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# Ground-Level Effects of Supersonic Transports in the Stratosphere

Harold S. Johnston

*Department of Chemistry, and Inorganic Materials Research Division, Lawrence Berkeley Laboratory, Berkeley, California*

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Ozone in the stratosphere serves to screen the surface of the earth from the destructive middle-ultraviolet radiation that comes from the sun. As sketched in Figure 1, solar radiation is screened out, or not, by the atmosphere, depending on the wavelength of the radiation. The very energetic, far-ultraviolet radiation is removed high in the atmosphere. Molecular oxygen ($O_2$) in the stratosphere completes the removal of this radiation, and in doing so oxygen is converted to ozone ($O_3$). The ozone, so formed, is the only effective screen of the surface of the earth against middle-ultraviolet radiation.

Middle ultraviolet radiation is particularly unwelcome because of its damaging effect on DNA, the biological material that carries the genetic code. Ozone is the umbrella under which DNA can exist. Even though ozone removes most of the middle-ultraviolet radiation, some of this radiation reaches the surface of the earth, causing sunburn, skin cancer, snow blindness, plant damage, bacterial mutations, and other biological effects. Higher plants and animals have elaborate repair mechanisms against the damage caused by the small amount of middle-ultraviolet radiation that leaks through the ozone shield. Near-ultraviolet and visible radiation reaches the surface of the earth and provides light, heat, vitamin D, and photosynthesis.

In the natural ozone balance, the amount and the distribution of ozone in the stratosphere are largely determined by formation from solar radiation, destruction by natural oxides of nitrogen, and redistribution by air motions. The active oxides of nitrogen ($NO_x$) are formed by a well-understood photochemical reaction in the stratosphere, and the global rate of formation and removal of these oxides of nitrogen is now known.

Supersonic transports inject active nitrogen oxides directly into the stratosphere. If fleets of supersonic transports inject nitrogen oxides into the stratosphere, the amount of ozone will be reduced. The biologically damaging radiation that reaches the ground increases strongly as ozone is reduced. Quantitative estimates of the adverse biological effect can most readily be made in terms of additional human skin cancers, although the long-term genetic damage to plants and to plankton may be even more serious.

This Account reviews the history and current status of this subject.

## History of the Subject

In 1971 I stated that the oxides of nitrogen ($NO_x$) from 500 Boeing supersonic transports (SST) would be expected to reduce stratospheric ozone by about 23% as a worldwide average and by up to 50% near the most highly traveled corridor.[1] This prediction was confirmed by a simultaneous study that indicated about a 10% reduction of global ozone, but more or less than this figure depending on the (then unknown) background concentration of $NO_x$ in the natural stratosphere.[2]

These calculations were disputed in a statement that the reduction of ozone would be less than 0.1%.[3] For an $NO_x$ concentration three times greater than that predicted to reduce ozone by a factor of two,[1] an earlier study had concluded that nitrogen oxides in the stratosphere "may be neglected".[4] Thus in 1971 and early 1972 the potential of nitrogen oxides to reduce stratospheric ozone was "controversial". These four estimates are entered in Table I.

There are several components to the problem of ozone reduction by nitrogen oxide catalysts: the mass of $NO_x$ in the SST exhaust per unit mass of fuel, the amount and distribution of natural nitrogen oxides in the stratosphere, and the mean residence time of exhaust gases in the stratosphere, which determines the worldwide increase of stratospheric $NO_x$. Widely divergent values of each of these values were stated in 1971–1972. In 1970 Crutzen[5] proposed that the oxides of nitrogen are important in the natural ozone balance and estimated the natural background to be 12 parts per billion (ppb, $10^{-9}$ mole fraction). For

Harold Johnston is a native of Georgia. He was educated at Emory University and at California Institute of Technology (Ph.D., 1948); he has taught at Stanford, Cal Tech, and Berkeley (since 1957). His field of research is the kinetics of gas-phase reactions. Professor Johnston was awarded the 1974 ACS Award for Pollution Control Sponsored by Monsanto Company in recognition of the research described in this Account.

(1) H. S. Johnston, *Science*, **173**, 517 (1971); UCRL Report No. 20568, 1971, pp 1–106.
(2) A. A. Westenberg, "Effect of $NO_x$ on Stratospheric Ozone", Johns Hopkins University Technical Memorandum TG1186, March 1972.
(3) A. Goldburg, *Astronaut. Aeronaut.*, **10**, 56 (1972).
(4) "SCEP, Man's Impact on the Global Environment, Study of Critical Environmental Problems", The MIT Press, Cambridge, Mass., 1970.
(5) P. J. Crutzen, *Q. J. R. Meteorol. Soc.*, **96**, 320 (1970).

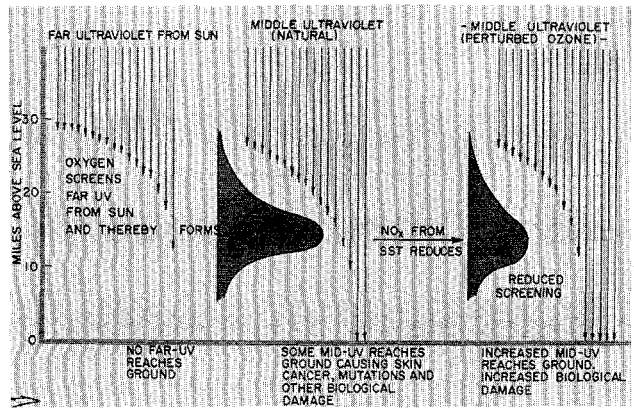


**Figure 1.** Qualitative representation of the role of ozone in the transmission of ultraviolet radiation to the ground.

**Table I**
**Controversy Concerning the Impact of 500 Boeing SST's on Stratospheric Ozone (1971–1972)**

| | Examples of values stated | Ref |
|---|---|---|
| I. $NO_x$ (as $NO_2$) in SST exhaust, g/kg of fuel | 65 | 4 |
| | 23 | 1 |
| | 4.5 | 3 |
| II. Ambient stratospheric $NO_x$, ppb | 100 | 3 |
| | 12 | 5 |
| | ~10 | 2 |
| | 6.6 | 1 |
| III. World-wide increase of stratospheric $NO_x$, ppb | 6.8 | 4 |
| | 2.4 | 1 |
| | 1.2 | 6 |
| | 1 | 3 |
| IV. World-wide decrease of stratospheric ozone, % | 23 | 1 |
| | ~10 | 2 |
| | <0.1 | 3 |
| | "may be neglected" | 4 |
| V. Biological effects | +8000 skin cancer cases, (U.S.) for 1% ozone decrease | 7 |
| | +8000 skin cancer cases (U.S) for 5% ozone decrease | 8 |
| | "Neutral environmental impact" | 3 |

this quantity Johnston[1] estimated 6.6 ppb and Goldburg[3] stated 100 ppb. In 1970 the Study of Critical Environmental Problems (SCEP)[4] had estimated $NO_x$ exhaust emissions to be 65 g (as $NO_2$) per kg of fuel; Johnston[1] used a figure of 23; and Goldburg[3] asserted that the value was 4.5. These widely divergent estimates are also listed in Table I.

In 1971 J. E. McDonald,[7] noting how ozone varies with latitude, pointed out the very strong variation of skin cancer incidence with latitude among uniform populations. McDonald estimated 8000 additional skin cancer cases per year in the United States for each 1% reduction in the average ozone. He thought, like most other atmospheric scientists at the time, that additional water from the SST would reduce ozone; but his contribution concerned the biological effect of reduced ozone, not its photochemical mechanism. Goldburg[3] reviewed McDonald's work, criticized his photochemical mechanism, and concluded that "the calculable impacts are moving toward neutral". An ad hoc panel of the National Academy of Sciences–National Research Council considered the biological implications of SST's in the Fall of 1971; in their report, published in 1973,[8] they estimated that at least 8000 additional skin cancer cases per year (U.S.) would follow a 5% ozone reduction. These statements also appear in Table I.

From Table I, it can be seen that in 1971–1972 strongly different statements were made about the essential components of the problem. The Department of Transportation (DOT) set up a large, interdisciplinary, research program (Climatic Impact Assessment Program, CIAP) in the Fall of 1971 to establish the facts and to resolve this controversy. More than 50 projects have been supported by CIAP; other U.S. agencies and foreign groups have cooperated in this effort. CIAP has encouraged open publication in the scientific literature of findings by their contractors. The Proceedings have been published for three CIAP conferences: (1) Feb 15–16, 1972, (2) Nov 14–17, 1972; and (3) Feb 26–March 1, 1974. An especially interesting article[9] is that by Grobecker, the director of CIAP. The Department of Transportation Report of Findings[10] was issued in March 1975, and the National Academy of Sciences–National Research Council released their independent report reviewing the CIAP findings in April 1975.[11]

The present Account focuses on the content of Table I and especially on the current status of each entry I through V. Finally, the DOT projections[9] for the period 1990–2025 are considered.

## Emission Index of $NO_x$ in SST Exhaust

At the second CIAP conference, Williams[12] reported measurements of pollutants from the Concorde engine (Olympus MK 602) under simulated supersonic cruise conditions. The measured emission of $NO_x$, calculated as $NO_2$, varied between 17.8 and 19.3 g/kg of fuel. This number is intermediate between the high and low values in Table I. For model calculations of the effect of SST's in the stratosphere, the emission index 18 g of $NO_2$/kg of fuel has been taken as standard in a number of cases. Although no engine was ever completed of the type that was to have been used in the Boeing SST, a smaller, somewhat similar engine was tested under simulated stratospheric conditions (Neely and Davidson[13]). They used two different methods of measuring NO in the

(6) L. Machta, "Global Effects of Contaminants in the Upper Atmosphere", American Institute of Chemical Engineers, 64th Annual Meeting, San Francisco, Calif., Nov 1971.
(7) J. E. McDonald, "Assessment of Possible SST Effects on the Incidence of Skin Cancer", Presentation at Boulder, Col., March 1971.
(8) Environmental Studies Board, "Biological Impacts of Increased Intensities of Solar Ultraviolet Radiation", National Academy of Sciences–National Research Council, Washington, D.C., 1973.
(9) A. J. Grobecker, *Acta Astronaut.*, 1, 179 (1974).
(10) A. J. Grobecker, S. C. Coroniti, and R. H. Cannon, Jr., Report of Findings, Department of Transportation, DOT-TST-75-50, Dec 1974.
(11) "Environmental Impact of Stratospheric Flight", National Academy of Sciences–National Research Council, 1975.
(12) M. R. Williams, Proceedings of the Second Conference on the Climatic Impact Assessment Program, DOT-TSC-OST-73-4, 1972, pp 180–193
(13) J. Neely and D. L. Davidson, ref 12, p 180.

exhaust and for unexplained reasons these methods differed by a factor of two. Depending on which of these analytical results one accepts, one finds that the Boeing SST would have produced $NO_x$ at a rate between two-thirds and four-thirds that of the Concorde. Until this question is resolved, modellers have usually assumed large advanced SST's and the Concorde SST to have about the same emission index, namely, 18 g of $NO_2$/kg of fuel.

### Ambient Stratospheric $NO_x$

Hard (1974) issued a summary of recent measurements of trace species in the stratosphere.[14] By now, many measurements have been made for nitrogen dioxide ($NO_2$), nitric oxide (NO), and nitric acid ($HNO_3$). These substances show substantial variation from time to time and from place to place. Relatively few simultaneous measurements have been made of NO and $NO_2$, the catalytically active species. Ackerman and coworkers[15] in May 1974 measured both NO and $NO_2$ between 20 and 36 km, band A of Figure 2. In the range of observations the observed $NO_x$ is close to that predicted in ref 1 (line B) and far less than that stated in ref 3 (line C). This scarcely came as a surprise, because with the amount of $NO_x$ asserted by Goldburg[3] the moon would always appear red from stratospheric $NO_2$.

The natural source of $NO_x$ in the stratosphere was discovered in 1971 by Crutzen,[16] and the magnitude of this source has been calculated by Crutzen, McElroy and McConnell,[17] Nicolet and Vergison,[18] Isaksen,[19] McElroy et al,[20] and others. There is good agreement between these investigators, and a value of about $\frac{3}{4} \pm \frac{1}{4}$ Mton $NO_2$ per year is indicated (megaton, Mton, $10^{12}$ g). This is in the middle of the range of values calculated by Crutzen (1971).

The primary natural process for $NO_x$ removal from the stratosphere is reversible conversion to nitric acid, transport of nitric acid into the troposphere, and rainout in the troposphere. Over a period of 2 years Lazrus and Gandrud[21] measured nitric acid profiles from northern Alaska to southern South America. From the observed gradient of nitric acid vapor and from a model of air motions calibrated against the removal of radioactive debris from the stratosphere, Lazrus and Gandrud[21] calculated the removal rate of $NO_x$ from the stratosphere to be between 0.5 and 1.5 Mton of $NO_2$ per year, in satisfactory agreement with the independently calculated source from $N_2O$ ($\frac{3}{4} \pm \frac{1}{4}$ Mton/year).

In the natural stratosphere, ozone is formed from the photolysis of oxygen

$$O_2 + uv \text{ (below 242 nm)} \rightarrow O + O \quad (1)$$
$$O + O_2 + M \rightarrow O_3 + M \quad (2)$$
$$\text{net: } 3O_2 + uv \rightarrow 2O_3$$

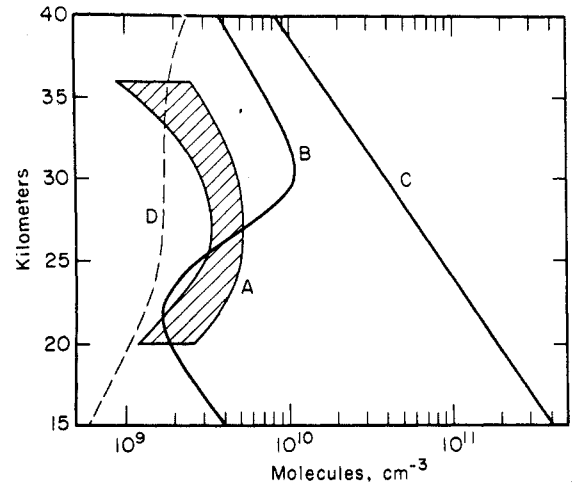


**Figure 2.** Observed (1974) and estimated (1971–1972) vertical profiles of $NO_x$, the sum of NO and $NO_2$. Band A corresponds to simultaneous measurements of NO and $NO_2$ by Ackerman et al. Curve B is that estimated for NO + $NO_2$ by Johnston in 1971. Curve C is that stated for NO + $NO_2$ by Goldburg[3] in 1972. Line D is the concentration of NO + $NO_2$ that would destroy ozone 3.5-fold faster than the rate of destruction of ozone by O + $O_3$.

The global rate of formation of ozone is readily calculated (Johnston and Whitten[22]). In the natural stratosphere, ozone is destroyed by several mechanisms. The most important mechanisms and the approximate contribution of each are as follows:

A. $NO_x$ catalytic cycle (about 70%, if NO + $NO_2$ is as great as curve D of Figure 2)

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (3)$$
$$O_3 + uv \rightarrow O_2 + O \quad (4)$$
$$NO_2 + O \rightarrow NO + O_2 \quad (5)$$
$$\text{net: } 2O_3 + uv \rightarrow 3O_2$$

B. $O_x$ reactions (about 20%)

$$O_3 + uv \rightarrow O_2 + O \quad (4)$$
$$O_3 + O \rightarrow 2O_2 \quad (6)$$
$$\text{net: } 2O_3 + uv \rightarrow 2O_2$$

C. $HO_x$ catalytic cycles (about 10%)

$$HO + O_3 \rightarrow HOO + O_2$$
$$O_3 + uv \rightarrow O_2 + O \qquad HO + O_3 \rightarrow HOO + O_2$$
$$O + HOO \rightarrow HO + O_2 \qquad HOO + O_3 \rightarrow HO + O_2 + O_2$$
$$\text{net: } 2O_3 + uv \rightarrow 3O_2 \qquad 2O_3 \rightarrow 3O_2$$

D. Transport to troposphere and destruction on the surface of the earth (less than 1%).[22,23]

The full chemical mechanism used in stratospheric studies involves 50 to 100 chemical reactions of measured rate constants (Garvin and Hampson[24]). The

(14) T. M. Hard, Technical Report, Transportation Systems Center, Cambve, Mass., Nov 1974.
(15) M. Ackerman, J. C. Fontanella, D. Frimont, A. Girard, N. Louisnard, and C. Muller, *Aeronom. Acta A, 133* (1974).
(16) P. J. Crutzen, *J. Geophys. Res.*, **76**, 7311 (1971).
(17) M. B. McElroy and J. C. McConnell, *J. Atmos. Sci.*, **28**, 1095 (1971).
(18) M. Nicolet and E. Vergison, *Aeronom. Acta*, **90**, 1 (1971).
(19) I. A. Isaksen, *Pure Appl. Geophys.*, **106–108**, 1438 (1973).
(20) M. McElroy, S. Wofsy, J. Penner, and J. McConnell, *J. Atmos. Sci.*, **31**, 287 (1974).
(21) A. L. Lazrus and B. W. Gandrud, *J. Atmos. Sci.*, **31**, 1102 (1974).
(22) (a) H. S. Johnston and G. Whitten, *Pure Appl. Geophys.*, **106–108**, 1468 (1973); (b) AGARD Conference on Atmospheric Pollution by Aircraft Engines, 1973.
(23) (a) L. Aldaz, *J. Geophys. Res.*, **74**, 6943 (1969); (b) A. W. Brewer and A. W. Wilson, *Q. J. R. Meteorol. Soc.*, **94**, 249 (1968).
(24) (a) D. Garvin and R. F. Hampson, Ed., "Chemical Kinetics Data Survey VII. Tables of Rate and Photochemical Data for Modelling of the Stratosphere", NBSIR 74-430, National Technical Information Service, Springfield, Va., 1974; (b) R. T. Watson, "Chemical Kinetics Data Survey VIII. Rate Constants of $ClO_x$ of Atmospheric Interest", NBSIR 74-516, National Technical Information Service, Springfield, Va., 1974; (c) E. E. Ferguson, *Ann. Geophys.*, **28**, 389 (1974).

full details of the chemistry are not described here, although they are considered by the modellers of stratospheric photochemistry.

## Increase in Stratospheric $NO_x$ from SST Operations

Grobecker[9] gives the number of SST's projected by various studies out to the year 2025. These projections include subsonic fleets as well as supersonic fleets. These numbers of aircraft were translated into mass of fuel expected to be burned each year at various altitude bands.[9] Supersonic transports that cruise near 17 km (Concorde-like) were projected to increase slowly from 1990 to 2025. Advanced supersonic transports that cruise near 20 km were projected to increase very rapidly from 1990 to 2025. On the further assumption that the emission index for $NO_x$ of future SST's remains the same as for current Concordes (an assumption that Grobecker emphasizes need not be so), the projected artificial $NO_x$ input from SST's between 15 and 21 km is 0.70 Mton/year in 1990 and 30 Mton/year in 2025. These artificial injections into the stratosphere are approximately equal to the natural source of NO in 1990 and about 40 times greater than the natural source in 2025. As noted above, the natural $NO_x$ in the stratosphere now destroys 70% of the ozone formed between 15 and 45 km.

Before 1990, the projected SST's are Concordes and Tupolevs. Such a plane cruises at about 17 km, uses an average of 20,000 kg of fuel/hr, is projected to be at cruise height about 2000 hr/year, and emits $NO_x$ (calculated as $NO_2$) at a rate of 18 g/kg of fuel. The emission from 375 Concorde-like SST's is about 0.27 Mton (as $NO_2$) per year (375 Concordes is the number projected to 1990 by the Environmental Protection Agency[25].) These emissions are over one-third the natural rate of formation of $NO_x$ in the stratosphere.[21]

## Reduction of Ozone by $NO_x$ from SST Exhausts

Including the first report of reduction of stratospheric ozone by nitrogen oxide catalysts from supersonic aircraft exhausts, there have been at least 12 different studies of this problem. These are listed in Table II with a reference code to Figure 3; the full references are given by Chang.[26] These 12 studies encompass a wide range of sophistication so far as atmospheric motions are concerned: simple box model, seven different models of vertical eddy transport, three models with vertical and north–south transport, and one model involving three-dimensional atmospheric motions. Elaborate calculations have been made involving only one-dimensional motion; for example, Chang[26] studied the effect of seasonal variations and of diurnal variations on the role of SST's in reducing ozone, including a full set of chemical reactions. Figure 3 gives the most recent results from the 12 modellers, with the results by Hunten[27] indicated by lines. The percentage reduction of global ozone is plotted against the global rate of insertion of $NO_2$ at 20 km in Figure 3. The solid line is Hunten's results for insertion of $NO_x$ at 20 km (Boeing SST); the dashed line is Hunten's results for insertion of $NO_x$ at 17 km (Concorde). The global average reduction of ozone for insertion of 1.8 Mton of $NO_2$/year at 20 km is included in Table II. This quantity corresponds to 500 Boeing SST's as they were described in 1971.

Considering the complexity of the problem and the wide range of methods used, there is satisfactory agreement among the 12 investigators (Table II and Figure 3). The causes of the spread were identified by

**Table II**
**Modellers Who Have Calculated the Reduction of Stratospheric Ozone as a Result of $NO_x$ from SST Exhaust, a Reference Code for Figure 3 and Calculated Ozone Reduction by 1.8 MT $NO_x$ (as $NO_2$) per Year Inserted at 20 km (Global Average)**

| No. | Author (year)[a] | Dimension of atmospheric motion | Ozone reduction, % |
|---|---|---|---|
| 1 | Johnston (1971) | Box | 23 |
| 2 | Crutzen (1974) | 1 | 9 |
| 3 | Hesstvedt (1974) | 2 | 12 |
| 4 | Chang (1974) | 1 | 8 |
| 5 | Stewart (1973) | 1 | 12[b] |
| 6 | McElroy et al (1974) | 1 | 11 |
| 7 | Whitten and Turco (1974) | 1 | |
| 8 | Shimazaki and Ogawa (1974) | 1 | 22 |
| 9 | Vupputuri (1974) | 2 | 9 |
| 10 | Widhopf (1974) | 2 | 16 |
| 11 | Cunnold et al (1974) | 3 | 12 |
| 12 | Hunten (1974) | 1 | 19 |
| | DOT (ref 10) | | 13.5 |
| | NAS (ref 11) | | 19 |

[a] For references, see Chang.[26] [b] As recalculated by Chang.[26]

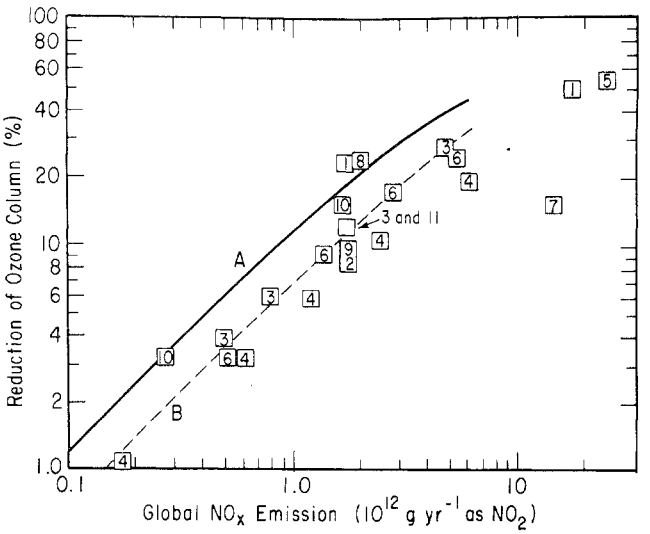


**Figure 3.** Calculated reduction of vertical ozone column in terms of the annual global rate of $NO_x$ (as $NO_2$) addition at 20 km. The authors of these calculations are given in Table II and references are given by Chang.[26] Curve A is that calculated by Hunten for $NO_x$ insertion at 20 km and curve B is that calculated by Hunten for $NO_x$ insertion at 17 km.

(25) *Fed. Regist.*, **39**, 26654 (1974).
(26) J. S. Chang, Proceedings of the Third Conference on the Climatic Impact Assessment Program, DOT-TSC-OST-74-15, 1974, pp 330–341.
(27) D. M. Hunten, submitted to *Science*.

means of an intensive analysis by Chang.[26] Also, some of the models of stratospheric motion were put to a sharp test[28] by seeing how well they predict the dissipation of carbon-14 produced by the nuclear bomb tests of 1961–1962. Of the one-dimensional models, Hunten's model gives the best quantitative prediction of the distribution and removal of carbon-14 over the period 1963–1970. The two-dimensional model of Widhopf[29] also gives a satisfactory prediction of the spread of stratospheric carbon-14 in the years after the nuclear bomb tests. The ozone reductions predicted by Widhopf or by Hunten are very nearly the same as the large reductions predicted in 1971.

For insertion of 1.65 Mton of $NO_2$/year at 20-km elevation and between 45 and 55°N latitude, Widhopf[29] found a maximum local ozone reduction of 41%, which is in close agreement with the 50% maximum local ozone reduction reported by Johnston[1] for an input of 1.8 Mton/year.

## Biological Effects

The principal biological effects of supersonic transports derive from the increase in band b ultraviolet radiation (uv-b, 280–320 nm) that reaches the surface of the earth after nitrogen oxides from the SST's reduce stratospheric ozone. Susceptible biological systems[7,8,10,11] include human skin, human and animal eyes, insects, plants, and plankton. Solar radiation is absorbed by ozone in the stratosphere, scattered by air molecules in the troposphere, and strongly scattered by particles and by clouds in the troposphere. For a given distribution of ozone and particles, the transmission and scattering of solar radiation are strong functions of solar angle. Realistic calculations of the transmission of solar radiation have been made by Green and coworkers.[30]

The absorption spectrum of ozone (Ackerman[31]) is given on a logarithmic scale in Figure 4. The peak absorption occurs at 255 nm. The quantity of sunlight transmitted by 0.23 cm (STP) of ozone as a function of wavelength is included in Figure 4. The sharp cutoff of sunlight near 300 nm is apparent.

The relative absorption spectrum of DNA and the spectrum for erythema (Setlow[32]) are also given by Figure 4. The shape of the DNA absorption curve and the shape of the ozone absorption curve are similar. Ozone in the stratosphere cuts out most solar radiation that would be absorbed by DNA. When DNA absorbs uv-b, the molecule is damaged, but the DNA chain is usually not broken (Smith[33]). Higher plants and animals have several processes that repair the DNA damage: one repair process is brought about by deep-violet visible light, one process involves cutting out the damaged portion of the DNA and replacing with a fresh section, and one process involves bypassing the damaged strand upon replication. Cells are

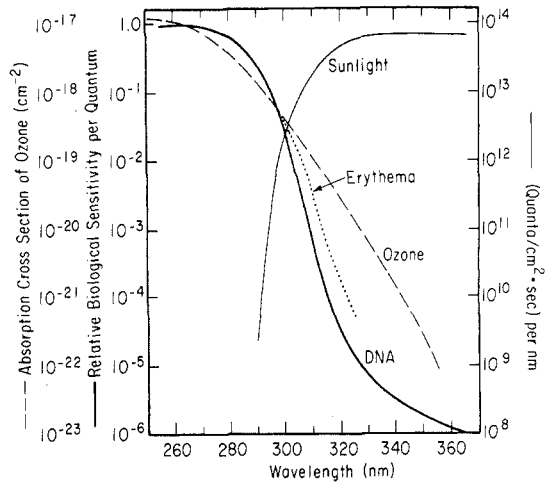


**Figure 4.** (A) Optical absorption cross section of ozone as a function of wavelength of radiation. (B) Relative biological activity spectrum for DNA and for erythema. (C) Transmitted radiation as a function of wavelength for 0.23 cm of $O_3$ and 25° zenith solar angle. The sharp cut-off near 300 nm is primarily due to absorption by ozone.

quickly killed by uv-b radiation if they lack repair mechanisms (Smith[33]).

The action spectrum for DNA damage is the product of transmitted sunlight with the DNA absorption curve. This action spectrum is sharply peaked, and the peak depends on the vertical column of ozone. The DNA damage is proportional to the area under action-spectrum curves. The erythema dose is the area under similar curves where the erythema sensitivity is used instead of the DNA absorption spectrum. For small decreases of ozone, DNA damage increases 2.5 times faster than the decrease of ozone;[32] for large decreases of ozone, the relative increase in DNA damage approaches the 2.3 power of the relative decrease of ozone.

Ozone is subject to natural variations in both time and place.[34] In north temperate and polar regions, the overhead ozone column is a maximum in February or March and a minimum in September or October, and there is a large difference (approaching 33%) between the average maximum and average minimum. In tropical regions the amount of ozone is very nearly the same throughout the year. The difference between polar winter maximum and tropical minimum is about 40%. In the late summer and early fall, the differences among polar, temperate, and tropical zones are only 10 or 15%. A moderate reduction in ozone in temperate zones in the summer or fall could bring the tropical distribution of radiation to the temperate zone. A large reduction of ozone in summer temperate zones or a moderate reduction in the tropics would set up a radiation distribution unlike any now on earth.

The differences in erythemal dose, averaged over hours of the day and seasons of the year, for various latitudes were calculated by Mo and Green.[30b] There is about a factor of four difference in erythemal dose between 50°N and the equator. Green and Mo[30a] constructed an "epidemiological index" which includes the factors of latitude, cloudiness, and ground reflection on erythemal dose. Urbach[35] gave the ex-

(28) H. S. Johnston, D. Kattenhorn, and G. Whitten, submitted to *J. Geophys. Res.*

(29) G. F. Widhopf, "Meridional Distributions of Trace Species in the Stratosphere and the Effect of SST Pollutants", American Geophysical Union Meeting, San Francisco, Calif., Dec 12–18, 1974.

(30) (a) A. E. S. Green, T. Sawada, and E. P. Shettle, *Photochem. Photobiol.*, **19**, 251 (1974); (b) T. Mo and A. E. S. Green, *ibid.*, **20**, 483 (1974).

(31) M. Ackerman in "Mesopheric Models and Related Experiments," G. Fiocco, Ed., D. Reidel Publishing Co., Dordrecht, Holland, 1971, pp 149–159.

(32) R. B. Setlow, *Proc. Natl. Acad. Sci. U.S.A.*, **71**, 3363 (1974).

(33) K. C. Smith, *Bioscience*, **24**, 45 (1974).

(34) H. U. Dütsch, *Adv. Geophys.*, **15**, 219 (1971).

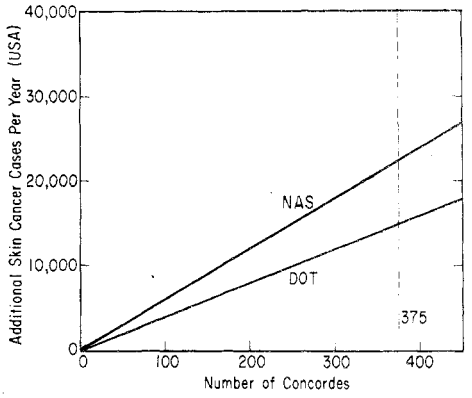


**Figure 5.** Increase in the number of skin cancer cases per year in the United States of America as a function of the number of Concorde supersonic aircraft according to the findings of the Department of Transportation[10] and according to the National Academy of Sciences.[11] The vertical dashed line represents 375 Concordes, the EPA estimates[25] for 1990.

pected increase (per $10^5$ population) in skin cancer in the United States as a function of percentage ozone reduction, according to Green's erythema function. For a susceptible population of 200 million, this increase in skin cancer cases is 8000/year for a 1% ozone reduction for the erythema action spectrum. A similar calculation gives over 11,000/year for the DNA action spectrum. It is interesting to compare these 1974 results with McDonald's 1971 statement,[7] Table I. McDonald said that a systematic 1% ozone reduction would increase the number of skin cancer cases in the United States by 8000/year, which agrees with current knowledge.[10,11]

There is a cause and effect chain: an increase of stratospheric $NO_x$ decreases ozone, increases uv-b at the ground, and increases skin cancer cases and other biological damage. The most immediate prospect for moving down this chain is the proposed fleet of Concorde SST's. The interesting quantity is the relation between number of Concordes and the increase in skin cancer cases. This calculation has been carried out both by the Department of Transportation[10] and the National Academy of Sciences–National Research Council.[11] The ultimate increase in skin cancer cases in the United States as a function of the number of Concorde-type SST's is given by Figure 5, as estimated both by DOT and NAS (based on a susceptible population of 200 million). According to NAS–NRC, the U.S. skin cancer cases increase at a rate of about 60/year for each Concorde or about 6000/year for 100 Concordes. For the EPA-predicted 375 Concordes by 1990, there would be an increase of 22,500 U.S. skin cancer cases per year. The NAS–NRC report estimates that the 375 Concordes would thereby cause 225 additional cancer deaths per year in the U.S.

## Beyond 1990

As can be seen from Figure 6, large increases in SST's are expected by Grobecker[9] after 1990. If there is no reduction in $NO_x$ emission index, the projected fleets of SST's lead to very great reductions of ozone. The percent ozone reductions derived from the NAS–NRC model and the percentage increase in biologically damaging ultraviolet radiation are given in Figure 6 for the years 1990, 2000, 2010, and 2020. The worldwide ozone is reduced by a factor of two in the year 2011, and it is reduced a factor of three by the year 2021. Biologically damaging radiation is doubled by the year 2001, increased more than fivefold by the year 2011, and is off-scale of anyone's model by the year 2020. The indicated increase in U.S. skin cancer cases is about a half million per year with the radiation distribution of the year 2001, and over 2 million per year for year 2011. The effects on plants and plankton may be much worse. Even if the emission index for $NO_x$ is reduced by a factor of 100, the SST fleets of 2025 would increase U.S. skin cancer cases by 35,000 per year.

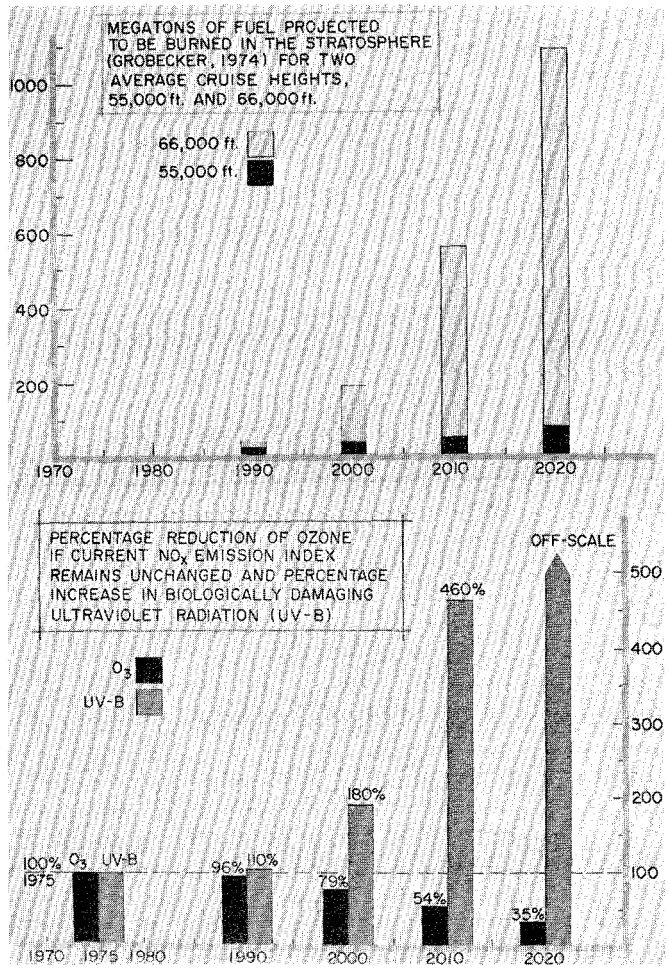


**Figure 6.** A prediction of future rates of fuel consumption by fleets of supersonic transports (1 Mton is $10^{12}$ g). The corresponding percentage decrease of global ozone and increase in DNA dosage for the period 1990–2025. Note that these 1974 predictions of future fleet sizes and 1974 calculations of the effect of $NO_x$ on ozone give much larger ozone reductions than a factor of two.

Most of the results presented in this report are for the year 1974. There has been a flood of new evidence during 1974. The major uncertainties of 1971–1972 have been resolved. The new evidence supports the thesis that $NO_x$ in the stratosphere reduces ozone and that the amount of $NO_x$ contributed by a few hundred SST's would be a serious matter.

(35) F. Urbach, D. Berger, and R. E. Davies, *Adv. Geophys.*, 18, 523 (1974).

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