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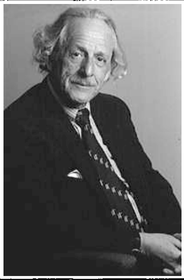

Current Comments®

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Ozone-Layer Depletion: Its Consequences, the Causal Debate, and International Cooperation

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Since the announcement of a thinning of the ozone layer over the Antarctic by UK scientists in 1985, world attention has been focusing on the causes of this phenomenon. There has been an intense debate on whether the thinning is a natural, cyclic phenomenon or is due to industrial effects, or a combination. This essay highlights current ISI® research fronts on photochemical processes and dynamics of the upper atmosphere.

In 1985 UK scientists reported a dramatic seasonal thinning of the ozone layer over Antarctica. This discovery raised the consciousness of both the world scientific community and government bodies. This new awareness has been underscored by the results of last autumn's Airborne Antarctic Ozone Experiment (AAOE), which reported the lowest ozone levels yet recorded for that time of the year.[1] Figure 1 depicts the Antarctic ozone thinning.

In 1979 we discussed ultraviolet radiation and its relationship to skin cancer.[2] In that essay, we briefly touched upon the ozone layer and the concerns at the time that it was being eroded. World attention has since been forcefully focused on the problem as a result of the dramatic findings by scientists.

The concern for the ozone layer around the world stems from the fact that this layer, primarily in the region 10 to 50 kilometers above the earth, screens out most of the damaging ultraviolet (DUV) radiation emitted by the sun.[3] Such wavelengths cause not only the discomfort of sunburn but also more grave effects such as skin cancer.[4]

Ozone is a triatomic allotrope of oxygen (a form of oxygen in which the molecule contains three atoms instead of two as in the common form) that accounts for the distinctive odor of the air after a thunderstorm or around electrical equipment. Ozone is an irritating, pale blue gas. In liquid form, it is explosive and toxic, even at low concentrations.[5] The allotrope's chemical constitution was established in 1872.[6] The word "ozone" was coined by French scientist C.F. Schoenbein in 1840 (from the Greek word *ozein*, to smell) to characterize a chemical species with a pronounced odor.[7]

Ozone Layer—Worldwide Concern

Our study on the most-cited 1985 physical-sciences articles[8] included a paper by J.C. Farman, British Antarctic Survey, Cambridge, UK, and colleagues entitled "Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction."[9] This paper was the first to describe the UK discovery of the precipitous thinning of the Antarctic ozone layer; the work has been discussed widely in the popular press and has been cited in over 120 subsequent publications through 1987. For some topics, this would not be particularly unusual; but in a field that is otherwise characterized by the slow accumulation of data, this number of cites is unusual.

Several expeditions investigating the upper atmosphere as well as the Antarctic ozone thinning have taken place since the British discovery, the most notable being the US-sponsored National Ozone Expeditions (NOZE) of the fall of 1986 and 1987;[10] the Stratosphere-Troposphere Exchange Project

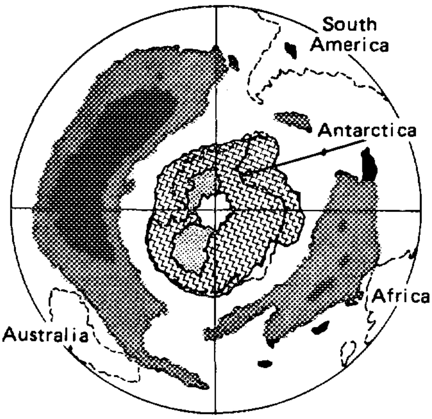

Figure 1: The ozone hole. The central hatchured area represents the Antarctic ozone hole, as mapped by the Total Ozone Mapping Spectrometer aboard the Nimbus-7 satellite. The lowest ozone concentration in this 15 September map is about 150 Dobson units. Typical values outside the hole are about 300 Dobson units. The dark arcs outside the hole are part of a ring of high ozone (up to 400 Dobson units) created by stratospheric circulation patterns. The springtime ring has been thinning, too.

in January 1987 off the Australian coast near Darwin[11] (involving researchers from the US, Australia, and China); as well as last fall's AAOE coordinated by US and United Nations (UN) agencies with scientists from other nations, including the UK, the USSR,[12] Argentina, Chile, France, and New Zealand.[13] Although the popular media reported that the NOZE and AAOE expeditions yielded conflicting findings, researchers have noted that actually the results of the two expeditions are in agreement.[5,14-16]

In December 1986, the US and the USSR agreed to jointly study the ozone layer, with exchange of ozone-layer data from the indigenous atmosphere above their homelands[17] and also to cooperate in studying the Antarctic's ozone hole in detail.[18]

In addition, government bodies have been active in efforts to enact legislation concerning ozone. There have been numerous international symposia on the subject in 1985, 1986, and 1987 sponsored by UN bodies such as the World Meteorological Organization, the UN Environmental Programme, and the Vienna and Geneva conventions. Table 1 lists associations, organizations, and agencies involved with the ozone-layer depletion issue.

ISI®'s *Index to Scientific & Technical Proceedings®* lists several symposia dealing with atmospheric ozone. These include a North Atlantic Treaty Organization (NATO) workshop on the effects of increased ultraviolet radiation on agricultural crops (held in the Federal Republic of Germany [FRG] in September 1983),[19] a specialty conference on ozone/oxidants standards sponsored by the Air Pollution Control Association (held in the US in November 1984),[20] and a European community-sponsored meeting on the physicochemical behavior of atmospheric pollutants (held in Italy during September 1986).[21]

Although most attention has been focused on the Antarctic, the ozone layer is also thinning in the Northern Hemisphere.[22] There is controversy about whether there is an area of decline centered over Spitzbergen, halfway between Scandinavia and the North Pole, as well as over northern Europe to Leningrad. The thinning apparently shows up as a cavity, although not as deep as the one in the Southern Hemisphere.[23]

Theories on Ozone Erosion

Atmospheric chemists have various theories on the photochemistry and mechanisms of ozone depletion. A 1953 paper entitled "Absorption coefficient of ozone in the ultraviolet and visible regions" was authored by E.C.Y. Inn and Y. Tanaka, National Aeronautics and Space Administration (NASA)/Ames Research Center, Moffett Field, California.[24] This work, dealing with basic research on ozone (photochemistry/absorption experiments), has been cited over 200 times since 1955. This paper is the subject of a *Citation Classic®* commentary[25] in which Inn recalls a vivid experience in dealing with the hazards of producing ozone:

> In a separate experiment, Yoshio [his research associate] had reached in through the

plastic sheeting to manipulate a stopcock in the gas handling system. A loud explosion occurred with bits of glass flying all over. The plastic sheeting did an excellent job of protecting our bodies, but his hand was hit by several bits of glass.... Fortunately, the injury was not serious, but the event left us with a deeper sense of caution in working with pure ozone.

Scientists have learned that stratospheric ozone can be decreased by any process that can lead to increased stratospheric amounts of ozone-destroying catalysts (such as oxides of nitrogen, chlorine, hydrogen, or bromine). Two graphic examples show this volatility: one molecule of nitric oxide can destroy tens of thousands of ozone molecules per day, and one chlorine atom can destroy almost one hundred ozone molecules per second.[14]

Although the exact mechanisms that cause ozone degradation over Antarctica are not fully understood, there are numerous hypotheses, including thinning due to forms of nitrogen oxide (NO_x), chlorofluorocarbons (CFCs), and atmospheric dynamics. It should be noted that, due to the "up-to-the-minute" research on ozone depletion, there are three 1986 research fronts in Table 2—#86-0596, #86-0975, and #86-1604—with high immediacy. These "hot" research fronts are identified by the number of core documents published in the most recent three years and by the number of published (citing) articles. The three research fronts on ozone rank among the top 3 percent for immediacy of all research fronts that were published in the years 1984-1986.

C2 Map Links NO_2 Research with Ozone Effects on Climate

Nitrogen emissions primarily result from human activity—such things as nuclear atmospheric tests[26] and high-altitude supersonic transport jets.[27] P.J. Crutzen, now at the Max Planck Institute for Chemistry, Mainz, FRG, suggested in the early 1970s that forms of nitrogen oxide have a profound effect on the atmosphere. His paper, "The influence of nitrogen oxides on the atmospheric ozone content,"[28] has been cited al-

Table 1: Selected list of associations, organizations, and agencies conducting research, establishing policy, and *providing education on ozone depletion and pollution.*

Alliance for Responsible CFC Policy
1901 North Ft. Myer Drive
Arlington, VA 22209

American Geophysical Union
2000 Florida Avenue, NW
Washington, DC 20009

British Antarctic Survey
Madingley Road
Cambridge CB3 0ET
United Kingdom

Environmental Defense Fund
444 Park Avenue South
New York, NY 10016

Health Effects Institute
215 First Street
Cambridge, MA 02142

International Association of Meteorology and Atmospheric Physics
P.O. Box 3000
Boulder, CO 80307

International Ozone Commission
Laboratory for Atmospheric Physics
Hobggerberg HPP
CH-8093
Zurich, Switzerland

NASA/Goddard Space Flight Center
Laboratory for Atmospheres
Greenbelt, MD 20771

National Oceanic and Atmospheric Administration Aeronomy Laboratory
325 South Broadway
Boulder, CO 80303

Sierra Club
730 Polk Street
San Francisco, CA 94109

Texas A&M University
Air Pollution Laboratory
Soil and Crop Sciences Department
College Station, TX 77843

US Antarctic Research Program
Polar Information Program
National Science Foundation
1800 G Street, NW
Washington, DC 20550

University of Florida
Interdisciplinary Center for Aeronomy and Other Atmospheric Sciences
311 Space Sciences Research Building
Gainesville, FL 32611

World Meteorological Organization
CP5, CH-1211
Geneva 20, Switzerland

World Resources Institute
1735 New York Avenue, NW
Suite 400
Washington, DC 20006

Table 2: The 1986 *SCI®/SSCI®* research fronts dealing with ozone pollution and depletion. A = number of core papers. B = number of citing papers.

Number	Name	A	B
86-0596	Mesospheric ozone and stratosphere and middle atmosphere	24	174
86-0691	Tropospheric ozone and windflow and ozone inflow concentrations	2	18
86-0975	Atmospheric trace gases and global climatic trends	39	317
86-1317	Ozone formation, organic traces in air, and photooxidations	9	89
86-1493	Ambient ozone and yield response of crops	8	50
86-1604	Polar stratospheric clouds and Antarctic ozone	11	75
86-2003	Formation of ozone and photolysis of nitrous oxide	2	51
86-3983	Large-scale atmospheric flows and circulation flow equilibria	5	44
86-6616	Arctic polar stratospheric clouds and El-Chichon volcanic cloud	5	32

most 300 times since its publication in 1970. Crutzen's chief work, concerning the importance of NO and NO_2 in controlling ozone concentrations and production rates, is core to and helps identify research front #86-0975, entitled "Atmospheric trace gases and global climatic trends." This front along with #86-0691, #86-1317, #86-2003, and #86-3983 constitutes five 1986 research fronts that make up, in part, Table 2.

These five fronts also help identify the C2 multidimensionally scaled map in Figure 2, which concerns atmospheric ozone and climatic conditions. This C2 map shows clusters of research fronts, rather than clusters of journal papers, as would be the case in a C1 map. The relationships between the groups of research fronts are shown graphically by a multidimensionally scaled map. Such a map has no absolute axis but represents related subject areas in two dimensions, where distance connotes the degree of relatedness. There is a third dimension, however, with this specific map. The size of the citing literature at each point is approximated by the sizes of the circles. The clusters of research fronts closest to the center of the map are the most highly cited, while those at the margins are the least cocited, in respect to the subject content of the map's center. The five ozone-related research fronts are all situated to the left in the map, with the research front #86-1587, entitled "Global weather," as the C2 center.

However, there is a major natural event—volcanism—that may be a factor in the effect of aerosols (a suspension of fine solid or liquid particles in gas) on the ozone layer. Research front #86-6616, entitled "Arctic polar stratospheric clouds and El-Chichon volcanic cloud," involves five core papers dealing largely with measurements of these stratospheric aerosols. In 1986 and 1987 there were over 50 papers published on this topic.

Chlorofluorocarbons: Widely Used, Suspected Major Impact

Chlorofluorocarbons, more commonly known as CFCs or Freons, are widely believed to be a direct factor in the ozone layer depletion over the Antarctic continent. CFCs were first synthesized in 1928 and first manufactured on a large scale by 1931.[29] Today they are widely used in air-conditioning units, refrigerators, styrofoam packaging, circuit-board-cleaning equipment, as well as other applications. Because of their nontoxicity, as well as ease of use, Freon output (CFC-11 and CFC-12, discussed later) has averaged over 720 kilotons per year for the past eight years.[30] CFCs' deleterious effect on ozone is the result of their longevity—CFC molecules that are able to ascend into the upper atmosphere have life spans of 75 to 100 years.[31] When CFCs come into contact with the sun's ultraviolet rays in the ozone layer, they begin to break down into component atoms, which include chlorine. These disassociated chlorine atoms can then prodigiously destroy ozone before they diffuse down into the lower atmosphere. (It was this volatility, in part, that caused the US in 1978 to ban spray-can aerosols—such as hair sprays and body deodorants—that used CFCs as the carrying agent.[32])

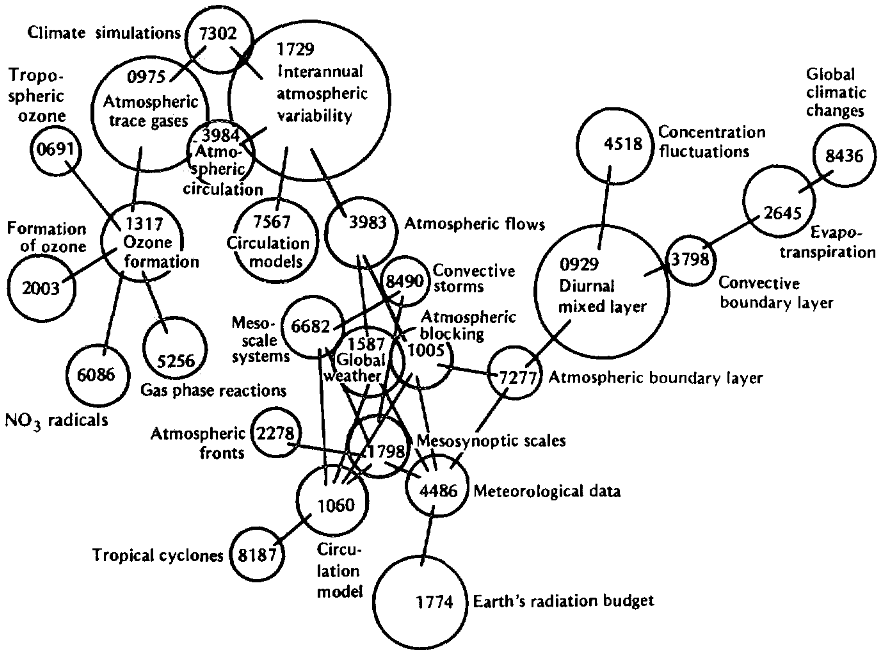

Figure 2: C2-level multidimensionally scaled map for research front #86-0330 on ozone formation and climatic changes.

The first person to notice that an inordinate amount of halogenated hydrocarbons were extant in the upper atmosphere was James E. Lovelock, Department of Applied Physical Sciences, University of Reading, UK. Lovelock published a paper on this topic with colleague R.J. Maggs and R.J. Wade, Department of Oceanography, University of Southampton, UK.[33] Apart from his work in this area, Lovelock has written a highly cited paper on the protective-action mechanism of glycerol against hemolysis by freezing and thawing. His commentary on this paper was published in *Current Contents*® in 1985.[34]

The concern that CFCs are the mechanism for depleting the ozone layer has prompted five major meetings of industrialized nations under UN auspices (in Austria in 1985; in Italy, the US, and Austria in 1986; and in Canada in 1987) in an attempt to curtail Freon production. At the meeting that took place in Montreal in September 1987, 23 of the 51 countries in attendance endorsed a plan to reduce world consumption and production of CFCs by 50 percent by 1999.[35]

Two classic papers that drew attention to the role of CFCs are by Mario J. Molina, now at the Jet Propulsion Laboratory, Pasadena, California, and F. Sherwood Rowland, Department of Chemistry, University of California, Irvine. "Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone" was published in *Nature* in 1974[36] and has been cited by over 500 papers. This work was the prelude to the 1975 paper on "Chlorofluoromethanes in the environment,"[37] which presented one of the first detailed reports on the chemical reactions of fluorocarbons after their release into the environment and their effect on ozone.

In correspondence[38] concerning his *Citation Classic* commentary[39] on the above paper, Rowland states that

> My own view is that the Antarctic ozone hole is the consequence of chlorine chemistry made much more prevalent by the continuing build-up in the atmosphere of ever higher concentrations of the chlorofluoromethanes and other long-lived organochlorine compounds manufactured and released to the atmosphere by mankind.

The 1975 paper has been cited over 300 times since its publication, with 9 cites in 1987. Rowland, Molina, and H. Johnston were among those who received the 1983 John and Alice Tyler Ecology-Energy Prize for their work on fluorocarbons.[40]

Susan Solomon, National Oceanic and Atmospheric Administration, Boulder, Colorado, also supports the theory that it is a chemical mechanism involving chlorine that destroys ozone.[41] She appears as a coauthor with Roland R. Garcia, National Center for Atmospheric Research, Boulder; Donald J. Wuebbles, Lawrence Livermore Laboratory, Livermore, California; and Rowland in research front #86-1604, "Polar stratospheric clouds and Antarctic ozone" (see Table 2).

Atmospheric Dynamics: Of Winds and Weather

A third hypothesis concerning ozone depletion over Antarctica (which occurs only in the spring) is that, in combination with chemicals, dynamic atmospheric processes contribute to ozone-layer erosion. The dynamists' explanation suggests that there have been Antarctic ozone holes in the past and that they will develop again in the future. According to a recent article in *THE SCIENTIST*™,[42] ozone measurements showed that the levels had risen appreciably from their September/October lows and that the most dangerous period had passed for the season.

There is heated debate concerning the role that dynamics plays and to what extent it affects the Antarctic hole. Some researchers believe that the winds have a major impact; others think atmospheric dynamics plays a less important role. According to Farman, CFCs have a much greater impact than atmospheric dynamics. He notes, for example, that

> a reading of about 125 Dobson units [a unit measurement of ozone] that we got in October was probably, without atmospheric effects, actually about 140 Dobson units. Chemical dynamics is most of it, I think, but with the enhancement of local cloud/winds dynamics, the readings we got resulted in 125 Dobson units.[14]

Owing to the unique weather system of the southern polar regions during the austral winter (the extreme cold causes the winds to remain in a specific, staid pattern[43]), some scientists have determined that atmospheric dynamics does play an important, temperature-linking role.[44]

Several dynamists are identified in research front #86-1604, "Polar stratospheric clouds and Antarctic ozone." The front contains 11 core papers, including 1 by Ka-Kit Tung, Clarkson University, Potsdam, New York, and colleagues at Atmospheric and Environmental Research, Inc., Cambridge, Massachusetts. Their 1986 paper "Are Antarctic ozone variations a manifestation of dynamics or chemistry?"[45] details the possible mechanics of how specific Antarctic atmospheric motions (such as air-current upwellings) could bring ozone-poor air from lower altitudes up into the stratosphere. Rowland, however, claims that

> Everyone, except perhaps Ka-Kit Tung, is now agreed that the postulated air-current upwellings simply don't happen. Perhaps this illustrates how [research-front] cores contain anti-correlated work. Tung's paper essentially denies a connection betweeen "Polar stratospheric clouds and Antarctic ozone," and yet gets included in the front for that reason.[15]

A 1986 paper by R.S. Stolarski and colleagues, NASA/Goddard Space Flight Center, Greenbelt, Maryland, entitled "Nimbus 7 satellite measurements of the springtime Antarctic ozone decrease,"[46] is also core to this front. This observational paper of satellite data suggests that the ozone depletion—which may involve chlorine—perhaps also embodies a mechanism that involves the cold temperatures and polar stratospheric clouds that form within the Antarctic vortex. It was one of the first papers to confirm the accuracy of the UK report of the decrease of ozone over the Antarctic continent.[16] Stolarski's other core paper, coauthored by R.J. Cicerone, University of Michigan, Ann Arbor, concerns the origins and chain reactions of stratospheric chlorine. This work, published in 1974 in the *Canadian Journal of Chemistry*,[47] has been cited over 160 times since publication and was the first to report the role of chlorine in the chain reactions of ozone depletion.

Table 3: *Selected list of journals reporting on ozone depletion and the ozone hole. Included are the 1986 impact* factors of these journals using different two-year bases. Impact is a measure of the frequency with which the "average article" in a journal has been cited in a particular year. A = title, editor, and publisher. B = 1984-1985. C = 1983-1984. D = 1982-1983. E = 1981-1982. F = 1980-1981. G = cited half-life. H = citing half-life.

A	B	C	D	E	F	G	H
Atmospheric Environment D.J. Moore, M. Benarie & J.P. Lodge, eds. Pergamon Journals, Ltd. Oxford, United Kingdom	1.63	1.88	1.81	1.57	1.36	4.7	6.3
Geophysical Journal of the Royal Astronomical Society Editorial Board Blackwell Scientific Publications, Ltd. Oxford, United Kingdom	1.72	1.90	1.78	1.71	1.71	7.3	7.5
Geophysical Research Letters A.J. Dessler, ed. American Geophysical Union Washington, DC	1.99	2.09	1.96	1.60	1.34	4.5	4.2
Izvestiya Akademii Nauk SSSR Fizika Atmosfery i Okeana A.M. Oboukhov, ed. Akademiya Nauk SSSR Moscow, USSR	0.26	0.34	0.33	0.31	0.26	6.3	7.5
Journal of Atmospheric and Terrestrial Physics G. Beynon, ed. Pergamon Press, Ltd. Oxford, United Kingdom	0.91	1.01	0.85	1.10	1.02	8.6	8.2
Journal of Climate and Applied Meteorology B.A. Silverman & A.D. Hecht, eds. American Meteorological Society Boston, MA	1.15	1.32	—	—	—	2.7	7.3
Journal of Geophysical Research—Atmospheres W.L. Chameides, ed. American Geophysical Union Washington, DC	1.10	2.38	—	—	—	2.4	5.5
Journal of the Atmospheric Sciences R.H. Johnson & W.H. Schubert, eds. American Meteorological Society Boston, MA	1.71	2.14	2.24	1.90	1.87	7.3	6.5
Monthly Weather Review J.B. Klemp & R. Rotunno, eds. American Meteorological Society Boston, MA	1.52	2.01	2.34	2.05	1.53	5.7	6.8
Quarterly Journal of the Royal Meteorological Society P.R. Jonas, ed. Royal Meteorological Society Berkshire, United Kingdom	1.90	2.13	2.34	1.84	1.82	9.5	6.8

Journal Impact and Half-Life Data

A selected list of journals reporting on ozone research appears in Table 3. Two important factors in citation analysis of journals are impact and half-life. Impact is a measure of the frequency with which the "average article" in a journal is cited. The 1986 impact factors are given in Table 3, using five different two-year bases. These data indicate that the impact for this field peaks later than the second or third two-year base (columns C and D).

While a journal's impact is an indication of its centrality to the literature, its half-life reflects the pace of discovery. The cited half-life figures for journals dealing with ozone research are also listed in Table 3 (column G). In this specific case, the cited half-life connotes the relative currency (for 1986 data) of the accumulated citations to the journals. Note that the *Journal of Geophysical Research—Atmospheres* has the lowest, or most current, 1986 cited half-life. This means that half the citations this journal received in 1986 were from articles published during the previous 2.4 years. Conversely, the *Journal of Atmospheric and Terrestrial Physics* has a half-life that extends back almost 9 years. The average cited half-life for journals on this subject is 5.9 years, which represents a longer period than that for, say, immunology journals (half-life of 4.3 years) or cancer research journals (4.8).[48] However, the cited half-life for geology journals is longer, at 7.3 years. Overall, the cited half-life of journals that report on ozone research is about one year lower than the average journal covered in the *Science Citation Index®* (*SCI®*) (6.8 years).

Citing half-life is the median age of the literature cited by a journal, giving an indication of the age of the literature that each journal cites. In 1986 the average citing half-life of ozone core journals was 6.6 years, which is almost identical to the average citing half-life (6.8) of all journals listed in the *SCI*. *Geophysical Research Letters* has the shortest citing half-life, with 4.2 years, while the *Journal of Atmospheric and Terrestrial Physics* has the longest, at 8.2 years.

Pathological Effects of Ozone Depletion

Much work has been done on effects of ultraviolet (UV) radiation on skin carcinoma levels. According to a 1986 review paper by S.H.H. Larsen, Institute of Physics, University of Oslo, and G. Volden, Department of Dermatology, University of Tromsö, Norway, Lentigo maligna is the only form of malignant melanoma clearly associated with UV radiation,[49] although scientists do have some evidence that, of the three ultraviolet wavelength bands (UV-A, UV-B, and UV-C), the most damaging are in the UV-B region.[50]

The latency period between UV radiation exposure and development of nonmelanoma skin cancer is long; this is why it first appears mainly during the fourth decade of life in the Caucasian population.[49] Work on dermatological consequences of UV radiation has been based on experiments with hairless mice. Isaac Willis and Julian M. Menter, Dermatology Research Unit, Morehouse School of Medicine, Atlanta, Georgia, exposed such mice to solar-simulating radiation. Groups of 20 mice were irradiated with selective UV filtration 5 days per week with 20 percent increases in dosage every sixth day for 40 days. The exposure simulated the projected ozone depletion, and the results showed significantly increased squamous cell carcinoma production.[51]

Ozone: Its Effects on Flora and Fauna

Besides work on ozone and its effects on animals and humans, there is also a large body of research on its effects on vegetation. Impact of ozone on plant life is the topic of research front #86-1493, "Ambient ozone and yield response of crops." Fifty papers published in 1986 cite a core of eight works.

Robert H. Biggs, University of Florida, Gainesville, Susan V. Kossuth, US Forest Service, Olustee, Florida, and A.H. Teramura, University of Maryland, College Park, grew soybeans in controlled-environment chambers for a period of four weeks. This crop exhibited lower yields as well as physical stress (stunting and leaf chlorosis) when exposed to increased DUV radiation.[52] The US Department of Agriculture's National Crop Loss Assessment Network estimates that ozone damage already costs US farmers two billion dollars annually in reduced crop yields.[53]

Ozone pollution also takes its toll on other flora as well—even hardier species such as trees. D. Wang and F.H. Bormann, Yale School of Forestry and Environmental Studies, New Haven, Connecticut, and D.F. Karnosky, Forestry Department, Michigan Technological University, Houghton, measured a 16 to 19 percent stunting in the growth (dry mass) among hybrid poplars, cottonwoods, and black locusts when these trees were exposed to outdoor ozone levels that were generally well within the current federal air-quality limit.[54]

Apparently other inhabitants of the ecosphere are also sensitive to the vagaries of an eroded ozone layer. Both phytoplankton and zooplankton have little protection against UV light. They structurally cannot devote much of their mass to shielding. John Calkins, Department of Radiation Medicine, University of Kentucky, Lexington, and Thorunn Thordardottir, Marine Research Institute, Reykjavík, Iceland, found that mobile plankton, when exposed to 10 percent more UV-B than normal, retreated to darker regions of the water. If the plankton are prevented from escaping the UV-B, they die within minutes. Calkins says that each species has a threshold of tolerance, and some are now at the brink. Plankton live within a 10-meter mixing area near the surface of the world's oceans. Calkins thinks that plankton could be viewed as a "mine canary," forewarning humankind that too much of the ozone layer is being destroyed.[55] This raises an important and as yet unanswered question: if one of the basic blocks of the ocean food chain is in such a precarious position, how much further stress would cause a deleterious impact?

It is ironic that while humans may be depleting the ozone layer above, they are manufacturing another ozone layer at ground level. These ozone emissions are the result of several factors: sunlight interacting with nitrogen oxides and hydrocarbons; domestic smog; auto exhausts; power plants; a combination of off-gassing from oil-based paints, gasoline, dry cleaners;[56] and so on. These emissions pose severe health problems to children, the elderly, and those who already suffer from asthma and bronchitis. Ozone-polluted air can cause shortness of breath, coughing, and throat irritation. Animal testing has shown that graver results could be in store—damaged lung tissue and immune systems.[57]

The US Environmental Protection Agency (EPA) has released statistics that 62 cities—including Philadelphia, where ISI is located—violated the federal ozone pollution standard from 1984 through 1986; Los Angeles, the perennial ozone pollution leader, tops the latest list. EPA's ozone limit is 0.12 parts per million. Los Angeles exceeded this by almost a factor of three (0.35 parts per million) on an average of 154 days each year in the 1984-1986 time frame. However, the number of cities violating the ozone limit has fallen from 76 cities during the previous reporting period of 1983-1985.[58]

In early December 1987, the US House of Representatives backed a plan to extend by eight months the 1977 Clean Air Act, which was to have expired on December 31, 1987.[59] In part, this act required all US cities to meet EPA-sanctioned ozone pollution limits. Over 60 cities could not comply by the deadline and thus were in danger of having both water-treatment and road-construction funding terminated by the federal government. This temporary reprieve by the US Congress illustrates the difficulties of legislating environmental policies into reality.

Ozone-Layer Solutions

The evidence at this point indicates that a combination of manufactured chemicals along with dynamic atmospheric processes are eroding the ozone layer. The primary culprits that humans can control are CFCs. Specifically, three of the Freons, CFC-11, CFC-12, and CFC-113,[15] are the ones that pose the most serious risk. In April 1987, the EPA convened an international panel of experts to explore substitutes. The panel identified several more benign alternatives, most notably CFC-123 and CFC-134a, and it found no barriers (environmental or technical) to their wide-scale production—other than the cost of synthesis. Instead of $.60 to $.70 (US) per pound, the new alternatives would cost between $1.25 and $4.00 per pound.[60]

It is apparent that the subject of ozone-layer depletion is a multifaceted problem, with no easily coined panaceas. The cutting edge of research is involved, and the demarcation between areas of hard and soft science is as yet not defined.

Of the nine research fronts concerning ozone, most point to an increased focus on the coupling of the chemistry with the dynamics of the earth's atmosphere. This finding from ISI's data has been borne out by recent announcements by two groups of researchers in California—the Jet Propulsion Laboratory (led by Molina and colleagues)[61] and SRI International in Menlo Park (led by M.A. Tolbert and colleagues).[62]

These two groups conducted studies centering on the chemistry that takes place in the polar stratospheric clouds. They found that chemical reactions on the cloud surfaces (involving CFCs, hydrogen, and nitrogen in the stratosphere, as well as ice) can create huge amounts of the forms of chlorine that vigorously destroy ozone molecules. This is due to a previously unexpected series of fast reactions that take place at the extremely cold stratospheric temperature of minus 90 degrees Celsius.

The atmospheric and the meteorological sciences are relatively young disciplines. Their venue is the whole sky—parts of which cannot be isolated and taken into the laboratory. Ironically, as with AIDS, the key to understanding the mechanisms of this practical problem is pure research. Practical solutions may not follow immediately, but it is clear that humankind cannot afford to stint in dealing with the ozone problem.

* * * * *

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