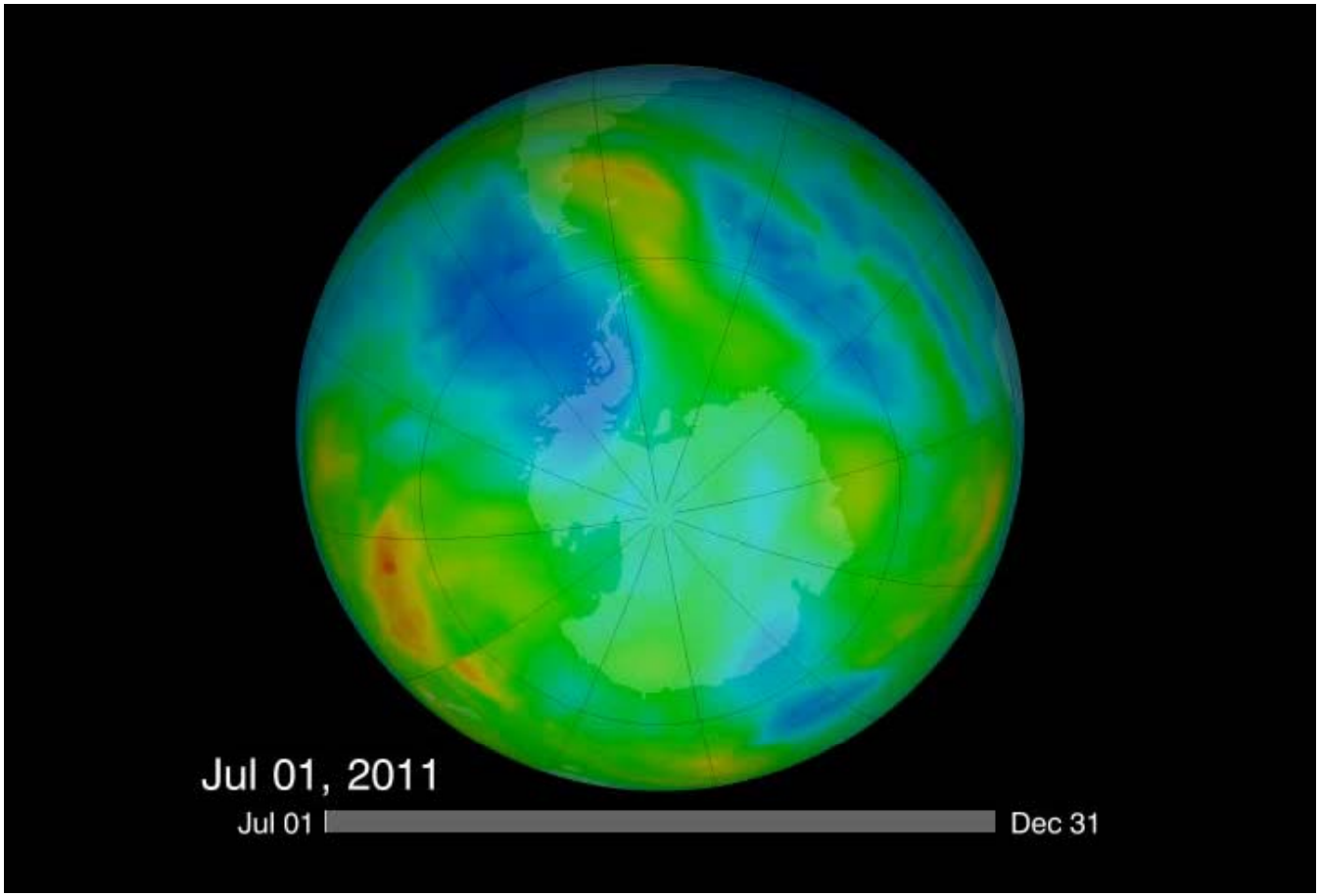
"To the Philosopher, the Physician, the Meteorologist, and the Chemist, there is perhaps no subject more attractive than that of Ozone."

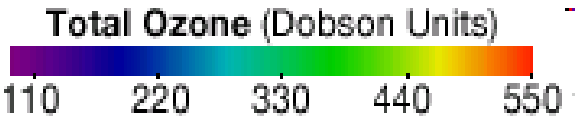
Cornelius B. Fox, *British chemist (1839-1884)*



2011 Antarctic ozone as seen from space

Source: NASA

ozonewatch.gsfc.nasa.gov



Current Assignments ...

For today:

- Read Section 9.8

For Lecture 12:

- Read Section 9.9

Office hours:
3-4 Tuesdays
& Thursdays

Suggested Conceptual Exercises:

- Chapter 9: 35, 37, 39

Homework #2

- Due 11:00 AM, Thursday, February 14

Writing Assignment #1

- Due 11:00 AM, Thursday, February 28

Tutorial #5

- Homework #1 will be returned and discussed

Review of Lecture 10

Textbook, Sections 9.3 - 9.7

- Light: particle or wave?
- The double slit experiment
- Electromagnetic wave theory of light
- Electromagnetic spectrum
- Solar radiation
- Blackbodies

Plan for Lecture 11

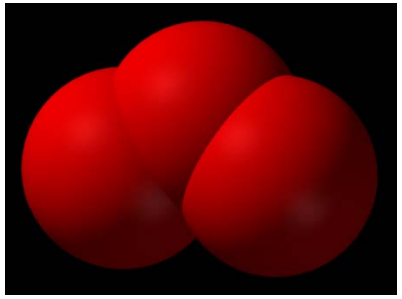
Textbook, Section 9.8

Ozone and ozone depletion

- What is ozone?
- What is happening to ozone?
- What causes ozone depletion?
- What will happen to ozone in the future?

What Is Ozone?

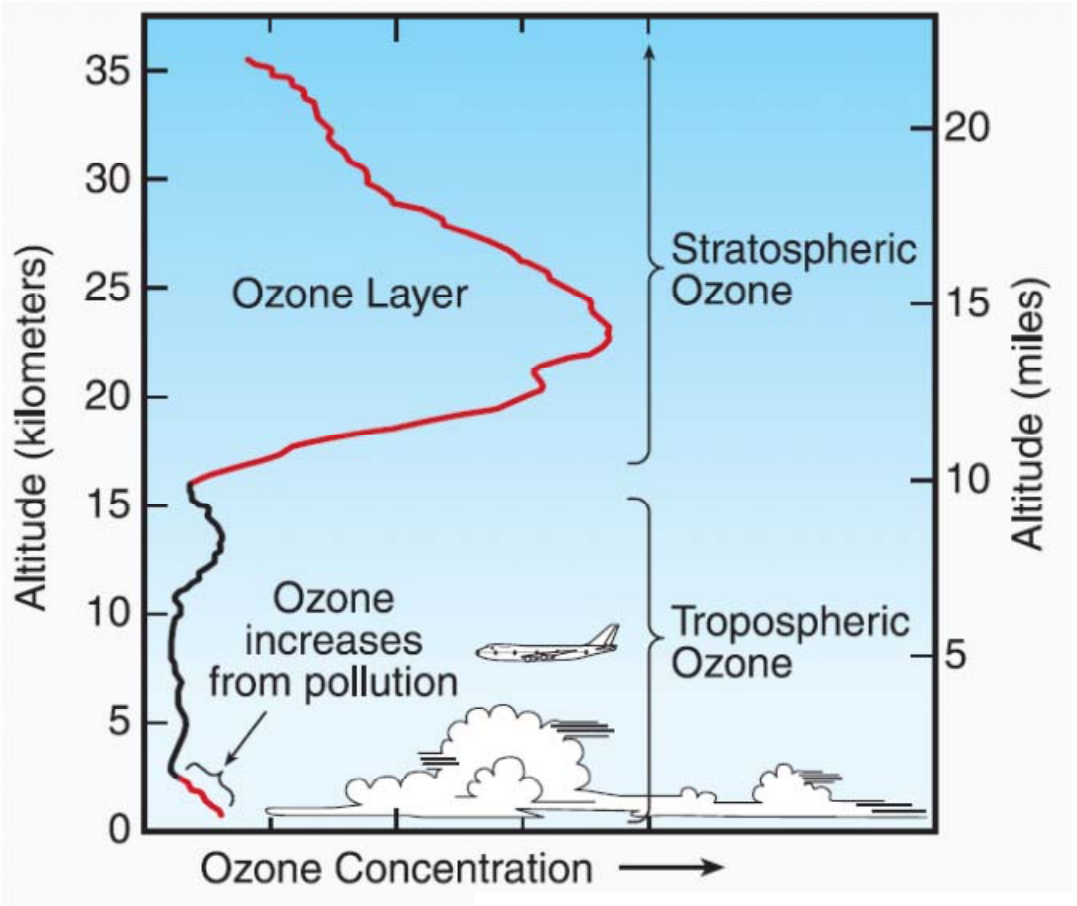
Stratospheric Ozone



http://en.wikipedia.org/wiki/Ozone

What is ozone?

- A special form of oxygen (O_3) that blocks harmful UV light from the Sun
- A very reactive gas, present in small but significant quantities in the atmosphere
- Its concentration depends on altitude, with most ozone lying in a layer 20 km thick centred at 25-30 km



WMO Ozone Assessment 2006

How Much Ozone Is There?

If all of the air in a column above us were compressed to surface pressure (0°C and 1 atm) …

…it would be a layer of air about 8 km thick.

If all of the ozone were separated out and compressed …

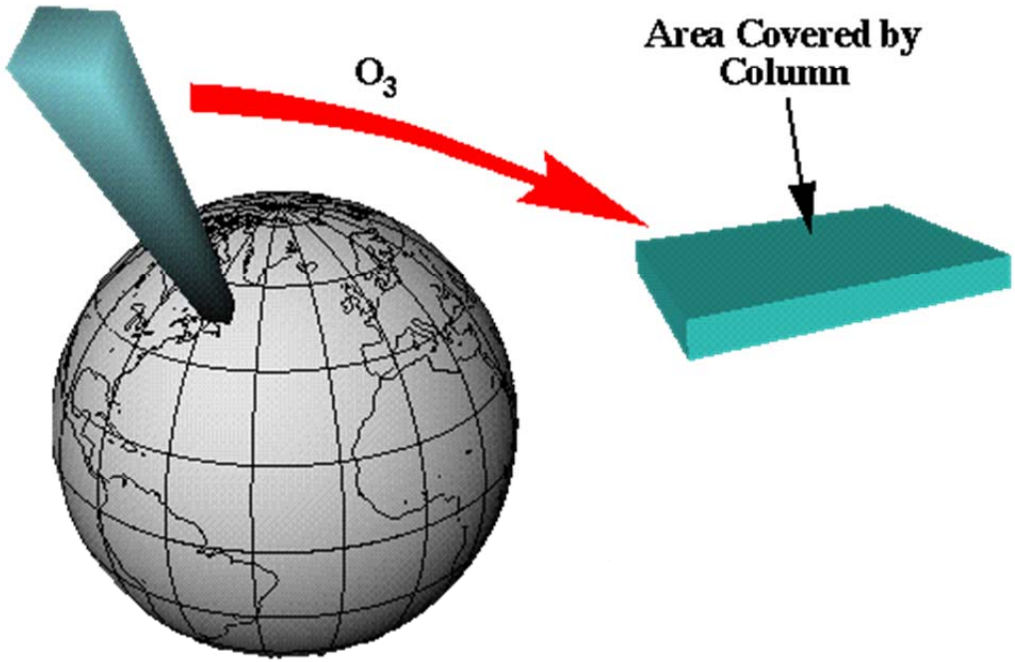
… it would make a layer of ozone about 3 mm thick!

About the thickness of 3 dimes!

Ozone is measured in Dobson Units (DU)

1 DU = 0.01 mm

300 DU = 3 mm



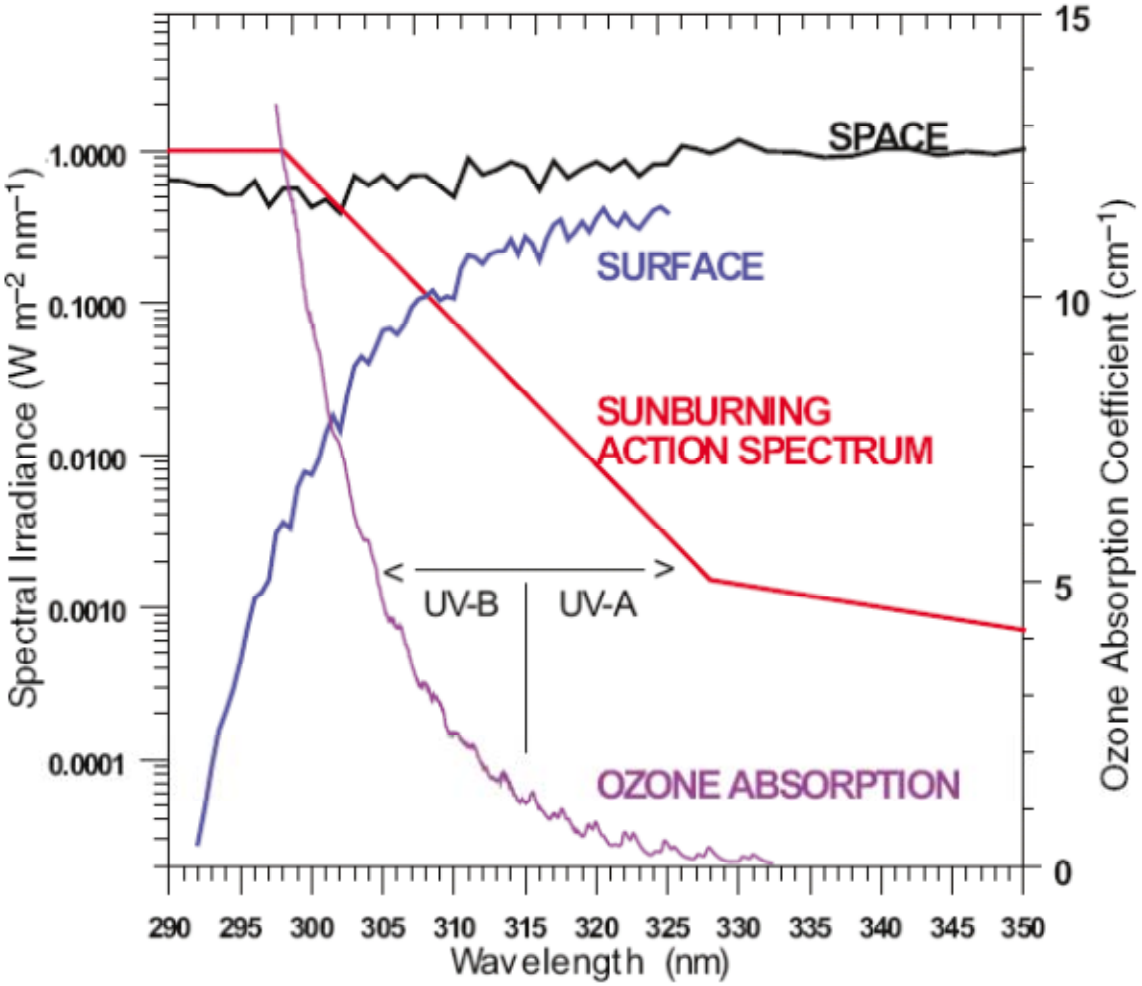
Composition of the Atmosphere

Ozone
<1 part per million (ppm)

Textbook
Table 9.1

Why Is Ozone Important?

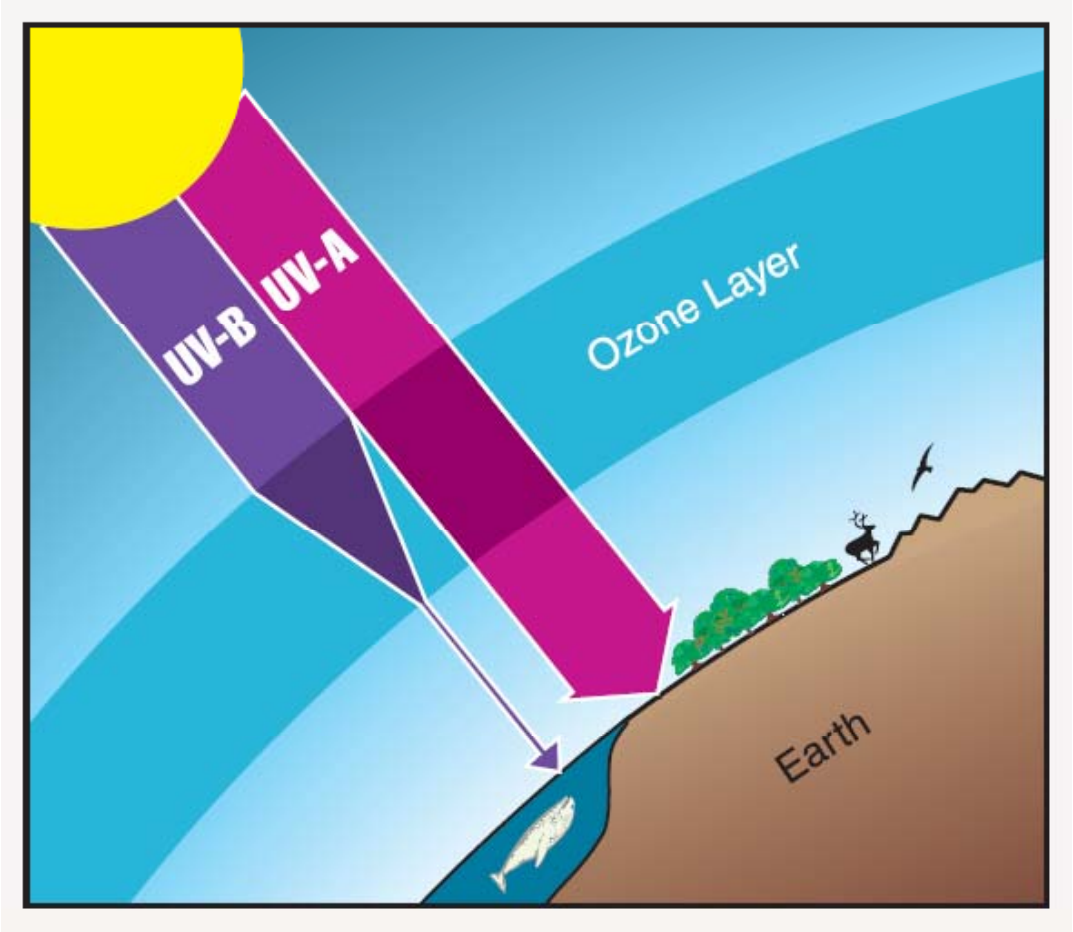
- Ozone layer acts as a filter for solar UV-B radiation
- Ozone heats the atmosphere - links with climate change



Kerr and Fioletov, Atmos-Ocean 2008

Ozone and Climate

- Ozone absorbs solar UV-B radiation (280-315 nm)
- This warms the stratosphere (~10-50 km)
- Ozone is also a greenhouse gas, absorbing IR radiation and heating the troposphere (0-10 km)



WMO Ozone Assessment 2010

Stratospheric Ozone - Chemistry

How is ozone created and destroyed?

(1) Chapman Cycle (1930) - oxygen-only reactions

- **Odd oxygen production:**

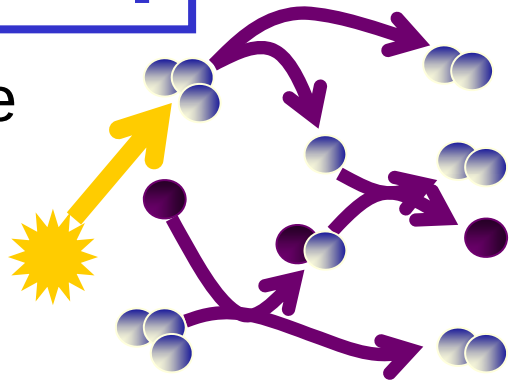
$$O_2 + h\nu \longrightarrow O + O$$
$$O + O_2 \xrightarrow{M} O_3$$

- **Odd oxygen destruction:**

$$O_3 + h\nu \longrightarrow O_2 + O$$
$$O + O_3 \longrightarrow 2\,O_2$$
$$[O + O \xrightarrow{M} O_2 \text{ slow}]$$

(2) Catalytic Cycles (1970s) - destroy ozone

$$X + O_3 \rightarrow XO + O_2$$
$$XO + O \rightarrow X + O_2$$
$$\overline{O + O_3 \rightarrow 2\,O_2}$$



- where reactive species X (= H, OH, NO, Cl, Br) is regenerated

Stratospheric Ozone - Chemistry

Odd oxygen production

$$O_2 + h\nu \longrightarrow O + O$$
$$O + O_2 \xrightarrow{M} O_3$$

Odd oxygen destruction

$$O_3 + h\nu \longrightarrow O_2 + O$$
$$O + O_3 \longrightarrow 2\,O_2$$
$$[O + O \xrightarrow{M} O_2 \quad \text{slow}]$$

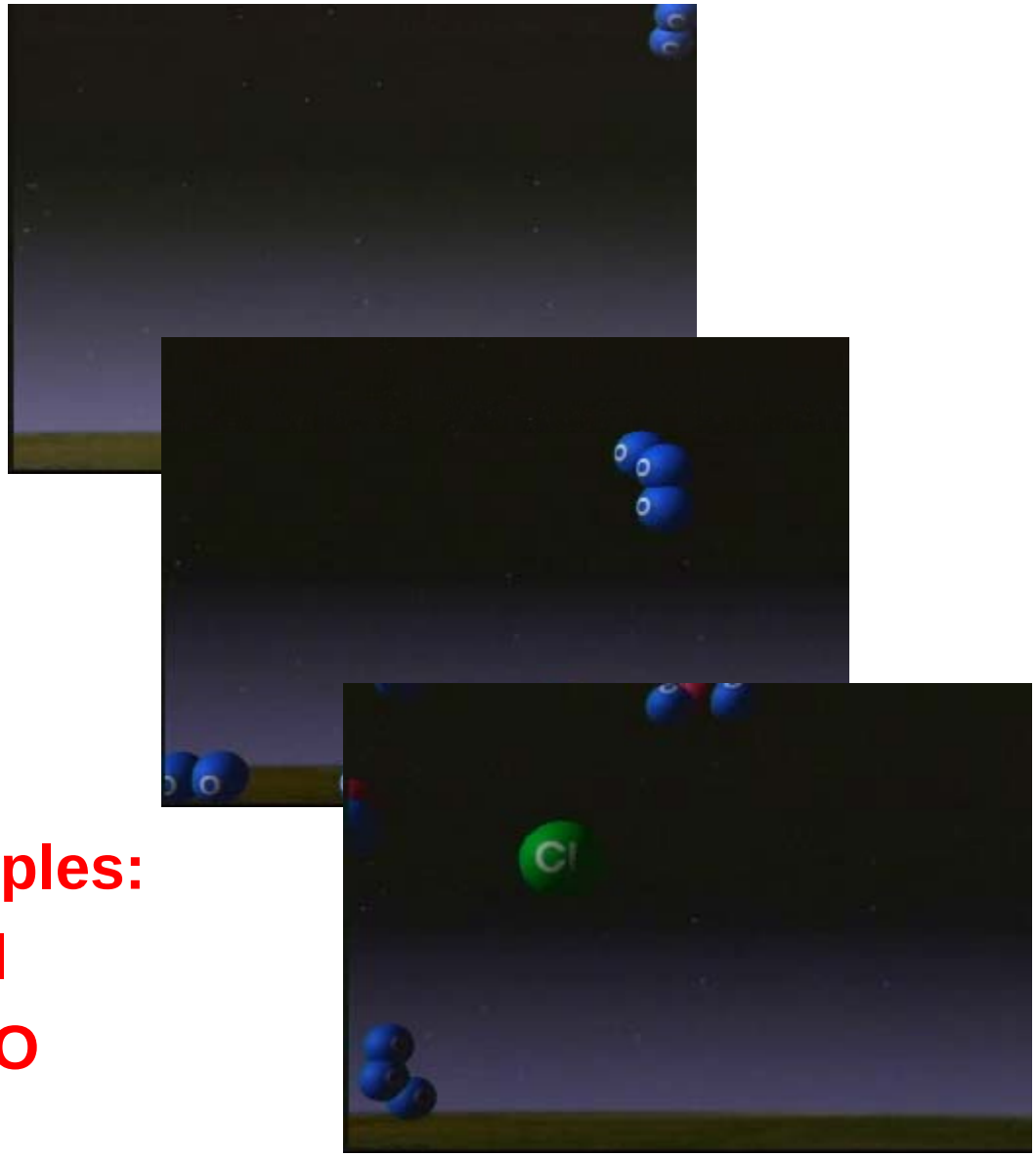
Catalytic cycles

$$X + O_3 \rightarrow XO + O_2$$
$$XO + O \rightarrow X + O_2$$
$$\overline{O + O_3 \rightarrow 2\,O_2}$$

Examples:

X = Cl

X = NO



http://ozonewatch.gsfc.nasa.gov/multimedia/index.html

What Is Happening to Ozone?

Antarctic Ozone Loss 1

- In 1985, a team of scientists from British Antarctic Survey reported that springtime stratospheric ozone column over their station at Halley Bay had decreased precipitously since 1970s.
- Occurs in September-November.
- No depletion was observed in other seasons.

Farman et al., Nature, 1985

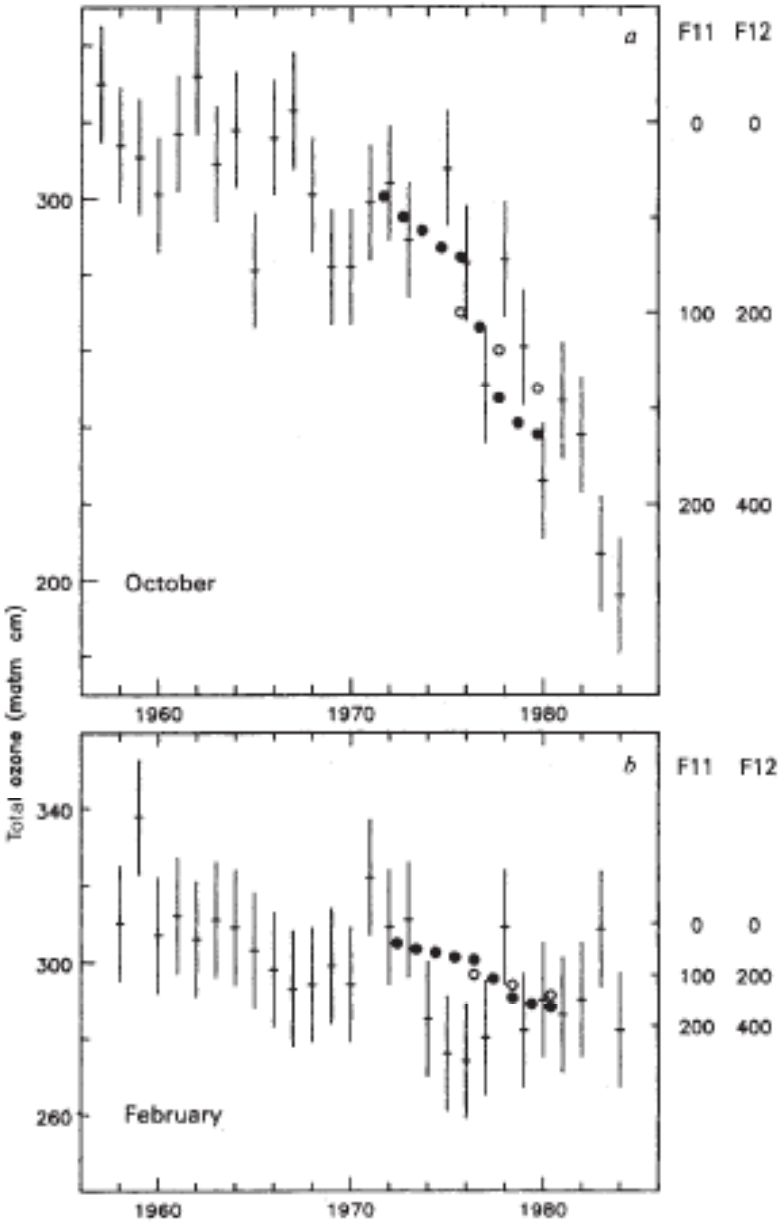


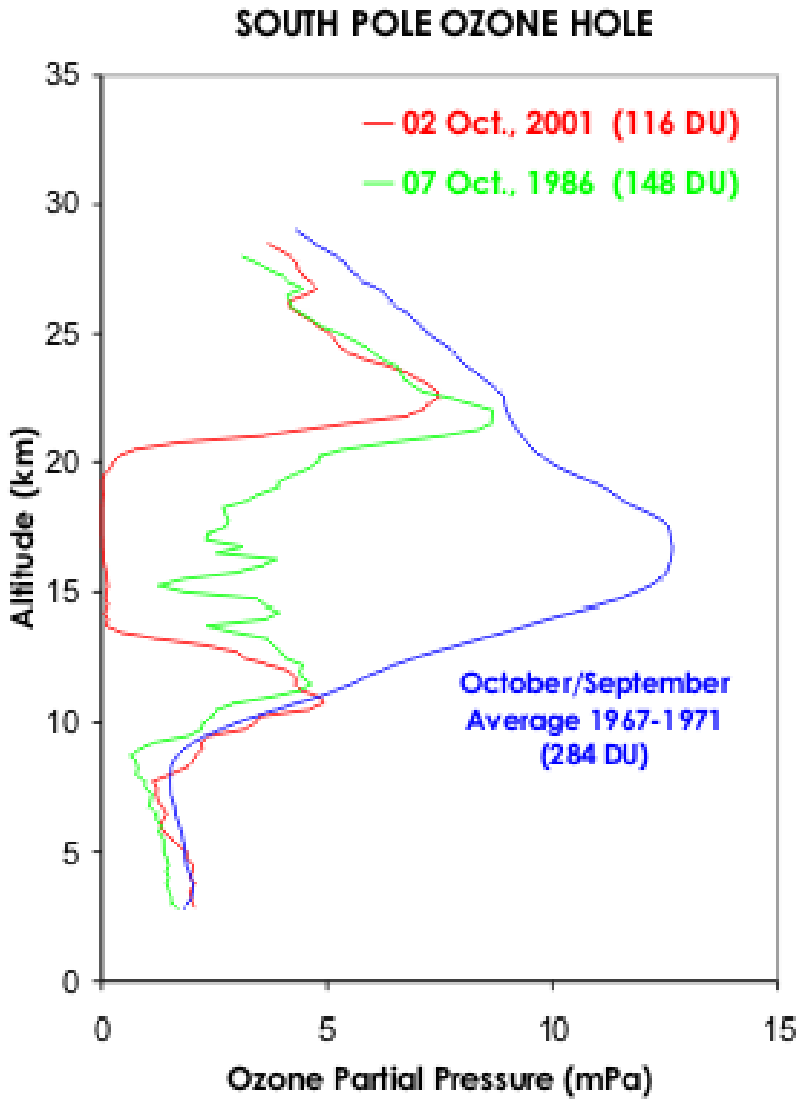
Fig. 2 Monthly means of total O_3 at Halley Bay, and Southern Hemisphere measurements of F-11 (●, p.p.t.v. (parts per thousand by volume) $CFCl_3$) and F-12 (○, p.p.t.v. CF_2Cl_2). *a*, October, 1957–84. *b*, February, 1958–84. Note that F-11 and F-12 amounts increase down the figure.

Antarctic Ozone Loss - 2

- Measured vertical profiles show that the depletion of ozone is essentially total in the lowest region of the stratosphere between 10-20 km, which normally contains most of the total ozone column in polar spring.

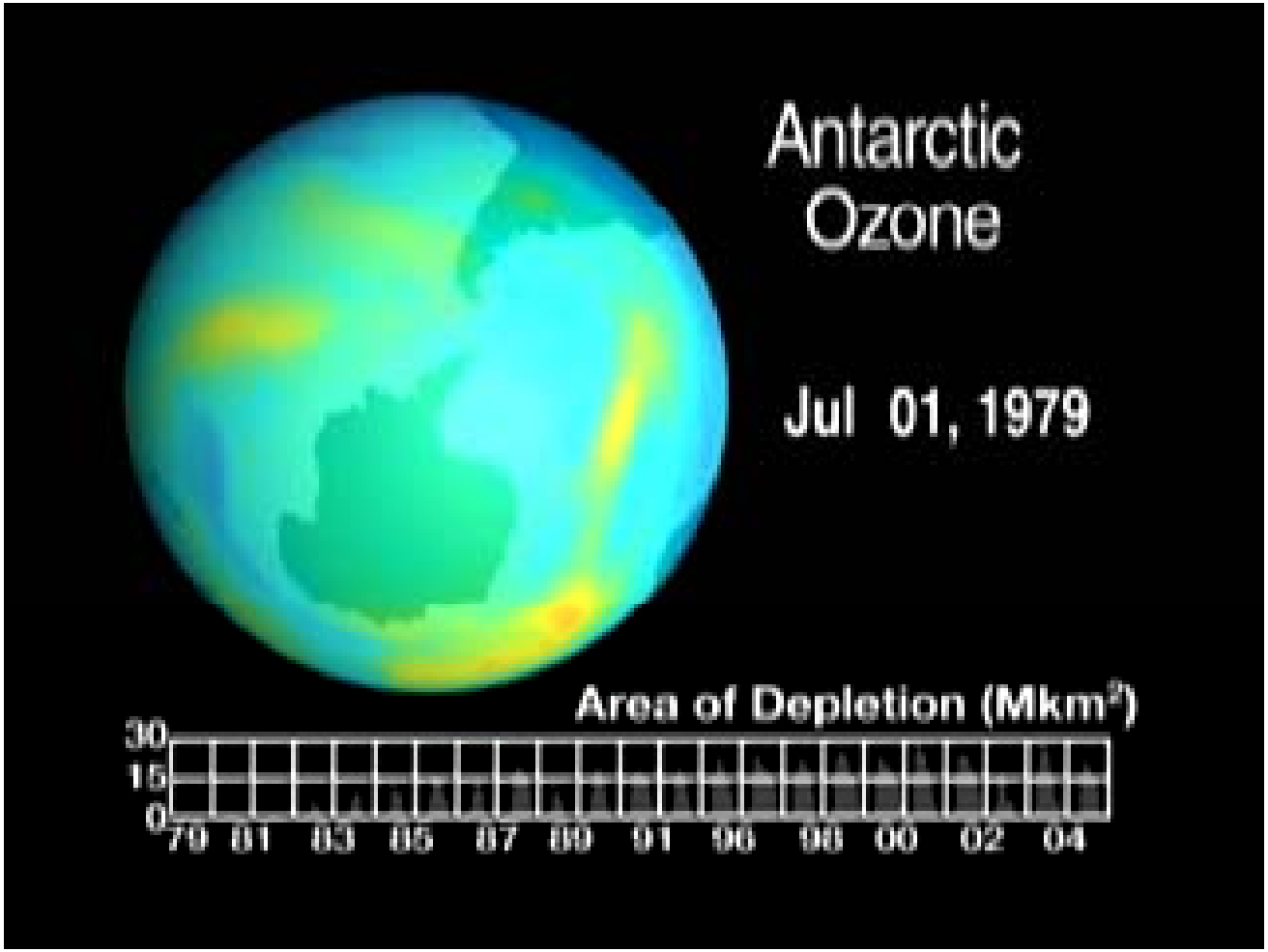
  Balloon-borne ozone profiles measured at South Pole in October:

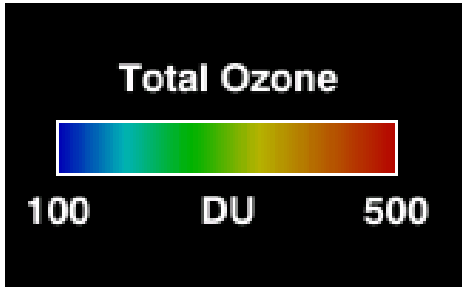
- blue = 1967-1971 average
- red = lowest total ozone recorded in 2001
- green = lowest total ozone recorded in 1986



NOAA CMDL http://www.cmdl.noaa.gov/ozwv/ozsondes/spo/index.html

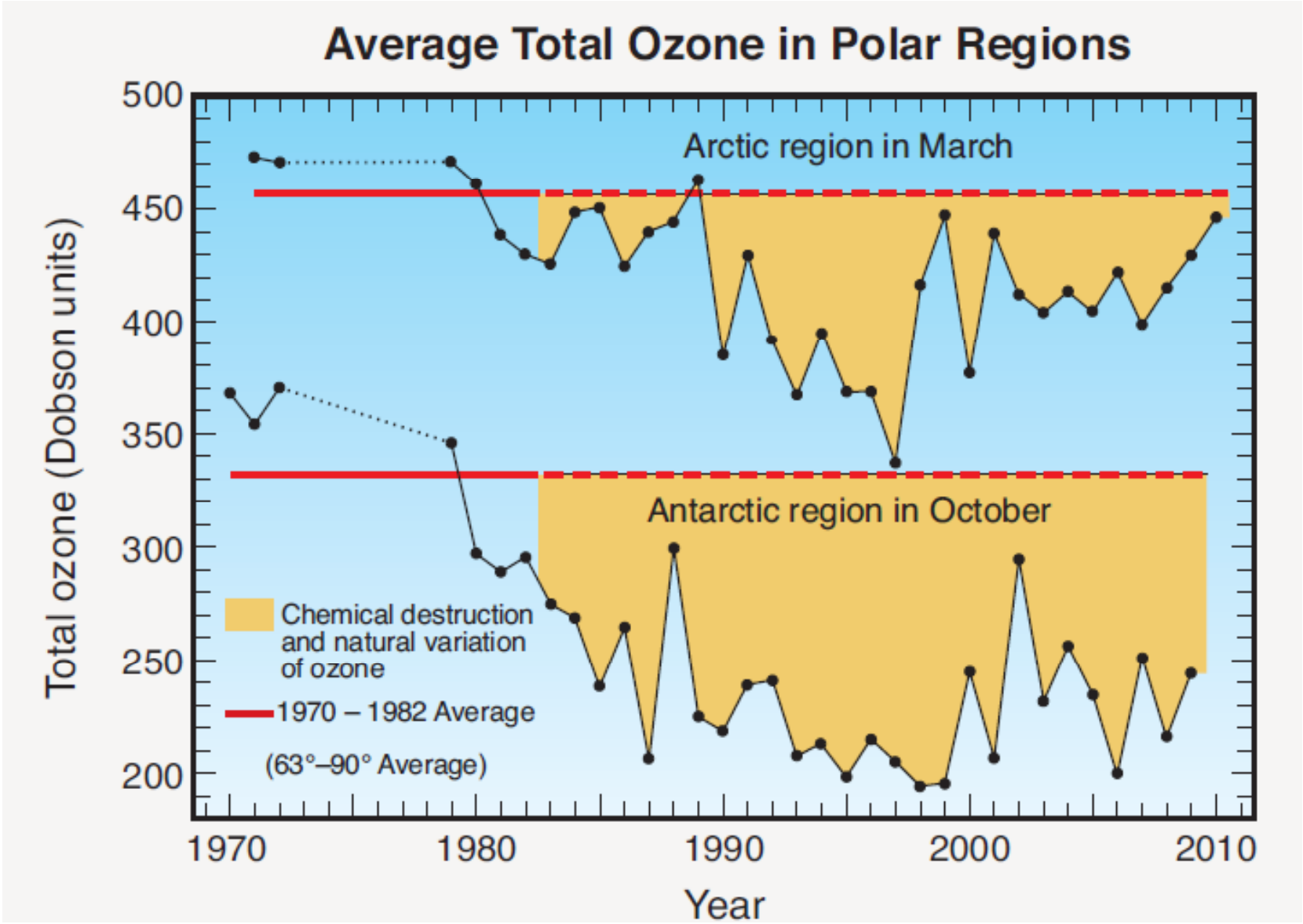
Antarctic Ozone Hole: 1979-2004





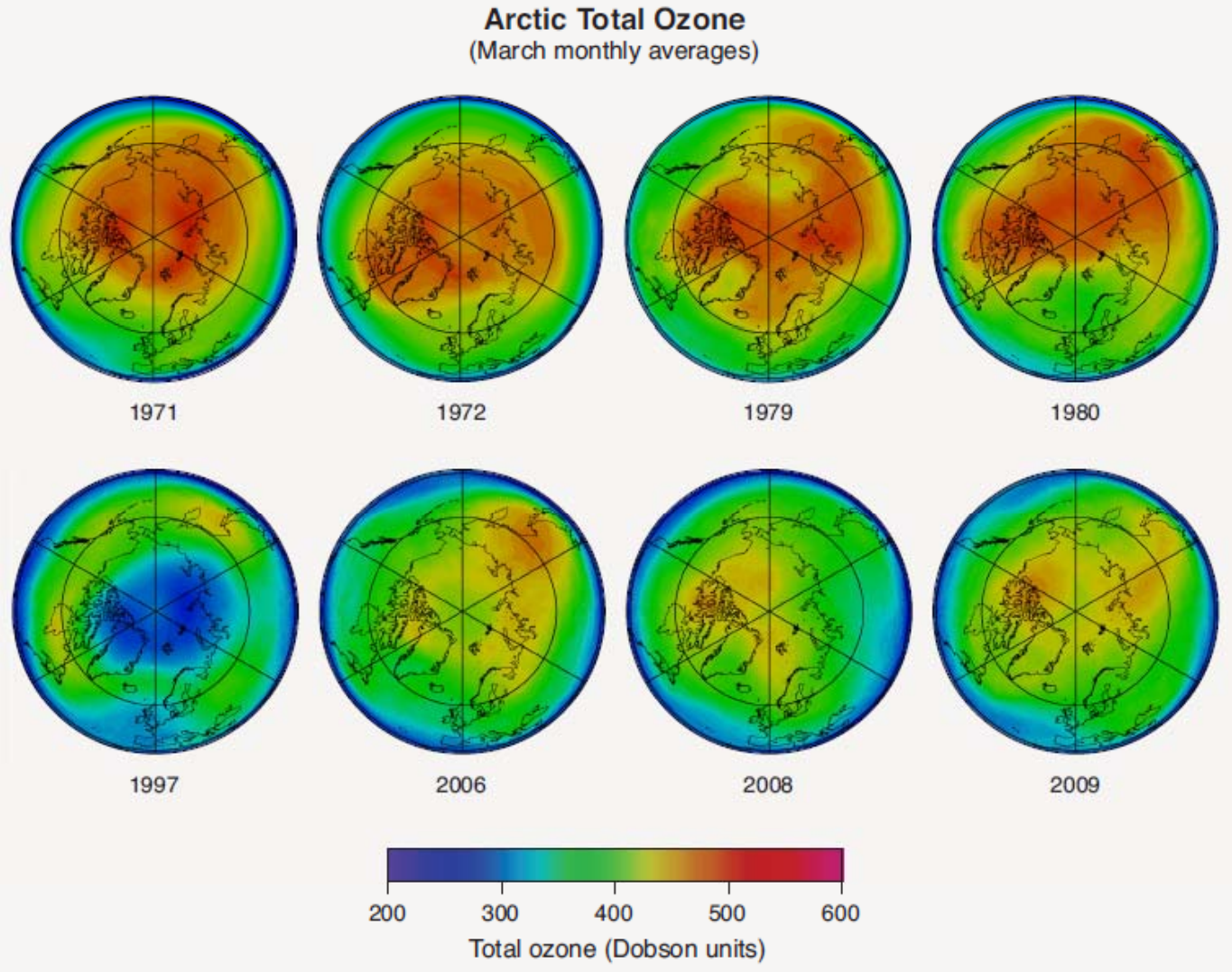
NASA/Goddard Space Flight Center Scientific Visualization Studio
http://svs.gsfc.nasa.gov/vis/a000000/a003100/a003137/index.html

Polar Total Ozone Trends



WMO Ozone Assessment 2010

Arctic Ozone: March Averages

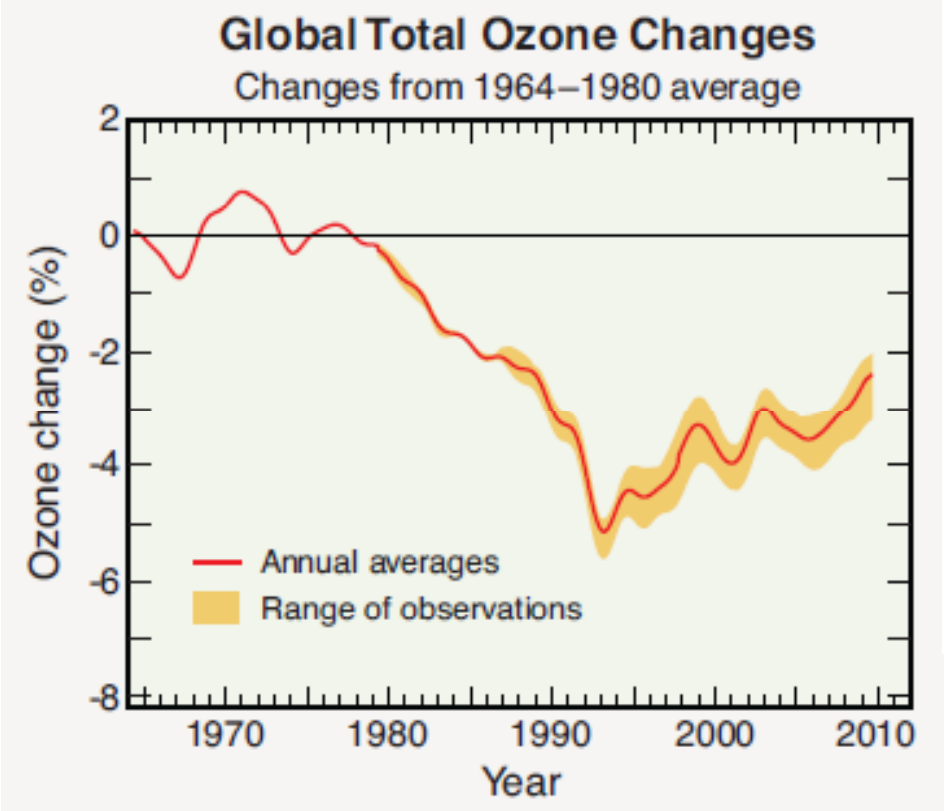


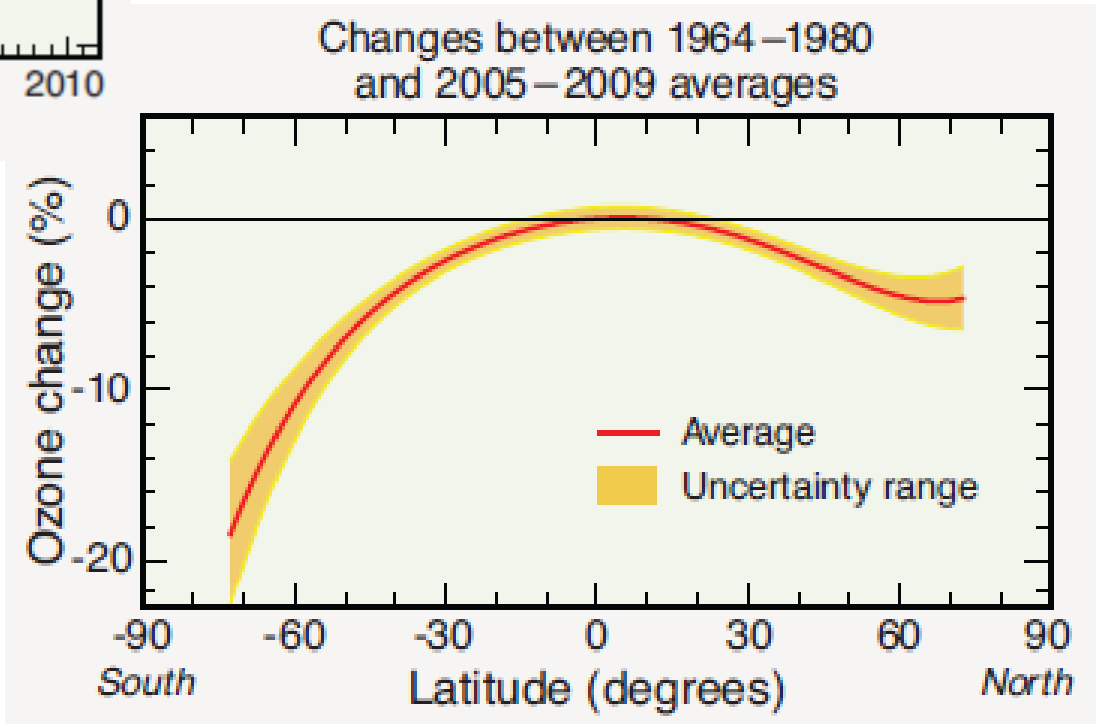
March monthly averaged total ozone from satellites.

Note how regions where ozone ~450 DU decrease from 1970s to 2000s

WMO Ozone Assessment 2010

Global Changes in Total Ozone



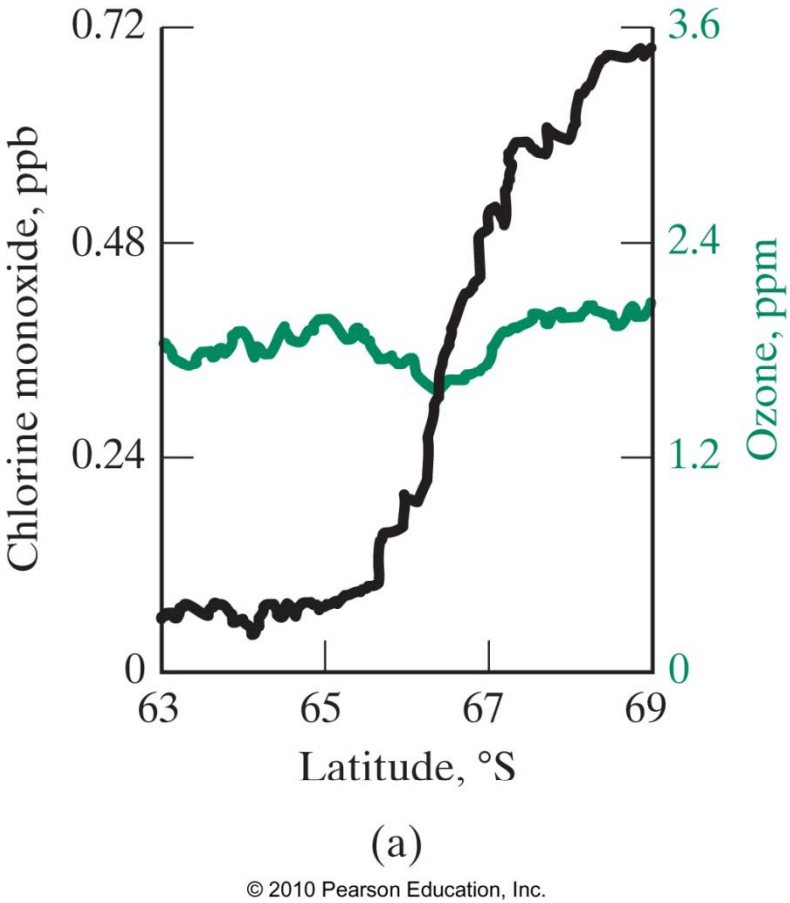


WMO Ozone Assessment 2010

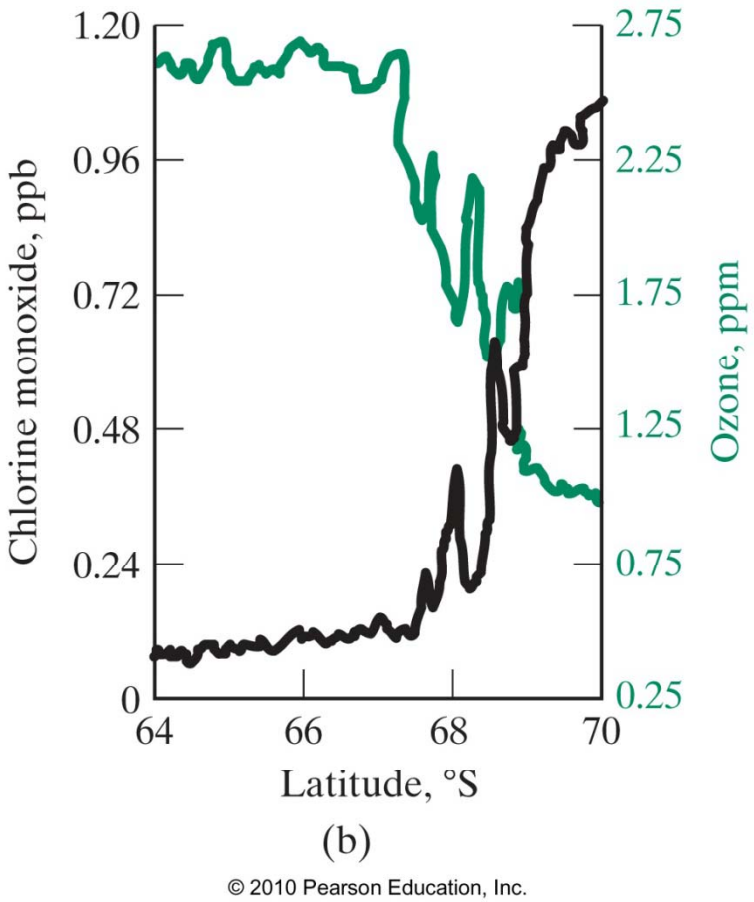
What Causes Ozone Depletion?

Atmospheric Measurements Provide Evidence ...

August 23, 1987



September 16, 1987



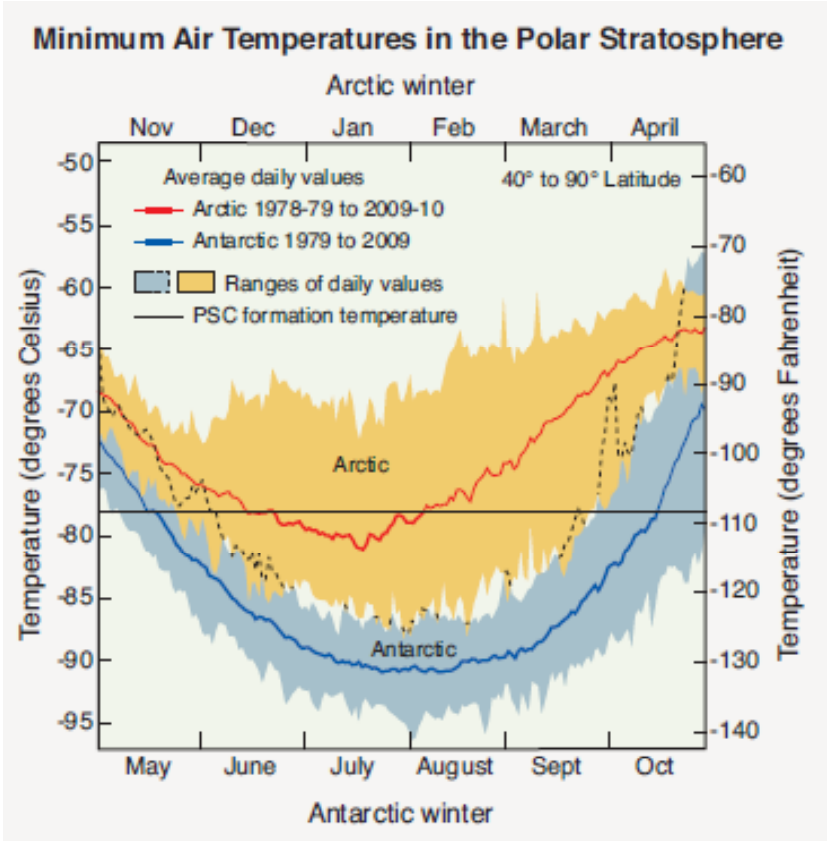
Polar Ozone Depletion Processes

(1) Formation of the winter polar vortex (band of westerly winds)

→ isolates cold dark air over the polar regions

(2) Low temperatures in the vortex, T<195 K

→ polar stratospheric clouds (PSCs) form in the lower stratosphere (liquid and solid HNO_3, H_2O, H_2SO_4)



WMO Ozone Assessment 2010

Polar Ozone Depletion Processes

(3) Dehydration and denitrification

→ remove water vapour and nitrogen oxides which would otherwise react with and neutralize chlorine

(4) Release of CFCs, mixing, and transport to the polar regions

→ enhanced levels of chlorine and other halogen species

(5) Heterogeneous reactions on the PSCs

→ convert inactive chlorine (HCl and $ClONO_2$) to reactive Cl_2

(6) Sunlight returns in the spring

→ UV radiation breaks Cl_2 apart to form Cl

(7) Catalytic chlorine cycles

→ destroy ozone, while recycling Cl

This continues until the Sun causes a dynamical breakdown of the winter vortex and PSCs evaporate.

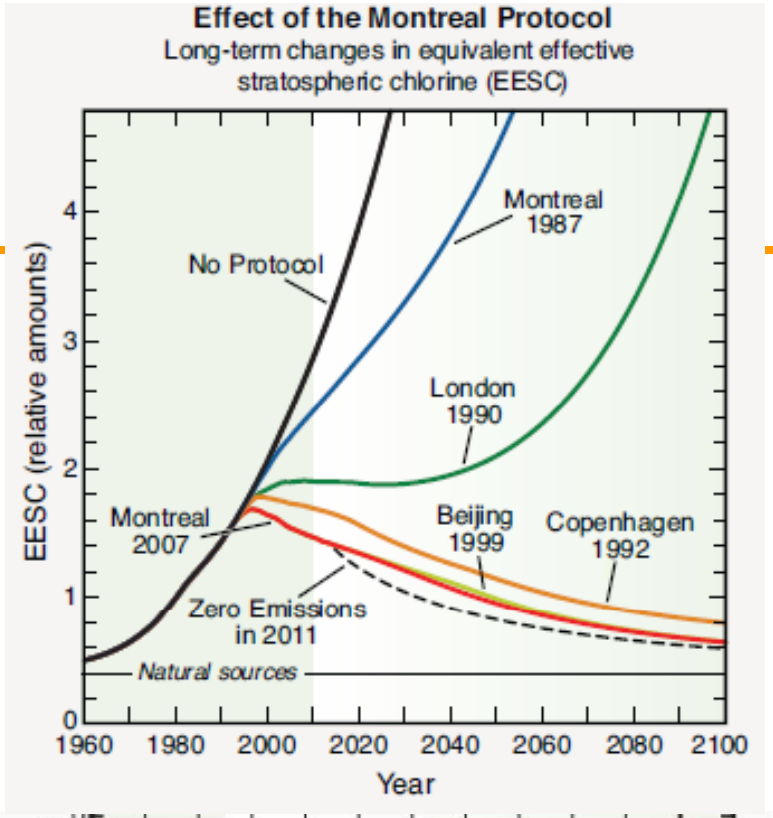
The Culprits...

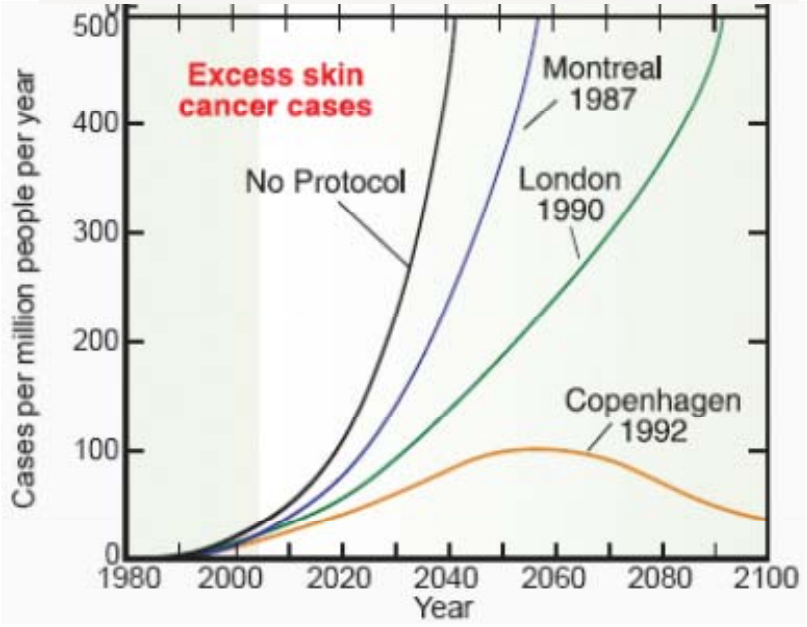
Textbook, Table 9.2

What Will Happen to Ozone in the Future?

Montreal Protocol & Its Amendments

- 1985 - *Vienna Convention for the Protection of the Ozone Layer*
- 1987 - *Montreal Protocol on Substances that Deplete the Ozone Layer (the **"Ozone Treaty"**)*
  - → Entered into force in 1989
  - → Established controls on halogen source gases
  - → Later strengthened by a series of Amendments



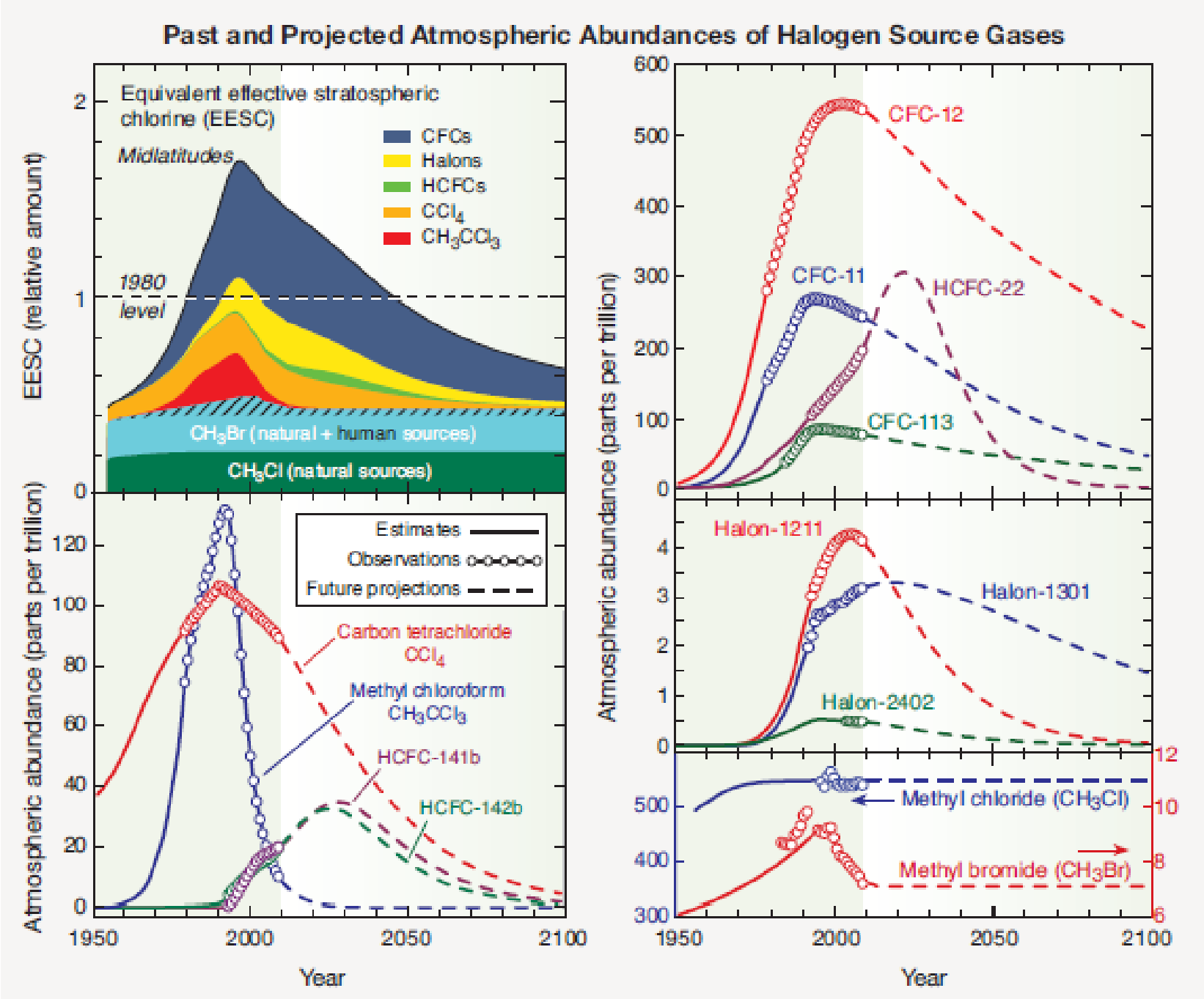


WMO Ozone Assessment 2006, 2010

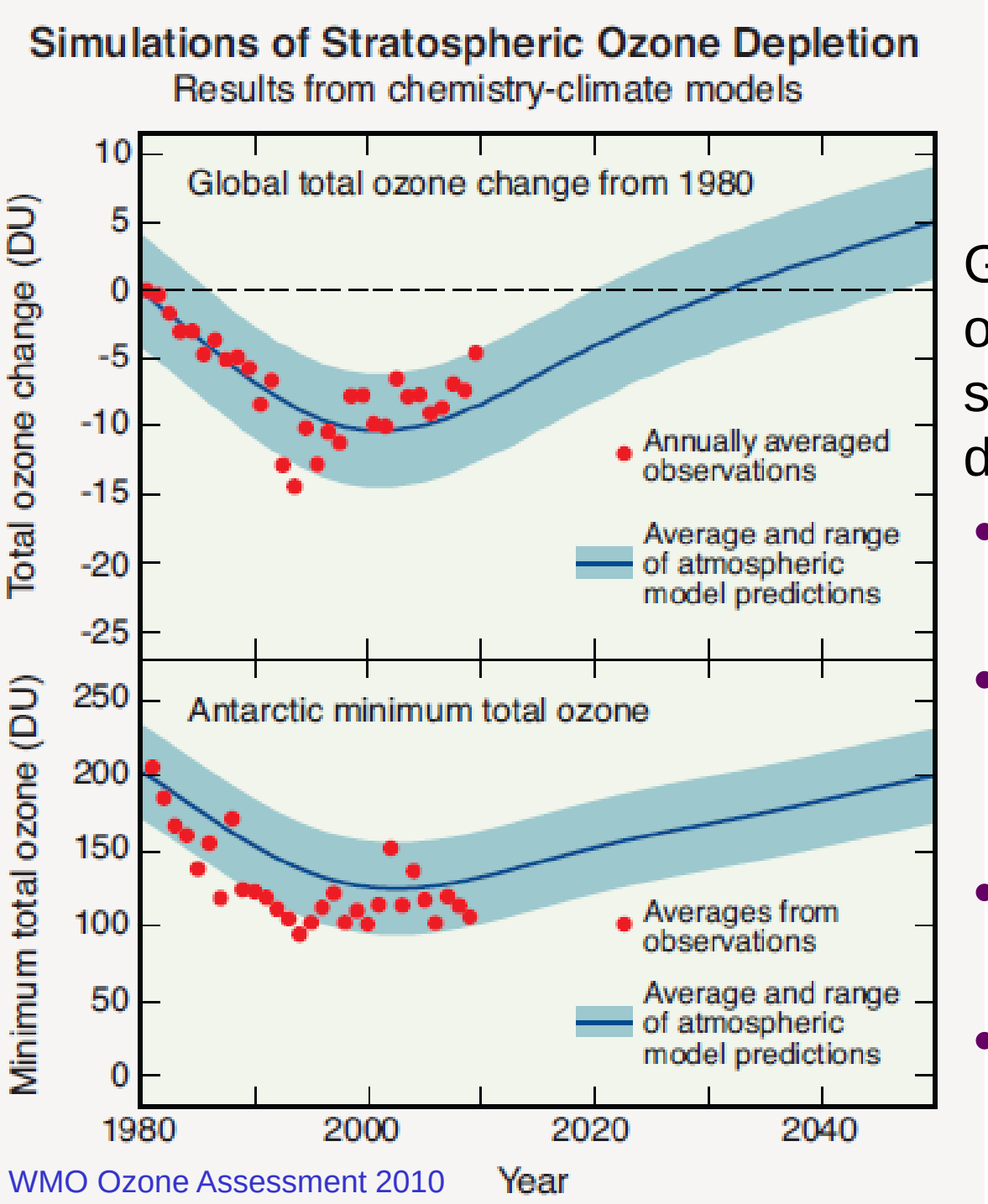
The Impact of the "Ozone Treaty": A Simplified View

The actual chlorine concentration in the stratosphere, compared with a prediction of what it would have been if there had been no treaty until 2010.

Textbook Figure 9.35



WMO Ozone Assessment 2010



Ozone Recovery

Gradual recovery of ozone is anticipated as stratospheric chlorine decreases.

- ozone turnaround in the Arctic likely before 2020
- vunerable to perturbations, such as volcanic aerosols
- coupled to stratospheric cooling
- extreme Arctic ozone loss is not predicted

What About Last Year's Arctic Ozone?

Ozone hole over Arctic hits record

CBC News

Posted: Apr 5, 2011 6:30 AM ET

Arctic ozone loss 'unprecedented,' scient say

Environment Canada cuts could disable future Canadian measuremer

By Emily Chung, CBC News

Posted: Oct 3, 2011 12:52 AM ET

THE GLOBE AND MAIL

ENVIRONMENT

Record Arctic ozone hole raises fears of worse to come

Singapore— Reuters

Published Monday, Oct. 03, 2011 6:38AM EDT

Published online 12 September 2011 | *Nature* 477, 257-258 (2011) | doi:10.1038/477257a

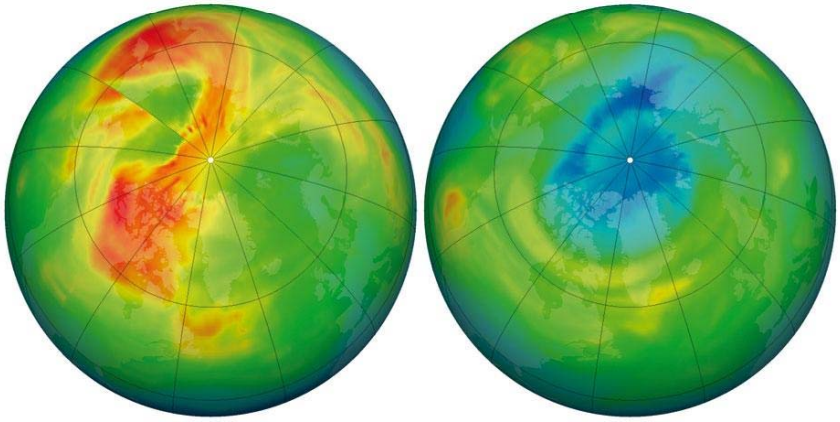
Corrected online: 15 September 2011

News

Canadian ozone network faces axe

Arctic monitoring stations hit by budget constraints.

2010 2011

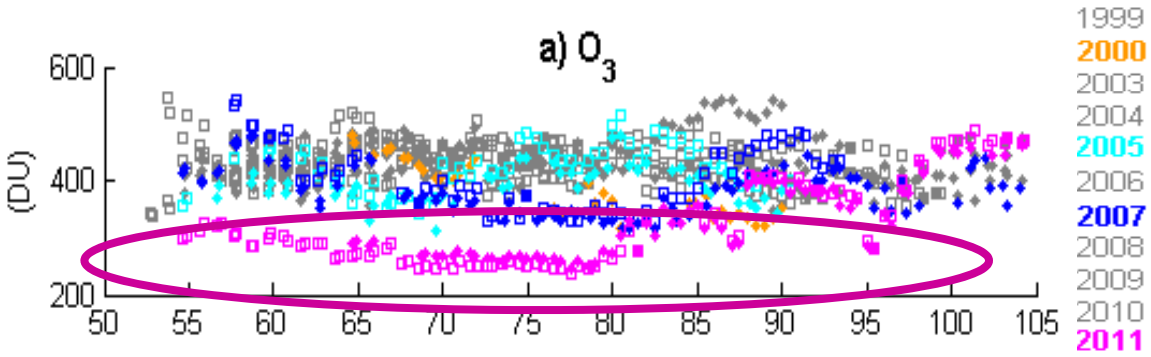


Arctic ozone levels hit a record low in 2011 (blue area, right), compared with a relative high (red) in 2010. (R. Simmon/NASA)

http://www.nature.com/news/2011/110912/full/477257a.html

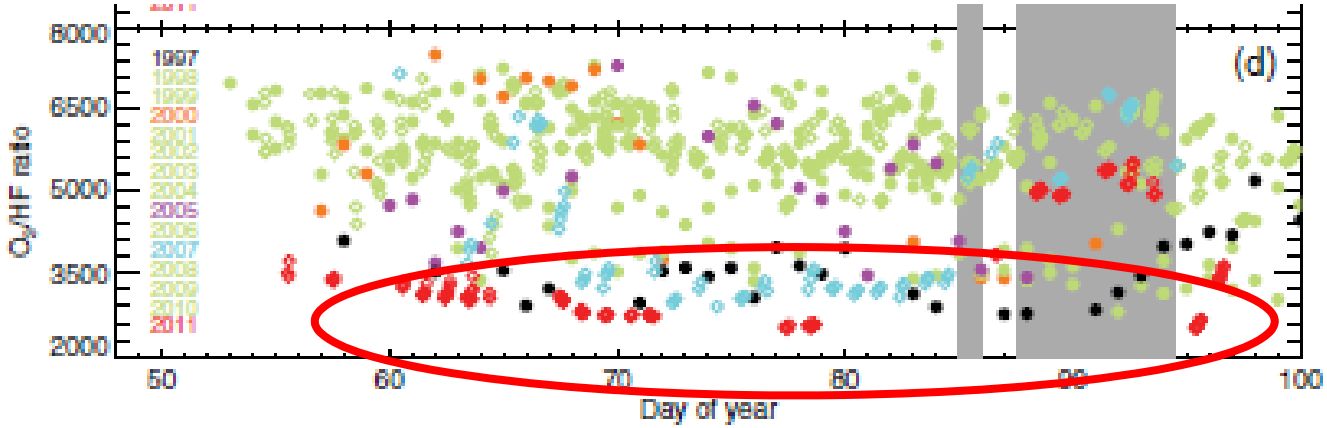
2011 Arctic Ozone

- Cold was the immediate culprit
- Large natural variability in Arctic winter stratosphere
- Issue of underlying long-term changes in the atmosphere



UV-visible measurements of total ozone at Eureka
C. Adams, *Geophysical Research Letters*, 2012

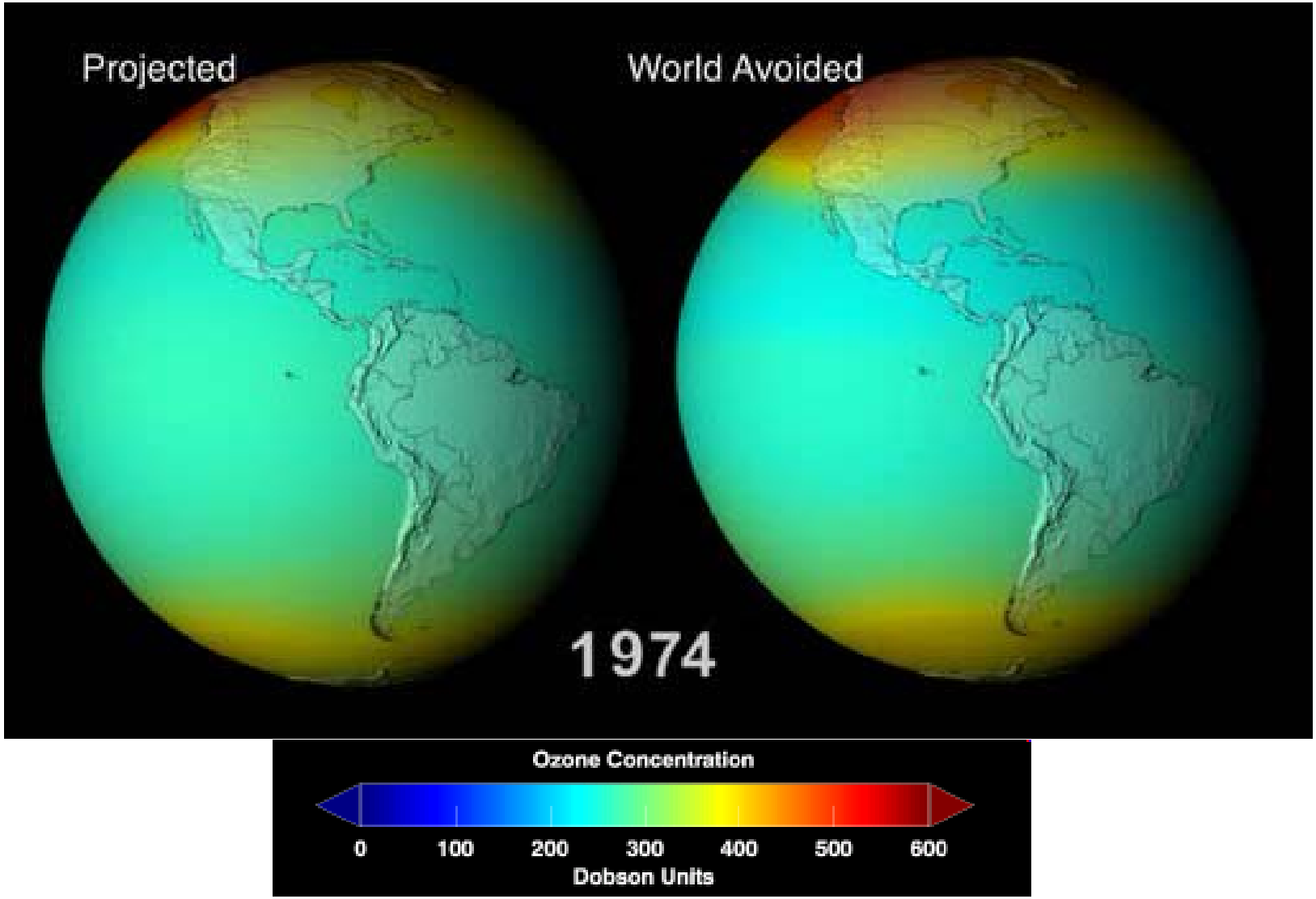
IR measurements of ozone at Eureka
R. Lindenmaier, *Atmospheric Chemistry and Physics*, 2012



What Would have Happened to the Ozone Layer if CFCs had not been Regulated?

- Led by NASA Goddard scientist Paul Newman, a team of atmospheric chemists simulated 'what might have been' if CFCs and similar ozone-depleting chemicals were not banned through the Montreal Protocol.
- The model -- including atmospheric chemical effects, wind changes, and solar radiation changes -- simulated what would happen to global concentrations of stratospheric ozone if CFCs were continually added to the atmosphere.
- The visualizations present two cases: the 'world avoided' case, where the rate of CFC emission into the atmosphere is assumed to be that of the period before regulation, and the 'projected' case, which assumes the current rate of emission, post-regulation. Both cases extrapolate to the year 2065.

What Would have Happened to the Ozone Layer if CFCs had not been Regulated?



http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003586/index.html

For Further Information

- WMO (World Meteorological Organization) Scientific Assessments of Ozone Depletion 2006 and 2010
  - →http://www.wmo.int/pages/prog/arep/gaw/ozone_2006/ozone_asst_report.html
  - →http://www.wmo.int/pages/prog/arep/gaw/ozone_2010/ozone_asst_report.html

- Our annual springtime campaigns at Eureka, Nunavut
  - → This year's campaign begins Feb. 25
  - → http://acebox.uwaterloo.ca/eureka/
  - → http://www.candac.ca

ACE Arctic Campaign 2013 PEARL • Eureka • Nunavut

CANDAC
Canadian Network for the Detection of Atmospheric Change

PEARL Polar Environment Atmospheric Research Laboratory