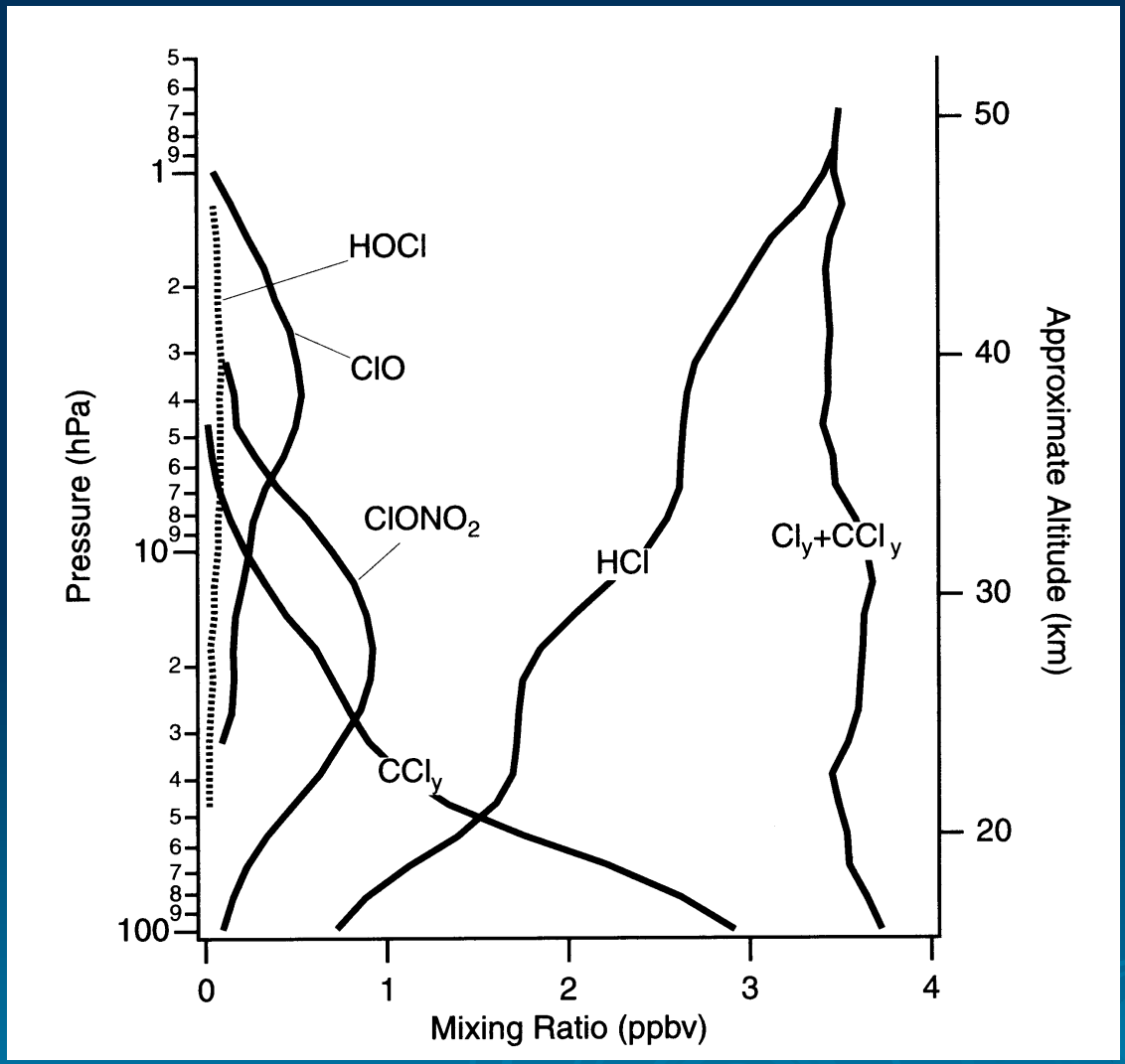
Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - Similarly to the NOx-catalyzed mechanism, the rate of O_3 loss by the ClOx-catalyzed mechanism can be calculated from knowledge of the concentrations of CFCs and other halocarbons, the residence time , and ClOx/Cly chemical partitioning



Catalytic Loss Cycles

Main chlorine species is HCl



- "CCl_y" refers to CFCs and other tropospheric sources of Cl
- Cl_y refers to the statospheric chlorine "family" of active and reservoir species

Catalytic Loss Cycles

- **Chlorine (Cl) Radicals**
  - *Nontoxic and nonreactive*: not destroyed in troposphere, rise to stratosphere & broken apart by photons:

R-Cl + UV photon = R + Cl

$$Cl + O_3 \rightarrow ClO + O_2$$
$$ClO + O \rightarrow Cl + O_2$$
$$net \quad O_3 + O \rightarrow 2O_2$$

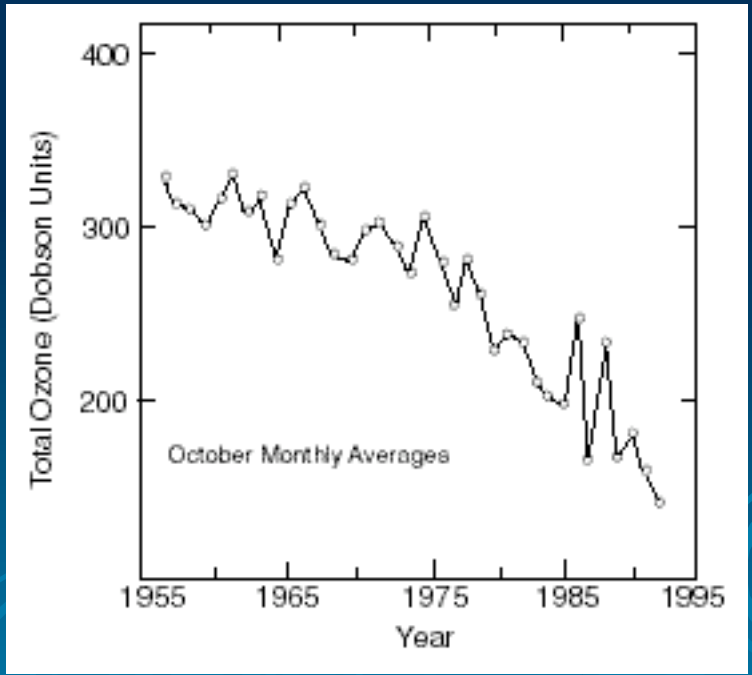
  - *Eventually* (long residence time in stratosphere!) *destroyed* e.g. by methane molecules:

$$Cl + CH_4 = HCl + CH_3$$

  - *Now largely banned* by Montreal Protocol (1987) and amendments, but *CFC catalyzed O_3 destruction will continue for decades*

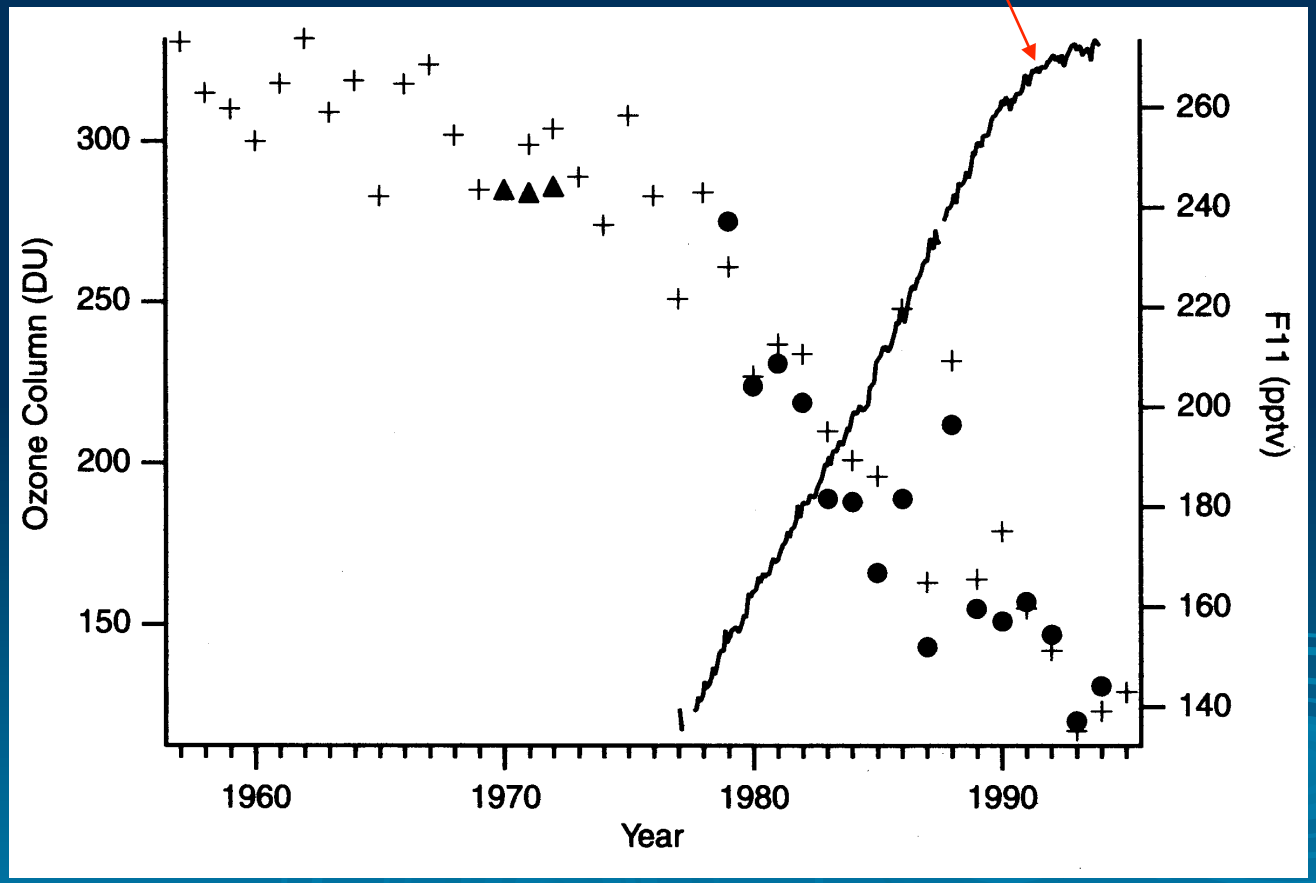
Catalytic Loss Cycles

- **POLAR OZONE LOSS**
  - In 1985, a team of scientist reported that springtime stratospheric O3 columns over their station at Halley Bay had decreased significantly
  - Depletion was confined to the spring months (Sep-Nov)



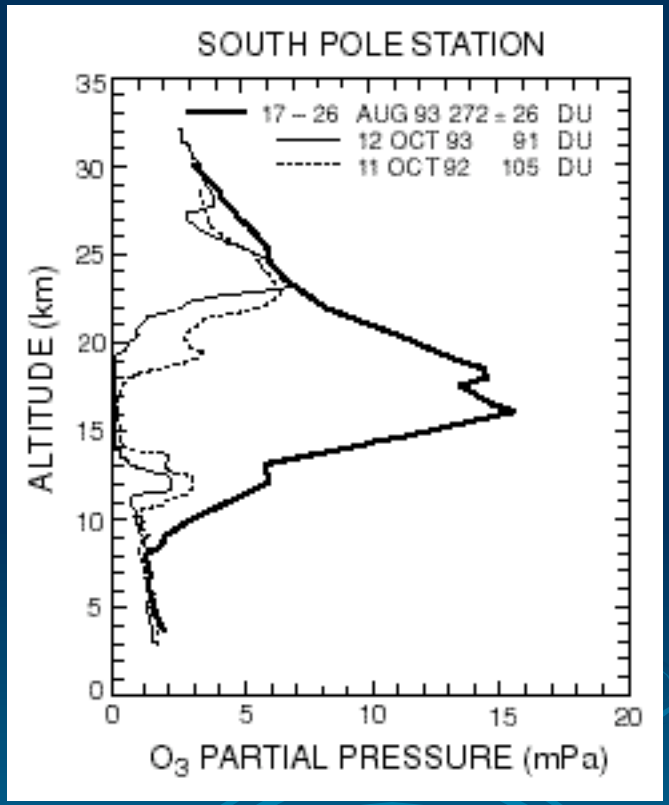
Detection of the Antarctic Ozone Hole

Crosses are BAS measurements; triangles and circles are NASA satellite measurements. Measurements are October averages.

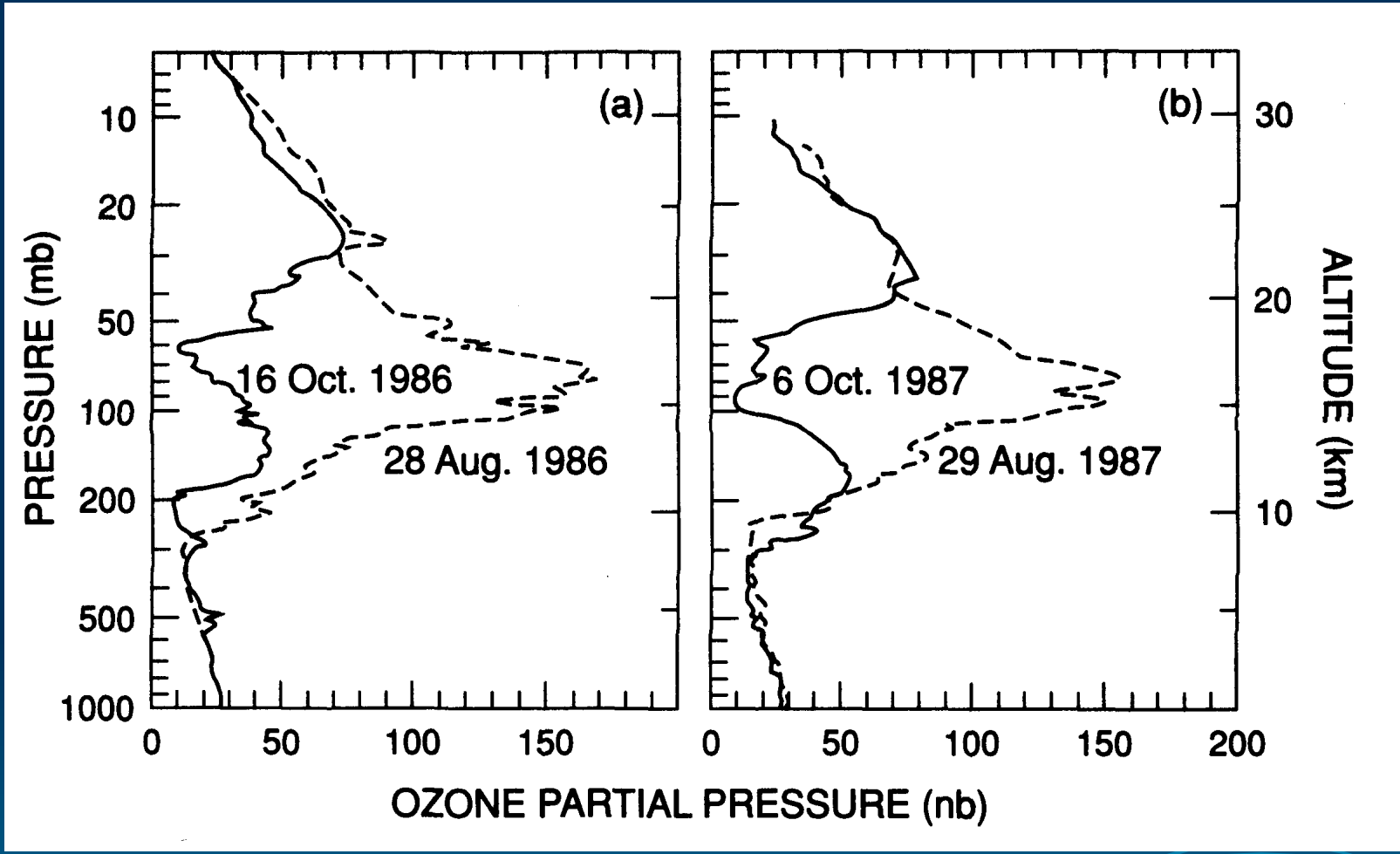


Catalytic Loss Cycles

- **POLAR OZONE LOSS**
  - Global satellite data confirmed the Halley Bay observations and showed that the depletion of stratospheric ozone extended over the totality of antarctic vortex in particularly at south pole
  - The depletion of O3 has worsened since 1985 and springtime O3 columns over Antarctica today are less than half of what they were in the 1960s
  - The depletion is in the region of 10-20 km

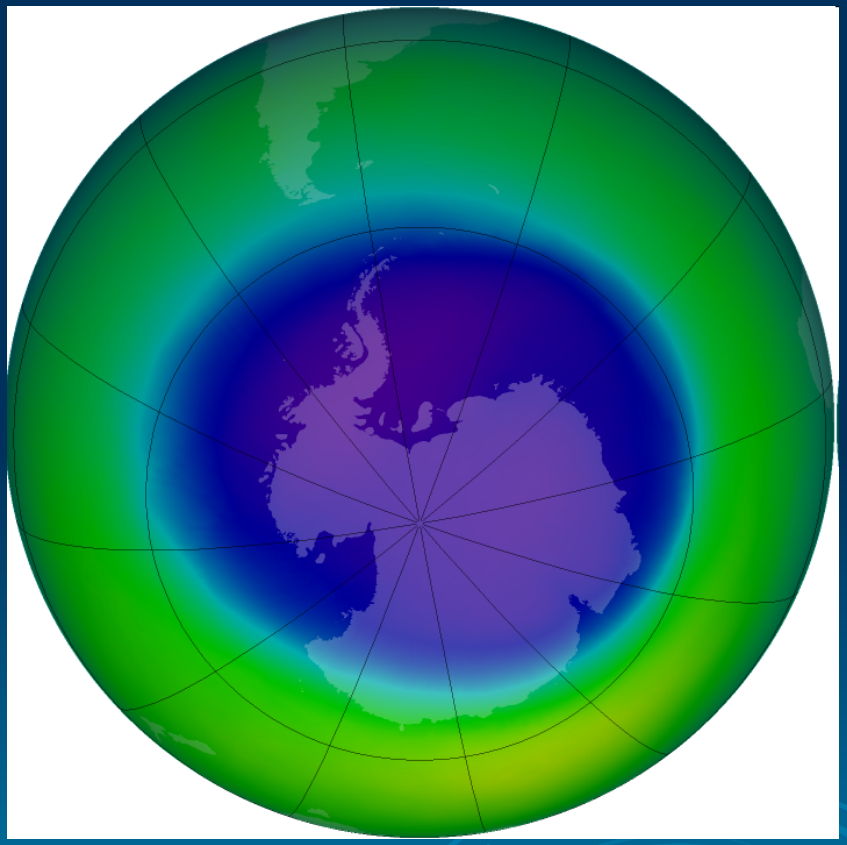


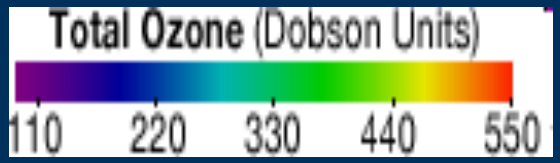
Concentration Profile during Ozone Hole



The "ozone hole" is a sudden, marked depletion of ozone – a loss of 50% or more of total column ozone – in the lower stratosphere of the Antarctic in the weeks after the Spring sunrise. In 1985 the area of the hole was 10 million sq. km (and growing yearly).

The "Ozone Hole"



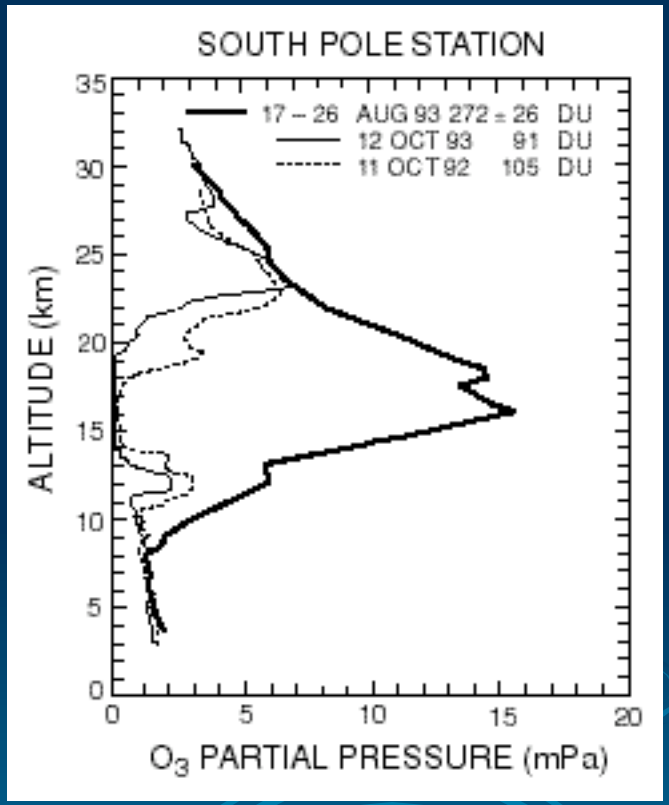


The ozone hole is the region over Antarctica with total ozone 220 Dobson Units or lower. (The avg total column ozone in the atmosphere is about 300 DU.)

Ozone hole in Sept 2005. Source: NASA

Catalytic Loss Cycles

- **POLAR OZONE LOSS**
  - Discovery of this “antarctic ozone hole” was a shock to atmospheric chemists
  - The Chapman mechanism and the Catalytic loss cycles could not explain the O3 depletion observed over Antarctica
  - Under the low light conditions in that region, concentrations of O atoms are very low, so that all chemical reactions discussed so far fails
  - SO WHAT WAS MISSING?



Catalytic Loss Cycles

- **Bromine (Br) Radicals**
  - Several aircraft missions were conducted in the late 1980s to understand the causes of antarctic ozone depletion
  - These studies found the depletion of O3 to be associated with exceptionally high ClO
  - Laboratory experiments showed that at such high ClO concentrations, a new catalytic cycle involving self-reaction of ClO could account fore most of the observed O3 depletion
  - This involves Br radicals

Catalytic Loss Cycles

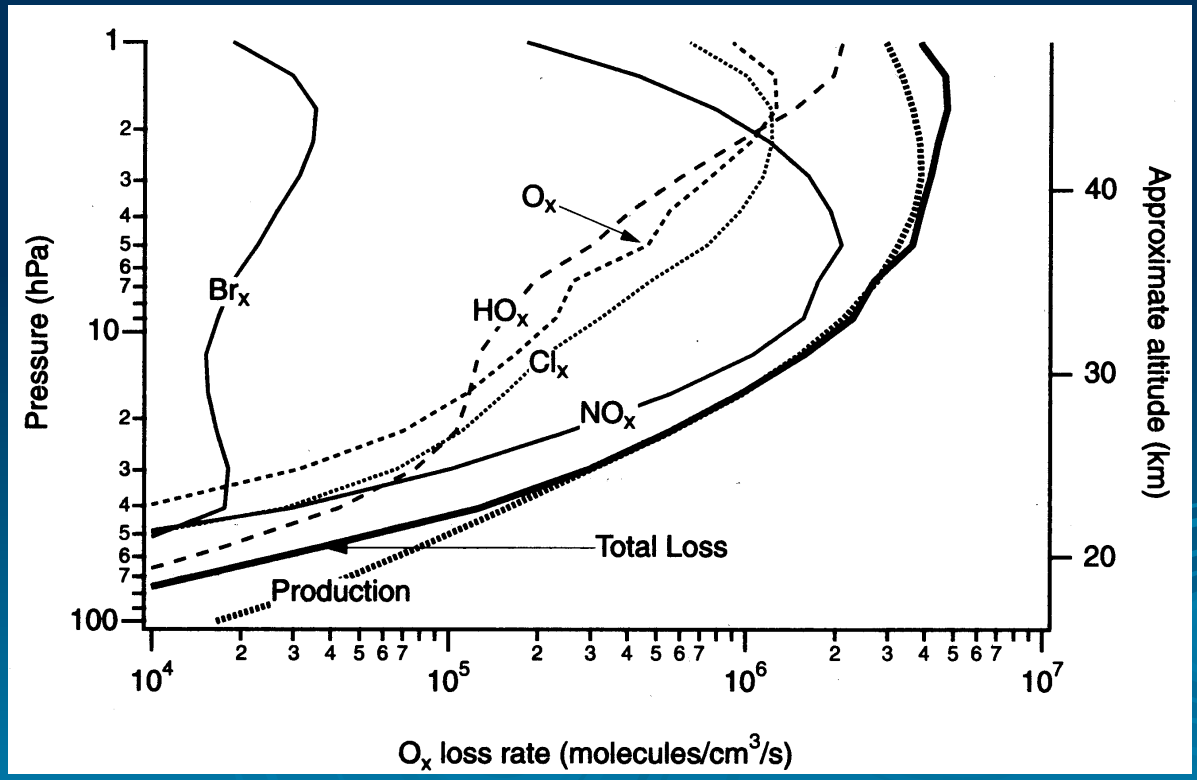
- **Bromine (Br) Radicals**
  - Br radicals produced in the stratospshere by photolysis and oxidation of anthropogenic Br-containing gases

$$CI + O_3 \rightarrow CIO + O_2$$
$$Br + O_3 \rightarrow BrO + O_2$$
$$BrO + CIO \rightarrow Br + CI + O_2$$

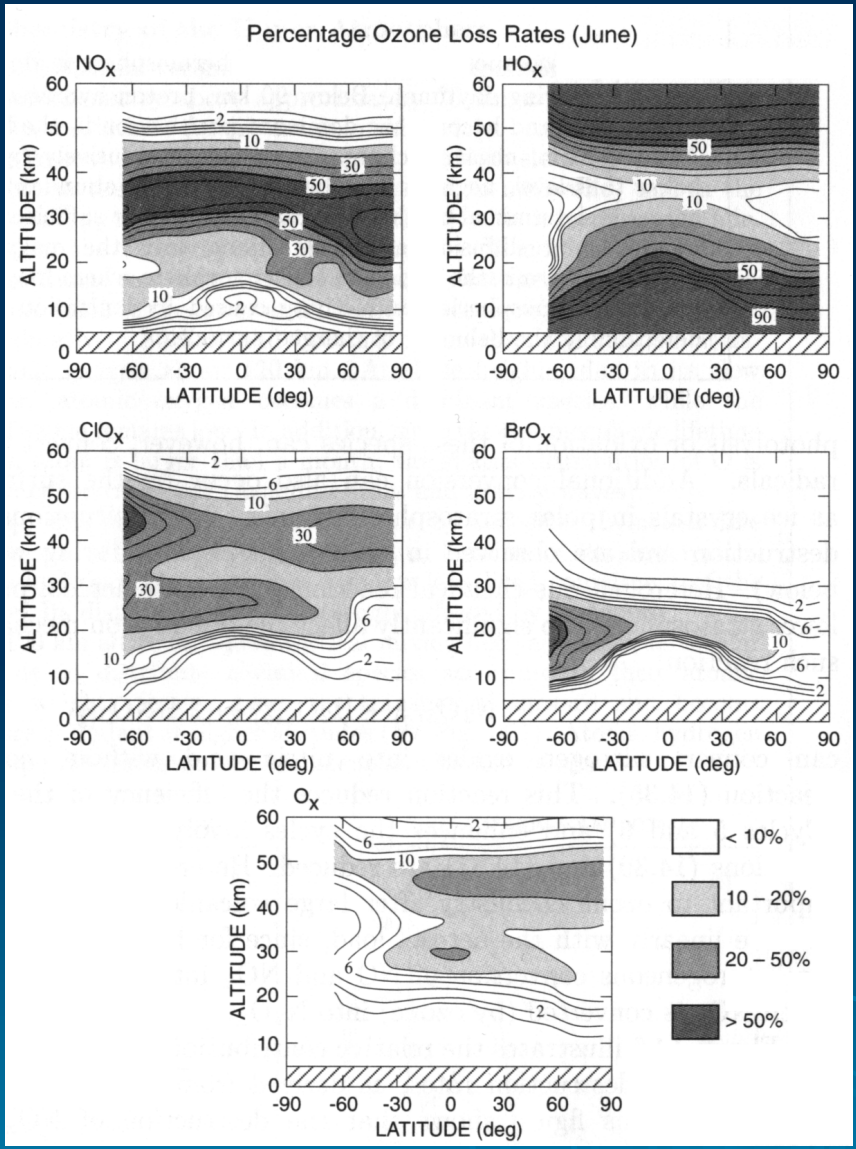
  - This catalytic cycle is made significant by the high concentrations of ClO over Antarctica
  - 70% of total O3 loss in the antarctic ozone hole is from ClO+ClO mechanism
  - 30% of total O3 loss in the antarctic ozone hole is from BrO+ClO mechanism

Relative Contributions to Ozone Loss

- **All Radicals**
  - Very approximate: 60% loss due to NOx, 20% due to Chapman ($O + O_3$), 20% due to all others.
  - NOx is the most important except for very high and very low in the stratosphere

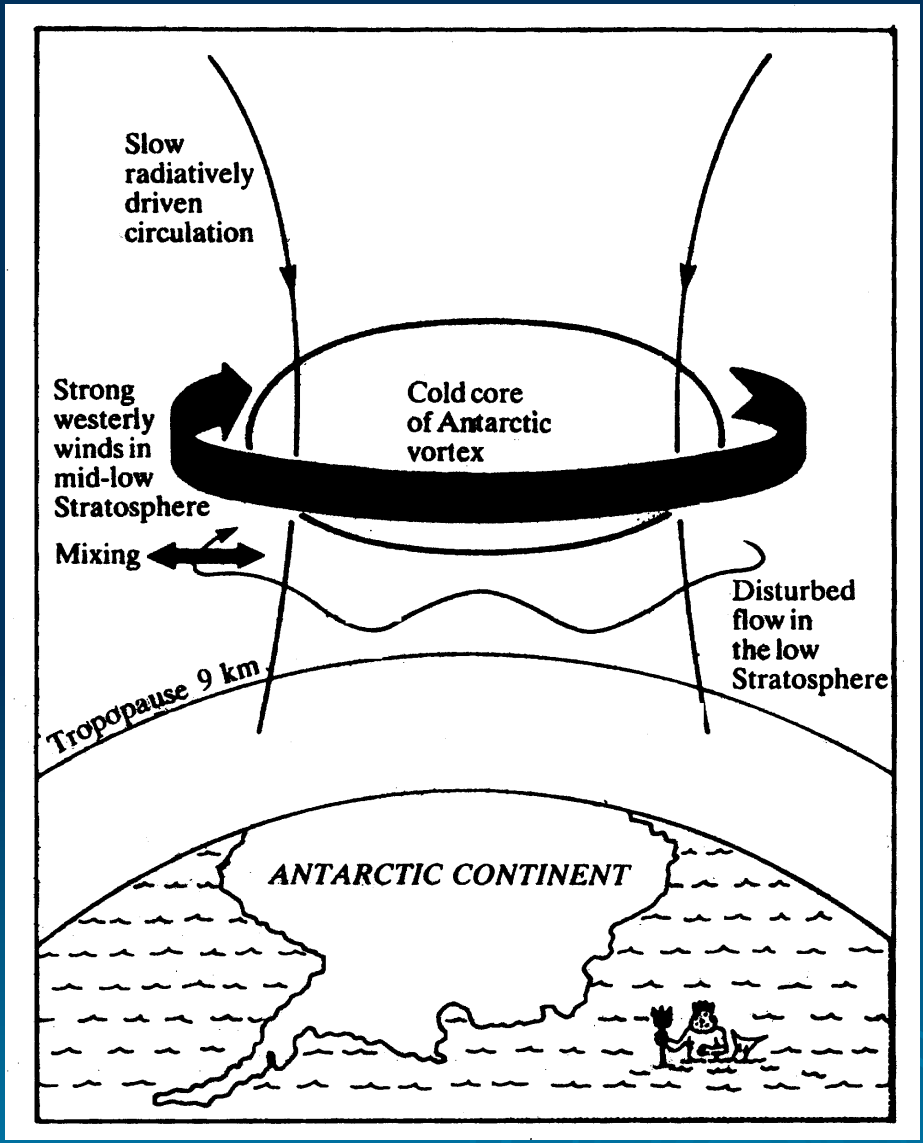


Relative contributions to ozone loss by family



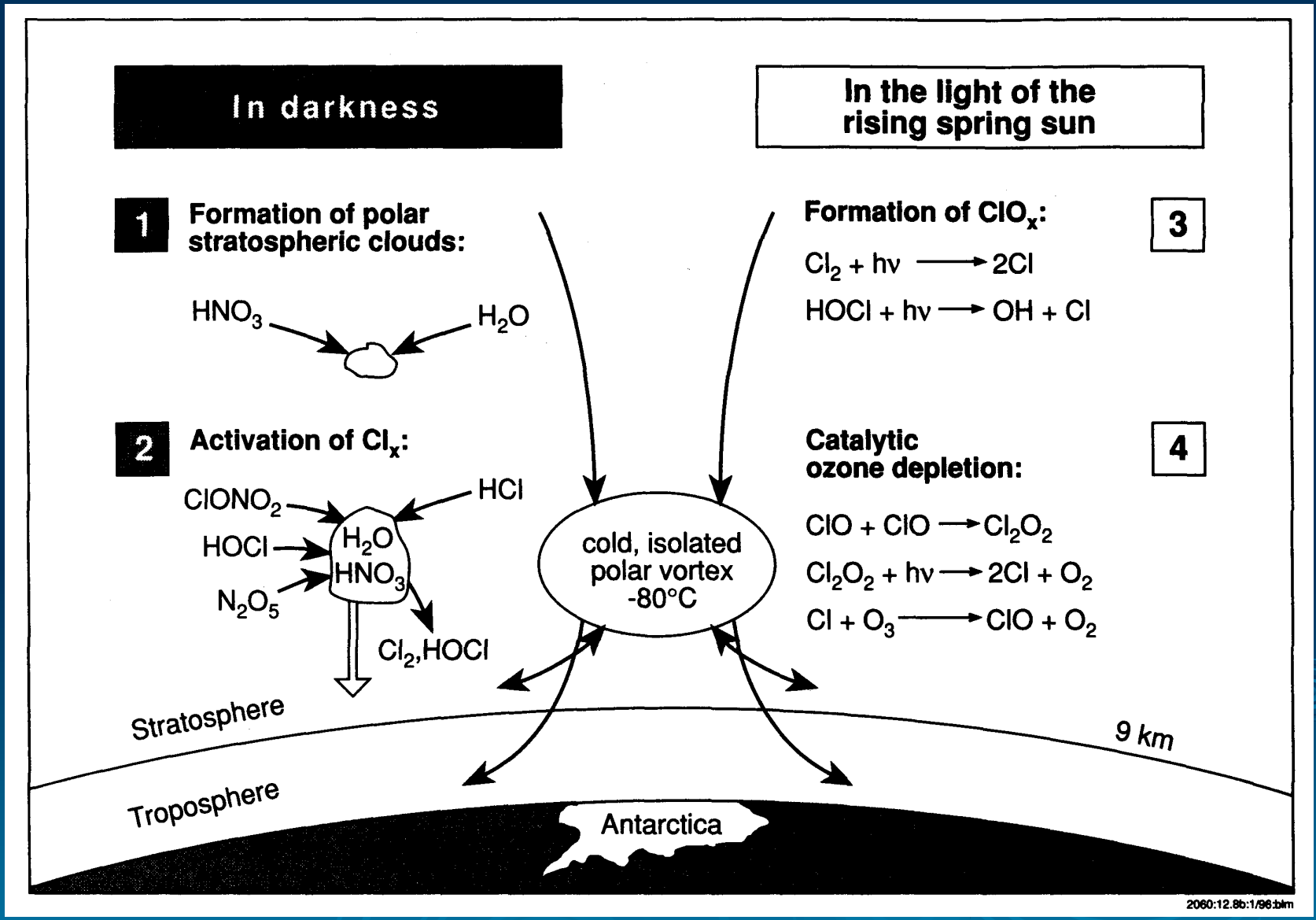
- Predictions from computer models
- Note that plots show *relative* contributions, not absolute rate of Ox destruction
- Remember that max Ox concentration is at about 25km, and max production/loss peaks at about 40km
- NOx is the most important family, particularly in the middle stratosphere.
- HOx is most important at top and bottom of stratosphere
- ClOx contributes up to 30% of loss under typical circumstances (exception: polar ozone holes)

Unique Feature of Antarctic Meteorology: Winter Vortex

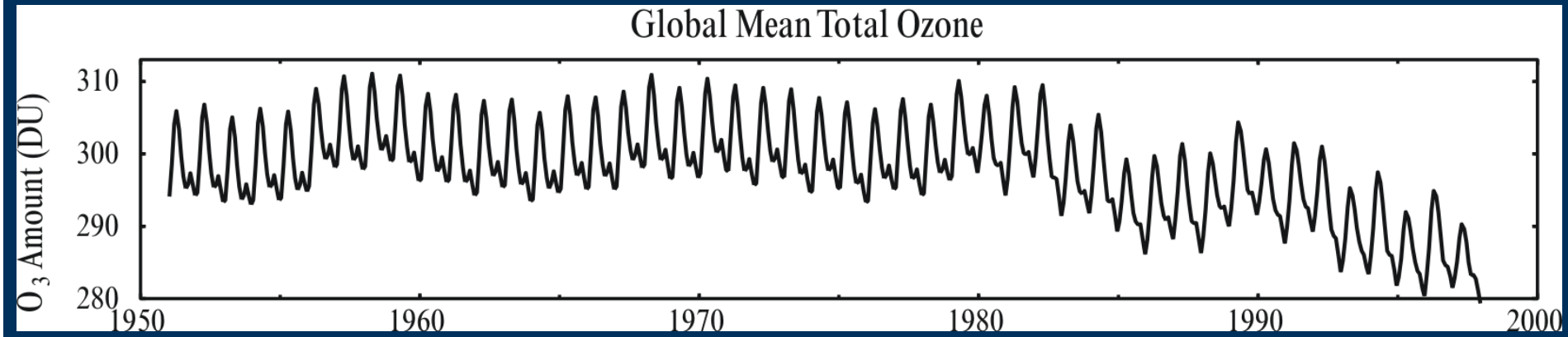


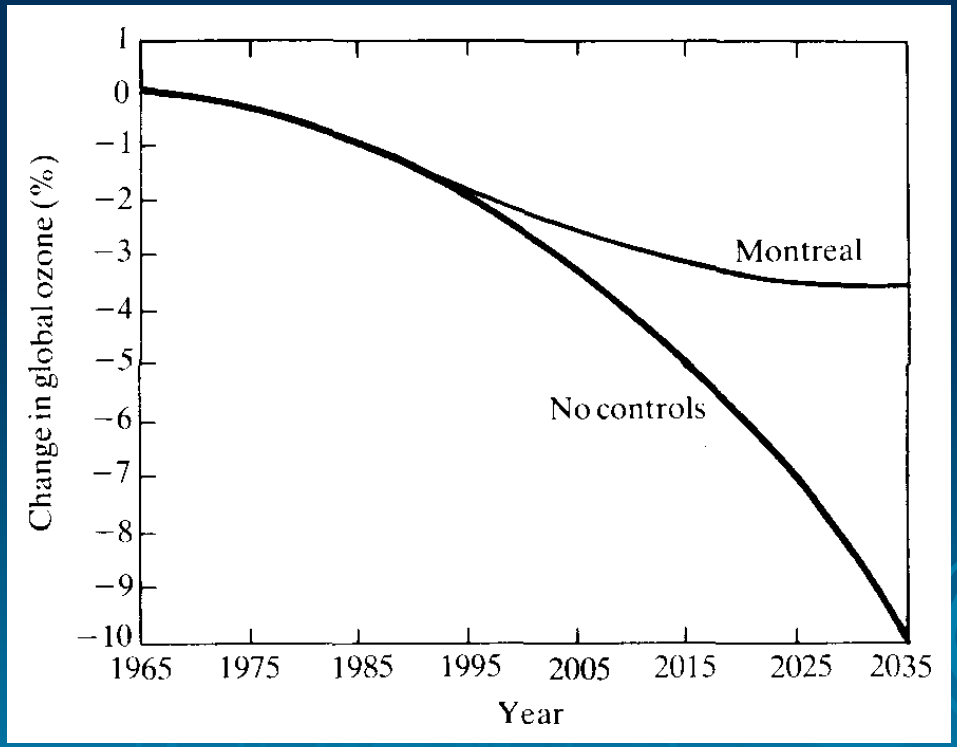
- Polar vortex develops during the winter
- Atmosphere is effectively isolated from the rest of the southern hemisphere
- Interior temperatures plummet during long winter night – large area is below 200K, and it can get as cold as 180K

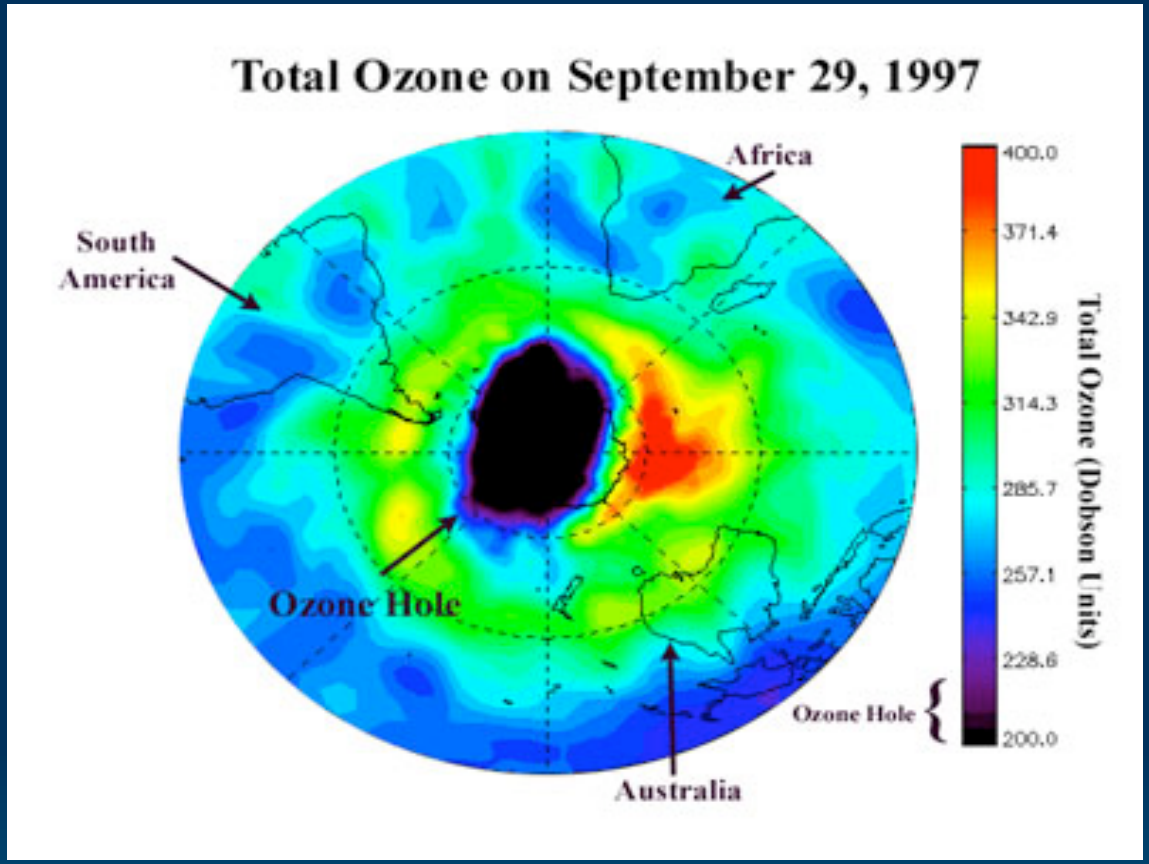
The Ozone Hole – Explained!



Global Ozone Depletion Trends



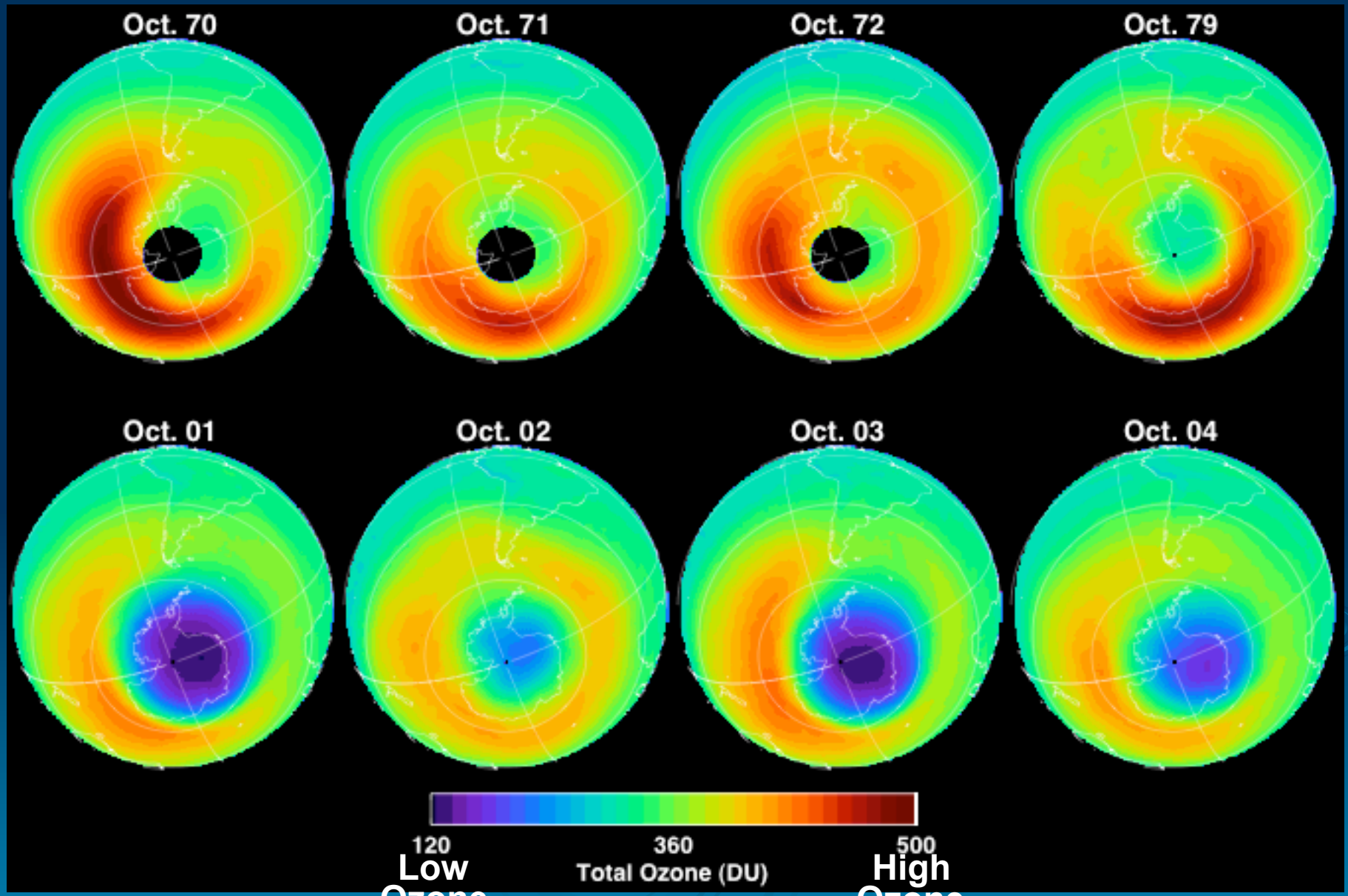




A combination of low temperatures and elevated chlorine and bromine concentrations are responsible for the destruction of ozone in the upper stratosphere thus forming a "hole". (Kerr, 1987)

www.met.sjsu.edu/~cordero/ education/education.htm

October Average Ozone Hole



Summary

- Ozone is the critical gas for screening solar UV radiation. Quality, long-term observations are critical for assessing change!
- Ozone loss resulted from human produced ozone destroying substances (ODS: CFCs and halons). These chemicals have extremely long lifetimes.
- ODSs have been regulated under international agreements and are slowly decreasing.
- Ozone levels are not getting worse, but we can't say that things are getting better (yet).
- The ozone hole will recover by about 2068.
  - Every year of delay in regulating ozone would have resulted in a 9 year delay of recovery.
- The impact of climate change on ozone recovery is very uncertain at present.