

Robert Parson FAQ

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----- **Subject:**

1. THE STRATOSPHERE

Subject: 1.1) What is the stratosphere?

The stratosphere extends from about 15 km to 50 km. In the stratosphere temperature increases with altitude, due to the absorption of UV light by oxygen and ozone. This creates a global "inversion layer" which impedes vertical motion into and within the stratosphere - since warmer air lies above colder air, convection is inhibited. The word "stratosphere" is related to the word "stratification" or layering. The stratosphere is often compared to the "troposphere", which is the atmosphere below about 15 km. The boundary - called the "tropopause" - between these regions is quite sharp, but its precise location varies between ~9 and ~18 km, depending upon latitude and season. The prefix "tropo" refers to change: the troposphere is the part of the atmosphere in which weather occurs. This results in rapid mixing of tropospheric air. [Wayne] [Wallace and Hobbs] Above the stratosphere lie the "mesosphere", ranging from ~50 to ~100 km, in which temperature decreases with altitude; the "thermosphere", ~100-400 km, in which temperature increases with altitude again, and the "exosphere", beyond ~400 km, which fades into the background of interplanetary space.

In the upper mesosphere and thermosphere electrons and ions are abundant, so these regions are also referred to as the "ionosphere". In technical literature the term "lower atmosphere" is synonymous with the troposphere, "middle atmosphere" refers to the stratosphere and mesosphere, while "upper atmosphere" is usually reserved for the thermosphere and exosphere. This usage is not universal, however, and one occasionally sees the term "upper atmosphere" used to describe everything above the troposphere (for example, in NASA's Upper Atmosphere Research Satellite, UARS.) -----

Subject: 1.2) How is the composition of air described? (Or, what is a 'mixing ratio'?) The density of the air in the atmosphere depends upon altitude, and in a complicated way because the temperature also varies with altitude. It is therefore awkward to report concentrations of atmospheric species in units like g/cc or molecules/cc. Instead, it is convenient to report the "mole fraction", the relative number of molecules of a given type in an air sample. Atmospheric scientists usually call a mole fraction a "mixing ratio". Typical units for mixing ratios are parts-per-million, billion, or trillion by volume, designated as "ppmv", "ppbv", and "pptv" respectively. (The expression "by volume" reflects Avogadro's Law - for an ideal gas mixture, equal volumes contain equal numbers of molecules - and serves to distinguish mixing ratios from "mass fractions" which are given as parts-per-million by weight.)

Thus when someone says the mixing ratio of hydrogen chloride at 3 km is 0.1 ppbv, he means that 1 out of every 10 billion molecules in an air sample collected at that altitude will be an HCl molecule. [Wayne] [Graedel and Crutzen]

Subject: 1.3) How does the composition of the atmosphere change with altitude? (Or, how can CFC's get up to the stratosphere when they are heavier than air?) In the earth's troposphere and stratosphere, most stable chemical species are "well-mixed" - their mixing ratios are independent of altitude. If a species' mixing ratio changes with altitude, some kind of physical or chemical transformation is taking place. That last statement may seem surprising - one might expect the heavier molecules to dominate at lower altitudes.

The mixing ratio of Krypton (mass 84), then, would decrease with altitude, while that of Helium (mass 4) would increase. In reality, however, molecules do not segregate by weight in the troposphere or stratosphere. The relative proportions of Helium, Nitrogen, and Krypton are unchanged up to about 100 km. Why is this? Vertical transport in the troposphere takes place by convection and turbulent mixing. In the stratosphere and in the mesosphere, it takes place by "eddy diffusion" - the gradual mechanical mixing of gas by motions on small scales. These mechanisms do not distinguish molecular masses. Only at much higher altitudes do mean free paths become so large that molecular diffusion dominates and gravity is able to separate the different species, bringing hydrogen and helium atoms to the top. The lower and middle atmosphere are thus said to be "well mixed." [Chamberlain and Hunten] [Wayne] [Wallace and Hobbs] Experimental measurements of the fluorocarbon CF₄ demonstrate this homogeneous mixing. CF₄ has an

extremely long lifetime in the stratosphere - probably many thousands of years. The mixing ratio of CF₄ in the stratosphere was found to be 0.056-0.060 ppbv from 10-50 km, with no overall trend. [Zander et al. 1992] An important trace gas that is *not* well-mixed is water vapor. The lower troposphere contains a great deal of water - as much as 30,000 ppmv in humid tropical latitudes. High in the troposphere, however, the water condenses and falls to the earth as rain or snow, so that the stratosphere is extremely dry, typical mixing ratios being about 5 ppmv. Indeed, the transport of water vapor from troposphere to stratosphere is even less efficient than this would suggest, since much of the small amount of water in the stratosphere is actually produced in situ by the oxidation of stratospheric methane. [SAGE II] Sometimes that part of the atmosphere in which the chemical composition of stable species does not change with altitude is called the "homosphere". The homosphere includes the troposphere, stratosphere, and mesosphere. The upper regions of the atmosphere - the "thermosphere" and the "exosphere" - are then referred to as the "heterosphere". [Wayne] [Wallace and Hobbs] -----

Subject: 2. THE OZONE LAYER -----

Subject: 2.1) How is ozone created? Ozone is formed naturally in the upper stratosphere by short wavelength ultraviolet radiation. Wavelengths less than ~240 nanometers are absorbed by oxygen molecules (O₂), which dissociate to give O atoms. The O atoms combine with other oxygen molecules to make ozone: $O_2 + h\nu \rightarrow O + O$ (wavelength < 240 nm) $O + O_2 \rightarrow O_3$ -----

Subject: 2.2) How much ozone is in the layer, and what is a "Dobson Unit" ? A Dobson Unit (DU) is a convenient scale for measuring the total amount of ozone occupying a column overhead. If the ozone layer over the US were compressed to 0 degrees Celsius and 1 atmosphere pressure, it would be about 3 mm thick. So, 0.01 mm thickness at 0 C and 1 at is defined to be 1 DU; this makes the average thickness of the ozone layer over the US come out to be about 300 DU. In absolute terms, 1 DU is about 2.7×10^{16} molecules/cm². The unit is named after G.M.B. Dobson, who carried out pioneering studies of atmospheric ozone between ~1920-1960. Dobson designed the standard instrument used to measure ozone from the ground. The Dobson spectrophotometer measures the intensity solar UV radiation at four wavelengths, two of which are absorbed by ozone and two of which are not [Dobson 1968b]. These instruments are still in use in many places, although they are gradually being replaced by the more elaborate Brewer spectrophotometers. Today ozone is measured in many ways, from aircraft, balloons, satellites, and space shuttle missions, but the worldwide Dobson network is the only source of long-term data. A station at Arosa in Switzerland has been measuring ozone since the 1920's (see <http://www.umnw.ethz.ch/LAPETH/doc/totozon.html>) and some other stations have records that go back nearly as long, although many were interrupted during World War II. The present worldwide network went into operation in 1956-57. -----

Subject: 2.3) How is ozone distributed in the stratosphere? In absolute terms: about 10^{12} molecules/cm³ at 15 km, rising to nearly 10^{13} at 25 km, then falling to 10^{11} at 45 km. In relative terms: ~0.5 parts per million by volume (ppmv) at 15 km, rising to ~8 ppmv at ~35 km, falling to ~3 ppmv at 45 km. Even in the thickest part of the layer, ozone is a trace gas. In all, there are about 3 billion metric tons, or 3×10^{15} grams, of ozone in the earth's atmosphere; about 90% of this is in the stratosphere.

Subject: 2.4) How does the ozone layer work? UV light with wavelengths between 240 and 320 nm is absorbed by ozone, which then falls apart to give an O atom and an O₂ molecule. The O atom soon encounters another O₂ molecule, however (at all times, the concentration of O₂ far exceeds that of O₃), and recreates O₃: $O_3 + h\nu \rightarrow O_2 + O$ $O + O_2 \rightarrow O_3$ Thus _ozone absorbs UV radiation without itself being consumed_; the net result is to convert UV light into heat. Indeed, this is what causes the temperature of the stratosphere to increase with altitude, giving rise to the inversion layer that traps molecules in the troposphere. The ozone layer isn't just _in_ the stratosphere; the ozone layer actually determines the form of the stratosphere. Ozone _is_ destroyed if an O atom and an O₃ molecule meet: $O + O_3 \rightarrow 2 O_2$ ("recombination"). This reaction is slow, however, and if it were the only mechanism for ozone loss, the ozone layer would be about twice as thick as it is. Certain trace species, such as the oxides of Nitrogen (NO and NO₂), Hydrogen (H, OH, and HO₂) and chlorine (Cl, ClO and ClO₂) can catalyze the recombination. The present ozone layer is a result of a competition between photolysis and recombination; increasing the recombination rate, by increasing the concentration of catalysts, results in a thinner ozone layer. Putting the pieces together, we have the set of reactions proposed in the 1930's by Sidney Chapman: $O_2 + h\nu \rightarrow O + O$ (wavelength < 240 nm) : creation of oxygen atoms $O + O_2 \rightarrow O_3$: formation of ozone $O_3 + h\nu \rightarrow O_2 + O$ (wavelength < 320 nm) : absorption of UV by ozone $O + O_3 \rightarrow 2 O_2$: recombination . Since the photolysis of O₂ requires UV radiation while recombination does not, one might guess that ozone should increase during the day and decrease at night. This has led some people to suggest that the "antarctic ozone hole" is merely a result of the long antarctic winter nights. This inference is incorrect, because the recombination reaction requires oxygen atoms which are also produced by photolysis. Throughout the stratosphere the concentration of O atoms is orders of magnitude smaller than the concentration of O₃ molecules, so both the production and the destruction of ozone by the above mechanisms shut down at night. In fact, the thickness of the ozone layer varies very little from day to night, and above 70 km ozone concentrations actually _increase_ at night. (The unusual catalytic cycles that operate in the antarctic ozone hole do not require O atoms; however, they still require light to operate because they also include photolytic steps. See Part III.) ----- #

Subject: 2.5) What sorts of natural variations does the ozone layer show? There are substantial variations from place to place, and from season to season. There are smaller variations on time scales of years and more. [Wayne] [Rowland 1991] We discuss these in turn

Subject: 2.5.a) Regional and Seasonal Variation Since solar radiation makes ozone, one expects to see the thickness of the ozone layer vary during the year. This is so, although the details do not depend simply upon the amount of solar radiation received at a given latitude and season - one must also take atmospheric motions into account. (Remember that both production and destruction of ozone require solar radiation.) The ozone layer is thinnest in the tropics, about 260 DU, almost independent of season. Away from the tropics seasonal variations become important. For example: Location Column thickness, Dobson Units Jan Apr Jul Oct Huancayo, Peru (12 degrees S) : 255 255 260 260 Aspendale, Australia (38 deg. S): 300 280 335 360 Arosa, Switzerland (47 deg. N): 335 375 320 280 St. Petersburg, Russia (60 deg. N): 360 425 345 300 These are monthly averages. Interannual standard deviations amount to ~5 DU for Huancayo, 25 DU for St. Petersburg. [Rowland 1991]. Day-to-day fluctuations can be quite large (as much as 60 DU at high latitudes). Notice that the highest ozone levels are found in the spring, not, as one might guess, in summer, and the lowest in the fall, not winter. Indeed, at high latitudes in the Northern Hemisphere there is more ozone in January than in July! Most of the ozone is created over the tropics, and then is carried to higher latitudes by prevailing winds (the general circulation of the stratosphere.) [Dobson 1968a] [Garcia] [Salby and Garcia] [Brasseur and Solomon] The antarctic ozone hole, discussed in detail in Part III, falls far outside this range of natural variation. Mean October ozone at Halley Bay on the Antarctic coast was 117 DU in 1993, down from 321 DU in 1956. -----

Subject: 2.5.b) Year-to-year variations. Since ozone is created by solar UV radiation, one expects to see some correlation with the 11-year solar sunspot cycle. Higher sunspot activity corresponds to more solar UV and hence more rapid ozone production. This correlation has been verified, although its effect is small, about 2% from peak to trough averaged over the earth, about 4% in polar regions. [Stolarski et al.] Another natural cycle is connected with the "quasibiennial oscillation", in which tropical winds in the lower stratosphere switch from easterly to westerly with a period of about two years. This leads to variations of the order of 3% at a given latitude, although the effect tends to cancel when one averages over the entire globe. Episodes of unusual solar activity ("solar proton events") can also influence ozone levels, by producing nitrogen oxides in the upper stratosphere and mesosphere. This can have a marked, though short-lived, effect on ozone concentrations at very high altitudes, but the effect on total column ozone is usually small since most of the ozone is found in the lower and middle stratosphere. Ozone can also be depleted by a major volcanic eruption, such as El Chichon in 1982 or Pinatubo in 1991. The principal mechanism for this is not injection of chlorine into the stratosphere, as discussed in Part II, but rather the injection of sulfate aerosols which change the radiation balance in the stratosphere by scattering light, and which convert inactive chlorine compounds to active, ozone-destroying forms. [McCormick et al. 1995]. This too is a transient effect, lasting 2-3 years. -----

Subject: 2.6) What are CFC's? CFC's - ChloroFluoroCarbons - are a class of volatile organic compounds that have been used as refrigerants, aerosol

propellants, foam blowing agents, and as solvents in the electronic industry. They are chemically very unreactive, and hence safe to work with. In fact, they are so inert that the natural reagents that remove most atmospheric pollutants do not react with them, so after many years they drift up to the stratosphere where short-wave UV light dissociates them. CFC's were invented in 1928, but only came into large-scale production after ~1950. Since that year, the total amount of chlorine in the stratosphere has increased by a factor of 4. [Solomon] The most important CFC's for ozone depletion are: Trichlorofluoromethane, CFCl_3 (usually called CFC-11 or R-11); Dichlorodifluoromethane, CF_2Cl_2 (CFC-12 or R-12); and 1,1,2 Trichlorotrifluoroethane, $\text{CF}_2\text{ClCFCl}_2$ (CFC-113 or R-113). "R" stands for "refrigerant". One occasionally sees CFC-12 referred to as "F-12", and so forth; the "F" stands for "Freon", DuPont's trade name for these compounds. In discussing ozone depletion, "CFC" is occasionally used to describe a somewhat broader class of chlorine-containing organic compounds that have similar properties - unreactive in the troposphere, but readily photolyzed in the stratosphere. These include: HydroChloroFluoroCarbons such as CHClF_2 (HCFC-22, R-22); Carbon Tetrachloride (tetrachloromethane), CCl_4 ; Methyl Chloroform (1,1,1 trichloroethane), CH_3CCl_3 (R-140a); and Methyl Chloride (chloromethane), CH_3Cl . (The more careful publications always use phrases like "CFC's and related compounds", but this gets tedious.) Only methyl chloride has a large natural source; it is produced biologically in the oceans and chemically from biomass burning. The CFC's and CCl_4 are nearly inert in the troposphere, and have lifetimes of 50-200+ years. Their major "sink" is photolysis by UV radiation. [Rowland 1989, 1991] The hydrogen-containing halocarbons are more reactive, and are removed in the troposphere by reactions with OH radicals. This process is slow, however, and they live long enough (1-20 years) for a substantial fraction to reach the stratosphere. Most of Part II is devoted to stratospheric chlorine chemistry; look there for more detail. -----

Subject: 2.7) How do CFC's destroy ozone? CFC's themselves do not destroy ozone; certain of their decay products do. After CFC's are photolyzed, most of the chlorine eventually ends up as Hydrogen Chloride, HCl, or Chlorine Nitrate, ClONO_2 . These are called "reservoir species" - they do not themselves react with ozone. However, they do decompose to some extent, giving, among other things, a small amount of atomic chlorine, Cl, and Chlorine Monoxide, ClO, which can catalyze the destruction of ozone by a number of mechanisms. The simplest is: $\text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2$ $\text{ClO} + \text{O} \rightarrow \text{Cl} + \text{O}_2$ Net effect: $\text{O}_3 + \text{O} \rightarrow 2 \text{O}_2$ Note that the Cl atom is a _catalyst_ - it is not consumed by the reaction. Each Cl atom introduced into the stratosphere can destroy thousands of ozone molecules before it is removed. The process is even more dramatic for Bromine - it has no stable "reservoirs", so the Br atom is always available to destroy ozone. On a per-atom basis, Br is 10-100 times as destructive as Cl. On the other hand, chlorine and bromine concentrations in the stratosphere are very small in absolute terms. The mixing ratio of chlorine from all sources in the stratosphere is about 3 parts per billion, (most of which is in the form of CFC's that have not yet fully decomposed) whereas ozone mixing ratios are measured in parts per million. Bromine concentrations are about 100 times smaller still. (See Part II.) The complete chemistry is very

complicated - more than 100 distinct species are involved. The rate of ozone destruction at any given time and place depends strongly upon how much Cl is present as Cl or ClO, and thus upon the rate at which Cl is released from its reservoirs. This makes quantitative predictions of future ozone depletion difficult. [Rowland 1989, 1991] [Wayne] The catalytic destruction of ozone by Cl-containing radicals was first suggested by Richard Stolarski and Ralph Cicerone in 1973. However, they were not aware of any large sources of stratospheric chlorine. In 1974 F. Sherwood Rowland and Mario Molina realized that CFC's provided such a source. [Molina and Rowland 1974][Rowland and Molina 1975] For this and for their many subsequent contributions to stratospheric ozone chemistry Rowland and Molina shared the 1995 Nobel Prize in Chemistry, together with Paul Crutzen, discoverer of the NOx cycle. (The official announcement from the Swedish Academy can be found on the web at <http://www.nobel.se/announcement95-chemistry.html> .) --

Subject: 2.8) What is an "Ozone Depletion Potential?" The ozone depletion potential (ODP) of a compound is a simple measure of its ability to destroy stratospheric ozone. It is a relative measure: the ODP of CFC-11 is defined to be 1.0, and the ODP's of other compounds are calculated with respect to this reference point. Thus a compound with an ODP of 0.2 is, roughly speaking, one-fifth as "bad" as CFC-11. More precisely, the ODP of a compound "x" is defined as the ratio of the total amount of ozone destroyed by a fixed amount of compound x to the amount of ozone destroyed by the same mass of CFC-11:
$$\text{Global loss of Ozone due to } x \text{ ODP}(x) = \frac{\text{Global loss of ozone due to } x}{\text{Global loss of ozone due to CFC-11}}$$
 Thus the ODP of CFC-11 is 1.0 by definition. The right-hand side of the equation is calculated by combining information from laboratory and field measurements with atmospheric chemistry and transport models. Since the ODP is a relative measure, it is fairly "robust", not overly sensitive to changes in the input data or to the details of the model calculations. That is, there are many uncertainties in calculating the numerator or the denominator of the expression, but most of these cancel out when the ratio is calculated. The ODP of a compound will be affected by: The nature of the halogen (bromine-containing halocarbons usually have much higher ODPs than chlorocarbons, because atom for atom Br is a more effective ozone-destruction catalyst than Cl.) The number of chlorine or bromine atoms in a molecule. Molecular Mass (since ODP is defined by comparing equal masses rather than equal numbers of moles.) Atmospheric lifetime (CH₃CCl₃ has a lower ODP than CFC-11, because much of the CH₃CCl₃ is destroyed in the troposphere.) The ODP as defined above is a steady-state or long-term property. As such it can be misleading when one considers the possible effects of CFC replacements. Many of the proposed replacements have short atmospheric lifetimes, which in general is good; however, if a compound has a short stratospheric lifetime, it will release its chlorine or bromine atoms more quickly than a compound with a longer stratospheric lifetime. Thus the short term effect of such a compound on the ozone layer is larger than would be predicted from the ODP alone (and the long-term effect correspondingly smaller.) (The ideal combination would be a short tropospheric lifetime, since those molecules which are destroyed in the troposphere don't get a chance to destroy any stratospheric ozone, combined with a long stratospheric lifetime.)

To get around this, the concept of a Time-Dependent Ozone Depletion Potential has been introduced [Solomon and Albritton] [WMO 1991]: Loss of ozone due to X over time period T $ODP(x,T) = \frac{\text{Loss of ozone due to X over time period T}}{\text{Loss of ozone due to CFC-11 over time period T}}$ As $T \rightarrow \infty$, this converges to the steady-state ODP defined previously. The following table lists time-dependent and steady-state ODP's for a few halocarbons [Solomon and Albritton] [WMO 1991]

Compound	Formula	Ozone Depletion Potential
		10 yr 30 yr 100 yr Steady State
CFC-113	$CF_2ClCFCl_2$	0.56 0.62 0.78 1.10
carbon tetrachloride	CCl_4	1.25 1.22 1.14 1.08
methyl chloroform	CH_3CCl_3	0.75 0.32 0.15 0.12
HCFC-22	CHF_2Cl	0.17 0.12 0.07 0.05
Halon - 1301	CF_3Br	10.4 10.7 11.5 12.5

Subject: 2.9) What about HCFC's and HFC's? Do they destroy ozone? HCFC's (hydrochlorofluorocarbons) differ from CFC's in that only some, rather than all, of the hydrogen in the parent hydrocarbon has been replaced by chlorine or fluorine. The most familiar example is $CHClF_2$, known as "HCFC-22", used as a refrigerant and in many home air conditioners (auto air conditioners use CFC-12). The hydrogen atom makes the molecule susceptible to attack by the hydroxyl (OH) radical, so a large fraction of the HCFC's are destroyed before they reach the stratosphere. Molecule for molecule, then, HCFC's destroy much less ozone than CFC's, and they were suggested as CFC substitutes as long ago as 1976. Most HCFC's have ozone depletion potentials around 0.01-0.1, so that during its lifetime a typical HCFC will have destroyed 1-10% as much ozone as the same amount of CFC-12. Since the HCFC's are more reactive in the troposphere, fewer of them reach the stratosphere. However, they are also more reactive in the stratosphere, so they release chlorine more quickly. The short-term effects are therefore larger than one would predict from the steady-state ozone depletion potential. When evaluating substitutes for CFC's, the "time-dependent ozone depletion potential", discussed in the preceding section, is more useful than the steady-state ODP. [Solomon and Albritton] HFC's, hydrofluorocarbons, contain no chlorine at all, and hence have an ozone depletion potential of zero. (In 1993 there were tentative reports that the fluorocarbon radicals produced by photolysis of HFC's could catalyze ozone loss, but this has now been shown to be negligible [Ravishankara et al. 1994]) A familiar example is CF_3CH_2F , known as HFC-134a, which is being used in some automobile air conditioners and refrigerators. HFC-134a is more expensive and more difficult to work with than CFC's, and while it has no effect on stratospheric ozone it is a greenhouse gas (though somewhat less potent than the CFC's). Some engineers have argued that non-CFC fluids, such as propane-isobutane mixtures, are better substitutes for CFC-12 in auto air conditioners than HFC-134a.

Subject: 2.10) *IS* the ozone layer getting thinner? There is no question that the ozone layer over antarctica has thinned dramatically over the past 15 years (see part III). However, most of us are more interested in whether this is also taking place at middle latitudes. The answer seems to be yes, although so far the effect are small. After carefully accounting for all of the known natural variations, a net decrease of about 3% per decade for the period 1978-1991 was found. This is a global average over latitudes from 66 degrees

S to 66 degrees N (i.e. the arctic and antarctic are excluded in calculating the average). The depletion increases with latitude, and is somewhat larger in the Southern Hemisphere. Over the US, Europe and Australia 4% per decade is typical; on the other hand there was no significant ozone loss in the tropics during this period. (See, however, [Hofmann et al. 1996] for more recent trends which appear to show a decline in some tropical stations.) The depletion is larger in the winter months, smaller in the summer. [Stolarski et al.] [WMO 1994] The following table, extracted from a much more detailed one in [Herman et al. 1993], illustrates the seasonal and regional trends in _percent per decade_ for the period 1979-1990:

Latitude	Jan	Apr	Jul	Oct
Example 65 N	-3.0	-6.6	-3.8	-5.6
Iceland 55 N	-4.6	-6.7	-3.1	-4.4
Moscow, Russia 45 N	-7.0	-6.8	-2.4	-3.1
Minneapolis, USA 35 N	-7.3	-4.7	-1.9	-1.6
Tokyo 25 N	-4.2	-2.9	-1.0	-0.8
Miami, FL, USA 5 N	-0.1	+1.0	-0.1	+1.3
Somalia 5 S	+0.2	+1.0	-0.2	+1.3
New Guinea 25 S	-2.1	-1.6	-1.6	-1.1
Pretoria, S. Africa 35 S	-3.6	-3.2	-4.5	-2.6
Buenos Aires 45 S	-4.8	-4.2	-7.7	-4.4
New Zealand 55 S	-6.1	-5.6	-9.8	-9.7
Tierra del Fuego 65 S	-6.0	-8.6	-13.1	-19.5

Palmer Peninsula (These are longitudinally averaged satellite data, not individual measurements at the places listed in the right-hand column. There are longitudinal trends as well. A recent reanalysis of the TOMS data yields trends that differ in detail from the above, being somewhat smaller at the highest latitudes. [McPeters et al. 1996].) It should be noted that one high-latitude ground station (Tromso in Norway) has found no long-term change in total ozone change between 1939 and 1989. [Larsen and Henriksen][Henriksen et al. 1992] The reason for the discrepancy is not known. [WMO 1994] Between 1991 and 1993 these trends accelerated. Satellite and ground-based measurements showed a remarkable decline for 1992 and early 1993, a full 4% below the average value for the preceding twelve years and 2-3% below the _lowest_ values observed in the earlier period. In Canada the spring ozone levels were 11-17% below normal [Kerr et al.]. By February 1994 ozone over the United States had recovered to levels similar to 1991, [Hofmann et al. 1994b] and in the spring of 1995 they were down again, to levels lower than any previous year other than 1993. [Bojkov et al. 1995] Sulfate aerosols from the July 1991 eruption of Mt. Pinatubo are the most likely cause of the exceptionally low ozone in 1993; these aerosols can convert inactive "reservoir" chlorine into active ozone-destroying forms, and can also interfere with the production and transport of ozone by changing the solar radiation balance in the stratosphere. [Brasseur and Granier] [Hofmann and Solomon] [Hofmann et al. 1994a] [McCormick et al. 1995] Another cause may be the unusually strong arctic polar vortex in 1992-93, which made the arctic stratosphere more like the antarctic than is usually the case. [Gleason et al.] [Waters et al.] In any event, the rapid ozone loss in 1992 and 1993 was a transient phenomenon, superimposed upon the slower downward trend identified before 1991. -----

Subject: 2.11) Is the middle-latitude ozone loss due to CFC emissions? That's the majority opinion, although it's not a universal opinion. The present trends are too small and the atmospheric chemistry and dynamics too complicated to allow a watertight case to be made (as _has_ been made for the far larger, but localized, depletion in the Antarctic Ozone hole; see Part III.). Other possible causes are being investigated. To quote from the 1991

Scientific Assessment published by the World Meteorological Organization, p. 4.1 [WMO 1991]: "The primary cause of the Antarctic ozone hole is firmly established to be halogen chemistry....There is not a full accounting of the observed downward trend in global ozone. Plausible mechanisms include heterogeneous chemistry on sulfate aerosols [which convert reservoir chlorine to active chlorine - R.P.] and the transport of chemically perturbed polar air to middle latitudes. Although other mechanisms cannot be ruled out, those involving the catalytic destruction of ozone by chlorine and bromine appear to be largely responsible for the ozone loss and are the only ones for which direct evidence exists." (emphases mine - RP) The Executive Summary of the subsequent 1994 scientific assessment (available on the Web at <http://www.al.noaa.gov/WWWHD/pubdocs/WMOUNEP94.html>) states: "Direct in-situ measurements of radical species in the lower stratosphere, coupled with model calculations, have quantitatively shown that the in-situ photochemical loss of ozone due to (largely natural) reactive nitrogen (NO_x) compounds is smaller than that predicted from gas-phase chemistry, while that due to (largely natural) HO_x compounds and (largely anthropogenic) chlorine and bromine compounds is larger than that predicted by gas-phase chemistry. This confirms the key role of chemical reactions on sulfate aerosols in controlling the chemical balance of the lower stratosphere. These and other recent scientific findings strengthen the conclusion of the previous assessment that the weight of scientific evidence suggests that the observed middle- and high-latitude ozone losses are largely due to anthropogenic chlorine and bromine compounds." [WMO 1994] For a contrasting view, see [Henriksen and Roldugin]. A legal analogy might be useful here - the connection between antarctic ozone depletion and CFC emissions has been proved beyond a reasonable doubt, while at middle latitudes there is only probable cause for such a connection. One must remember that there is a natural 10-20 year time lag between CFC emissions and ozone depletion. Ozone depletion today is (probably) due to CFC emissions in the 1970's. Present controls on CFC emissions are designed to avoid possibly large amounts of ozone depletion 30 years from now, not to repair the depletion that has taken place up to now. [Prather et al. 1996] -----

Subject: 2.12) If the ozone is lost, won't the UV light just penetrate deeper into the atmosphere and make more ozone? This does happen to some extent - it's called "self-healing" - and has the effect of moving ozone from the upper to the lower stratosphere. Recall that ozone is created by UV with wavelengths less than 240 nm, but functions by absorbing UV with wavelengths greater than 240 nm. The peak of the ozone absorption band is at ~250 nm, and the cross-section falls off at shorter wavelengths. The O₂ and O₃ absorption bands do overlap, though, and UV radiation between 200 and 240 nm has a good chance of being absorbed by either O₂ or O₃. [Rowland and Molina 1975] (Below 200 nm the O₂ absorption cross-section increases dramatically, and O₃ absorption is insignificant in comparison.) Since there is some overlap, a decrease in ozone does lead to a small increase in absorption by O₂. This is a weak feedback, however, and it does not compensate for the ozone destroyed. Negative feedback need not imply stability, just as positive feedback need not imply instability. Numerical calculations of ozone depletion take the "self-healing" phenomenon into

account, by letting the perturbed ozone layer come into equilibrium with the exciting radiation. ----- Subject: 2.13) Do Space Shuttle launches damage the ozone layer? Very little. In the early 1970's, when little was known about the role of chlorine radicals in ozone depletion, it was suggested that HCl from solid rocket motors might have a significant effect upon the ozone layer - if not globally, perhaps in the immediate vicinity of the launch. It was immediately shown that the effect was negligible, and this has been repeatedly demonstrated since. Each shuttle launch produces about 200 metric tons of chlorine as HCl, of which about one-third, or 68 tons, is injected into the stratosphere. Its residence time there is about three years. A full year's schedule of shuttle and solid rocket launches injects 725 tons of chlorine into the stratosphere. This is negligible compared to chlorine emissions in the form of CFC's and related compounds (~1 million tons/yr in the 1980's, of which ~0.3 Mt reach the stratosphere each year). It is also small in comparison to natural sources of stratospheric chlorine, which amount to about 75,000 tons per year. [Prather et al. 1990] [WMO 1991] [Ko et al.] See also the [sci.space](#) FAQ, Part 10, "Controversial Questions", available by anonymous ftp from rtfm.mit.edu in the directory pub/usenet/news.answers/space/controversy, and on the world-wide web at: <http://www.cis.ohio-state.edu/hypertext/faq/usenet/space/controversy/faq.html>

Subject: 2.14) Will commercial supersonic aircraft damage the ozone layer? Short answer: Probably not. This problem is very complicated, and a definitive answer will not be available for several years, but present model calculations indicate that a fleet of high-speed civil transports would deplete the ozone layer by < 2%. [WMO 1991, 1994] Long answer (this is a tough one): Supersonic aircraft fly in the stratosphere. Since vertical transport in the stratosphere is slow, the exhaust gases from a supersonic jet can stay there for two years or more. The most important exhaust gases are the nitrogen oxides, NO and NO₂, collectively referred to as "NO_x". NO_x is produced from ordinary nitrogen and oxygen by electrical discharges (e.g. lightning) and by high-temperature combustion (e.g. in automobile and aircraft engines). The relationship between NO_x and ozone is complicated. In the troposphere, NO_x makes ozone, a phenomenon well known to residents of Los Angeles and other cities beset by photochemical smog. At high altitudes in the troposphere, similar chemical reactions produce ozone as a byproduct of the oxidation of methane; for this reason ordinary subsonic aircraft actually increase the thickness of the ozone layer by a very small amount. Things are very different in the stratosphere. Here the principal source of NO_x is nitrous oxide, N₂O ("laughing gas"). Most of the N₂O in the atmosphere comes from bacteriological decomposition of organic matter - reduction of nitrate ions or oxidation of ammonium ions. (It was once assumed that anthropogenic sources were negligible in comparison, but this is now known to be false. The total anthropogenic contribution is estimated at 8 Tg (teragrams)/yr, compared to a natural source of 18 Tg/yr. [Khalil and Rasmussen].) N₂O, unlike NO_x, is very unreactive - it has an atmospheric lifetime of more than 150 years - so it reaches the stratosphere, where most of it is converted to nitrogen and oxygen by UV photolysis. However, a small fraction of the N₂O that reaches the stratosphere reacts instead with oxygen atoms (to be precise, with the

very rare electronically excited singlet-D oxygen atoms), and this is the major natural source of NO_x in the stratosphere; about 1.2 million tons are produced each year in this way. This source strength would be matched by 500 of the SST's designed by Boeing in the late 1960's, each spending 5 hours per day in the stratosphere. (Boeing was intending to sell 800 of these aircraft.) The Concorde, a slower plane, produces less than half as much NO_x and flies at a lower altitude; since the Concorde fleet is small, its contribution to stratospheric NO_x is not significant. Before sending large fleets of high-speed aircraft into the stratosphere, however, one should certainly consider the possible effects of increasing the rate of production of an important stratospheric trace gas by as much as a factor of two. [CIC 1975] In 1969, Paul Crutzen discovered that NO_x could be an efficient catalyst for the destruction of stratospheric ozone: [Crutzen 1970] $\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2$
 $\text{NO}_2 + \text{O} \rightarrow \text{NO} + \text{O}_2$ ----- net: $\text{O}_3 + \text{O} \rightarrow 2 \text{O}_2$ (For this and other contributions to ozone research, Crutzen, together with Rowland and Molina, was awarded the 1995 Nobel Prize in Chemistry. The official announcement from the Swedish Academy is available at <http://www.nobel.se/announcement95-chemistry.html> .) Two years later, Harold S. Johnston made the connection to SST emissions. Until then it had been thought that the radicals H, OH, and HO₂ (referred to collectively as "HO_x") were the principal catalysts for ozone loss; thus, investigations of the impact of aircraft exhaust on stratospheric ozone had focussed on emissions of water vapor, a possible source for these radicals. (The importance of chlorine radicals, Cl, ClO, and ClO₂, referred to as - you guessed it - "ClO_x", was not discovered until 1973.) It had been argued - correctly, as it turns out - that water vapor injection was unimportant for determining the ozone balance. The discovery of the NO_x cycle threw the question open again. Beginning in 1972, the U.S. National Academies of Science and Engineering and the Department of Transportation sponsored an intensive program of stratospheric research. [CIC 1975] It soon became clear that the relationship between NO_x emissions and the ozone layer was very complicated. The stratospheric lifetime of NO_x is comparable to the timescale for transport from North to South, so its concentration depends strongly upon latitude. Much of the NO_x is injected near the tropopause, a region where quantitative modelling is very difficult, and the results of calculations depend sensitively upon how troposphere-stratosphere exchange is treated. Stratospheric NO_x chemistry is extremely complicated, much worse than chlorine chemistry. Among other things, NO₂ reacts rapidly with ClO, forming the inactive chlorine reservoir ClONO₂ - so while on the one hand increasing NO_x leads directly to ozone loss, on the other it suppresses the action of the more potent chlorine catalyst. And on top of all of this, the SST's always spend part of their time in the troposphere, where NO_x emissions cause ozone increases. Estimates of long-term ozone changes due to large-scale NO_x emissions varied markedly from year to year, going from -10% in 1974, to +2% (i.e. a net ozone gain) in 1979, to -8% in 1982. (In contrast, while the estimates of the effects of CFC emissions on ozone also varied a great deal in these early years, they always gave a net loss of ozone.) [Wayne] The discovery of the Antarctic ozone hole added a new piece to the puzzle. As described in Part III, the ozone hole is caused by heterogeneous chemistry on the surfaces of stratospheric cloud particles. While these clouds are only found in polar regions, similar chemical

reactions take place on sulfate aerosols which are found throughout the lower stratosphere. The most important of the aerosol reactions is the conversion of N_2O_5 to nitric acid: $\text{N}_2\text{O}_5 + \text{H}_2\text{O} \rightarrow 2 \text{HNO}_3$ (catalyzed by aerosol surfaces) N_2O_5 is in equilibrium with NO_x , so removal of N_2O_5 by this reaction lowers the NO_x concentration. The result is that in the lower stratosphere the NO_x catalytic cycle contributes much less to overall ozone loss than the HO_x and ClO_x cycles. Ironically, the same processes that makes chlorine-catalyzed ozone depletion so much more important than was believed 10 years ago, also make NO_x -catalyzed ozone loss less important. In the meantime, there has been a great deal of progress in developing jet engines that will produce much less NO_x - up to a factor of 10 - than the old Boeing SST. The most recent model calculations indicate that a fleet of the new "high-speed civil transports" would deplete the ozone layer by 0.3-1.8%. Caution is still required, since the experiment has not been done - we have not yet tried adding large amounts of NO_x to the stratosphere. The forecasts, however, are good. [WMO 1991, Ch. 10] [WMO 1994] Very recently, a new complication has appeared: *in situ* measurements in the exhaust plume of a Concorde aircraft flying at supersonic speeds indicate that the ground-based estimates of NO_x emissions are accurate, but that the exhaust also contains large amounts of sulfate-based particulates [Fahey et al. 1995]. Since reactions on sulfate aerosols are believed to play an important role in halogen-catalyzed ozone depletion, it may be advisable to concentrate on reducing the sulfur content of the fuels that are to be used in new generations of supersonic aircraft, rather than further reducing NO_x emissions.

Aside_: One sometimes hears that the US government killed the SST project in 1971 because of concerns raised by H. S. Johnston's work on NO_x . This is not true. The US House of Representatives had already voted to cut off Federal funding for the SST when Johnston began his calculations. The House debate had centered around economics and the effects of noise, especially sonic booms, although there were some vague concerns about "pollution" and one physicist had testified about the possible effects of water vapor on ozone. About 6 weeks after both houses had voted to cancel the SST, its supporters succeeded in reviving the project in the House. In the meantime, Johnston had sent a preliminary report to several professional colleagues and submitted a paper to *Science*. A preprint of Johnston's report leaked to a small California newspaper which published a highly sensationalized account. The story hit the press a few days before the Senate voted, 58-37, not to revive the SST. (The previous Senate vote had been 51-46 to cancel the project. The reason for the larger majority in the second vote was probably the statement by Boeing's chairman that at least \$500 million more would be needed to revive the program.)

Subject: 2.15) What is being done about ozone depletion? The 1987 Montreal Protocol (full text available on the world-wide web at <http://www.unep.org/unep/secretar/ozone/treaties.htm>) specified that CFC emissions should be reduced by 50% by the year 2000 (they had been *increasing* by 3% per year.) This agreement was amended in London in 1990, to state that production of CFC's, CCl_4 , and halons should cease

entirely by the year 2000. Restrictions were also applied applied to other CI sources such as methylchloroform. (The details of the protocols are complicated, involving different schedules for different compounds, delays for developing nations, etc.) The phase-out schedule was accelerated by four years by the 1992 Copenhagen agreements. A great deal of effort has been devoted to recovering and recycling CFC's that are currently being used in closed-cycle systems. For more information about legal and policy issues, see the books by [Benedick] and [Litvin], and the following web sites: <http://www.unep.org/unep/secretar/ozone/home.htm> <http://www.unep.ch/ozone/> (European mirror site for above) <http://www.epa.gov/docs/ozone/index.html> <http://www.ciesin.org/TG/OZ/ozpolic.html> Recent NOAA measurements [Elkins et al. 1993] [Montzka et al. 1996] show that the rate of increase of halocarbon concentrations in the atmosphere has decreased markedly since 1987. It appears that the Protocols are being observed. Under these conditions total stratospheric chlorine is predicted to peak at 3.8 ppbv in the year 1998, 0.2 ppbv above 1994 levels, and to slowly decline thereafter. [WMO 1994] Extrapolation of current trends suggests that the maximum ozone losses will be [WMO 1994]: Northern Mid-latitudes in winter/Spring: 12-13% below late 1960's levels, ~2.5% below current levels. Northern mid-latitudes in summer/fall: 6-7% below late 1960's levels, ~1.5% below current levels. Southern mid-latitudes, year-round: ~ 11% below late 1960's levels, ~2.5% below current levels. Very little depletion has been seen in the tropics and little is expected there. After the year 2000, the ozone layer will slowly recover over a period of 50 years or so. The antarctic ozone hole is expected to last until about 2045. [WMO 1991,1994] Some scientists are investigating ways to replenish stratospheric ozone, either by removing CFC's from the troposphere or by tying up the chlorine in inactive compounds. This is discussed in Part III. -----

Subject: 3. REFERENCES FOR PART I A remark on references: they are neither representative nor comprehensive. There are hundreds of people working on these problems. Where possible I have limited myself to articles that are (1) available outside of University libraries (e.g. Science or Nature rather than archival journals such as J. Geophys. Res.) and (2) directly related to the "frequently asked questions". I have not listed papers whose importance is primarily historical. (I make an exception for the Nobel-Prize winning work of Crutzen, Molina and Rowland.) Readers who want to see "who did what" should consult the review articles listed below, or, if they can get them, the WMO reports which are extensively documented.

----- **Subject: Introductory Reading** [Garcia] R. R. Garcia, "Causes of Ozone Depletion", Physics World April 1994 pp 49-55. [Graedel and Crutzen] T. E. Graedel and P. J. Crutzen, Atmospheric Change: an Earth System Perspective, Freeman, NY 1993. [Rowland 1989] F.S. Rowland, "Chlorofluorocarbons and the depletion of stratospheric ozone", American Scientist 77, 36, 1989. [Rowland and Molina 1994] F. S. Rowland and M. J. Molina, "Ozone depletion: 20 years after the alarm", Chemical and Engineering News, 15 Aug. 1994, pp. 8-13. [Zurer] P. S. Zurer, "Ozone Depletion's Recurring Surprises Challenge Atmospheric

Scientists", *Chemical and Engineering News*, 24 May 1993, pp. 9-18. -----
----- Subject: Books and Review Articles [Benedick] R. Benedick, *Ozone Diplomacy*, Harvard, 1991. [Basseur and Solomon] G. Basseur and S. Solomon, *Aeronomy of the Middle Atmosphere*, 2nd. Edition, D. Reidel, 1986 [Chamberlain and Hunten] J. W. Chamberlain and D. M. Hunten, *Theory of Planetary Atmospheres*, 2nd Edition, Academic Press, 1987 [Dobson 1968a] G. M. B. Dobson, *Exploring the Atmosphere*, 2nd Edition, Oxford, 1968. [Dobson 1968b] G. M. B. Dobson, "Forty Years' research on atmospheric ozone at Oxford", *Applied Optics*, *7*, 387, 1968. [CIC 1975] Climate Impact Committee, National Research Council, *Environmental Impact of Stratospheric Flight*, National Academy of Sciences, 1975. [Johnston 1992] H. S. Johnston, "Atmospheric Ozone", *Annu. Rev. Phys. Chem.* *43*, 1, 1992. [Ko et al.] M. K. W. Ko, N.-D. Sze, and M. J. Prather, "Better Protection of the Ozone Layer", *Nature* *367*, 505, 1994. [Litvin] K. T. Litvin, *Ozone Discourses*, Columbia 1994. [McElroy and Salawich] M. McElroy and R. Salawich, "Changing Composition of the Global Stratosphere", *Science* *243*, 763, 1989. [Rowland and Molina 1975] F. S. Rowland and M. J. Molina, "Chlorofluoromethanes in the Environment", *Rev. Geophys. & Space Phys.* *13*, 1, 1975. [Rowland 1991] F. S. Rowland, "Stratospheric Ozone Depletion", *Ann. Rev. Phys. Chem.* *42*, 731, 1991. [Salby and Garcia] M. L. Salby and R. R. Garcia, "Dynamical Perturbations to the Ozone Layer", *Physics Today* *43*, 38, March 1990. [Solomon] S. Solomon, "Progress towards a quantitative understanding of Antarctic ozone depletion", *Nature* *347*, 347, 1990. [Wallace and Hobbs] J. M. Wallace and P. V. Hobbs, *Atmospheric Science: an Introductory Survey*, Academic Press, 1977. [Wayne] R. P. Wayne, *Chemistry of Atmospheres*, 2nd. Ed., Oxford, 1991. [WMO 1988] World Meteorological Organization, *Report of the International Ozone Trends Panel*, Global Ozone Research and Monitoring Project - Report #18. [WMO 1989] World Meteorological Organization, *Scientific Assessment of Stratospheric Ozone: 1991*, Global Ozone Research and Monitoring Project - Report #20. [WMO 1991] World Meteorological Organization, *Scientific Assessment of Ozone Depletion: 1991*, Global Ozone Research and Monitoring Project - Report #25. [WMO 1994] World Meteorological Organization, *Scientific Assessment of Ozone Depletion: 1994*, Global Ozone Research and Monitoring Project - Report #37. The Executive Summary of this report is available on the World-Wide Web at <http://www.al.noaa.gov/WWWHD/pubdocs/WMOUNEP94.html> -----
----- Subject: More Specialized References [Bojkov et al. 1995] R. D. Bojkov, V. E. Fioletov, D. S. Balis, C. S. Zerefos, T. V. Kadygrova, and A. M. Shalamjansky, "Further ozone decline during the northern hemisphere winter-spring of 1994-95 and the new record low ozone over Siberia", *Geophys. Res. Lett.* *22*, 2729, 1995. [Basseur and Granier] G. Basseur and C. Granier, "Mt. Pinatubo aerosols, chlorofluorocarbons, and ozone depletion", *Science* *257*, 1239, 1992. [Crutzen 1970] P. J. Crutzen, "The influence of nitrogen oxides on the atmospheric ozone content", *Quart. J. R. Met. Soc.* *90*, 320, 1970. [Elkins et al. 1993] J. W. Elkins, T. M. Thompson, T. H. Swanson, J. H. Butler, B. D. Hall, S. O. Cummings, D. A. Fisher, and A. G. Raffo, "Decrease in Growth Rates of Atmospheric Chlorofluorocarbons 11 and 12", *Nature* *364*, 780, 1993. [Fahey et al. 1995] D. W. Fahey, E. R. Keim, K. A. Boering, C. A. Brock, J. C. Wilson, H. H.

Jonsson, S. Anthony, T. F. Hanisco, P. O. Wennberg, R. C. Miake-Lye, R. J. Salawich, N. Louisnard, E. L. Woodbridge, R. S. Gao, S. G. Donnelly, R. C. Wamsley, L. A. Del Negro, S. Solomon, B. C. Daube, S. C. Wofsy, C. R. Webster, R. D. May, K. K. Kelly, M. Loewenstein, J. R. Podolske, and K. R. Chan, "Emission Measurements of the Concorde Supersonic Aircraft in the Lower Stratosphere", *Science* **270**, 70, 1995. [Gleason et al.] J. Gleason, P. Bhatia, J. Herman, R. McPeters, P. Newman, R. Stolarski, L. Flynn, G. Labow, D. Larko, C. Seftor, C. Wellemeyer, W. Komhyr, A. Miller, and W. Planet, "Record Low Global Ozone in 1992", *Science* **260**, 523, 1993. [Henriksen and Roldugin] K. Henriksen and V. Roldugin, "Total ozone variations in Middle Asia and dynamics meteorological processes in the atmosphere", *Geophys. Res. Lett.* **22**, 3219, 1995. [Henriksen et al. 1992] K. Henriksen, T. Svenoe, and S. H. H. Larsen, "On the stability of the ozone layer at Tromso", *J. Atmos. Terr. Phys.* **55**, 1113, 1992. [Herman et al.] J. R. Herman, R. McPeters, and D. Larko, "Ozone depletion at northern and southern latitudes derived from January 1979 to December 1991 TOMS data", *J. Geophys. Res.* **98**, 12783, 1993. [Hofmann and Solomon] D. J. Hofmann and S. Solomon, "Ozone destruction through heterogeneous chemistry following the eruption of El Chichon", *J. Geophys. Res.* **94**, 5029, 1989. [Hofmann et al. 1994a] D. J. Hofmann, S. J. Oltmans, W. D. Komhyr, J. M. Harris, J. A. Lathrop, A. O. Langford, T. Deshler, B. J. Johnson, A. Torres, and W. A. Matthews, "Ozone Loss in the lower stratosphere over the United States in 1992-1993: Evidence for heterogeneous chemistry on the Pinatubo aerosol", *Geophys. Res. Lett.* **21**, 65, 1994. [Hofmann et al. 1994b] D. J. Hofmann, S. J. Oltmans, J. M. Harris, J. A. Lathrop, G. L. Koenig, W. D. Komhyr, R. D. Evans, D. M. Quincy, T. Deshler, and B. J. Johnson, "Recovery of stratospheric ozone over the United States in the winter of 1993-94", *Geophys. Res. Lett.* **21**, 1779, 1994. [Hofmann et al. 1996] D. J. Hofmann, S. J. Oltmans, G. L. Koenig, B. A. Bodhaine, J. M. Harris, J. A. Lathrop, R. C. Schnell, J. Barnes, J. Chin, D. Kuniyuki, S. Ryan, R. Uchida, A. Yoshinaga, P. J. Neale, D. R. Hayes, Jr., V. R. Goodrich, W. D. Komhyr, R. D. Evans, B. J. Johnson, D. M. Quincy, and M. Clark, "Record low ozone at Mauna Loa Observatory during winter 1994-95: A consequence of chemical and dynamical synergism?", *Geophys. Res. Lett.* **23**, 1533, 1996. [Kerr et al.] J. B. Kerr, D. I. Wardle, and P. W. Towsick, "Record low ozone values over Canada in early 1993", *Geophys. Res. Lett.* **20**, 1979, 1993. [Khalil and Rasmussen] M. A. K. Khalil and R. Rasmussen, "The Global Sources of Nitrous Oxide", *J. Geophys. Res.* **97**, 14651, 1992. [Larsen and Henriksen] S. H. H. Larsen and T. Henriksen, "Persistent Arctic ozone layer", *Nature* **343**, 134, 1990. [McCormick et al. 1995] M. P. McCormick, L. W. Thomason, and C. R. Trepte, "Atmospheric effects of the Mt Pinatubo eruption", *Nature* **373**, 399, 1995. [McPeters et al. 1996] R. D. McPeters, S. M. Hollandsworth, and C. J. Seftor, "Long-term ozone trends derived from the 16-year combined Nimbus 7/Meteor 3 TOMS Version 7 record", *Geophys. Res. Lett.* **23**, 3699, 1996. [Molina and Rowland 1974] M. J. Molina and F. S. Rowland, "Stratospheric sink for chlorofluoromethanes: chlorine atom-catalyzed destruction of ozone", *Nature* **249**, 810, 1974. [Montzka et al. 1996] S. A. Montzka, J. H. Butler, R. C. Myers, T. M. Thompson, T. H. Swanson, A. D. Clarke, L. T. Lock, and J. W. Elkins, "Decline in the Tropospheric Abundance of Halogen from Halocarbons: Implications for

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Subject: Internet Resources This list is preliminary and by no means comprehensive; it includes a few sites that I have found particularly useful and which provide good starting points for further exploration. Probably the most extensive collection of online resources is that provided by the Consortium for International Earth Science Information Network: <http://sedac.ciesin.org/ozone/> It includes links to many other documents, including on-line versions of some of the original research papers. At the present time portions of the site are very much under construction. Lenticular Press publishes a multimedia CD-ROM (for Apple Macintosh) containing ozone data and images, as well as a hypertext document similar to this FAQ. For sample images and information about ordering the CD, see <http://www.lenticular.com/> Note that these samples are copyrighted and may not be further distributed. The NOAA Aeronomy Lab: <http://www.al.noaa.gov/> , has the text of the Executive Summary of the 1994 WMO Scientific Assessment, <http://www.al.noaa.gov/WWWHD/pubdocs/WMOUNEP94.html> The United Nations Environmental Program (UNEP) Ozone Secretariat: Main page <http://www.unep.org/unep/secretar/ozone/home.htm> (Nairobi, Kenya). Mirror site <http://www.unep.ch/ozone/> (Geneva, Switzerland). The US Environmental Protection Agency has an ozone page that includes links to both science and policy resources: <http://www.epa.gov/docs/ozone/index.html> Some of the more interesting scientific web pages include: The Centre for Antarctic Information and Research (ICAIR) in New Zealand: <http://icair.iac.org.nz/ozone/index.html> Environment Canada: <http://www.doe.ca/ozone/index.htm> The TOMS home page: <http://jwocky.gsfc.nasa.gov/> The EASOE home page: <http://www.atm.ch.cam.ac.uk/images/easoe/> The UARS Project Definition page: http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/UARS_project.html The

HALOE home page: <http://haloedata.larc.nasa.gov/home.html> The British Antarctic Survey: <http://www.nbs.ac.uk/public/icd/jds/ozone/> The ETH Zuerich Institute for Atmospheric Science <http://www.umnw.ethz.ch/LAPETH/lapeth.html> The Institute for Meteorology at the Free University of Berlin: <http://strat-www.met.fu-berlin.de/> The Climate Prediction Center's TOVS Total Ozone Analysis page: <http://nic.fb4.noaa.gov:80/products/stratosphere/tovsto/> The USDA UV-B Radiation Monitoring Program Climate Network, http://uvb.nrel.colostate.edu/UVB/uvb_climate_network.html