Effects of Cruise-Altitude Pollution

Anthony J. Broderick*
Department of Transportation, Transportation Systems Center, Cambridge, Mass.

This paper presents a brief, relatively nontechnical summary of present understanding of the environmental effects of aircraft emissions during high-altitude-cruise operation. It is shown that the effects of nitric oxide and water on ozone are relatively well established, but that the possible climatic consequences of emissions are, at best, poorly understood.

Introduction: The Atmosphere

NINETY-NINE percent of our atmosphere is contained inside a shell surrounding the Earth to a height of only about 23 miles. On an equivalent scale, if the Earth were the size of an apple, the atmosphere would be only about as thick as the skin. The enormous power and energy contained within the atmosphere often is observed in thunderstorms, hurricanes, typhoons, and other violent microscale and mesoscale phenomena; yet it is only within the last few years that we have come to appreciate the fragility of its dynamic chemical balance. Much of this understanding has been brought about by participants in the U.S. Department of Transportation's Climatic Impact Assessment Program (CIAP), and similar studies sponsored by other governments.

The region of the atmosphere in which we live is called the *troposphere;* it extends from the ground up to the "tropopause," an altitude of about 11 km (36,000 ft). Above the tropopause, the *stratosphere* extends to a height of about 50 km (164,000 ft). Generally speaking, the troposphere is characterized by very rapid vertical and horizontal mixing and a temperature which decreases as altitude increases. The stratosphere, on the other hand, is characterized by a relative absence of vertical mixing and a temperature which is constant or increases with increasing altitude. The boundary between these two regions of the atmosphere, the tropopause, is defined by meteorologists as, basically, the altitude at which temperature ceases to decrease with increasing altitude. The exact height of the tropopause varies according to lattitude and season, being highest in the tropics (18 km, 59,000 ft) and lowest in the polar winter (8 km, 26,000 ft), and even varies by several kilometers or more during the passage of storms. The atmosphere is dynamic, changing rapidly from day to day and more slowly and predictably with the seasons.

Routine commercial aircraft flight in the stratosphere is a product of the "jet age." Winter flights from New York to Europe, or Moscow to Vladivostok, are flights in the lower stratosphere, in the 9- or 10- to 12-km region (30,000–40,000 ft). The new supersonic transports (SST's) which are being built to serve these routes will cruise considerably higher, in the 15–18-km range (50,000–60,000 ft). New models of long-range subsonic aricraft also are designed to cruise routinely at higher altitudes; for example, the 747 SP will cruise routinely in the 12–14 km (40,000–45,000 ft) region. The tropopause does not represent an actual physical barrier in the atmosphere, and its precise location varies on both a daily and seasonal basis. Pollution of the lower stratosphere by conventional aircraft flying in the vicinity of the tropopause is, however, somewhat less severe than that caused by SST's, which cruise well into the stratosphere. Pollutants are dispersed less rapidly with increasing flight altitude in the stratosphere; SST exhaust products can remain up to two years. (Vertical mixing becomes less intense as penetration into the stratosphere increases.)

In the last few years, several studies have been published which report on the emissions of jet aircraft engines (e.g., Refs. 1 and 2). The following paragraphs briefly discuss the effects of water and oxides of nitrogen on ozone and climate, and the effects of sulfur dioxide and carbon dioxide on climate.

Presented as Paper 75-1016 at the AIAA Aircraft Systems and Technology Meeting, Los Angeles, Calif., Aug. 4–7, 1975; submitted Sept. 19, 1975; revision received April 15, 1976. This paper represents the author's personal views, and does not necessarily reflect any policy or position of his employer or any other organization with which he is associated. It has benefitted greatly from discussions with T.M. Hard and R.C. Oliver.

Index categories: Air Transportation Systems; Atmospheric, Space, and Oceanographic Sciences; Airbreathing Propulsion, Subsonic and Supersonic.

*Physicist, Environmental Measurements Branch, Biotechnology Div.

Stratospheric Ozone

The lack of vertical mixing in the stratosphere, mentioned earlier, is an indirect result of the vertical distribution of atmospheric ozone. The stratospheric "layer" of ozone is critical to the biosphere, because it absorbs most of the powerful solar ultraviolet radiation which could otherwise harm life on the Earth's surface. In absorbing this solar energy, the ozone (and the air containing it) is heated, with the result that a kind of "thermal inversion" layer is created in the stratosphere. It is the stable air associated with this permanent thermal inversion which characterizes the dynamics of the stratosphere.

The amount of ozone present in the stratosphere is a function of many complex and competing chemical and transport actions. A reasonable understanding of ozone behavior requires, therefore, a knowledge of the balance between the chemical reactions and dynamic motions which produce and transport ozone (its "sources") and the mechanisms of its destruction (the "sinks"), for derivation of the steady-state average (equilibrium) concentration of stratospheric ozone. In the early 1960's several attempts to balance these reactions were deemed "successful" (e.g., Ref. 3), but by the late 1960's more accurate analyses of the chemical reactions of importance showed atmospheric scientists that there were large gaps in their understanding of this matter. At that time, attempts to balance the source and sink terms of the chemical-dynamic realtionship were unsuccessful, since they indicated that nearly twice as much ozone was being produced per unit of time as was being destroyed. It was then that Crutzen[4] pointed out that naturally-occurring oxides of nitrogen (NO_x) could be assigned the role of a major sink of ozone in the stratosphere, and that reasonable estimates of their concentration would result in a fairly satisfactory balance of the sources and sinks of ozone. Working independently, Johnston[5] called attention in 1971 to the potential danger of SST-engine oxides-of-nitrogen emmissions, which might upset the natural balance, and lead to a decrease in atmospheric ozone concentration.

Nitric oxide destroys ozone in a *catalytic* manner. Though the complete chemical-reaction scheme is very complex, the most important reaction is as follows. A nitric oxide molecule first reacts with an ozone molecule, resulting in the production of one molecule of oxygen and one of nitrogen dioxide. The nitrogen dioxide molecule in turn combines with an oxygen atom (which would otherwise have formed an ozone molecule) to produce an oxygen molecule and a nitric oxide molecule. The cycle has then gone full circle: having destroyed two ozone molecules, the nitric oxide molecule remains to begin another ozone-destruction cycle. Thus, because of the catalytic nature of this chemical-reaction chain, and others of somewhat lesser importance, very small amounts of nitric oxide can destroy surprisingly large amounts of ozone, and will continue to do so until the nitric oxide is removed physically from the stratosphere by the natural process of slow downward vertical transport to the troposphere. (More accurately, it is nitric acid, eventually formed from nitric oxide, which is removed by downward transport and eventual rainout; this chemical and transport chain is the major sink for stratospheric nitric oxide.)

As mentioned earlier, downward transport is slow in the stratosphere, and the average rate of removal of aircraft emissions is dependent upon the altitude, season, and latitude at which they are injected. Thus, emissions of oxides of nitrogen from conventional subsonic jet aircraft are less worrisome than the same emissions at the higher altitudes at which supersonic aircraft would fly. This is a key finding of the CIAP study, and is illustrated in Fig. 1.†

From this graph, the number of aircraft (read on the horizontal scale) flying at a given altitude which would cause a given reduction in the ozone column (read on the vertical scale), as estimated by CIAP, may be determined. As emissions of oxides of nitrogen are reduced, or the altitude at which the aircraft cruise is lowered, or both, the problem becomes less severe, i.e., more traffic may be tolerated before a given reduction occurs. The greatest uncertainty in these effects is for flight in the region of the tropopause, as in subsonic cruise. As shown in the CIAP report,[1] our estimates for these relationships conceivably may be in error by as much as a factor of 10.

Note that the oxone-reduction estimates of Fig. 1 are presented as "Northern Hemisphere" values. In fact, these are CIAP[1] estimates of the long-term ozone reductions which would be realized in the 30 deg.–60 deg. N latitude belt for a fleet with traffic predominantly in the same region. The Northern hemisphere value (or "corridor" value; see Fig. 2) is twice the calculated global-average ozone reduction for the same traffic. We now recognize that a "corridor effect" as such, with disproportionate ozone reduction directly beneath heavy traffic concentrations, does not occur. Rather, north-south transport by air motions acts to distribute exhaust pollutants horizontally in the stratosphere before they diffuse upward high enough to act on the ozone layer. The net result, with traffic distributions concentrated in the 30 deg.–60 deg. N latitude band as they are today, is relatively uniform but there are lower ozone reductions south of about 30 deg. N, and increasingly higher ozone reductions north of 30 deg. N, reaching a maximum near the pole.

Effects of Reduced Ozone

The direct effect of catalytic reduction of stratospheric ozone by oxides of nitrogen is an increase in the amount of

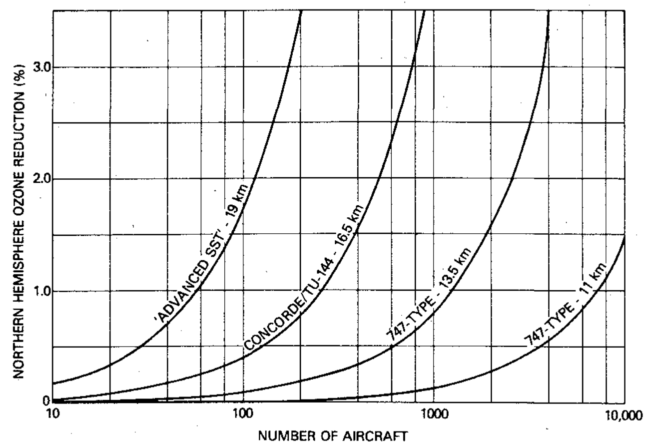

Fig. 1 CIAP-estimated ozone reduction, assuming 1974 engine technology.

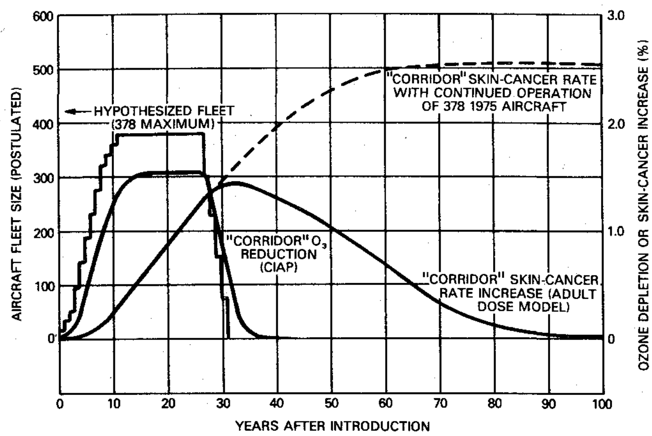

Fig. 2 Time dependence of aircraft effects.

middle-uv radiation which strides the Earth's surface. Perhaps the most widely discussed effect associated with a decrease in the amount of the ozone shield is the projected resulting increase in the incidence of skin cancer in humans.

There are three main types of skin cancers: malignant melanoma, basal-cell carcinoma, and squamous-cell carcinoma. Malignant melanoma has an associated high mortality rate, whereas the nonmelanoma types result in death very infrequently (and even then, probably as a result of near-total lack of treatment). There are good data on the geographic distribution of the incidence of melanoma; they show a high correlation between increasing incidence and decreasing latitude (moving toward the equator). Since the amount of ozone in the atmosphere decreases with decreasing latitude, and the sun's rays travel through an increasingly shorter path as it comes more directly overhead, the amount of uv radiation striking the ground increases with decreasing latitude. Thus, it might be expected that one could associate increased incidence of melanoma with decreasing ozone amounts, as was observed by James McDonald in 1971.[6] To date, however, biologists have been unable to provide any information which indicates a causal relationship, and CIAP developed no specific indications that decreased ozone will result in increased incidence of malignant melanoma, although there is concern that it might.

On the other hand, decreasing the amount of ozone in the stratosphere is expected to result in an increase in the rate of incidence of the nonmelanoma forms of skin cancer. In laboratory tests with animals, these types of skin cancer have been linked definitely to excessive exposure to uv light, and they are found most frequently in exposed areas of the body in members of light-skinned races. Although they are only

†It was assumed for these calculations that an advanced SST would burn 6×17^7 kg of fuel at 19.5 km and 3×10^6 kg of fuel at 16.5 km each year, in each case with an emission index of 18 g of NO_2 per kg of fuel burned; for the Concorde, these figures were assumed to be 3×10^7 kg fuel at 16.5 km and 4×10^6 kg at 13.5 km, with an emission index of 18; for the 747 types, 2×10^7 kg fuel with an emission index of 15 was assumed at cruise altitudes of either 11 km or 13.5 km as shown.

rarely fatal, the need for medical attention, and the potential for disfigurement and associatead mental anguish, make an increase in the incidence of this disease something to be avoided. Very roughly speaking, the incremental increase in skin-cancer incidence in the United States, which might be attributed to an incremental decrease of 0.5% in average ozone concentration, is 1%. For small changes in ozone concentration this relationship remains the same, e.g., a 1% decrease in ozone would probably result in an increase of about 2% in the incidence of nonmelanoma skin cancer. (At present, a very rough figure for the incidence of skin cancer in the United States is 300,000 cases per year.)

It has been asserted[1,2] that increased uv-radiation levels resulting from decreased ozone also might be harmful to plant life, but specifics in this regard have proven very difficult to pin down. Laboratory tests on some plants have tended to confirm such a relationship, but tightly controlled tests in so-called "growth chambers" have been less conclusive, and attempts to verify such a conclusion by field tests largely have indicated no such direct effect.

Other effects which have been associated loosely with ozone levels include increased weathering of materials, especially those of organic polymer base, increased aging and similar effects on human skin, decreased forest resources, and reduction in populations of certain aquatic species. These and other deleterious effects were described more fully in the CIAP *Final Report.*[1] It must be made clear, however, that many (if not nearly all) of these claimed adverse effects of increased uv radiation are speculative. A particular species might be affected adversely, but, again, it might not. Indeed, the effects might even be beneficial. It is clear that more research on some of these matters would be desirable, but we are far from being able seriously to consider corrective steps based only on loose assertions.

Climate Change

"Climate" generally is taken to mean the typical long-term behavior of weather events, usually considered over a period of at least several decades, for a given geographical region or over the globe as a whole. Even though it usually is discussed in such terms as "average rainfall" or "mean temperature," the climate of a region includes unpredictable and often undesirable extremes of flood, drought, and hot and cold spells. For reasons which are not yet understood, climate fluctuates over irregular intervals of hundreds to thousands of years. Over recorded history, however, there have been no major changes in climate measured over a period as short as one or even two generations. It generally is accepted that this "smoothing" of climate fluctuations is the result of the influence of the oceans, whose large heat capacity tends to act as a "flywheel" in damping out any possible climatic pulsations so that their effects are felt slowly.

Changes in the rate of heating of the Earth's surface would be extremely difficult to define accurately until several decades had passed, during which data had been carefully collected and analyzed on a global scale. Over the last few centuries, natural changes of the magnitude attributed to worst-case effects of pollution of the stratosphere by aircraft have taken place. They have served to demonstrate that climate change is far from uniform over the globe. Regions of Canada, Europe, and the USSR, for example, would be likely to experience more of a change in average temperature than, say, the U.S. and Mexico. Smaller areas in any or all of these regions might experience still greater changes.

More important even than average temperature changes, though, might well be the associated change in other climatic variables. For example, the number of frost-free days in a given growing season is far more significant than the average seasonal temperature to farmers, and, though they are related, frost-free days cannot be derived reliably from a knowledge of average temperature alone. In marginal growing zones, an almost imperceptible lowering of average temperature could conceivably shorten the growing season enough to render the region virtually useless for growing those crops which are presently only marginally profitable. More critical still is the number of seasons, in a series, in which the weather has been such as to preclude production of a successful crop. (This determines the suitability of a region for growing particular crops.)

Changes in precipitation and winds, both of which are linked to temperature through a series of complex interrelationships, severely complicate attempts to assess the impact of climate change. For example, decreased temperature by itself might be expected to result in lower productivity for some crops, but it also slows the rate at which water evaporates from the soil and the plant itself. Now, if the crop is grown in a region where the limiting factor in yield is soil moisture, a small decrease in average temperature would probably increase that crop yield; conversely, if the region is not moisture-limited, decreased yield would be expected.

Several constituents of aircraft exhaust have been postulated to be potential sources of climatic change through alteration of the atmospheric and surface temperatures of the earth. Carbon dioxide and water-vapor emissions might build up in the stratosphere enough that they would trap in the atmosphere a measurable amount of the heat which normally would have escaped to outer space, thus causing an increase in global average surface temperature (the "greenhouse" effect). Emissions of oxides of nitrogen, if permitted in such quantities that significant amounts of stratospheric ozone were destroyed, indirectly might cause added cooling of the Earth's surface from the lowered stratospheric ozone concentration. Nitrogen dioxide, on the other hand, is thought to compensate somewhat for the ozone's effect by indirectly causing surface warming. And last, the effects of increased stratospheric aerosol concentration, which might result from gas-to-particle conversion of sulfur dioxide emissions, are postulated to lead to cooling, by decreasing the amount of sunlight striking the Earth's surface.

Our present understanding of climate, and the factors which influence its change, is insufficient to permit reasonably accurate predictions of the net climatic change which might be caused by stratospheric flight. It also must be strongly emphasized that the present state of climate modeling would not permit the accurate forecast of any regional effects, even if the average hemispheric effect were known with certainty. It is perhaps reasonable, however, to place most-probable limits on the changes which might occur. Thus, the National Academy of Sciences[2] drew the following conclusion (applicable to a fleet of roughly 1,000 "advanced SST's" or, equivalently, some 18,000 747-SP types): "...it is the opinion of the scientists working in this field that climate changes resulting from aircraft emissions in the stratosphere would not be large. The prevailing opinion seems to be that high-altitude flight operations...would produce long-term global surface temperature changes of no more than a few tenths of a degree Celsius, and global rainfall would not be altered by more than ±5 percent...," with estimated maximum regional temperature changes of perhaps 1°C and maximum regional variations in precipitation of ±10%. True, these are large changes, but the size of the fleet associated with these changes is almost unbelievable, representing an investment of nearly one-half of today's U.S. Gross National Product!

Discussion

The preceding paragraphs have touched briefly on this writer's view of the major conclusions which may be drawn after about four years of intensive study of an exceedingly complex issue. In the remaining sections, some interpretations of the implications of these findings are discussed.

Time-Dependent Effects

It is important to recognize, as was pointed out by McDonald,[6] that skin cancer appears to result from cumulative excessive exposure to uv radiation. Thus, effects of an increase in uv dose are not felt immediately, but are delayed for up to 50 years or more.[7] This is illustrated in Fig. 2. Its detailed assumptions concerning fuel flow, emission index, or time at cruise are not relevant for this discussion. Note, however, that the calculation arbitrarily assumed that a fleet of 378 aircraft (of the Concorde type) would be built up over a period of about 10 years, would operate at full capacity for about 15 years, and would then phase out in about five more years. During this period, ozone reduction would increase, lagging the fleet buildup by a couple of years, to an equilibrium level of about 1.5%. After the fleet has been phased out, ozone returns to its natural level within a couple of years. Skin-cancer rates, however, never reach the equilibrium level for this case; the maximum increase in skin-cancer incidence is only about half of what it would be if the 378-aircraft fleet were operated indefinitely. This is because it is believed that skin cancer is a product of cumulative exposure—not an instantaneous result of increased exposure. This detail may be important for some studies, and generally is not recognized. Similar effects, though possibly less pronounced, can be demonstrated for climatic change.[7]

Interactions among Pollutants

As is evident from the earlier discussion of climatic effects, the net effect of cruise-altitude pollution is a sum of separately considered individual effects, some of which may tend to cancel others. Calculations presented in the CIAP report[1] were not clear in this regard, in part because of a lack of information at the time of its writing. It is only reasonable, however, to remember that summed effects of all pollutants must be considered from what might be called a "systems" viewpoint before conclusions regarding stratospheric "impact" can be drawn.

Specifically, the CIAP report[1] mentions that exhausted water vapor tends to warm climate, through the greenhouse effect, but no attempt was made to report a net estimate of climatic change. The reader therefore may be misled inadvertently; it is not possible for the sulfur-related cooling to take place in the absence of water-related warming, since both substances are present in the exhaust. To complicate matters, ozone reduction and increased oxides of nitrogen in the stratosphere also affect climate, albeit to a magnitude less than that of sulfur-related pollution. If all these effects were considered, one might ask how the results would differ from those derived for particles alone. The only reasonable answer is that we don't know, since it has yet to be done in any systematic way. It would not be surprising, however, to find that the net climatic (i.e., surface temperature) effect thus calculated was actually smaller than that attributed to particles only, and even possibly of opposite sign! But in the absence of any well-accepted theory of climate, we shouldn't take seriously even these complex calculations. To put it another way, "...if current physically comprehensive [climate] models are inadequate to answer some of our questions, then certainly we should be wary of basing broad national or international decisions on handwaving arguments or back-of-the evelope calculations..."[8]

The reduction of ozone by oxides of nitrogen is also an effect which should not be treated in isolation. Water vapor, when added to the stratosphere, may tend to increase ozone levels, though this effect is not yet well established. Thus, according to our current understanding, the amount of ozone reduction is a function of the sum of ozone reduction from oxides of nitrogen and ozone increase from water vapor. A rough estimate[9] shows these effects to be about equal when the emission index for oxides of nitrogen is about 0.3 g/kg of fuel. (The emission of water vapor is, of course, fixed for hydrocarbon fuels at about 1250 g/kg fuel burned.) Ozone-reduction estimates for fleets of aircraft with very low cruise-altitude emissions of NO_x must take into account the effect of water, which may or may not turn out to be significant; further study is needed to even be certain of its sign.

On the subject of interactions, it is worthwhile to note that reasoned thinking leads to something of a dilemma. In the face of admittedly imperfect knowledge, is it reasonable to "balance" effects calculated to be of opposite sign? This could be construed as a dangerous business, akin to tampering with the fate of mankind by viewing the atmosphere as an experimental "mixing bowl," pouring in individually toxic ingredients whose net effect, we hope, is nil. To some extent, this criticism is valid. But it seems reasonable, when individual effects are vanishingly small, to proceed in this manner for individual emission sources (but not for the sum of independent sources). For large effects, of course, where a mistake in calculations clearly could lead to serious consequences, such an approach would be irresponsible. Finding the boundary between these two situations is a difficult matter of public policy.

Other Threats to Ozone

Public attention has recently been drawn to several other possible "threats" to the integrity of the ozone layer. In general, especially for small values of ozone reduction (say, up to a few percent), all of the individual effects are linearly additive. The effect which has received most attention is that from fluorocarbons used as propellants in aerosol cans, refrigerants, blowing agents, and so on. According to the IMOS report,[10] such substances are believed already to have resulted in a reduction of 0.5-1% in stratospheric ozone—perhaps as much as 2%. Because of the long atmospheric lifetimes peculiarly associated with these chemicals, IMOS further estimated that releases which already have occurred eventually may result in peak ozone reductions of 1.3-3%.

Even more ironic, however, is the recent notoriety which has been given to agricultural fertilizers.[11] The major source of naturally-ocurring stratospheric nitric oxide is nitrous oxide, which is produced naturally by biological systems in the process of denitrification. The theory is that man's increased use of nitrogen fertilizers for agriculture may increase significantly the amount of nitrous oxide produced at the Earth's surface. This nitrous oxide would diffuse upward into the stratosphere and be converted to NO by reactions initiated by solar radiation. This anthropogenically increased nitric oxide then would reduce the ozone concentration through the familiar catalytic cycle.

Other voices of concern have been raised concerning nitric oxide produced in atmospheric nuclear-weapons tests, bromine compounds, and the Space Shuttle exhaust. The message from this cacophony seems clear—it is necessary to obtain national and international agreement on what might be called an "air quality standard" for stratospheric ozone. How much ozone reduction, from all sources combined, is a "tolerable" amount? Unfortunately, there seems little hope that this most basic step will be taken, for it involves consideration of another question: How many additional cases of skin cancer are tolerable? It is all too possible that a piecemeal approach will be followed, with separate regulatory ground rules being set for aircraft, fluorocarbons, agricultural fertilizer, etc. Let us hope that this does not occur, and that the basis for regulation of each is a common one, with a goal of maximum environmental protection per dollar of expenditure.

Historical Note

A decade ago, our understanding of the factors governing stratospheric ozone concentration was quite limited. Ozone concentration in the stratosphere is controlled by a balance between its continuous production, by photodissociation of molecular oxygen, and its loss, by other means. Until 1964, "Chapman chemistry," involving only oxygen, was thought to be adequate to explain these mechanisms.[12] In 1964, Hampson[13] proposed that loss of ozone by reaction with active hydrogen species also might play a role in maintaining the ozone balance; this theory was subsequently explored by Hunt.[14] Both recognized that experimental observations indicated the presence of less ozone than would be expected from classical Chapman chemistry, and Hunt postulated that a catalytic cycle involving water and the hydroxyl radical, with acknowledged assumptions about their unknown rates of reaction, might be sufficient to explain this "ozone deficit." Later, Hampson[15] noted that if this postulated destruction of ozone by water occurred, then SST traffic would decrease ozone. This was carried further in a model calculations presented by Leovy[16] and Harrison.[17] But by this time, the hypothesis of Hampson had become accepted by many. Thus, it was not surprising that a "Study of Critical Environmental Problems" in the summer of 1970 concluded that increased water vapor from SST traffic would cause a reduction in stratospneric ozone.[18] But the study considered this effect of added water vapor in the stratosphere to be the least important, since "the reduction[was] estimated to lie well within the present day-to-day and geographical variability of ozone." Most ironic, however, was their statement that "it is...unlikely that [the involvement of NO_x] in ozone photochemistry is...significant."[18]

That was the state of the art in 1970, when the "SST debate" was raging. Most atmospheric scientists had accepted an hypothesis based on chemical reactions whose rates had never been measured! The then-acknowledged reduction of ozone by the water vapor emitted by a fleet of 500 SST's (estimated at 3.8% by Harrison, then at Boeing[17]) was thought to be rather insignificant. Biologists were somewhat perplexed when a physicist then suggested that this seemingly trivial ozone reduction could have profound consequences. Accepting the thinking of some of the best atmospheric scientists, McDonald[6] maintained that for each 1% reduction in average ozone concentration, we could expect an increase of 6000 cases of skin cancer per year in the U.S. At the same meeting, two people presented calculations which demonstrated that ozone-destroying reactions of aircraft-emitted NO_x in the stratosphere far exceeded the ozone reduction expected from the water vapor in exhaust.[19] Before this theory of NO_x even had been debated widely, the Congress voted not to continue funding development of a commercial U.S. SST. About five months later, in August of 1971, the Congress approved a 1970 Department of Transportation request to initiate the Climatic Impact Assessment Program (CIAP). In January 1975, the DOT released its final report on that program.

To complete this brief resume of the history, let me point out that as we now understand things, the added water vapor from stratospheric aircraft exhaust may actually act to *increase* ozone concentration.[20] (Destruction of ozone by naturally occurring oxides of nitrogen is mitigated somewhat by added water; a preliminary analysis for aircraft, however, shows that the destruction of ozone by NO_x in the exhaust considerably outweighs this small mitigating effect of water in the exhaust at current NO_x emission levels.)

Concluding Remarks

This paper has presented the essential conclusions we feel can be drawn after the first four years of a continuing international effort to analyze the potential effects of anthropogenic disturbance of the stratosphere. The tortuous path followed by the "SST debate," which sometimes resulted in acrimonious exchanges, left many people confused. The aircraft industry has come under fire for not having had the answers to questions which seem, in educated retrospect, to have been straightforward. Atmospheric scientists have been accused of "crying wolf," since it appears that water will not, after all, reduce ozone. It has been difficult to get opposing groups to refrain from constantly taking adversary positions, and sit down for a mutually educational discussion.

The subject of stratospheric pollution is exceedingly complex, and it will be many years before we have even a reasonably good understanding of just the major mechanisms involved. Atmospheric transport, especially of materials injected directly into the region within a few kilometers of the tropopause, is poorly understood. Our understanding of stratospheric chemistry is better, but perhaps deceptively so. Less than five years ago we did not appreciate the significance of oxides of nitrogen in maintaining the ozone balance, and the discovery of its importance seems to have turned water from a "destroyer" of ozone into a "creator." It was only about 18 months ago that it was shown that fluorocarbons, in the ubiquitous "aerosol" spray, may pose a far more serious long-term threat to the integrity of the ozone layer. In this case, damage which some consider significant may be inevitable, because of past releases of the chemical. Nuclear-weapons tests, agricultural fertilizers, the Space Shuttle—the list is growing rapidly. What can we safely conclude now, regarding aircraft?

1) Emissions of oxides of nitrogen from high-altitude aircraft are expected to reduce the level of stratospheric ozone, in amounts consistent with the early estimates of Johnston.[5]

2) A decrease in stratospheric ozone is expected to result in an increase in the incidence of nonfatal types of skin cancer in susceptible populations, in an amount consistent with the early projections of McDonald.[6]

3) There is greatest uncertainty in the effects of emissions injected near the tropopause, where subsonic aircraft tend to cruise. This uncertainty is sufficiently large that further study is called for before quantitative conclusions can be drawn about the effects of subsonic aircraft emissions.

4) Our understanding of climate is, at present, insufficient to permit any accurate quantitative forecast of the effects of reasonably-sized injections of the aforementioned pollutants on a global scale, much less on any regional scale.

5) Any ultimate effect of aircraft emissions will be the sum of individual effects from each substance emitted. Our present understanding indicates that the net effect on climate per se will be exceedingly small, and probably negligible, for all reasonable fleet forecasts extending through the 20th century.

References

[1]Grobecker, A. J., Coroniti, S. C., and Cannon, R. H., Jr., "The Effects of Stratospheric Pollution by Aircraft," U.S. Department of Transportation, Washington, D.C., Rept. DOT-TST-75-50, 1974.

[2]"Environmental Impact of Stratospheric Flight," National Academy of Sciences, Climatic Impact Committee, 1975, Washington, D.C.

[3]Prabhakara, C., "Effects of Non-Photochemical Processes on the Meridional Distribution and Total Assessment of Ozone in the Atmosphere," *Mon. Weather Review,* Vol. 91, 1963, pp. 411 ff.

[4]Crutzen, P. J., "The Influence of Nitrogen Oxides on the Atmospheric Ozone Content," *Quarterly Journal of the Royal Meteorological Society,* Vol. 96, 1971, pp. 320-325.

[5]Johnston, H. S., "Reduction of Stratospheric Ozone by Nitrogen Oxide Catalysts from SST Exhaust," *Science,* Vol. 173, 1971, pp. 517-522.

[6]McDonald, J., Presentation before the Department of Commerce Technical Advisory Board on Environmental Aspects of the Supersonic Transport, Boulder, Colo., March 17-18, 1971.

[7]Oliver, R. C., "Environmental Aspects of Time-Varying Fleets," Memorandum, May 6, 1974, Institute for Defense Analyses, (private communication.)

[8]Smagorinsky, J., "Global Atmospheric Modeling and Numerical Simulation of Climate," *Weather and Climate Modification,* W. N. Hess, ed., Wiley, New York, 1974, p. 685.

[9]Oliver, R. C., Memorandum, July 1974, Institute for Defense Analyses, (private communication).

[10]Federal Task Force on Inadvertent Modification of the Stratosphere, *Fluorocarbons and the Environment,* Council on Environmental Quality, Washington, D.C., 1975.

[11]"Nitrogen Fertilizers Ranked Worse than Aerosol Spray for Ozone Layer,"*Boston Evening Globe,* June 23, 1975.

[12]Chapman, S., "A Theory of Upper-Atmosphere Ozone," *Mem. Royal Meteorological Society,* Vol. 3, 1930, pp. 103-125.

[13]Hampson, J., "Photochemical Behavior of the Ozone Layer," TN 1627/64, 1964, CARDE, Valcartier, Quebec, Canada.

[14]Hunt, B. G., "Photochemistry of Ozone in a Moist Atmosphere," *Journal of Geophysical Research,* Vol. 71, 1966, pp. 1385–1398.

[15]Hampson, G., "Atmosphere," TN 1738/66, 1966 CARDE, Valcartier, Quebec, Canada.

[16]Leovy, C., "Atmospheric Ozone: An Analytic Model for Photochemistry in the Presence of Water Vapor," *Journal of Geophysical Research,* Vol. 74, 1969, pp. 417–426.

[17]Harrison, H., "Stratospheric Ozone with Added Water Vapor: Influence of High Altitude Aircraft," *Science,* Vol. 170, 1970, pp. 734–736.

[18]*Man's Impact on the Global Environment,* Report of the Study of Critical Environmental Problems (SCEP), Massachusetts Institute of Technology Press, Cambridge, Mass., 1970

[19]Johnston, H. and Westenberg, A.A., Presentations before the Department of Commerce Technical Advisory Board on Environmental Aspects of the Supersonic Transport, Boulder, Colo., March 17-18, 1971.