Lecture 10: The Antarctic Ozone Hole

II. THE POLAR VORTEX

The polar stratospheric regions of both hemispheres are surrounded by a stream of high winds blowing from west to east. This jetstream is commonly referred to as the polar night jet. The Antarctic polar vortex is the region poleward of this jet stream core. During winter, the jet stream can reach speeds of over 100 mph at altitudes of 70,000 ft. The Antarctic polar vortex completely circumnavigates the continent of Antarctica. Figure II.1 displays a plot of temperatures and winds for August 1, 1994 at 4 different levels in the stratosphere.

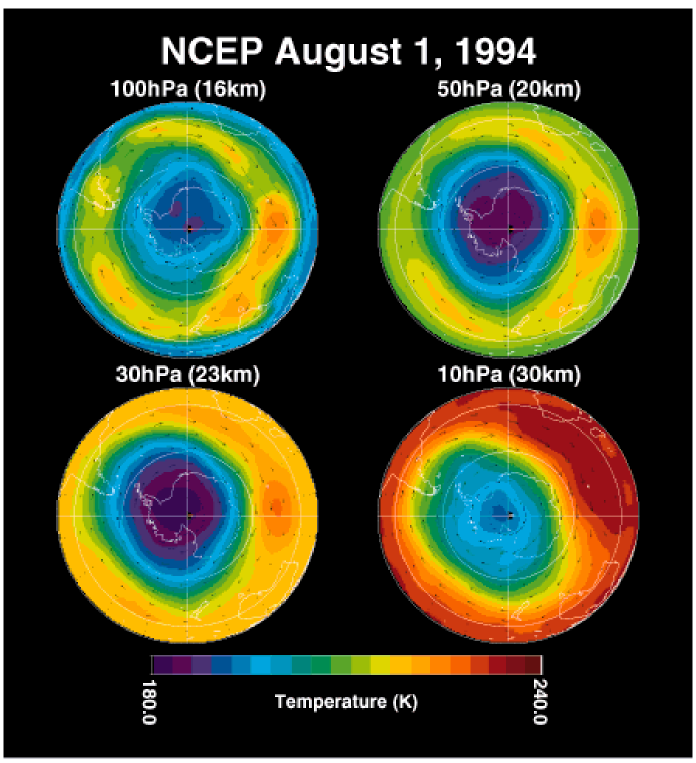

Figure II.1

As is clear from the figure, extremely cold temperatures are found over Antarctica during the winter, averaging about 183 K (–130 F) at 50 hPa (20 km) in early August. These cold temperatures are contained interior of a strong westerly flow regime. The winds are predominantly west-to-east, with a rather weak north-south component. These cold temperatures within the polar vortex are necessary for the formation of polar stratospheric clouds (PSC's) which form at temperatures below about –80 C. The presence of PSC's enables heterogeneous chemical reactions to take place on the surfaces of these particles, freeing the non-reactive forms of chlorine to a form which can produce ozone destruction.

A. Winds

The westerly circulation of the polar vortex is strongest in the upper stratosphere and builds up over the course of the winter. This extremely strong westerly jet is known as the polar night jet. The importance of this polar night jet is that it acts as a barrier to north-south transport. Because of this barrier, ozone rich air in the mid-latitudes cannot be transported into the ozone hole region during winter.

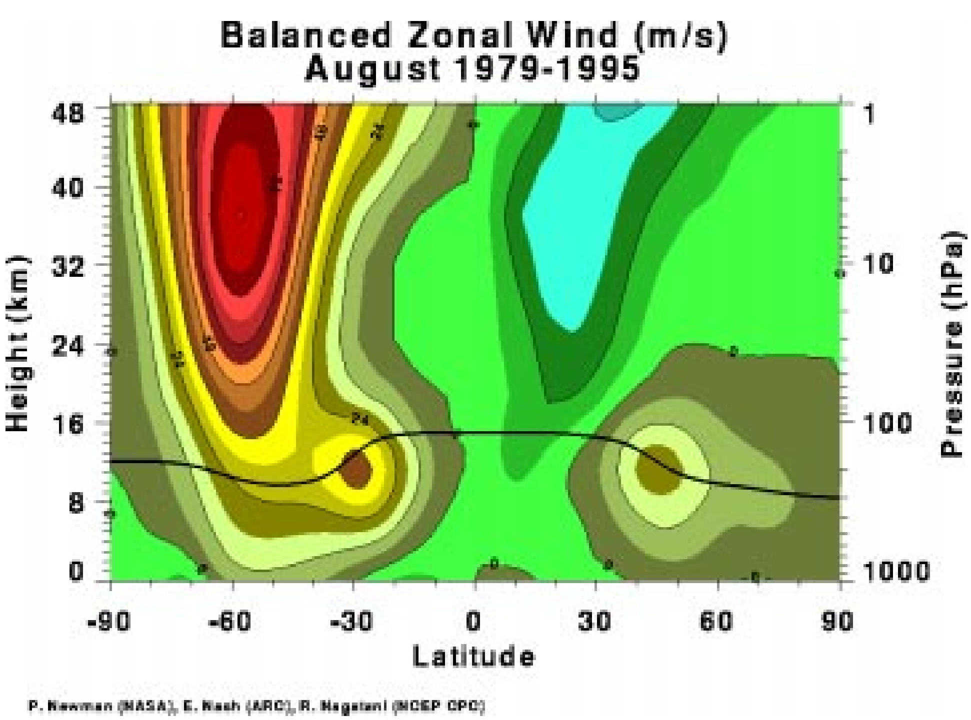

Figure II.A.1

Figure II.A.1 displays the longitudinally averaged winds for August in the southern hemisphere. These 'zonal' winds are averaged both in longitude and time over a 17 year period. The peak August wind value is 84 m/s (190 mph) at about 37 km (5 hPa). This peak tends to occur at about 60S. A weaker jet maximum is found in the upper troposphere, centered at about 30 S and 12 km, and is referred to as the subtropical jet. The tropopause is defined by a break in the vertical temperature distribution, and separates the troposphere and stratosphere (indicated by the thick black line).

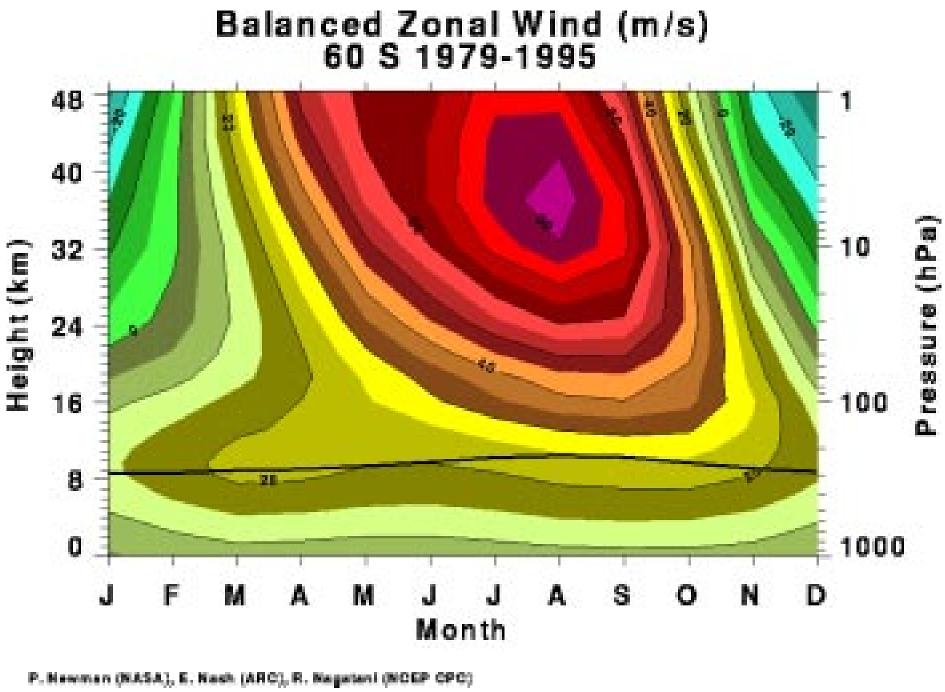

Figure II.A.2

The evolution of the polar night jet over the course of the winter is illustrated in Fig. II.A.2 in an altitude versus time contour plot. The polar vortex begins to develop in early spring, and is fully developed by May. At lower levels, the vortex develops at a somewhat slower rate, becoming fully developed in the June–July period. This vortex development is also illustrated in Fig. II.A.3 in a latitude versus time plot showing the evolution of the winds on the 50 hPa (approximately 20 km) surface.

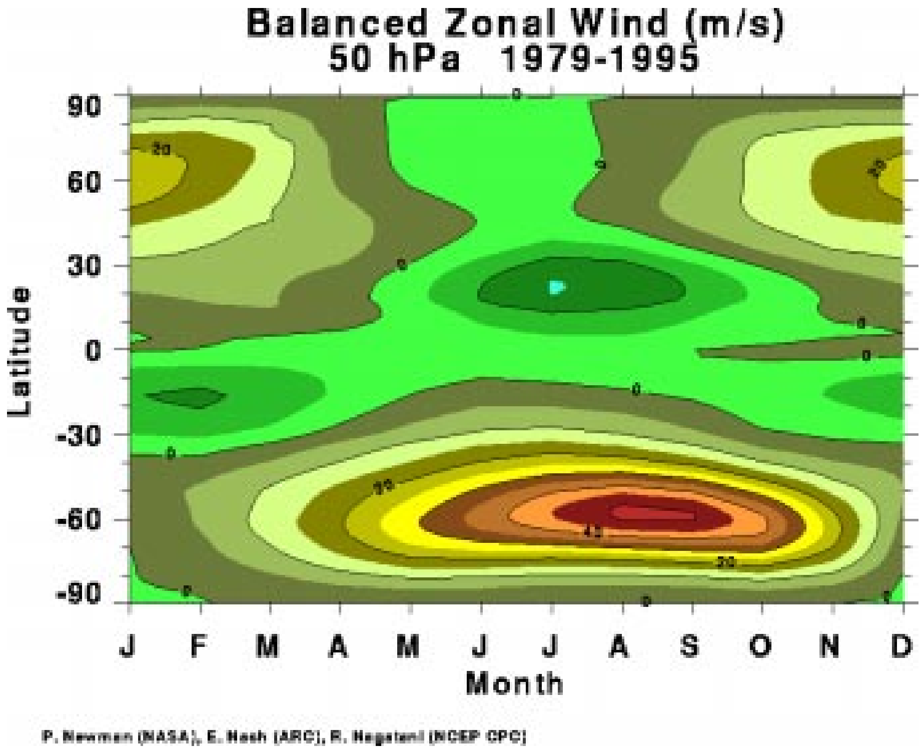

Figure II.A.3

The polar night jet begins to develop in early fall (February-April) and reaches its maximum wind speed in the August–September time frame, and then breaks up in the November-December time period. As is seen in Figure II.A.1, the polar night jet is almost always centered at about 60S. In contrast to this southern polar night jet, the northern hemisphere polar jet is weaker in mid-winter, and has decreased in strength by late winter. The southern polar night jet breaks up in October–December period, nearly 2 full months later in the spring period than the northern polar night jet. The location of Antarctic stations are generally well poleward of the polar jet stream. The key aspect of the polar vortex is that it acts as a barrier to horizontal transport of air. This isolation of the polar vortex is a key ingredient to polar ozone loss, since the vortex region can evolve without being disturbed by the more conventional chemistry of the midlatitudes.

B. Temperatures

The polar vortex temperatures are extremely cold during the winter period. Fig. II.B.1 displays a multiyear longitudinally averaged (i.e., zonal mean) plot of temperature for August.

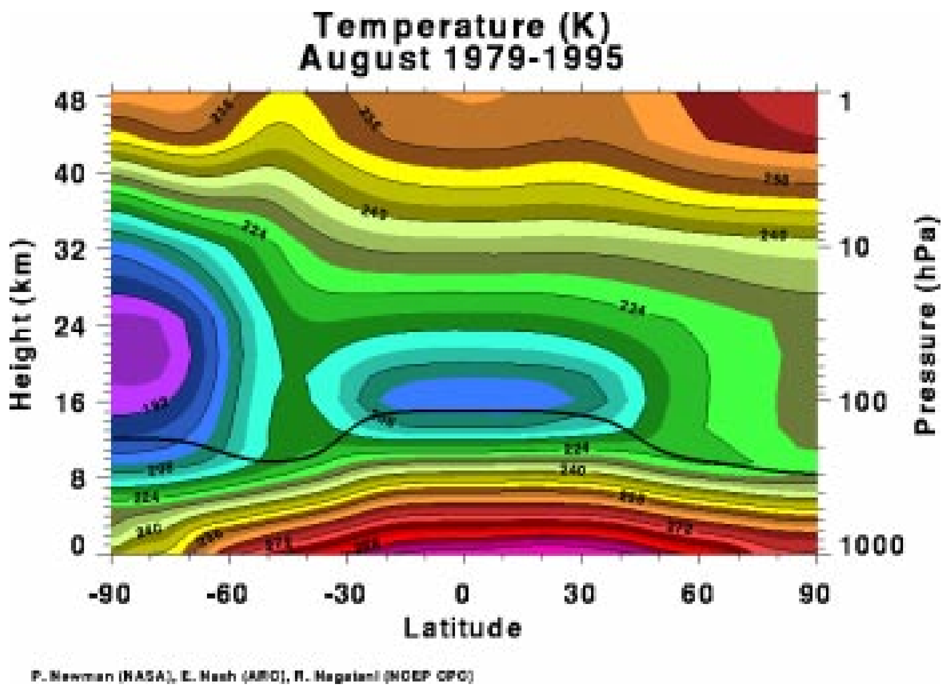

Figure II.B.1

Temperatures are below 192 K (–114 F) over a deep layer (15–27 km), and extending from the pole to 70S. These cold temperatures develop during the polar night because of the lack of solar heating, the strong infrared cooling to space, and the lack of strong dynamical wave activity to warm the pole.

The tropopause separates the troposphere and stratosphere is indicated by the thick black line. The tropopause is basically defined by the temperature minimum between the stratosphere and troposphere. The tropopause is typically near about 16 km (53,000 ft.) in the tropics, about 10 km (33,000 ft.) in the midlatitudes, and approximately 12 km (40,000 ft.) in the polar region.

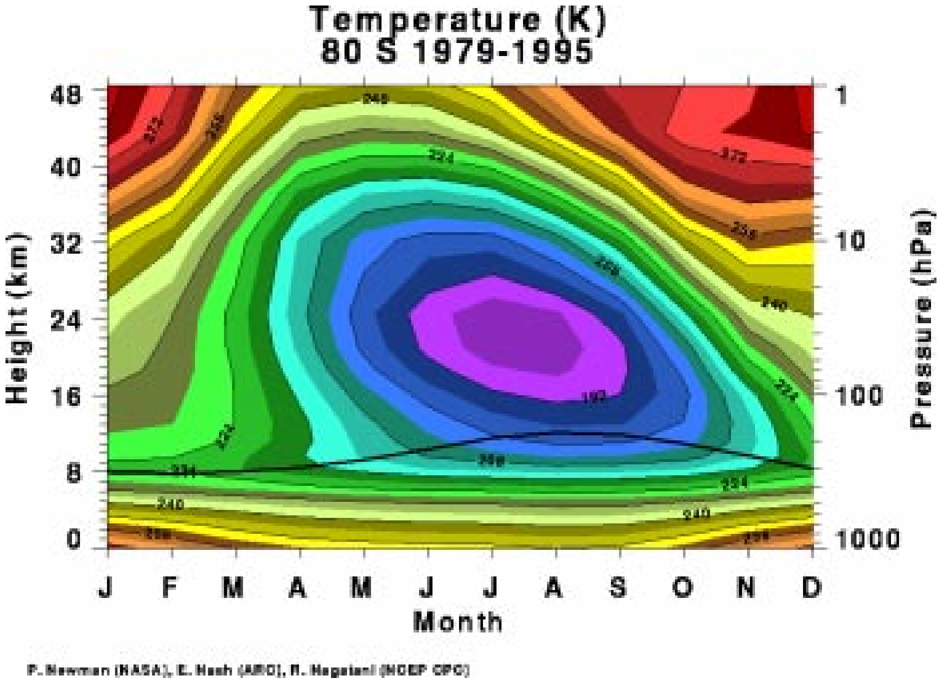

Figure II.B.2

The temporal evolution of these cold temperatures is illustrated in Fig. II.B.2 with a longitudinally averaged (i.e., zonal mean) plot of the temperatures at 80S as a function of altitude. The polar region cools over the course of the fall period at all altitudes. This cooling is extremely strong at the highest altitudes in early fall (40–48 km), with warming beginning in the June-July period. The coldest temperatures (i.e., temperatures less than 192 K) first appear in July at approximately 24 km (30 hPa). These cold temperatures begin to appear at lower altitudes later in the season. Hence, at the higher altitudes, the coldest period is in early winter, while at the lower stratospheric altitudes, the coldest temperatures are in late-winter. The temperatures rapidly warm during the breakup of the polar vortex. This breakup occurs earliest at the highest altitudes, and occurs the latest at the lowest altitudes. Because the ozone hole is observed at the lower altitudes below 30 km (100,000 ft.), the temperature region of greatest concern is between 10 and 30 km.

The cold temperatures inside of the polar vortex are crucial to the large polar ozone losses. Polar stratospheric clouds (PSCs) are the key to this loss process. These PSCs have been observed in both the Arctic and Antarctica for quite some time (Stanford and Davis, 1974; Stanford 1977). McCormick et al. (1982) showed that PSC sightings from satellite data were strongly correlated with the cold temperatures below approximately 195 K. Both McElroy et al. (1986) and Solomon et al. (1986) recognized that polar stratospheric clouds which formed in the cold temperatures of polar night, could provide efficient sites for heterogeneous chemical reactions. Hence, it is the cold temperatures of the lower stratosphere which provide the first element in understanding the Antarctic ozone hole.

C. Potential Vorticity

Potential vorticity is a quantity which is derived from wind and temperature fields, and is conserved in the atmosphere over time periods ranging from weeks to days. Whereas the temperature and wind speeds of a particular air parcel might vary in time, the potential vorticity remains almost the same from day-to-day. Hence, potential vorticity is a fundamental diagnostic of air motion in the stratosphere (see Holton, 1992 for a more complete discussion of potential vorticity).

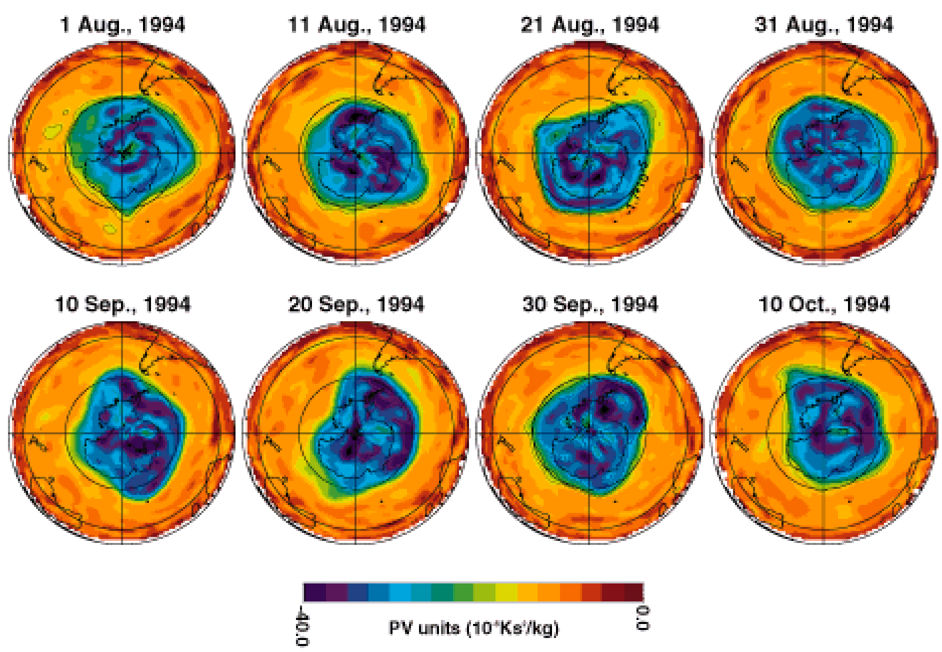

Figure II.C.1

Potential vorticity is primarily utilized to identify the polar vortex. Figure II.C.1 displays a set of images of potential vorticity during the southern winter of 1994 near about 18km (an isentropic value of 440K). This period encompasses the development of the Antarctic ozone hole. Note the very low (potential vorticity is negative in the southern hemisphere) values of potential vorticity over the pole (indicated by the purple colors), and the somewhat higher values in the mid-latitudes (indicated by the orange colors). The edge of the polar vortex (indicated by the dark lines) indicates the location of the polar night jet stream.

The importance of the polar vortex is that it acts to form a barrier to transport of material out of the polar vortex. McIntyre (89) argued that the Antarctic vortex ought to be highly contained because of the barrier set up by the sharp transition in potential vorticity values between the polar and mid-latitude regions. The containment occurs because a northward displacement of the low Antarctic potential vorticity will act to create a flow field that will displace this air back towards the south. The containment of the Antarctic vortex has been demonstrated with both trace gas observations (e.g. Schoeberl et al., 1989) and with modeling studies (e.g. Bowman 1993).

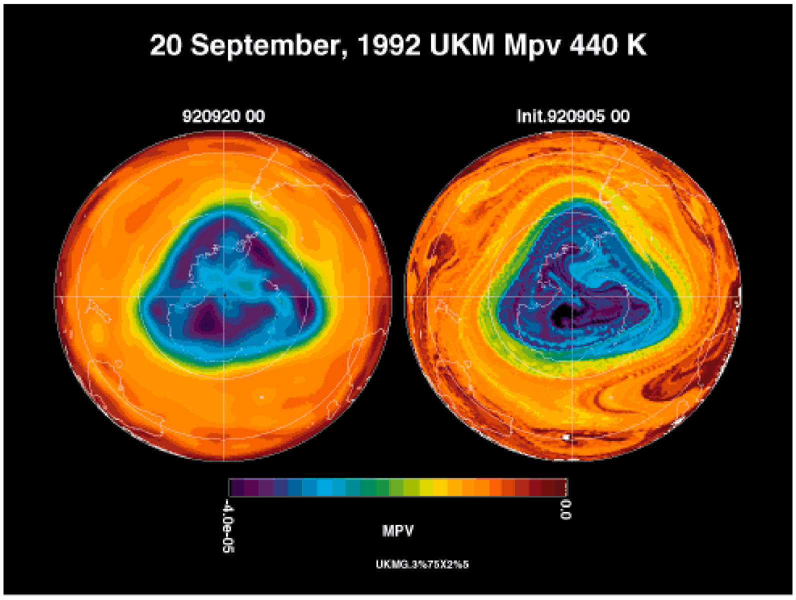

Figure II.C.2

Figure II.C.2 displays a plot of potential vorticity on September 20, 1992 as constructed from a 6,624 parcel trajectory run. The plot is on a 440K isentropic surface, and the trajectories are initialized with potential vorticity on August 31. The 440K level is near 18 km, and hence is centered on time and vertical region of maximum ozone loss. The plot displays a number of key features. First, the potential vorticity values from the August 31 initialization are of a similar magnitude to the analyzed potential vorticity, indicating that potential vorticity is a conserved quantity during the ozone hole period. Second, the trajectory model is produced at a higher resolution than the analysis, and reveals details of structure that are not resolved by the analysis. Third, the 15 day trajectory run shows virtually no escape of air into the mid-latitudes, illustrating the containment of the Antarctic polar vortex. This transport barrier is a crucial element of the ozone hole theory.

The barrier to transport caused by the potential vorticity prevents infusions of air into the ozone depleted region over Antarctica. In addition, nitrogen compounds that might inhibit ozone loss by reacting with chlorine are also not transported over Antarctica. Hence, polar ozone loss processes can occur undisturbed until the polar vortex breakup in late November.

D. Heating

The stratosphere is primarily heated by absorption of solar UV radiation by ozone (known as shortwave heating), while the stratosphere is primarily cooled by emission of IR radiation to space by carbon dioxide and ozone (known as long-wave cooling). During the polar winter, the Antarctic stratosphere cools off quite dramatically as the solar UV heating by ozone ends. Figure II.D.1 displays a 17-year average of net heating (sum of the shortwave heating and longwave cooling) in the stratosphere at 20 km as computed from the Goddard radiation model.

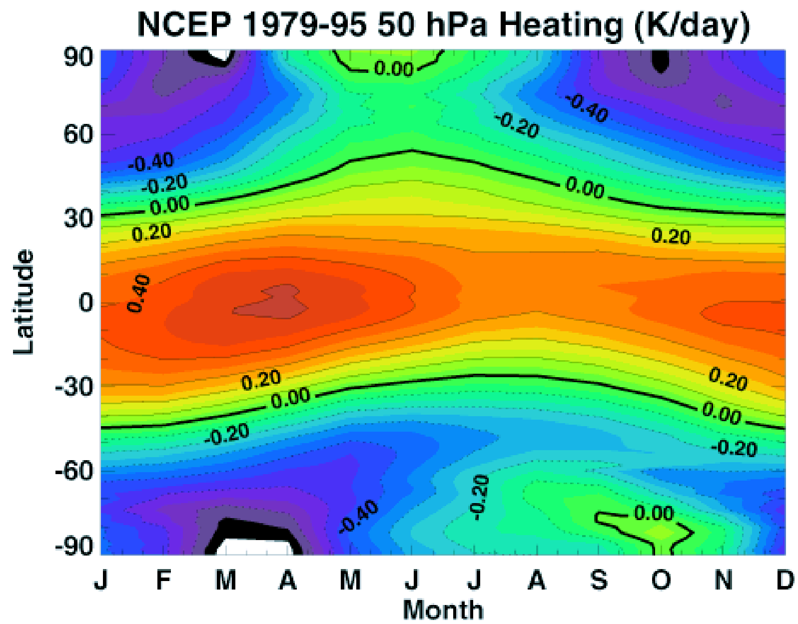

Figure II.D.1

During the March–April period, the stratosphere cools quite dramatically as the sun goes down over the pole in late March. However, this process does not continue indefinitely, since the stratospheric temperatures become cold enough that longwave radiation is now absorbed in the stratosphere by ozone and carbon dioxide. By August, the temperatures have become extremely cold, and the net cooling is near zero. Net cooling remains extremely small until after the polar vortex breakup in late-November, when the polar region has warmed to relatively high temperatures, and IR cooling to space again becomes important.

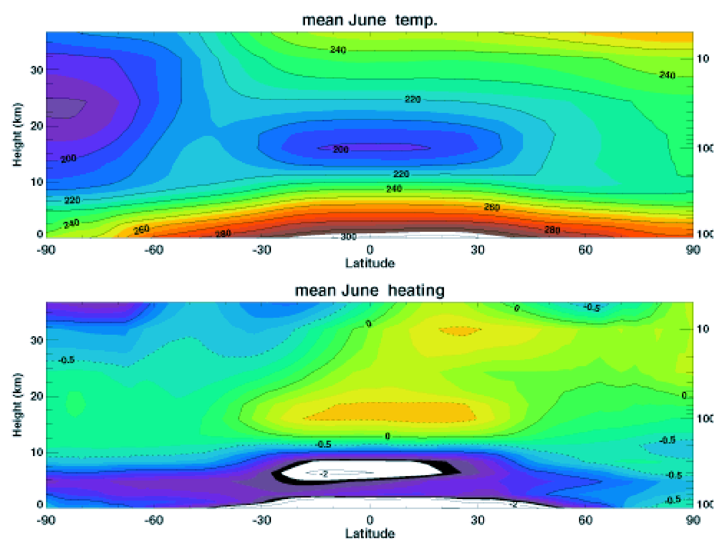

Figure II.D.2

Figure II.D.2 displays the 17-year June longitudinally averaged temperatures (top) and heating rates (bottom). Between 22 and 25 km, mean temperatures have fallen below 190 K. These temperatures are cold enough that the cooling rate has become quite small. These heating rates are extremely important, since cooling air descends, while warming air rises. In the tropics, the heating causes rising motion, while the polar cooling causes sinking motion.

E. Transport

Because of the prevailing westerly winds in the polar (see section II.A), air tends to move in a clockwise sense when viewed from space above the South Pole. The air at the 50 hPa (approximately 20 km) level circles the pole on about a 4-6 day time period in mid-winter.This basic background circulation is illustrated in Figure II.E.1 with a set of trajectories initialized on September 20, 1992 at 00 Greenwich mean time and run forward for 3 days to September 24, 1992 at 00 Greenwich mean time (superimposed on an image of total ozone for September 21, 1992).

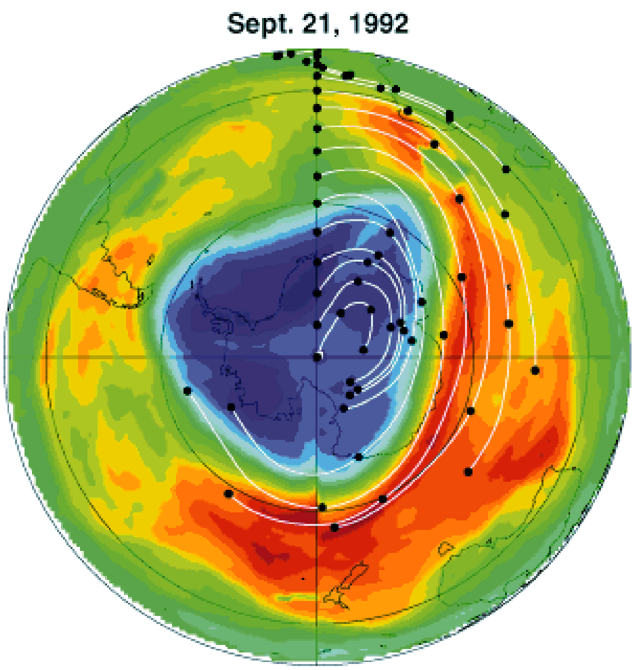

Figure II.E.1

These trajectories represent the motion of a piece of air, or the location of a balloon that is released in the flow. The air parcels move in a clockwise sense (white lines) around the polar vortex, with the greatest movement near the core of the jet stream (the parcel location at 00 Greenwich mean time is indicated by the black dot). The motion is predominantly west-to-east, with relatively small displacements in the north-south directions (for the reasons discussed in section II.C). Note that the fastest motion of the air parcels occurs near the edge of the ozone hole in the core of the jet stream.

Because air parcels are relatively isolated inside the polar vortex, the vertical motion of air is extremely important for diagnosing the evolution of the ozone hole. One of the original theories of the ozone hole cause was based on the transport of low ozone air from the troposphere into the lower stratosphere. Rosenfield et al. [1994] has shown that the air inside the ozone hole during the September time period (i.e. air below 20 km) has descended from altitudes near 25 km over the course of the SH winter. Similar observations have been determined via observations of the descent rates of long lived tracers in the UARS satellite data (Schoeberl et al., 95).

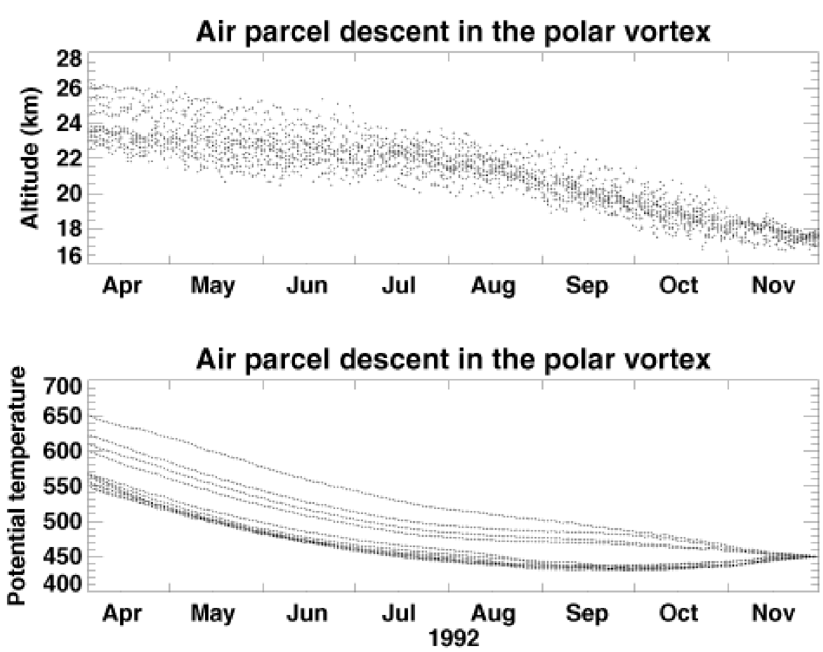

Figure II.E.2

Figure II.E.2 shows the motion of 10 air parcels contained within the polar vortex from early April to the end of November 1992. The top panel of the figure shows the descent of these parcels from their initial altitudes between 23 and 26 km, to a final altitude of about 17.5 km (an average descent rate of about 0.9 km/month). The lower panel displays the evolution in potential temperature of the parcels, indicating a mean descent rate of between 12.5 and 25 K/month.

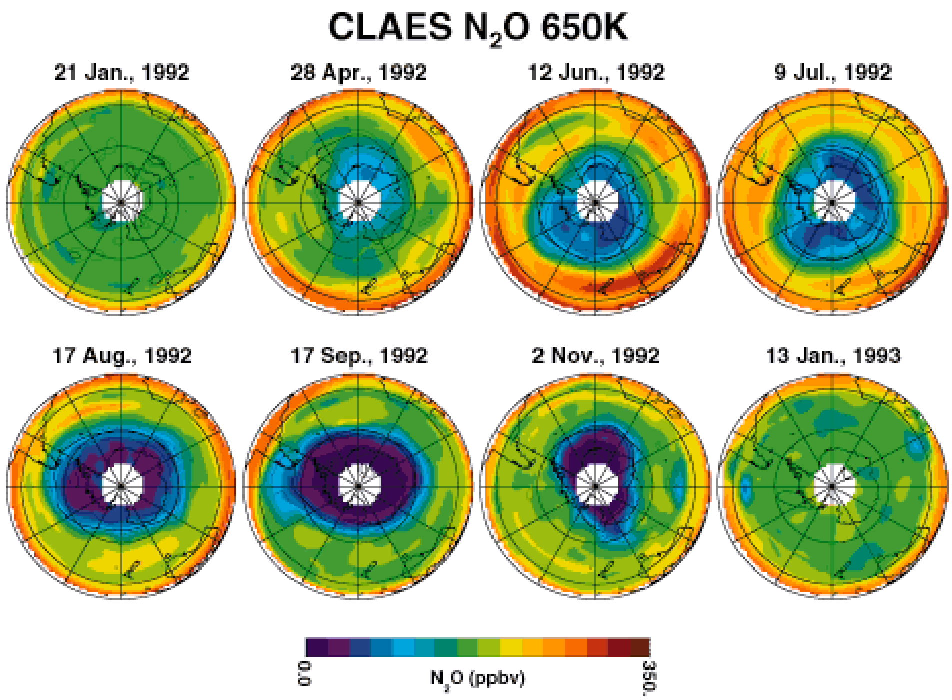

Figure II.E.3

Nitrous oxide (N_2O) is a crucial diagnostic of stratospheric motion. Figure II.E.3 displays a plot of N_2O at 650K (approximately 24 km) for 8 days in 1992 as measured by the CLAES instrument aboard the UARS satellite. N_2O has a tropospheric source from both biogenic and industrial processes, and an upper stratospheric sink by reactions with O atoms, and by being broken up by solar UV radiation (i.e. photolysis). Because these loss processes are quite slow, N_2O has a very long lifetime in the lower stratosphere, and can be used to trace atmospheric motion. Since N_2O in the troposphere is very high and N_2O values in the upper stratosphere are quite low (see Figure I.B.2.2 to see a vertical profile of N_2O over Antarctica), high N_2O in the lower stratosphere is an indicator of air that has troposphere characteristics, while low N_2O air in the lower stratosphere is characteristic of air that has been in the upper stratosphere. Superimposed on the Figure II.E.3 are contours showing the boundary of the Antarctic polar vortex. Initially in January, the N_2O values are low over much of the southern hemisphere. As the vortex begins to form (28 April1992 panel), N_2O continues to decrease as low N_2O air from the upper stratosphere is transported downward into the polar vortex. This process continues through the September period, and the vortex breaks up in late November mixing the low N_2O into the mid-latitudes. In addition to the low N_2O values in the polar region, the CLAES observations also reveal high N_2O in the tropics, providing evidence of the tropical uplifting from the troposphere. The CLAES N_2O observations provide clear evidence for: 1) strong downward motion into the polar vortex, 2) isolation of the polar vortex from mid-latitude influence, 3) vertical uplift in the tropics, and 4) confirmation that potential vorticity is an extremely important diagnostic of the ozone hole.

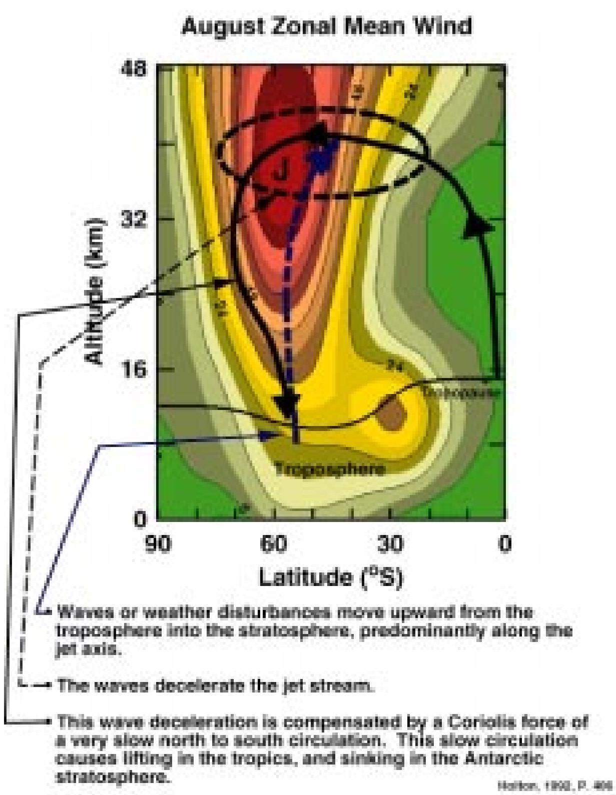

Figure II.E.4

The basic winter stratospheric circulation is summarized in Figure II.E.4. This basic circulation is rising motion in the tropics and sinking motion in the polar region. This basic circulation has been recognized since the early work of Brewer (49) on water vapor observations, and is now known as the Brewer-Dobson circulation. Details within this circulation in the polar region produce the characteristic 'collar' of high ozone that is observed in Figure I.B.1.2. The reasons for this basic circulation are a result of weather systems ('waves') that propagate into the stratosphere from the troposphere, depositing energy that acts to decelerate the polar jet stream. A very weak poleward circulation develops to balance this wave driven deceleration, thus maintaining the polar jet, and producing the gentle uplift in the tropics and sinking motion in the polar region.