Lecture 10:
The Antarctic Ozone Hole

III. Basic Ozone Observations

The basic ozone hole observations have been discussed in the introduction in the context of the discovery of the Antarctic ozone hole. In this section, we will review this structure in greater detail, beginning with the horizontal structure and vertical structure, including a discussion of the day-to-day variability of the ozone hole, a discussion of the growth of the ozone hole during the August-September time period, and finally a discussion of the decay of the ozone hole in the November-December time period.

A. Horizontal Structure

The ozone hole is almost longitudinally symmetric. Figure III.A.1 displays TOMS total ozone October averages for the months 1970 through 1990. The early years in Figure III.A.1a display a low of total ozone over Antarctica that is slightly offset towards the southern Atlantic ocean. This structure appears consistently (as is apparent in Figure III.A.1b) through the 80s and into the 90s, with a basic difference that the values of ozone within the low continues to decrease as a function of time.

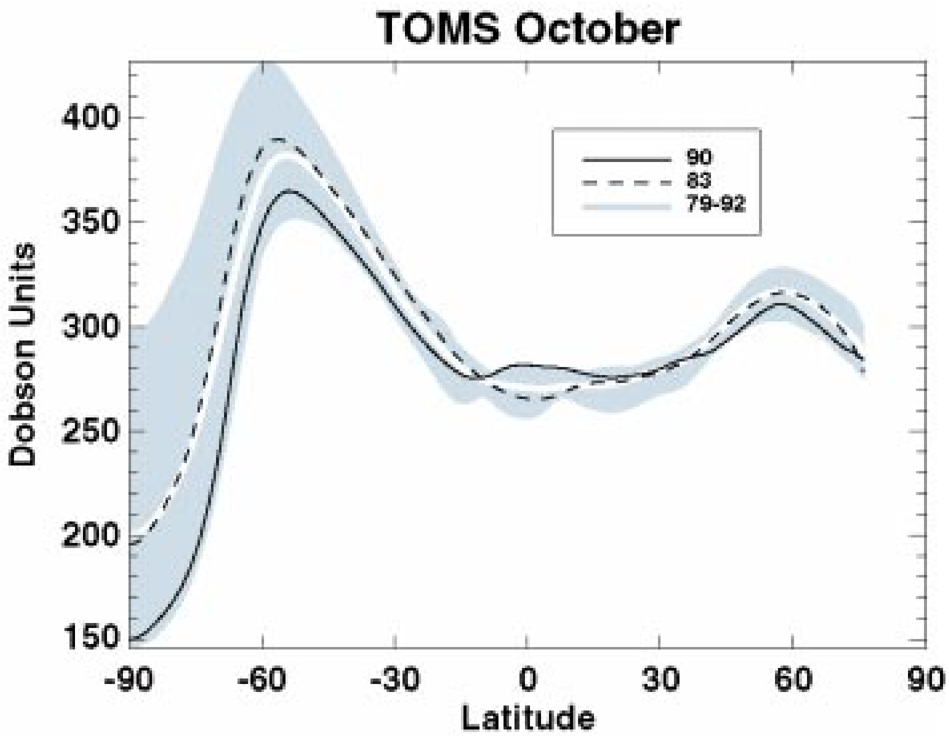


Figure III.A.1

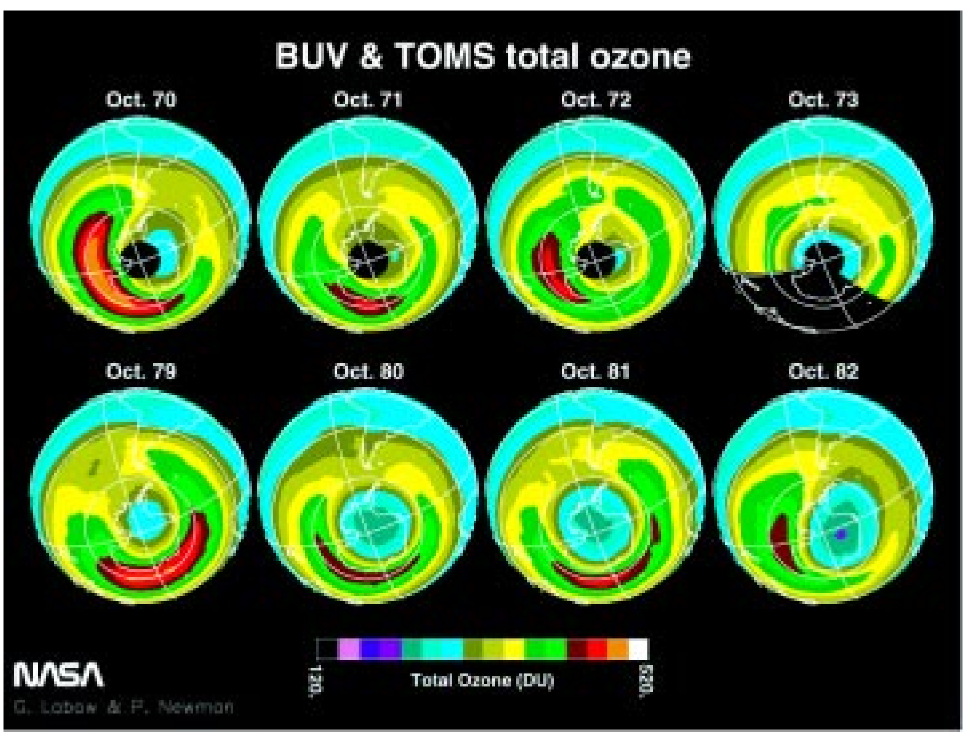


Figure III.A.1a

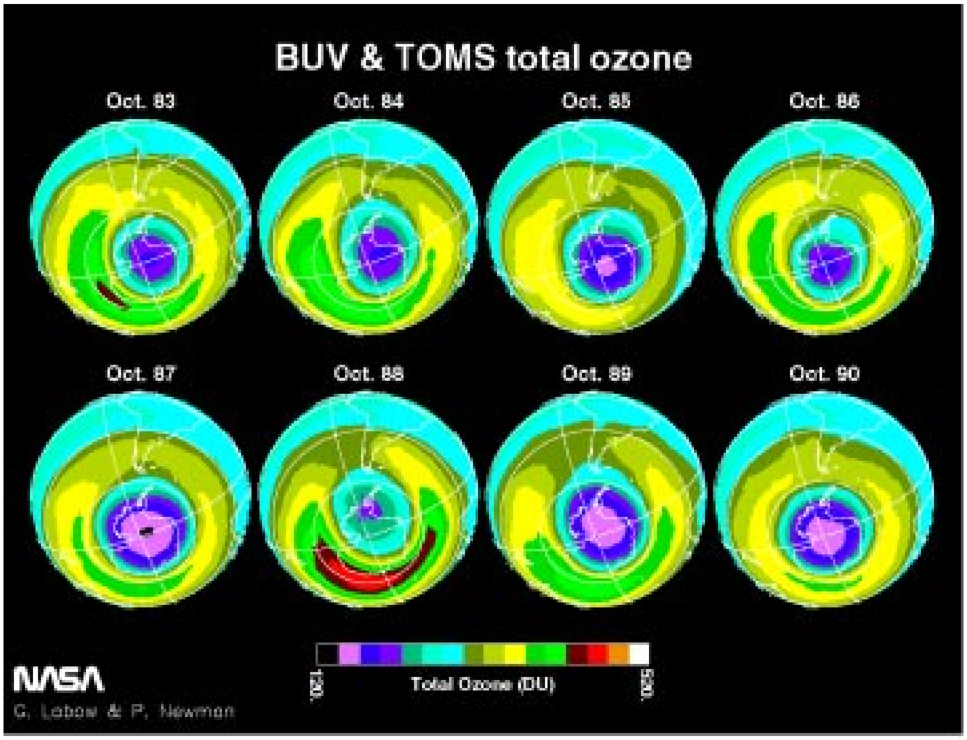


Figure III.A.1b

The wave structure of Figure III.A.1 can be illustrated by subtracting off the longitudinal average from these total ozone fields. Figure III.A.2 displays this difference.

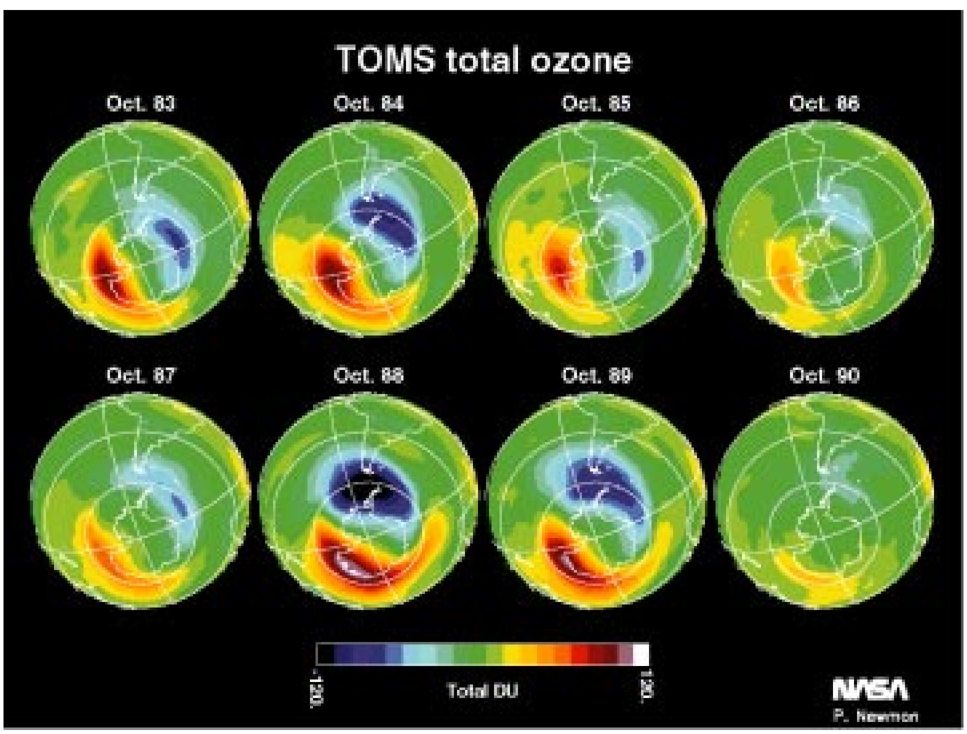


Figure III.A.2

Note that the October fields are dominated by a single low in the south Atlantic region, and a single high near 150W. This high/low structure is known as a “wave-1” pattern. The wave-1 has its maximum amplitude near 60S, falling off to a near zero amplitude near 40S. The total ozone longitudinal average (subtracted from Figure III.A.2) is plotted in Figure III.A.3.

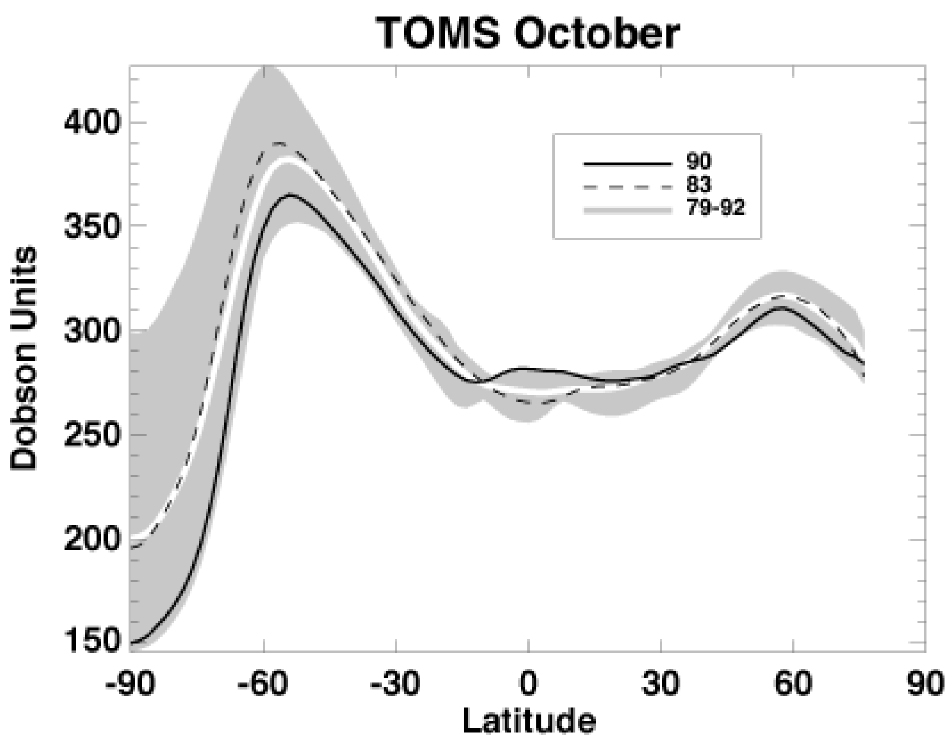


Figure III.A.3

As was shown in Figure I.B.1.4, total ozone values are low over Antarctica, building to a mid-latitude maximum, and then falling to low values in the tropical region. Prior to 1980, the October average values in the polar region were greater than 280 DU.

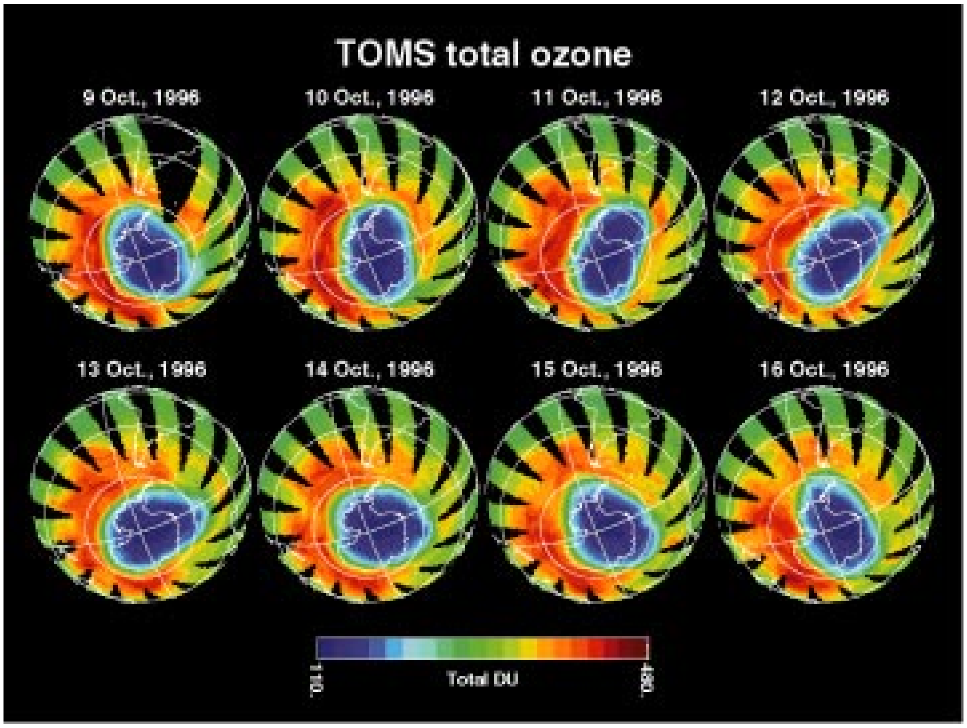


Figure III.A.4

The daily structure of the ozone hole is illustrated in Figure III.A.4 for October 1996 using TOMS Earth Probe satellite data. As is evident from this sequence of daily false color images, the ozone hole tends to be highly mobile (as was evident in the images of total ozone over Syowa station in 1983, Figure I.B.1.7). A typical pattern that develops is the elongation of the ozone hole that slowly rotates eastward. In Figure III.A.4 the panel for 10 October shows an ozone hole that is generally centered on the pole, but is elongated towards the tip of South America. On 11 October, this elongation axis is oriented towards the South Atlantic, and the hole continues to rotate in a clockwise sense over this 8 day period. Such elongations result in quasi-periodic passages of extremely low ozone values over sites such as the Antarctic Peninsula (e.g. see the ozone difference between 12 and 16 October at Cape Horn). Such large variability in overhead ozone is not typical of sites such as the South Pole, deep within the ozone hole.

B. Vertical ozone structure

Since ozone is produced in the stratosphere via the photolysis of oxygen molecules, ozone mixing ratios (the fraction of ozone molecules to the total number of molecules) are largest in the middle stratosphere in the tropics. The Brewer-Dobson circulation transports these high ozone concentrations towards the pole, and down into the middle and lower stratosphere. Figure III.B.1 displays a longitudinally averaged image of ozone observations from the Nimbus-7 SBUV instrument in October 1987.

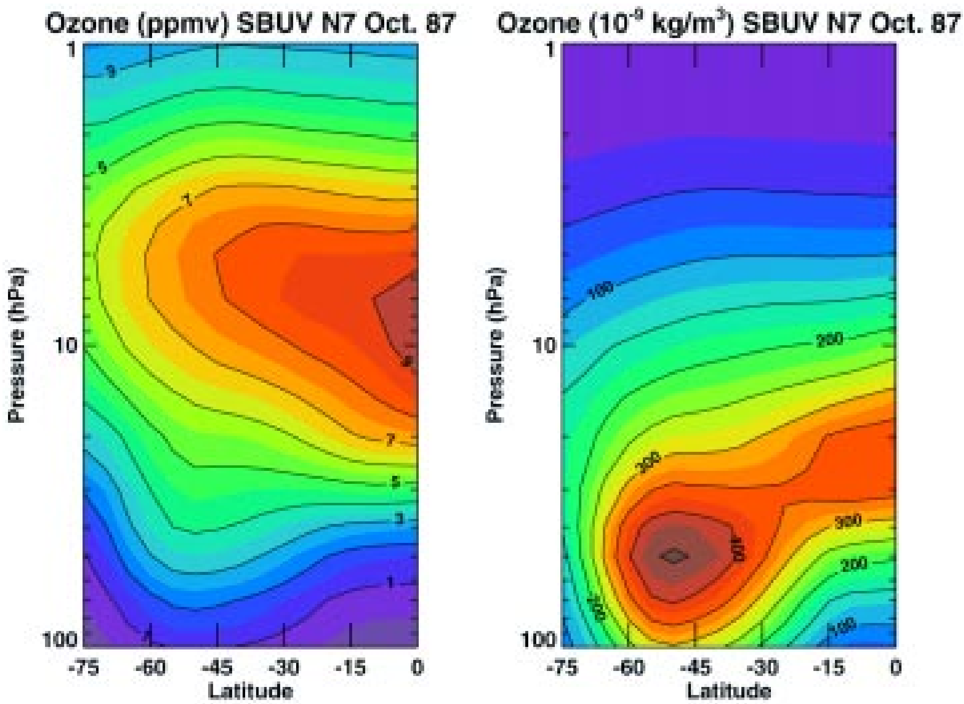
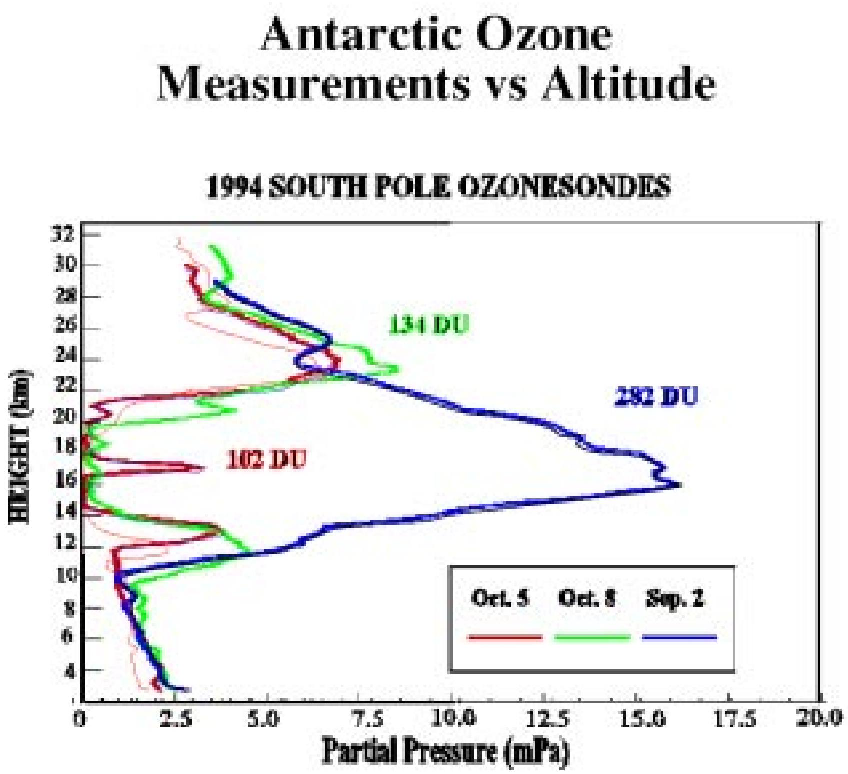


Figure III.B.1

The left panel displays ozone mixing ratio, while the right panel displays ozone density. As is apparent in the right panel, most of the ozone is contained in the lower stratosphere between about 18 and 28 km (70 hPa to 20 hPa). Over Antarctica, both the ozone density and mixing ratios were extremely low during 1987. The important features of these images are: 1) low ozone values in the lower stratosphere over the Antarctic region which result from chemical loss processes, 2) high ozone values in the mid-latitudes resulting from the poleward and downward circulation near the edge of the polar vortex, 3) low tropical values of ozone in the tropical region resulting from the upward lifting of low ozone air, and 4) the increasing ozone values with altitude which are caused by production of ozone via oxygen molecule photolysis. The SBUV observations poorly resolve the lower stratosphere, and hence the SBUV instrument is not an adequate monitor of the ozone hole loss processes which predominantly occur in the lower stratosphere.



Ozone partial pressure (mPA) profiles at the South Pole, measured by balloon borne ozonesondes. The profile on 2 September 1994, before depletion began, is compared with profiles for 5 October and 8 October 1994, during the minimum ozone period.

(from NOAA/CMDL home page http://www.cmdl.noaa.gov)

Figure III.B.2

Vertical ozone profiles observed with ozonesondes at South Pole station provide a clear picture of the evolution of the ozone hole as the sun rises over Antarctica during the August-September period. Figure III.B.2 shows a sequence of profiles acquired at South Pole station in 1994. This plot displays ozone partial pressure rather than mixing ratio or density as displayed in Figure III.B.1. Partial pressure is the fraction of the total pressure resulting from ozone, and is approximately proportional to density (dividing partial pressure by the local temperature yield ozone density). The figure shows two key features of the ozone hole: 1) the ozone hole is largely confined to the 14-22 km region over Antarctica, and 2) virtually 100% of the ozone is destroyed in this 14-22 km region between early August and late September.

C. Ozone annual cycle

The annual cycle of total ozone over Antarctica is displayed in Figure III.C.1. This figure shows Nimbus-7 TOMS total ozone as a function of time and latitude. The data are averaged over both time (1979-92) and longitude. The large bite out in the figure in the polar region during the winter months results from the inability of TOMS to make measurements during polar night, since the TOMS observations are based on a solar UV back scatter technique.

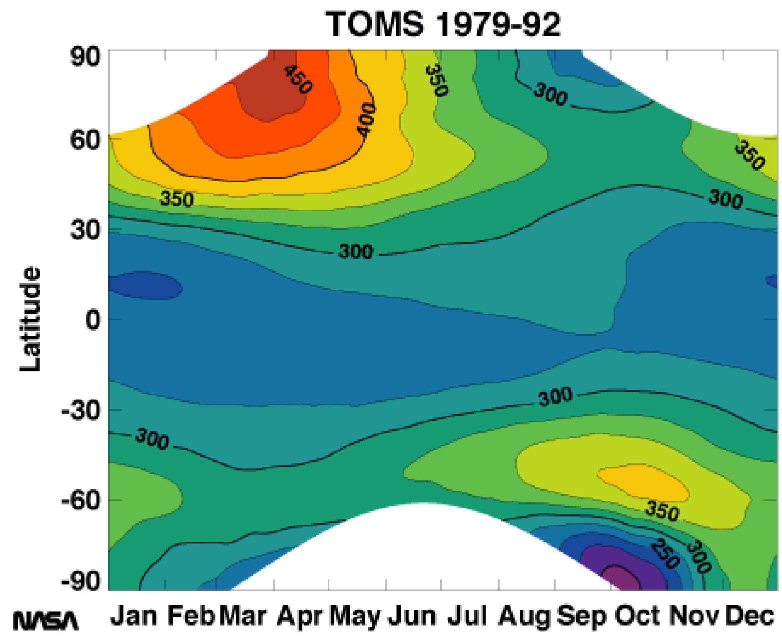


Figure III.C.1

During October, ozone values are seen to be extremely low over Antarctica, and a collar of high ozone is seen in the 40-70S region with low values also in the tropics (see Figure III.A.1). The high collar of ozone in the mid-latitudes is almost always present, with the exception of the summer period. The collar reaches its largest values in late October as a result of the continual accumulation of ozone in the lower stratosphere that is driven by the poleward and downward transport.

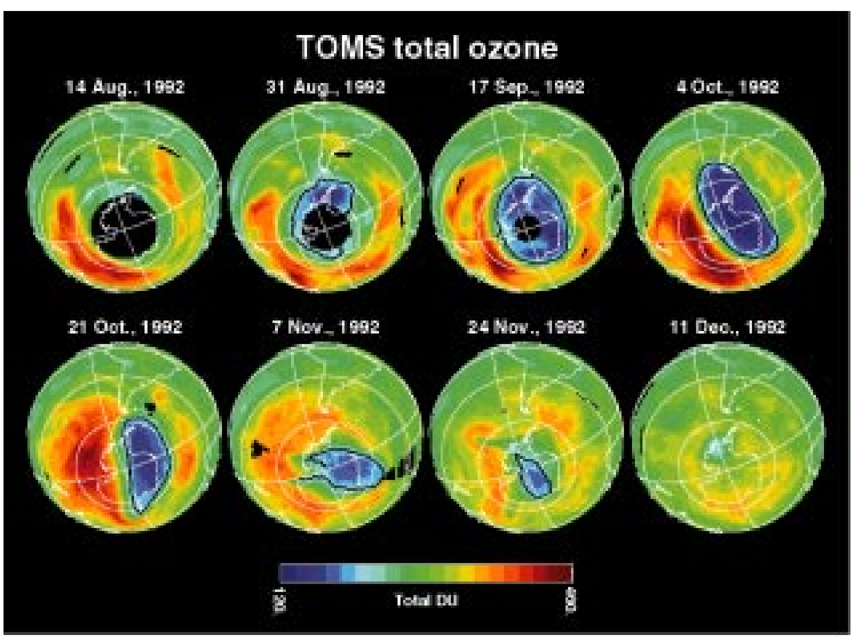


Figure III.C.2

The evolution of the ozone hole from August to early September is illustrated with a set of Nimbus-7 TOMS total ozone images during 1992 in Figure III.C.2. Again, regions of polar night are not observable by TOMS. The images show a deepening ozone hole from mid-August to early October, and a disappearing ozone hole after early October (as is clear from Figure III.C.1). The high ozone collar region increases in strength during this August-September period, and is quite strong by early October. The minimum value of ozone over Antarctica on October 4, 1992 is 126 DU at 81S, 1W. The minimum TOMS value for each day in 1992 is plotted as the solid line in Figure III.C.3, while the minimum ozone values in 1996 are plotted as the dots.

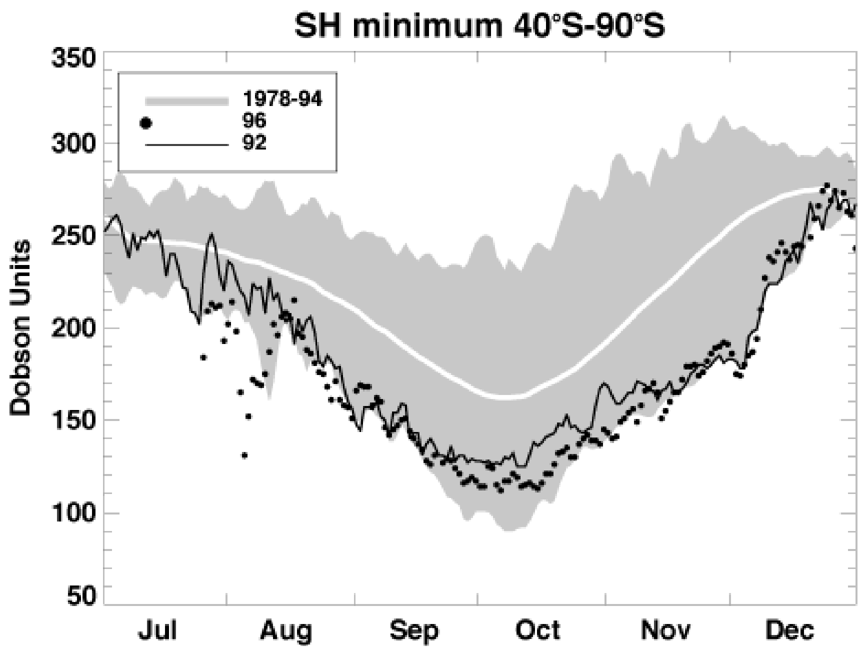


Figure III.C.3

The average minimum values for each date is the solid white line, while the range of minimum values is plotted as the gray shading. The gray shading shows that while both 1992 and 1996 had extremely low total ozone values, the record low observations were observed in 1993 and 1994. The largest losses of total ozone occur during the August through September period, while slow recovery of ozone begins in October and is complete by mid-December.

A second diagnostic of the severity of the ozone hole is the total surface area with ozone values less than 220 DU. The heavy black line on each panel of Figure III.C.2 indicates a total ozone value of 220 DU. This 220 DU contour is a reasonable representation of the ozone hole, since: 1) it cleanly separates the low total ozone from the high total ozone, 2) it is a value of total ozone that was not observed over Antarctica prior to 1979 (and hence represents a region of real ozone loss with respect to the historic record), and 3) it is relatively insensitive to variations in absolute calibration variations. In early August, there is only a small region with values below 220 DU near the Antarctic peninsula near the edge of polar night. By mid-September, the area of the ozone hole has greatly expanded to well over 20 million square kilometers. The area contained within the 220 DU contour has been plotted in Figure III.C.4.

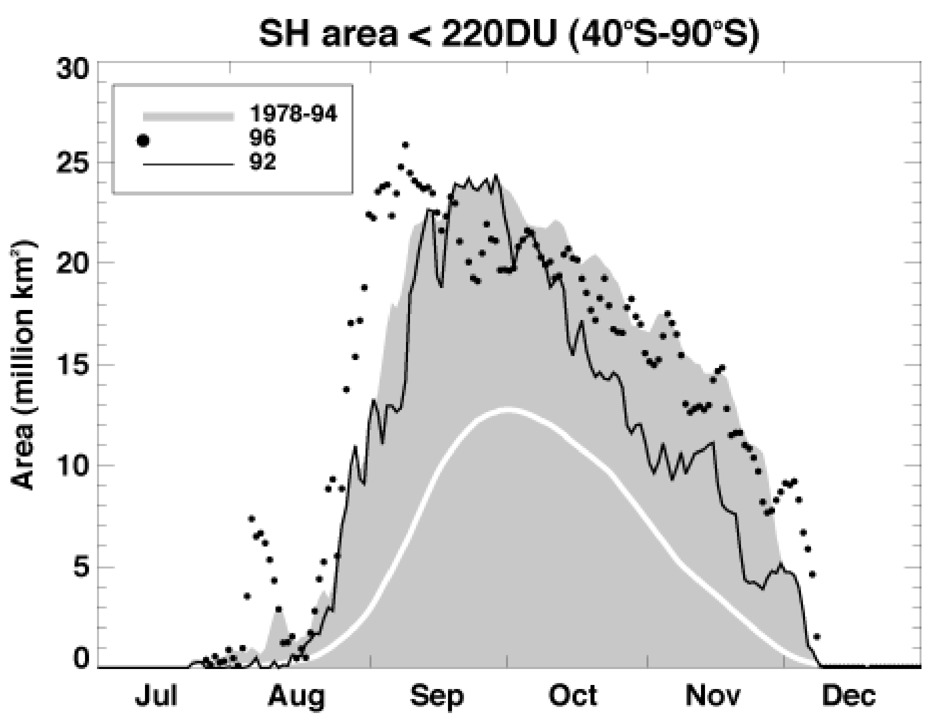


Figure III.C.4

As with the minimum total ozone value over Antarctica, the average size for the years 1979-1994 is plotted as the thick white line, while the gray shading displays the range of area values observed on each day over the 16 year period. As is clear from the plot, the size of the ozone hole generally reaches its maximum extent by late-September, and begins to contract starting in early October. The hole is not well resolved in August because of polar night, but is clearly observable by early September. The whole is nearly gone by mid-December.

The average size of the ozone hole can be determined by averaging the daily values displayed in Figure III.C.4 between early September, and mid-October. This average is shown in Figure III.C.5 for all of the years 1979 to 1996 (1995 is omitted since no TOMS instrument was in orbit in 1995). The average values are displayed as the heavy yellow dots, while the vertical red lines show the range of observations for a particular year.

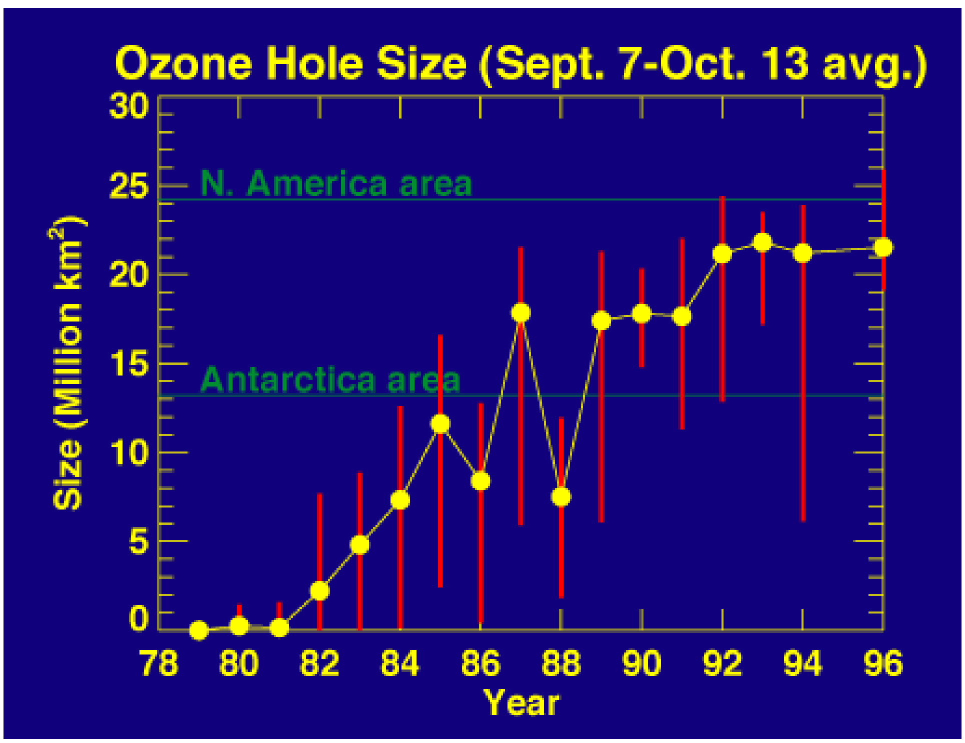


Figure III.C.5

In 1992, the average size of the ozone hole was slightly less than 22 million square kilometers, but that the hole exceeded 24 million square kilometers in late September. The average size in 1996 was nearly the same as in 1992, but the hole exceeded 26 million square kilometers in early September. The maximum size of the ozone hole is approximately the same size as the North American continent.

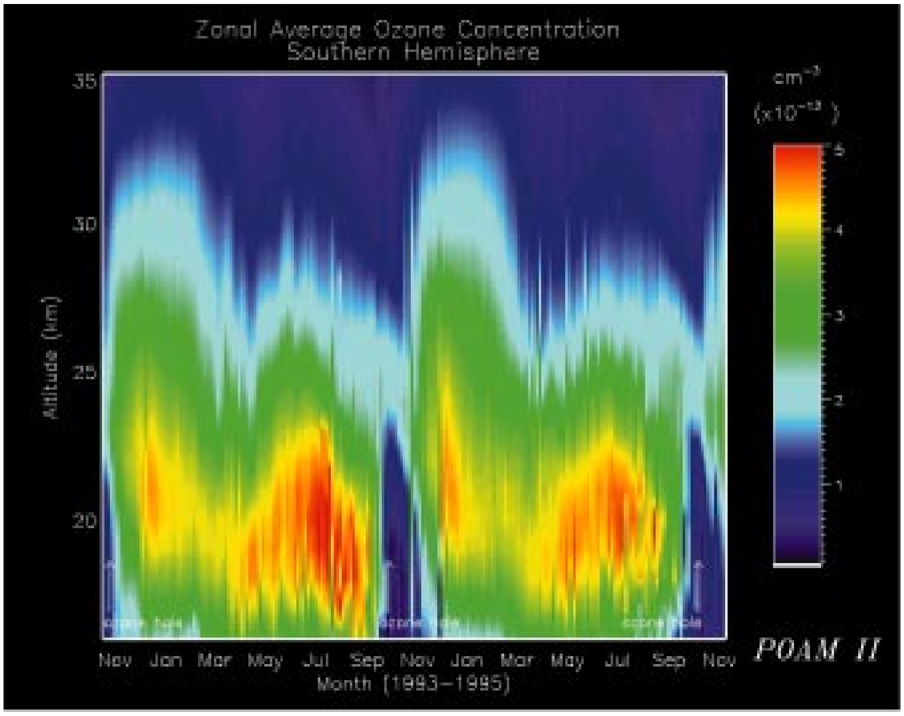


Figure III.C.6

The development of the ozone hole develops quite rapidly over a broad altitude range as the sun rises over Antarctica in the spring. Figure III.C.6 shows ozone number density observations from the POAM satellite (number density is the number of ozone molecules in a given volume of air) between 15 and 35 km from November 1, 1993 to November 1, 1995. At 20 km, the ozone number density values fall from peak concentrations of about $5x10^{12}$ $/cm^3$ to nearly zero over the August–September period in the altitude range from the lowest observations (16 km) to 22 km (in excellent agreement with the South Pole balloon observations in Figure III.B.2). Ozone number density values recover in the November–December period.

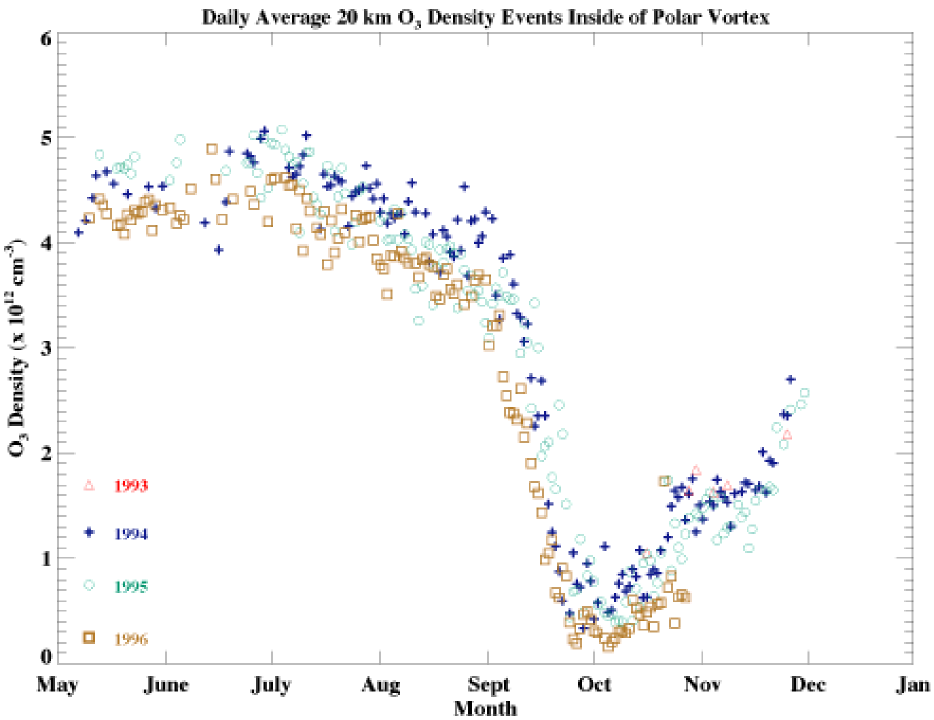


Figure III.C.7

The decrease of ozone observed by POAM can be more easily seen in the dramatic decrease of ozone at 20 km in Figure III.C.7. Ozone values gently decrease in July and August, and rapidly decrease during September to near zero by late-September, with a steady recovery in the October–December period. The column amount between 12 and 20 km from South Pole balloon observations also shows this remarkable change of ozone (Figure III.C.8), with ozone decreases of over 100 DU between mid-August and early October.

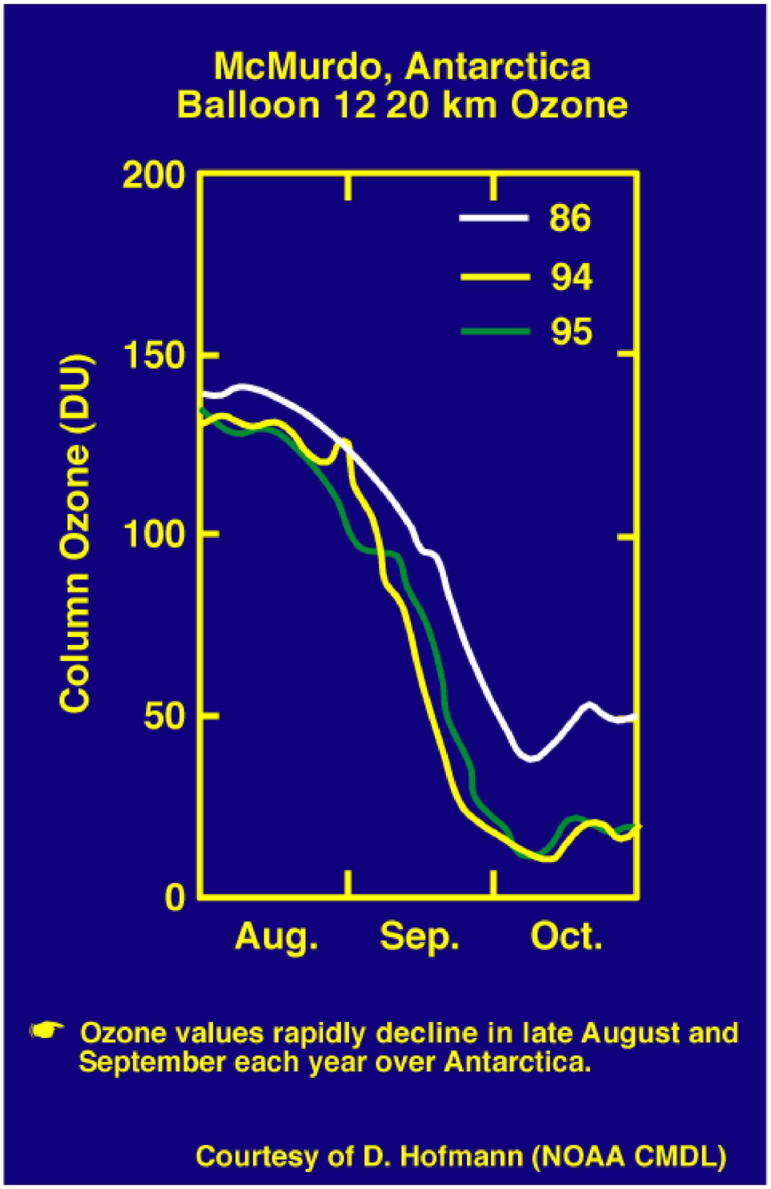


Figure III.C.8

While the development of the ozone hole is discernible from column ozone observations (TOMS) over the hemisphere, this instrument provides little information on the vertical structure of the ozone hole. The balloon profiles and satellite profiles from POAM provide excellent vertical information on the ozone hole, but fail to give a hemispheric perspective on the hole. The MLS instrument on the UARS satellite provides information on both the vertical and horizontal structure of the ozone hole. Figure III.C.9 shows a series of MLS false color images of ozone on the 500 K isentropic surface (approximately 22 km).

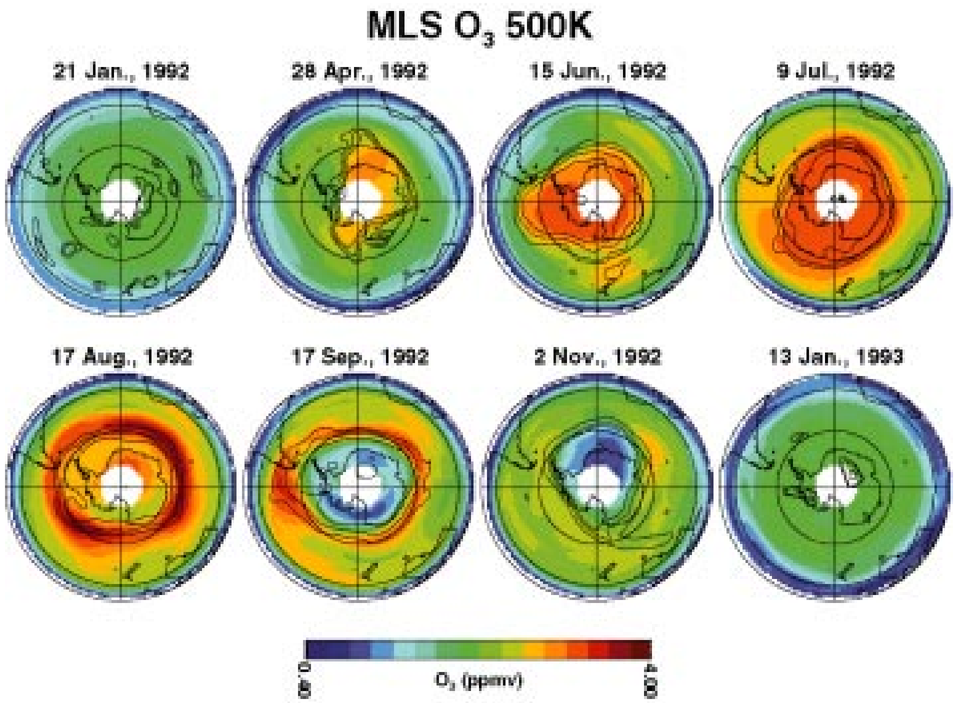


Figure III.C.9

The January period shows a relatively flat ozone field, with steadily increasing ozone through the winter period. By mid August, ozone values have begun to decrease inside the polar vortex (denoted the black lines on the plots), and by mid-September the ozone values are nearly zero in the polar region. Ozone is still relatively low in early November, but the ozone hole has completely disappeared by December. Again, as discussed in section III.E, these images show: 1) the ozone hole development in the August-September period, 2) the build up of ozone in the lower stratosphere by downward advection of high ozone mixing ratios from the upper stratosphere, 3) the containment of the ozone depletion region, and 4) the recovery of ozone after November.

D. Ozone hole breakup

After the ozone hole loss period in the August-September period, ozone values within the hole begin to gradually rise to more normal levels. The is recovery is apparent in Figures III.C.2 (ozone hole maps), III.C.3 (minimum ozone values over Antarctica), III.C.4 (ozone hole areal coverage), III.C.6 vertical distribution of ozone), and III.C.7 (ozone concentrations at 20 km). The recovery is driven largely by the breakup of the polar vortex, and the horizontal transport of high mid-latitude ozone values into the polar region.

Figure II.A.2 shows how the vortex breaks down via the steady decrease of wind speeds during the spring period. As the wind decreases, the barrier to transport between the mid-latitudes and the polar region weakens, and high ozone values are swept over Antarctica. The breakup of the vortex begins first at higher altitudes (36 km in August), and gradually moves downward such that the breakup at 16 km occurs in early December. Hence, the period of ozone recovery first appears at the higher altitudes, and gradually descends to lower altitudes. This recovery is evident in Figure III.C.6, where the low ozone values inside the hole (purple) first increase at the higher altitudes, with later recovery at lower altitudes.

The steady filling of the depleted region from the top downward manifests itself in the column concentrations as a gradual rise in the minimum total ozone concentration (see Figures III.C.2 and III.C.3), and a steady decline of the ozone hole area (see Figure III.C.4). The recovery of ozone at a single station is quite dramatic, as high ozone concentrations are swept over Antarctica (see Figures I.B.1.5 and I.B.1.6).

The ozone hole observations are summarized in Fig. III.C.10. First, the hole is a seasonal phenomena that develops in August and September, has reached its largest extend and deepest values in early October, and breaks up in early December. Second, the ozone hole was weakly observable as far back as the mid-1970's, and was easily observable by the early 1980's. Third, the ozone hole constitutes a 60% reduction in total column ozone concentrations, and a 100% local loss in the 12-20 km layer. Fourth, the ozone hole is associated Antarctic polar vortex and the cold winter temperatures.

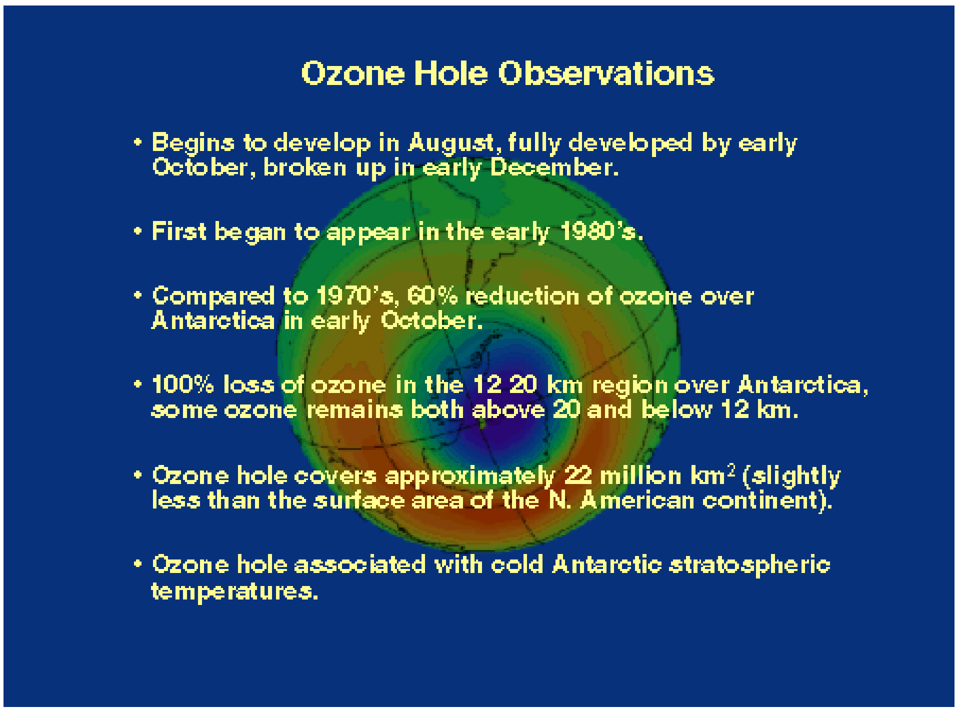


Figure III.C.10