Atmospheric effects of a nuclear war

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While millions would die immediately as a result of the direct effects of a nuclear war, the initial 'survivors' could face a grim dark world with freezing temperatures and many of the ecosystems destroyed. This article is based on a recent study organised by the Royal Swedish Academy of Sciences.

Compared to the effort that has gone into the development and deployment of nuclear warheads and delivery systems, very little work has been done on determining the actual effects of nuclear war. Certainly much is known about the immediate effects of the nuclear explosions—the damage caused by the blast, thermal radiation, and radioactivity—and such data may be used to estimate the number of persons killed directly. Even though hundreds of millions, possibly more than a billion people would be killed outright, there would be many survivors of the immediate effects.

Many government and military leaders no longer equate nuclear war with the immediate and total annihilation of mankind; the possibility of fighting a 'limited nuclear war' has recently been discussed at high government levels. It is, therefore, important to evaluate what the longer term effects of a nuclear war are. The evaluation of the environmental effects of a nuclear war was the goal of a recent study organised by *Ambio*,[1] the environmental journal of the Royal Swedish Academy of Sciences. Scientists from both East and West contributed articles evaluating as best possible the effects of nuclear war on the oceans, the atmosphere, agriculture, global supplies of food and freshwater, human behaviour, and the global economic consequences—especially for the third world. Our task was to evaluate the atmospheric effects of a nuclear war.[2] Here we summarise the main findings of that study in the light of more recent work done by ourselves and other investigators.

Nuclear war scenario

Many nuclear war scenarios are possible. Our work is based on a reference scenario adopted for the *Ambio* study.[3] In this scenario, it is assumed that less than one half of the nuclear arsenals of both the US and USSR are utilised. In 1985, the combined arsenals of the NATO and Warsaw Pact nations will contain more than 60 000 nuclear weapons having a total explosive energy of more than 13 000 megatons (1 megaton = 1 Mt, the explosive equivalent of one million tonnes of TNT). The *Ambio* scenario assigns targets to 14 737 warheads having a total explosive energy of 5742 Mt. The northern hemisphere receives 5569 Mt while the southern hemisphere receives only 173 Mt. For this scenario the sizes of individual warheads vary between 0.1 Mt and 10 Mt with an average of about 400 Kt (1 Kt = 1 kiloton of TNT).

An important aspect of this hypothetical targeting scenario is that 30 per cent of the explosive energy is directed against cities. Both military bases and industrial establishments are usually close to cities. Thus, even though the doctrine of 'mutually assured destruction' may have been supplanted by one of 'nuclear war fighting,' it seems inevitable that urban areas would be targets in a nuclear war.

Before looking at the environmental consequences of nuclear war, and in order to put things in a proper perspective, it is important to consider the direct effects of the nuclear explosions. Hugh Middleton of the Clinical School in Cambridge estimated the casualties for this particular scenario.[4]

> Of an urban population of nearly 1.3 billion in the Northern Hemisphere, about 750 million would be killed outright and some 340 million seriously injured. Furthermore, of the 200 million initial 'survivors' many of them would perish from the latent effects of radiation as well as infectious diseases like cholera, tuberculosis and dysentery.'

Fires

The explosions of many thousands of nuclear warheads would ignite as many fires, and it would not be possible to extinguish them because of nuclear contamination and loss of water lines, fire equipment and expert personnel. Besides the fires in urban and industrial centres, vast forest conflagrations would start, extensive grasslands and agricultural fields would burn, and it is likely that many natural gas and oil wells would be ruptured, releasing huge quantities of oil and natural gas, much of which would also catch fire. In our estimation, the most serious atmospheric effects of a nuclear war would result from these conflagrations. Thick layers of smoke would form, thereby limiting the penetration of sunlight to the earth's surface. With most of the solar radiation being absorbed high in the atmosphere, temperatures over the northern hemisphere continents would be substantially reduced. The extreme modification of the temperature structure of the atmosphere would be expected to alter patterns of circulation and precipitation drastically.

Once the fires have ceased to burn and most of the soot is removed from the atmosphere, it is possible that the northern hemisphere would be blanketed by photochemical smog formed from the oxides of nitrogen, carbon monoxide and hydrocarbons produced by the fires.

Urban and forest fires

City centres and the surrounding urban areas contain enormous quantities of combustible materials such as lumber, fabrics, synthetic polymers and asphalt. These materials would be exposed by the blast and ignited by the intense thermal pulse of the explosion. The shock wave also would rupture natural gas lines and other containers of hydrocarbon fuels and thus start fires throughout the cities in the same manner as in earthquakes. The relatively small atomic bombs exploded over Hiroshima (~12 Kt) and Nagasaki (~22 Kt) resulted in conflagrations that completely burned out areas of 13 km^2 and 7 km^2, respectively.[5]

Based on the results of nuclear weapon tests,[6] the pulse of thermal radiation from a 400 Kt explosion appears to be capable of igniting many materials, such as draperies and furnishings, found within an area of about 150 km^2, which corresponds to the area receiving a total radiant flux of at least 20 cal cm^{-2}. Thinner fuels like news-

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papers and dry forest fuels (*eg* leaves, pine needles and rotting wood) will ignite at a radiant flux of about 5 cal cm^{-2}. It is clear that only a moderate fraction—perhaps 35 per cent or less—of the weapons available for a nuclear war would be required to burn out all cities of the northern hemisphere having populations greater than 100 000.

The *Ambio* scenario targets 1124 cities with 4970 warheads having a total explosive yield of 1941 Mt. The calculated burnt out area, assuming that, on average, 375 km^2 of land area burns for each megaton of explosive yield, is more than 700 000 km^2. For the purposes of the sample calculations below, we will assume as a conservative estimate that a total urban area of 500 000 km^2 would burn in a nuclear war.

Large areas of forest lands would also be ignited. Approximately 40 per cent of the land surface is covered with forests, and a detailed analysis of the *Ambio* scenario indicates that about 22 per cent of the non-urban targets are in forested regions. The degree of fire-spread is difficult to estimate because it depends critically on meteorological conditions and is therefore seasonally dependent. As a working hypothesis we have assumed that a total forest area of 1 million km^2 would burn in the wake of a nuclear war. This figure could well be an underestimate, particularly if the war were to occur in the summer.

Smoke and soot

The burning of 500 000 km^2 of urban areas and 1 000 000 km^2 of forest would produce a few hundred million tonnes of smoke particulates. A detailed analysis of fuel loadings in cities suggests that they contain an average of about 40 kg m^{-2} of combustible material,[7] although city centres may contain several hundred kg m^{-2}. The average forest biomass[8] is about 20 kg m^{-2}. Considering that some of the combustibles would be buried by collapsing buildings, we assume that only 50 per cent of the available material in cities would burn. For forest fires where the thick tree trunks are seldom completely burnt, we assume that only 20 per cent of the biomass is burnt. To determine the total smoke emission it is necessary to treat the various categories of combustibles separately, since the particle compositions and emission factors vary for different materials (*eg*, wood, plastics, fossil fuels and asphalt). In this way, it is estimated that the smoke produced by fires in cities, industry and forests would be about 3×10^{14} g (300 m t), of which about 8.4×10^{13} g (84 m t) would be elemental carbon.[7] This amount is particularly significant since carbon has an extremely high absorptivity towards sunlight.

The bulk of mass (>90 per cent) of smoke aerosol typically consists of particles with diameters less than 1 μm, and the maximum particle number density occurs at a diameter of about 0.1 μm.[9]

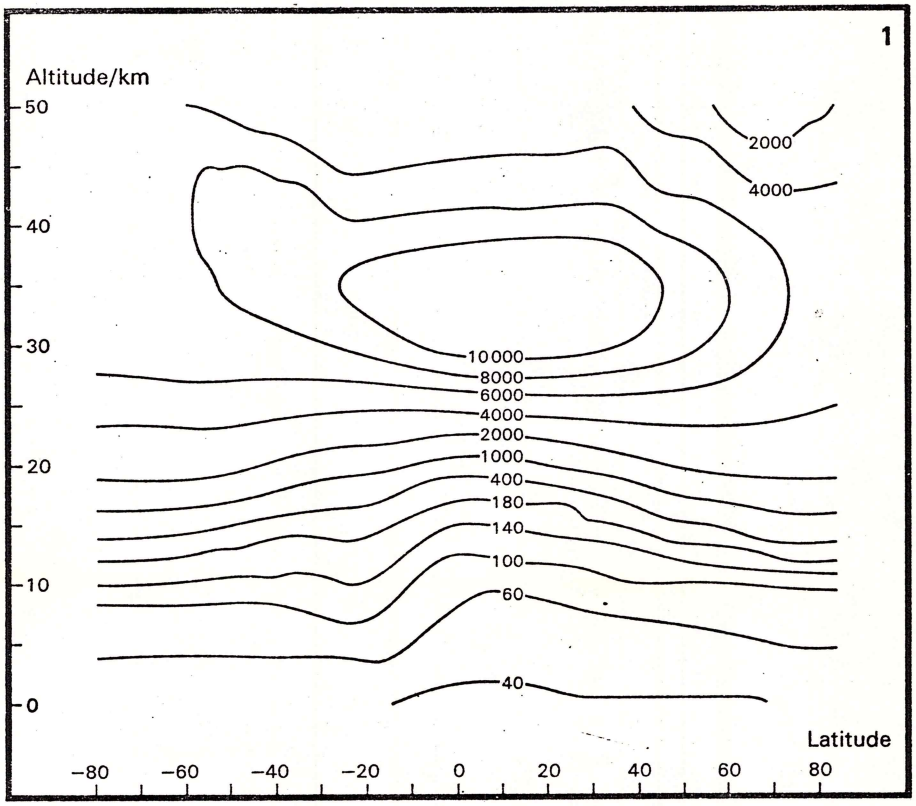

Fig. 1. Ozone mixing ratios (ppbv) in the atmosphere now, as calculated by a two-dimensional model of atmospheric chemistry and dynamics for 1 August.

Because of their small size, the average residence time of 0.1–1 μm particles in the atmosphere is quite long—about 10 days in the lower troposphere and about 30 days in the upper troposphere. The residence time of any aerosol that penetrates the stratosphere is longer than a year.

Darkness

Assuming that the fires are ignited and burn over a three-day period, the huge smoke clouds, produced by city and forest fires and containing about 300 m t of aerosol, would cover most of the land surface in the 30–60° latitude belt.[7] The area covered by smoke clouds would then be about 6×10^{13} m^2, so that on average, the vertical column would contain about 5 g m^{-2} of smoke aerosol or about 1.4 g m^{-2} of elemental carbon. The calculation of the transmission of light to the earth's surface is complex since both scattering and absorption must be taken into account. However, by considering only absorption, an upper limit for the transmission of light through the soot layer can be easily calculated.

The mass absorption coefficient of fresh elemental carbon particles[10] has been found to be in the range 5–20 m^2 g^{-1} with an average value of about 10 m^2 g^{-1}. Coagulation leads to the formation of larger aerosol particles, which absorb sunlight less efficiently for a given mass. For this somewhat aged aerosol, we, therefore, assume an absorption coefficient of 6 m^2 g^{-1}. The absorption optical depth is the product of this number and 1.4 g m^{-2} (the amount of elemental carbon in the vertical column). Thus, after about three days the average absorption optical depth is 8.4. For a directly overhead sun, the transmission or fraction of sunlight reaching the earth's surface would be below 10^{-4}.

This estimate is based only on fires in cities and forests. Large forest fires in arctic regions are commonly accompanied by huge fires in peat bogs, that may burn over two metres in depth without any possibility of being extinguished.[11] The production of aerosol by such fires has not been included in the above estimate, nor does it include contributions from fires in oil and gas wells. Although these could be very important, as they may provide a long lasting source of particulate matter to the atmosphere, they are quite difficult to quantify and depend on the scenario chosen.

The darkness would be further enhanced by the entrainment of huge quantities of dust by the fireballs of warheads exploded at the ground, as would be expected for attacks on missile silos and other hardened targets. Much of this dust would be carried into the lower stratosphere. The amount of submicron-sized dust particles injected into the atmosphere is again scenario-dependent, but could be as much as a few hundred million tonnes. Although dust particles are much less absorbing than soot particles, they effectively scatter radiation so as to increase the albedo of the earth–atmosphere system (*ie* backscatter to space) and increase the average path length of a light ray through the atmosphere.

As the smoke and dust clouds spread and the absorbing particles are removed by rain, sunlight would begin to penetrate again to the surface. For example, if we assume that the average

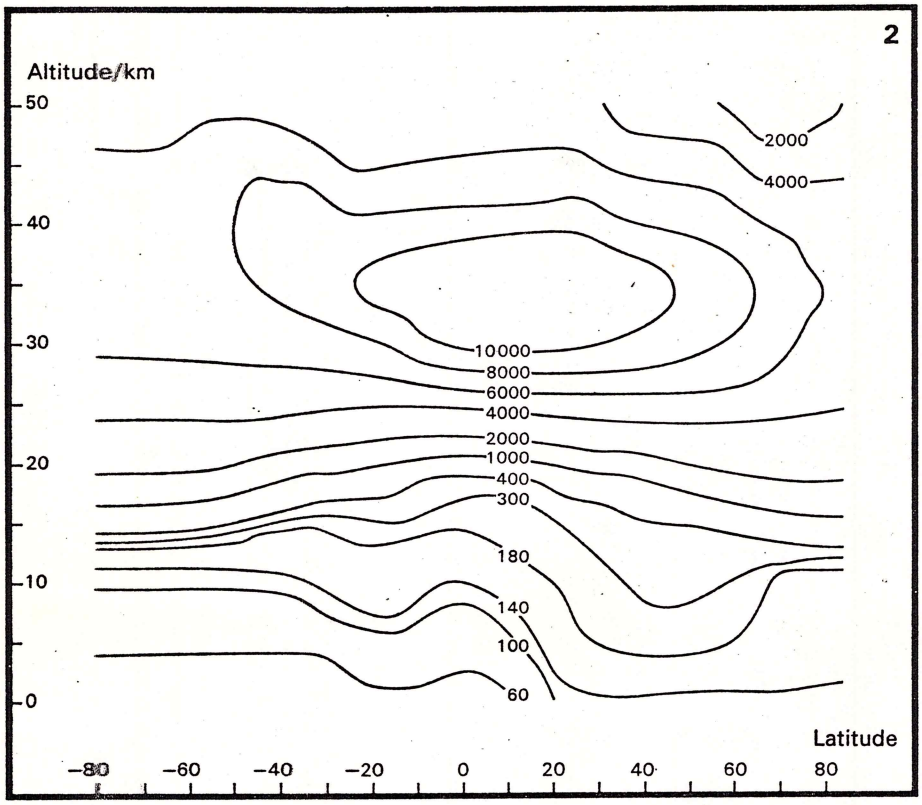

Fig. 2. Ozone mixing ratios (ppbv) on 1 August, 50 days after the beginning of the nuclear war. Inputs from forest fires and oil and gas well fires as described in the text.

particulate residence time in the atmosphere would be 10 days, approximately the same as in the lower regions of the present troposphere, the penetration of sunlight to the ground would remain below 1 per cent for about one week and below 10 per cent for about two weeks.[7] However, it seems likely that the removal rate for particulate matter would be much slower in the post-nuclear war atmosphere. The solar heated clouds would tend to rise to high altitudes where removal processes are slow, and the temperature inversion created by the dark clouds would tend to reduce the rate of vertical transport.[7]

If the average rain-out time were increased to 30 days, light levels would remain below 1 per cent for about two weeks and below 10 per cent for a month. By this time the smoke and dust clouds would cover about 70 per cent of the northern hemisphere.[7] If a significant fraction of the soot were to enter the stratosphere, the darkness would be extended considerably, and the southern hemisphere might be affected as well.[2,7]

Meteorological and climatic effects

In the normal atmosphere most of the solar radiation that is not scattered back to space is absorbed at the earth's surface. This results in the formation of the atmospheric layer known as the troposphere (~0–12 km altitude) in which the temperature decreases with increasing altitude. In the highly perturbed atmosphere following a nuclear war, very little sunlight would reach the surface. Instead, most sunlight would be absorbed in the soot-laden atmosphere, resulting in subfreezing temperatures over land surfaces[12] and a heating of air at higher altitudes. As a result of this strong temperature inversion the lower atmosphere would be very stable with respect to vertical mixing, especially over the continents, thereby suppressing cloud formation and precipitation scavenging of pollutants. This effect could prolong the lifetime of the particulate matter in the atmosphere, and thus extend the post-war period of darkness and low temperatures.

Because of the large heat capacity of the mixed layer of the ocean, the ocean surface temperature would not change much, and the combination of warm air over the oceans and cold air over the continents would lead to abnormal patterns of air circulation and precipitation, the details of which are difficult to predict. The combination of darkness and temperature excursions below freezing would be particularly devastating to plant and animal life if a nuclear war were to occur during the growing season.

Photochemical smog

The ingredients of photochemical smog are oxides of nitrogen, hydrocarbons and sunlight. Oxides of nitrogen are produced both in the nuclear fireballs by heating air to very high temperatures and in the combustion of fuels containing fixed nitrogen. The explosion of 5742 Mt of nuclear weapons is expected to produce 29 Tg (1 Tg = 1 Teragram $= 1\times10^{12}$ g) of nitric oxide (NO).[13] An additional 20 Tg of NO would be expected as a result of fires in cities and forests. These fires would also inject approximately 700 Tg of carbon monoxide and a few tens of Tg of reactive hydrocarbons such as ethene and propene into the atmosphere.[14] The formation of a photochemical smog, however, is highly dependent on the duration of sunlight blockage by the smoke layer (since it is sunlight that drives the chemical reactions).

We modelled one particular scenario that included attacks on natural gas and oil wells. For this scenario we allowed natural gas to be released (75 per cent burnt and 25 per cent unburnt) into the atmosphere at a rate equal to the present rate of industrial usage. *Figures 1* and *2* compare the ozone mixing ratios as a function of both altitude and latitude for the normal atmosphere and for the atmosphere 50 days after the start of the war. In the northern hemisphere, levels of ozone at ground level increase from about 30 ppbv (parts per 10^9 by volume) to levels approaching 160 ppbv for some weeks following the war.

These high ozone levels would be accompanied by high concentrations of other oxidants such as peroxyacetyl nitrate (PAN) and would be very harmful to both plant and animal life. However, we emphasise that the formation of smog is dependent on long-term fires such as might occur if oil and gas wells were targeted and is probably of secondary importance to the effects of smoke aerosol.

Ozone shield depletion

Although ozone is undesirable at ground level because of its toxicity to both animals and plants, ozone in the stratosphere (~12–50 km altitude) provides a protective shield against harmful ultraviolet radiation from the sun. Although oxides of nitrogen tend to cause ozone levels in the lower atmosphere to increase, in the upper atmosphere where the chemical composition and light spectrum are quite different, oxides of nitrogen (NO and NO_2) act as catalysts for ozone destruction *via* the cycle of reactions:[15]

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$
$$O_3 + h\nu \rightarrow O_2 + O$$
$$\text{Net: } 2O_3 \rightarrow 3O_2$$

We have modelled the atmospheric chemistry following a nuclear war using a two-dimensional model coupling chemical reactions and atmospheric dynamics. Our model does not predict significant ozone depletion in the stratosphere for *Ambio's* nuclear war scenario. This is because very few weapons having yields greater than 1 Mt are used in this scenario based on modern arsenals. Only explosions having yields greater than 1 Mt result in fireballs that rise completely into the stratosphere.

Previous studies of the atmospheric effects of nuclear war have emphasised the possible ozone depletions.[16,17] For this reason, we also evaluated the effects of a second scenario identical to that adopted for the 1975 study of the US National Academy of Sciences.[15] This

scenario considers a 10 000 Mt war in which the weapon yields are distributed equally between 1 Mt and 10 Mt weapons (*ie* 5000 1 Mt and 500 10 Mt explosions). The model calculations indicate an initial depletion of the ozone column of greater than 50 per cent throughout most of the northern hemisphere with an exponential recovery time of about three years; this is in good agreement with previous studies. Thus, should the warring nations choose to use their larger yield weapons, large reductions in the protective ozone shield are to be expected. This would result in a several-fold increase of biologically damaging uv radiation reaching the earth's surface.

Conclusions

For many weeks following a nuclear war, the atmosphere would be loaded with particulate matter to such an extent that the amount of sunlight reaching the surface of the earth would be substantially reduced. The absorption of most of the sunlight in the atmosphere rather than at the earth's surface would result in freezing temperatures, particularly near the interiors of the continents, and would drastically change the dynamical structure of the atmosphere.

The reduction of sunlight coupled with low temperatures would be extremely damaging to crops and entire ecosystems, should the nuclear war occur during the growing season. Additional damage by solar uv radiation would result if the stratospheric ozone shield is also reduced. The latter would occur if the nuclear powers chose to use their larger nuclear warheads in the exchange. The time scale for recovery of the ozone shield is of the order of a few years, and the several-fold increase in biologically damaging ultraviolet radiation would also severely affect crop yields.

These atmospheric changes would also have important human health effects, and such effects would be in synergism with radiation exposure, lack of adequate food supplies and lack of medical care. The darkened sky would undoubtedly add to the psychological stress of the initial survivors.

The atmospheric effects of a nuclear war would damage many natural ecosystems. For example, most of the phytoplankton and herbivorous zooplankton in the northern hemisphere oceans could die if blackout conditions of, at most, 1 per cent sunlight penetration lasted for ~one month in July and August or three months in January.[18] This effect is due to the fast consumption rate of phytoplankton by zooplankton in the oceans. A darkening of this magnitude, as a result of the dust created by the impact of a large extraterrestrial body, has been discussed recently as a possible explanation of the massive extinctions which took place at the Cretacious–Tertiary boundary about 65 million years ago.[19]

This article reviews the atmospheric effects of a nuclear war that have thus far been identified as potentially important. Most of these effects are quite complex and difficult to model. Several new studies of the environmental effects of nuclear war are in progress or have been completed recently. These include the *Conference on the long-term worldwide biological consequences of nuclear war*, held on 31 October and 1 November in Washington, a new study by the US National Academy of Sciences to be released by the end of this year, a major international study to be started under the auspices of the International Council of Scientific Unions, and an internal study at the Lawrence Livermore National Laboratory in California.

A study organised through the Division of Atmospheric Research at CSIRO in Australia is examining the effects of nuclear war on the southern hemisphere. There have been two recent symposia on the environmental effects of nuclear war at regional meetings of the American Association for the Advancement of Science, and the American Geophysical Union will sponsor a symposium on 7 December in San Francisco. It is hoped that this new interest in the environmental effects of nuclear war will lead to a new understanding and increase the awareness of all people so as to help prevent such a holocaust from ever occurring.

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Alan W. Johnson 1917–1982

The Society, and indeed the whole chemical community, suffered a grievous loss caused by the sudden death on 5 December 1982 of one of its well-loved senior members, Professor Alan W. Johnson, at the early age of 65. He had retired as professor of chemistry at the University of Sussex only two months earlier and on 5 October a very well-attended symposium was held in London in his honour, at which both former associates and friends participated.

Born in Newcastle-upon-Tyne on 29 September 1917, he was educated at Morpeth Grammar School and then part-time at Rutherford College whilst working for three years in industry. He won a Royal Exhibition to Imperial College in London in 1936 where he went on to do postgraduate and postdoctoral work with Professor I. M. (later Sir Ian) Heilbron and me, on the synthesis of vitamin A. During four years with ICI Dyestuffs (now Organics) Division at Manchester he continued to make contributions to the adolescent field of acetylene chemistry and consolidated his reputation with his two volumes on *The chemistry of the acetylenic compounds*.

He was awarded the coveted Meldola Medal of the Royal Institute of Chemistry in 1946, one of the rare occasions on which it has been given to someone in industry. Later that year, he went to Cambridge as one of the first ICI Fellows, subsequently becoming a lecturer and Fellow of Christ's College. There he was introduced to and became deeply involved in natural product research in association with Professor A. R. (now Lord) Todd. His participation in the unravelling of one of the last major structures, that of vitamin B_{12}, by mainly chemical methods was the outstanding achievement of this period, but there was also pioneering work, on insect pigments, actinomycin and the tropolones, all revealing quite novel structures that aroused great interest.

In 1955 he was appointed Sir Jesse Boot professor and head of the department of chemistry at Nottingham. Here, with a group of able and enthusiastic coworkers, including D. Dolphin, R. Grigg and I. T. Kay, in addition to continuing some of the Cambridge activities, he embarked on synthetic work in the tetrapyrrole series. Routes from pyrrolic intermediates to the novel corrinoid structure (of vitamin B_{12}) were discovered and pioneering observations were made on the effect of coordinated metal ions in ligand reactivity, both here and in the porphyrins. Important contributions were made to porphyrin synthesis, particularly notable being the rational stepwise synthesis of 1-bromo-19-methylbilin derivatives, readily cyclised to porphyrins in high yield.

He moved to a chair at the University of Sussex in 1968 where he became honorary director of the Unit of Invertebrate Chemistry and Physiology established there by the Agricultural Research Council. He carried on with his synthetic and exploratory studies on porphyrins but he also returned to earlier Cambridge work on the nature of root exudates which stimulate germination of parasitic weeds and *eg*, synthesised (in quantity) analogues of the natural strigol which were highly effective in protecting