I. The Winners of the Blue Planet Prize

1997

1997

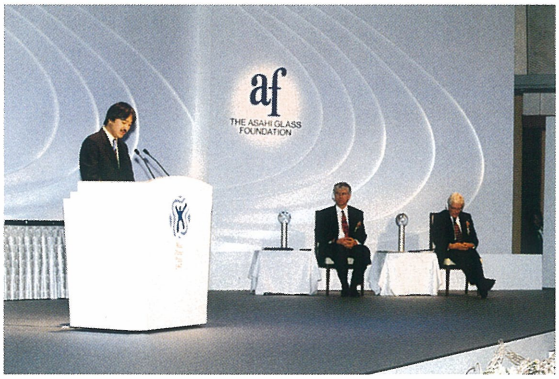
Blue Planet Prize

Dr. James E. Lovelock (U.K.)

Honorary Visiting Fellow of Green College, Oxford University

Conservation International (CI) (Headquartered in U.S.A.)

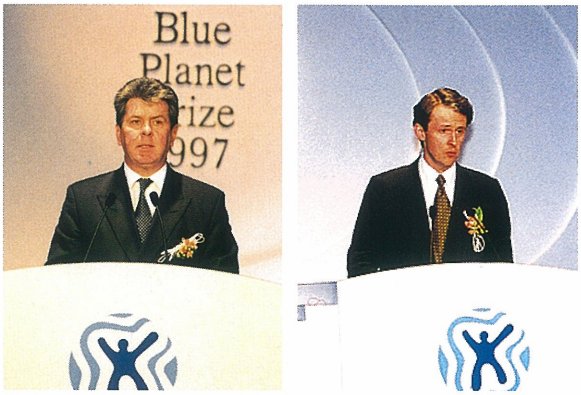
At the 1997 Blue Planet Prize Awards Ceremony, the opening slides conveyed a message to children to remind us of our responsibilities to future generations and raise the question of what each one of us can do to leave our beautiful planet intact and habitable.



His Imperial Highness Prince Akishino congratulates the laureates.

Their Imperial Highnesses Prince and Princess Akishino at the Congratulatory Party.

Dr. James E. Lovelock accepts the 1997 Blue Planet Prize.



Sir David John Wright, Ambassador of the United Kingdom to Japan (left), and Christopher J. LaFleur, Chargé d'Affaires ad interim of the United States to Japan (right), congratulate the laureates.

Dr. Russell A. Mittermeier, representing CI, accepts the 1997 Blue Planet Prize.

The Blue Planet Prize Commemorative Lectures.

Prior to the awards ceremony, the award recipients meet the press. From right: Dr. Mittermeier; Dr. Lovelock; Chairman Jiro Furumoto; and Osamu Shiragami, senior executive director of the Foundation.

Profile

Dr. James E. Lovelock

Honorary Visiting Fellow of Green College, Oxford University

Education and Academic and Professional Activities

1919	Born in July in the United Kingdom.
1941	B.Sc., Chemistry, University of Manchester.
1941-1961	Medical Research Council, National Institute for Medical Research, London.
1948	Ph.D., Medicine, London School of Hygiene and Tropical Medicine.
1954-1955	Visiting Scientist, Harvard University Medical School, U.S.A.
1955	CIBA Foundation Award for Research in Aging.
1958-1959	Visiting Scientist, Yale University Medical School, U.S.A.
1959	D.Sc., Biophysics, University of London.
1961-1964	Professor of Chemistry, Baylor College of Medicine, University of Houston, U.S.A.
1964-1974	Visiting Professor, Department of Chemistry, University of Houston, U.S.A.
1964-1989	Visiting Professor, Department of Cybernetics, University of Reading, U.K.
1974	Fellow, Royal Society of London.
1975	M.S. Tswett Award for Chromatography.
1980	Award for Chromatography, American Chemical Society.
1986	Silver Medal and Prize, Plymouth Marine Laboratory.
1988	Norbert Gerbier Prize, World Meteorological Association.
1990	Commander, Order of the British Empire; Amsterdam Prize for the Environment, Royal Netherlands Academy of Arts & Sciences.
1993—	Honorary Visiting Fellow, Green College, Oxford University, U.K.
1996	Volvo Environment Prize.

In 1957, Dr. James E. Lovelock invented the electron capture detector (ECD), a device for use in gas chromatography that can detect tiny amounts of chemical compounds in the atmosphere and elsewhere on Earth. This device made it possible to detect halogenated compounds and nitrous oxide, even at levels of only one part per trillion (ppt), thus revolutionizing our understanding of the atmosphere and pollutants.

Dr. Lovelock used his own invention in 1970 to detect chlorofluorocarbons (CFCs) in air masses over Ireland. In 1973, the ECD was used to discover the existence of CFCs in the oceans and atmosphere throughout the Atlantic region from the Antarctic to the English Channel. The CFCs were particularly abundant in areas surrounding industrialized countries. These discoveries eventually led to the theory that CFCs destroy stratospheric ozone.

In the 1960s, Dr. Lovelock was invited by the U.S. National Aeronautics and Space Administration (NASA) to join one of their research teams. He became involved with the NASA program studying Mars and, while making comparisons between the atmospheres of Mars and of Earth, became interested in the special properties of the Earth's atmosphere. Dr. Lovelock, building on his broad background in chemistry and medicine, then formulated the Gaia Hypothesis, now the Gaia Theory. This hypothesis was first stated in 1972 and was later developed through an ongoing collaboration with the eminent American biologist Lynn Margulis.

The Gaia Hypothesis sought to describe the Earth from a comprehensive point of view, not in specialized, fragmented terms. Gaia could be understood as a control system for the Earth and offered a new way of looking at our planetary biosphere. It developed a new way of viewing our entire world and helped raise interest in the environment all around the globe.

Essay

The Evolution of the Earth

Dr. James E. Lovelock

June 2001

The American scientist Alfred Lotka published a small book, *Physical Biology*, in 1925. In it he wrote.

> It is not so much the organism or the species that evolves, but the entire system, species and environment. The two are inseparable.

As a follower of Alfred Lotka, I want to take his suggestion further and consider evolution as a science that is as much about the rocks and oceans as about the living things that inhabit them. In this view, what evolves is an Earth system that can move gradually for long periods under an ever-warming sun. But as it evolves, sudden changes punctuate its gradual evolution; such as the appearance of oxygen, or a glaciation, or a species like humans. Evolution is also punctuated by external events, such as the impact of planetesimals or the appearance of a species like photosynthesisers, or humans, that change the global environment. Whether internally or externally driven, these events change the whole system—material environment and organisms—neither of them separately.

Lotka's view of evolution passed almost unnoticed in his time and it was not until NASA in the 1960s began exploring our planetary neighbourhood that this broader, transdisciplinary view of the Earth was revisited. As part of NASA's exploration team, it led me to propose in a paper in *Nature* in 1965 that life and its environment are so closely coupled that the presence of life on a planet could be detected merely by analysing chemically the composition of its atmosphere. This proposal is now part of NASA's astrobiology program and they aim to use it in the search for life on extra-solar planets.

When we look at the Earth using one of these life detectors, we see an atmosphere that, apart from the noble gases, has a composition almost wholly determined by the organisms at the surface. So tightly coupled is life with the atmosphere, that if some catastrophe removed all life from the Earth without changing anything else, the atmosphere and surface chemistry would rapidly—in geological terms—move to a state similar to Mars or Venus. These are dry planets with atmospheres that are dominated by carbon dioxide and close to the chemical equilibrium state. By contrast, we have a cool wet planet with an unstable atmosphere that somehow stays constant and always fit for life. The odds against such stability are close to infinity. Science is about probabilities, so we are forced to consider the difficult but more probable alternative: something regulates the atmosphere. What is it? It has to be something connected

with life at the surface because we know that the atmospheric gases—oxygen, methane and nitrous oxide—are almost wholly biological products, while others, nitrogen and carbon dioxide, have been massively changed in abundance by organisms. Moreover, the climate depends on atmospheric composition and there is evidence that the Earth has kept a fairly comfortable climate ever since life began in spite of a 30% increase in solar luminosity. Together these facts led me to propose in a 1969 paper in the *Journal of the American Astronautical Society* that the biosphere was regulating the atmosphere in its own interests. Two years later, I started collaborating with the American biologist, Lynn Margulis, and we published a paper in *Tellus* in which we stated:

> The Gaia hypothesis views the biosphere as an active adaptive control system able to maintain the Earth in homeostasis.

This idea was so contradictory to the views of evolutionary biologists that it was not long before the Canadian and British biologists, Ford Doolittle and Richard Dawkins, challenged it. They pointed out that global regulation by the organisms could never have evolved because the organism itself was the unit of selection, not the Earth. In time, I found myself agreeing with them. They were right; there was no way for organisms by themselves to evolve so that they could regulate the global environment. But I wondered could the whole system—organisms and environment together—evolve self-regulation? In 1981, I redrafted the hypothesis as an evolutionary model, Daisyworld, that was intended to do no more than show that self-regulation can take place on a planet where organisms evolve by natural selection in a responsive environment. The model was one that Alfred Lotka might have made had computers been available in his time. Following the model, the Gaia hypothesis was restated as follows:

> The evolution of organisms and their material environment proceeds as a single tight-coupled process from which self-regulation of the environment at a habitable state, appears as an emergent phenomenon.

At about the same time, Andrew Watson, Mike Whitfield and I suggested a mechanism for climate control by the Earth system, namely the biologically assisted reaction between atmospheric carbon dioxide and calcium silicate in soil and on rocks. This process could regulate both climate and CO_2 at a level comfortable for plants. Soon other putative regulation mechanisms were discovered, such as the connection between ocean algae, dimethyl sulphide gas, clouds and climate. By the end of the 1980s, there was sufficient evidence and models of the hypothetical system to justify calling it the Gaia Theory.

The name Gaia was not popular with scientists and, as a consequence, the theory has developed under the pseudonyms, geophysiology and Earth System Science. Because most Earth System scientists are geologists or geochemists, the science has lacked biological wisdom. Earth System scientists included the biota in their models, but did so as if ecosystems were passive reservoirs, like the sediments or the ocean, something unable to respond actively to change, still less able to evolve by natural selection or include biodiversity. In the biologi-

cal community, the Gaia Theory was almost wholly rejected, and Earth System Science was ignored so far as evolution was concerned. Then, in the mid–1990s the eminent scientist William Hamilton became interested in the Gaia Theory. He accepted what was by then the strong evidence that the environment was regulated at a state comfortable for the biota. He saw it as a challenge to explain how this could happen as a consequence of evolution through natural selection. He published with Tim Lenton one paper on the cloud algal system. Sadly, he died shortly afterward, but his colleague, Peter Henderson, continues to model systems of biological evolution that include the material environment.

What Bearing Does This New View of Evolution Have On Current Environmental Concerns and What Practical Use Is It?

1) It draws our attention to the biological infrastructure of the Earth, namely microorganisms. Lynn Margulis first pointed out their significance and that they still play an important, if not major part, in planetary regulation. Bacteria were the whole biosphere for three-billion years before multicellular organisms like us and trees came on the scene.

2) In the real world, organisms grow in a material environment where growth is strongly constrained by the laws of physics and chemistry. When these constraints are included in evolutionary biology models, it becomes possible to build a wide range of stable model systems. Tim Lenton and Stephan Harding have separately explored imaginary ecosystems with different environmental or species properties. Their models offer insight into the nature of the Earth system and into the need for biodiversity. Biodiversity is usually valued for its aesthetic or human medicinal qualities; we think that biodiversity is an important part of planetary self-regulation.

3) We see the interglacial period that we are now in as a pathological state of the Earth System and see the ice ages as the normal state of the Earth system. In the present interglacial, all of the regulation systems so far proposed appear to be in positive feedback towards climate change. In other words, any change, either to hotter or colder, is amplified not resisted. This applies to the mechanisms for pumping down CO_2 from the atmosphere, for cloud production by algae and for the Daisyworld-like behaviour of the boreal and tropical forests. In addition, geophysical feedbacks, such as the effect of ice cover, are also in positive feedback. An interglacial like now can be seen as a period when regulation has temporarily failed and certainly no time to add more greenhouse gases or deplete biodiversity.

Many biologists, including E.O. Wilson, Norman Myers and Peter Raven, consider that we are in the midst of a great extinction as a consequence of the denial of land for natural habitats by its use for agriculture. In debates on this topic, the great diversity of organisms, especially in equatorial regions, is sometimes regarded as if it were a stable natural state. I wonder if instead

we should regard the diversity of natural ecosystems as an indication that the Earth itself is continuously but gently, perturbed. Even the single environmental variable, temperature, is perturbed on the short time-scale of diurnal change, and through the yearly march of the seasons, to the alternation of glaciations with warm periods like now. Our models suggest that biodiversity is a symptom of perturbation during a state of comparative health. What seems important for sustenance is not so much biodiversity as such, but potential biodiversity, the capacity of a healthy system to respond through diversification when the need arises. In tropical forest and other regions under threat, destroying diversity will reduce the numbers of rare species. Among them may be those able to flourish and sustain the ecosystem when the next large environmental change takes place. The loss of biodiversity seldom occurs alone. It is part of the destructive process of converting natural ecosystems to farmland. It is the whole process, the loss of diversity and the loss of the potential of the region to sustain biodiversity, that makes the large-scale replacement of natural ecosystems with farmland so dubious an act.

The Gaia Theory is not contrary to Darwin's great vision; it is like neoDarwinism, a new look at Darwin's evolutionary theory. I suspect it will be some time before biologists and geologists collaborate closely enough for us to see the emergence of a truly unified Earth System science. William Hamilton, in a television interview, referred to the Gaian view of evolution as Copernican, but, he added, we await a Newton to explain how it works.

Lecture

Travels with an Electron Capture Detector

Dr. James E. Lovelock

This afternoon I will tell you about the invention of the Electron Capture Detector, how this simple device helped to start the environmental movement and how, later, some of its measurements led me to the idea of the Earth as the self-regulating system, Gaia.

The Electron Capture Detector, which henceforward I will call the ECD, was invented almost exactly 41 years ago in October 1956. In those days, it was usual for scientists to make, or at least design, their own instruments. Most laboratories then had a workshop with metal working tools, lathes and milling machines, and scientists were expected to be able to use them. Electronic devices were made by hand using thermionic vacuum tubes manufactured for use in radio and sound equipment. Because we made our own equipment, we understood its limitations and capabilities. Such insight is denied most scientists today that use commercial instruments without understanding what goes on inside the decorous case of their chromatograph, spectrometer or other device. The greatest advantage to come from making one's own apparatus is that sometimes it is an invention whose novelty makes it years in advance of anything available in the marketplace.

In 1956, I was trying to discover the cause of the damage suffered by living cells when they were frozen. We had successfully frozen and reanimated small animals—hamsters—and we were now moving on to see if animals as large as a rabbit could be reanimated after freezing. I had found that most of the damage by freezing was to cell membranes. These are made of lipid protein complexes and sensitivity to cold seemed to depend in part on the fatty acid composition of the lipids.

To quantify my work, I needed accurate analyses of these fatty acids. It so happened that Archer Martin and Tony James, inventors of gas chromatography, were working in the same institute just one floor above me. I knew that their instrument had first been used to analyse fatty acids so I asked them if they could analyse those of my membrane lipids. They were enthusiastic to try until I showed them the quantity I had for analysis. It was a few micrograms. Martin said "Sorry, but we cannot do it for you. We need milligrams not micrograms. Go back and prepare a much larger sample." Then, as an afterthought one of them said, "Alternatively you could invent a more sensitive detector than our gas density balance."

At the National Institute, it was the tradition never to read the literature, especially not textbooks, before doing an experiment. Senior scientists warned that our job was to make the literature not read it. It was a recipe that worked well for me. Had I read the literature of ionisation phenomena in gases before doing my experiments, I would have been hopelessly discouraged and confused. Instead, I did some experiments. Fortunately, we were not hampered, like now, by a well-intentioned but hindering health and safety bureaucracy. Scientists who used dangerous chemicals or radioactive materials were expected to be personally responsible.

There was some risk, but I doubt if under the stifling restrictions of today I would have had the persistence to carry on with so uncertain a project as the infant Electron Capture Detector.

I first invented the Argon Detector—a device that used excited argon atoms to ionise the vapours of organic compounds. This was the sensitive detector that I had been seeking for fatty acid analysis. Until the even better flame ionisation detector displaced it, it served me and many other biochemists around the world for the analysis of minute traces of fatty acids and other lipids. Serendipitously, during the work leading to the argon detector, I discovered the ECD. Like the argon detector, it was a simple diode ion chamber. But with the ECD, nitrogen was the carrier gas and the chamber was polarised by only a few volts instead of the kilovolt needed by the argon detector.

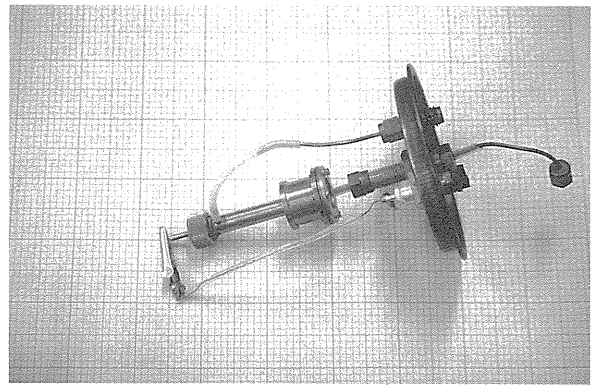


Figure 1. The electron capture detector.

I was fascinated by the strange behaviour of the ECD, but a full investigation of its scientific basis was far from that of the freezing problem I was expected to work on. It says much about the management of the Institute that I was allowed to spend any time on it at all. The physics of thermal energy electrons was hardly what the physicians running the Medical Research Council expected of me. I recall asking the director, Sir Charles Harington, " Can I spend some of my time finding out how the ECD works?" I added, "There is no certainty that it will be of practical use, but to me it is fascinating science." He replied "I am happy to leave it entirely to your own judgement. This is a scientific institute, and so long as what you do is good science, I am not much concerned about its immediate medical value."

My curiosity about the strange and anomalous behaviour of the ECD made me return to work with it whenever there was a spare moment. In 1958, I was invited to spend a year at Yale University by Dr. Lipsky. Here, I had the opportunity to work full-time on detectors, and by the end of 1959, was able to reduce the ECD to practice as a detector little different from those now in use. The ECD gives no response whatever to over 99.9 per cent of all organic compounds. Those few it does detect are often of biological and medical interest. Among them were compounds important in oxidative metabolism, such as the acids of the Krebs cycle, steroid and thyroid hormones, and coenzymes. It also detects substances that are poisons of this system, such as the nitro- and halo-phenols, and it was uniquely sensitive to chemical car-

cinogens. It is this selective response to poisons that makes it so useful in environmental studies. The detector was then, and still is, the most sensitive, easily portable and inexpensive analytical device in existence. So exquisitely sensitive that if a few litres of a rare perfluorocarbon were allowed to evaporate somewhere in England, we could with a little effort detect it in a 3-cubic-metre sample of the air here in Japan a week or so later, and within two years it would be detectable anywhere in the world. This extraordinary sensitivity to perfluorocarbons, which otherwise are wholly inert and harmless, has been put to use in methods for tracing the movement of air masses across whole continents and also for mass transfer experiments in the oceans.

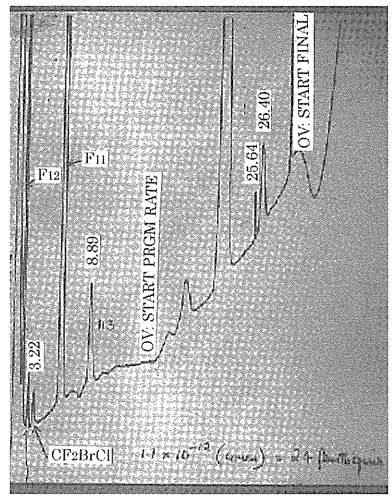


Figure 2. Chromatogram showing the detection of 1 part per trillion of the halon BCF.

What Makes it Work?

It was easy enough to understand the detector qualitatively, but a quantitative theoretical understanding of its operation eluded me until I worked with Drs. Wentworth and Chen at the University of Houston. We found that the electron attachment to molecules was sometimes reversible, but also could be irreversible and followed by the dissociation of the molecule. In the 1960s when we did this work, computers were not generally available and, because of this, the numerical solution of the detector equations was beyond us. By 1970, simple computers became available, and I was able to solve the detector equations and understand the theory of its operation. This analysis led to the invention of the constant current method for its operation, which is now used in almost all commercial equipment.

I find it helpful to think of the detector as a small reaction vessel holding a dilute suspension of the reagent chemical gaseous free electrons. We often forget that the free electron is a simple chemical and as much a fundamental particle of chemistry as it is of physics.

While I was improving and trying to understand the mechanism of detection by electron capture, serious scientists were applying the detector to the practical analysis of pesticide residues in foodstuffs. It was already known from conventional chemical analysis that DDT

was present, at levels down to the detection limit of one part per million, in foodstuffs and in the fat of animals and humans. Conventional wet chemistry was not well suited to the comprehensive study of pesticide distribution. A more rapid, sensitive and discriminatory method was needed. In the United States, Watts and Klein of the FDA, and in the United Kingdom Goulden and his colleagues at Shell, pioneered the use of the ECD. They were soon joined by analysts worldwide, who used gas chromatographs equipped with ECDs to establish a global database of the distribution of halogenated pesticides, and soon this data were the hard facts of the environmental movement. When it was realised that pesticides like DDT and Dieldrin were distributed throughout the global environment and when it was shown that they were in the fat of Antarctic penguins and in the milk of nursing mothers in Finland, there was a recognition that pollution was no longer just a local problem; we humans were affecting the environment on a global scale. The data about the distribution of pesticides and their poisonous effect on birds of prey led Rachel Carson to write her seminal book, *Silent Spring*. A book that warned the world of the ultimate consequences if these chemicals continued to be used by farmers in their unceasing battle against all forms of life that are not livestock or crops. It was a book that was bound to affect the course of politics, and in many parts of the world, her gloomy forecast of a silent spring has come true. Not as she predicted by pesticide poisoning alone, but simply by habitat destruction.

When I first heard that the electron capture detector was being used this way, I was delighted. I shared with Rachel Carson her concern over damage to natural ecosystems. Some parts of the chemical industry reacted in a shameful and foolish way by trying to discredit her as a person. It did not work; in fact it made Rachel Carson the first saint and martyr for the infant and innocent green movement. All seemed set for the green movement to lead us into a seemly and sensible way of living with the natural world. As you know, it did not happen like this. Sadly, the environmental agenda has had to proceed at the normal slow pace of human politics.

Independent Science

In April 1961, I received a letter from Dr. Silberstein, Director of Space Flight Operations for NASA. It was an invitation to join with them in their exploration of the moon. We have to remember that in 1961, space flight was barely a few years old. Many scientists still looked on it as fanciful and a waste of time and money. To me, who had grown up on science fiction, the invitation was like a dream come true. This invitation was the spur that led me to leave a safe, tenured, well-paid job at the National Institute for Medical Research for the uncertainties of independence and working from home.

Soon, lunar exploration became commonplace, and the new interest was in planning an automated laboratory to send to Mars to look for life. In the early 1960s, not much was known about Mars. Its surface was poorly visible through telescopes, and it was easy to imagine that the seasonal wave of darkening that moved across the planet was due to the growth of vegetation. My colleagues at the JPL were busy designing instruments to test for life or life-like chemicals on the Martian surface. They were trying to put into practice in an automated form the very procedures that they were familiar with in their own laboratories here on Earth. Some

of these experiments involved applying Martian soil to culture media to see if organisms would grow. Others looked for metabolism to see if oxygen was produced in sunlight or CO_2 in the dark. I found this detailed reductionist approach to life detection for Mars unconvincing. It could fail to detect the presence of life for many reasons. It might not be bacterial, the experiment might land at a barren site—or Martian biochemistry might be different. I suggested that they try a more general experiment, such as a top-down view of the whole planet instead of a local search at the site of landing. The experiment I proposed was simply to analyse the chemical composition of the Martian atmosphere. If the planet were lifeless, then it would be expected to have an atmosphere determined by physics and chemistry alone and be close to the chemical equilibrium state. But if the planet bore life, organisms at the surface would be obliged to use the atmosphere as a source of raw materials and as a depository for wastes. Such a use of the atmosphere would change its chemical composition. It would depart from equilibrium in a way that would show the presence of life. Dian Hitchcock joined me then, and together we examined atmospheric evidence from the infra-red astronomy of Mars. We compared this evidence with that available about the sources and sinks of the gases in the atmosphere of the one planet we knew bore life, Earth. We found an astonishing difference between the two atmospheres. Mars was close to chemical equilibrium and dominated by carbon dioxide, but the Earth was in a state of deep chemical disequilibrium. In our atmosphere, carbon dioxide is a mere trace gas. The coexistence of abundant oxygen with methane and other reactive gases are conditions that would be impossible on a lifeless planet. Even the abundant nitrogen and water are difficult to explain by geochemistry. No such anomalies are present in the atmospheres of Mars or Venus. Their existence in the Earth's atmosphere signals the presence of living organisms at the surface. Sadly, we concluded, Mars was probably lifeless.

The first sight of the Earth from space as a dappled white and blue sphere filled our minds with wonder and delight. We saw, for the first time, how beautiful was the Earth and began to regard it as an icon like those of the great religions. In a similar way, the top-down view of atmospheric chemistry gathered at JPL was for me, in scientific terms, a revelation of the Earth. The analysis revealed the atmosphere as a gas mixture like that of the intake manifold of an internal combustion engine: oxygen and combustible gases mixed. Different from the exhausted, carbon dioxide dominated atmospheres of Mars and Venus. Much more than this, I knew that the chemical composition of the atmosphere was stable for long periods compared with the residence times of its gases. One afternoon in 1965 at the JPL in California, when thinking about these facts, the thought came to me in a flash that such constancy required the existence of an active control system.

Then, I lacked any idea of the nature of the control system, except that the organisms on the Earth's surface were part of it. I learnt from astrophysicists that stars increase their heat output as they age and that our Sun has grown in luminosity by 25% since life began. I realised that, in the long term, climate also might be actively regulated. The notion of a control system involving the whole planet and the life upon it was now firmly established in my mind. Sometime near the end of the 1960s I discussed this idea with my near neighbour, the novelist William Golding. He suggested the name Gaia as the only one appropriate for so powerful an entity.

I first stated the Gaia Hypothesis in 1972 in the journal, *Atmospheric Environment.* My proposal was "the biosphere interacts actively with the environment so as to hold it at an optimum of its own choosing." The proposal was based on arguments drawn from the atmospheric chemistry of the Earth and Mars. Soon after I began a collaboration and friendship with the biologist Lynn Margulis that has continued to this day. Lynn, from her wide knowledge and deep understanding of organisms—especially microorganisms—put flesh on the bare bones of my physical chemistry.

I now realise that the early statements of the Gaia Hypothesis were misleading. Worse, enthusiasts of the idea began to speak of the Earth as a living organism—not as we said "the Earth behaves like a living organism." These misunderstandings led to heavy criticism from biologists that still persists 25 years later. Sharpened by these criticisms, the Gaia Hypothesis evolved. Now, we see Gaia as a system made from the living organisms of the Earth, and from their material environment, the two parts tightly coupled and indivisible. Gaia theory views the self-regulation of the Earth's climate and chemical composition as emergent properties of the system.

My colleague, Andrew Watson, succinctly expressed the step that distinguishes Gaia theory from previous evolutionary theories. It lies in the tightness of the coupling between the organisms and their physical environment. Almost everyone, he said, now accepts that life profoundly influences the environment. This is now the conventional wisdom among geochemists, and a considerable change from their view pre-Gaia. It is equally obvious, he continued, that life is influenced by and adapts to the environment. This is the older wisdom that has prevailed throughout this century. Therefore, life and the environment are a coupled feedback system, where changes in one element will affect the other, and this may in turn feed back on the original change. The real debate is, then, how important and how tight is the coupling? Does it, as we believe, confer new properties on the system, such as enhanced stability or behaviour like a living organism? I see this coupling strong enough that we will not properly understand Earth history until we think of the system as just that, a whole system, and stop trying to understand its parts in isolation from one another. Gaia theory is testable and is developing normally in the Earth sciences, and in time will either be accepted or rejected on the evidence.

Among the insights that come from a Gaian approach is the idea that planetary life can never be sparse. A planet with sparse life could never self-regulate. We should keep this in mind as we destroy the natural ecosystems of the Earth to provide farmland for ourselves. The geophysical and geochemical evolution of the terrestrial planets is progressive and towards states like those of Mars and Venus now.

Thinking about Gaia led me to explore the natural world. I was curious to know how elements like sulphur and iodine that are scarce on the land surface, but plentiful in the oceans, are transferred back from the sea to the land in sufficient quantities to keep the land fertile.

The opportunity to start exploring came in 1968 when we purchased a holiday cottage in far Western Ireland on the shores of Bantry Bay. It was sited on the slopes of Hungry Hill, a small mountain of warm sandstone slabs, which looked out over the broad Atlantic. Here, during walks along the beach, I collected the different species of macroalgae—seaweed. I put

the specimens into empty jars and later examined their volatile emissions, using a simple gas chromatograph. Summer holidays at Adrigole led serendipitously to another discovery about the atmosphere. On days when the air drifted from the East, from Europe, it became hazy and the visibility range fell from over 50 kilometers to less than one kilometer. I wondered if we were seeing a polluted air mass that had travelled intact more than 1,000 kilometers to western Ireland.

Figure 3. The cottage laboratory in Ireland.

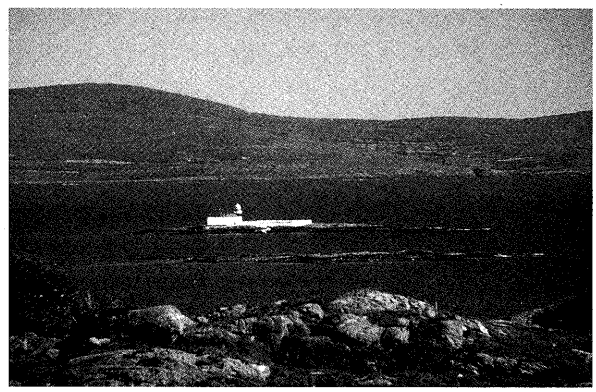


Figure 4. Clear air seen from the Adrigole cottage.

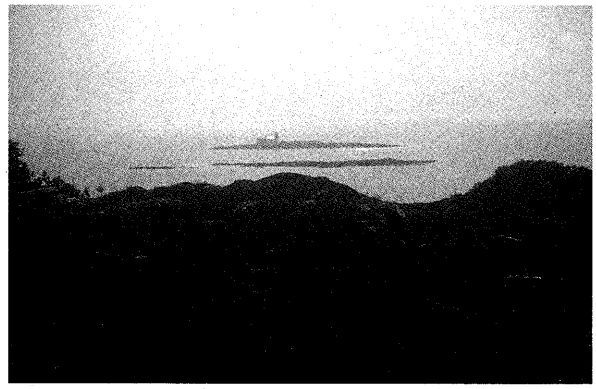


Figure 5. Smog seen from the Adrigole cottage.

I had the idea that it should be possible to decide if the haze was a natural phenomenon, or was man-made, by measuring the level of CFCs, the aerosol propellant gases in it. The CFCs are unique among chemicals in the atmosphere in being unequivocally of industrial origin. Other chemicals have both natural as well as man-made sources. My idea was that if the haze was pollution, it would come from an urban industrial area and in it there would be more of these CFCs than in clean Atlantic air. On the first few days of our holiday the air was sparkling clear, and I was surprised to find a small but easily measurable quantity, 50 parts per trillion of F11, in the air. A few days later, the wind shifted and an easterly drift of air blew from Europe. With it came the haze and the confirmation of my idea about the origin of the smog. For in the hazy air, there were 150 parts per trillion of F11, three times as much as in the clear air. So the haze was man-made. Later investigations showed it to be photochemical smog, rich in ozone, and to have come from Southern France and Italy, having drifted in the wind nearly 1,000 miles carrying the exhaust fumes of the millions of cars of European holiday makers.

There, this small investigation might have ended, but being curious and having no employer to tell me what I should be doing, I wondered about the 50 parts per trillion of CFC in the clean Atlantic air. Had it drifted across the Atlantic from America, or more important, were the CFCs accumulating in the Earth's atmosphere without any means for their removal? To find out, the only thing to do would be to travel by ship to the Southern Hemisphere and back and measure the CFCs as the ship travelled across the world. I had another reason to make the voyage. I wanted to know if there were molecular species of the elements sulphur and iodine released from the oceans in sufficient quantities to account for the rate of mass transfer of these elemental cycles. I tried for grant support to make these investigations, but without success. Being an independent, the lack of support was not a deterrent, and my wife agreed to support the expedition from our housekeeping budget.

The apparatus I used was so simple I was able to make it in a few days. It ran without failure throughout the six-month voyage. The total cost of the research, including the apparatus, was about 40,000 Yen. But the discoveries of the voyage required three *Nature* papers for their publication.

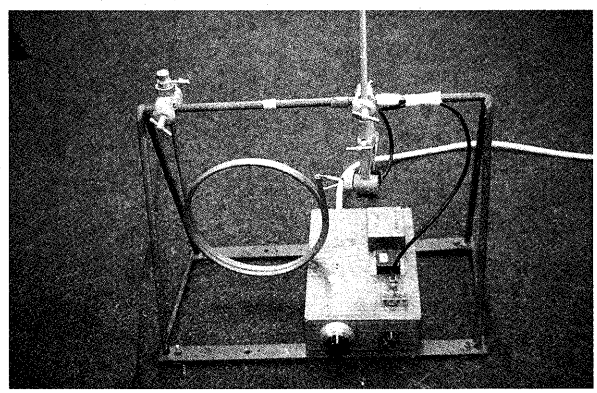


Figure 6. Gas chromatograph used on the Shackleton to analyse the CFCs.

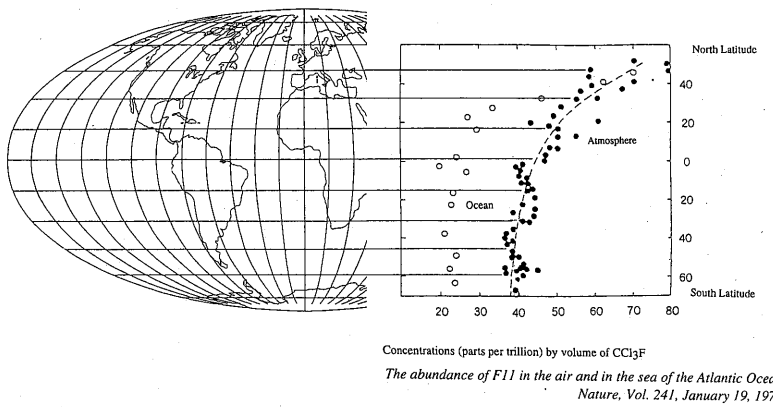


Figure 7. The abundance of F11 in the air and in the sea of the Atlantic Ocean.

This journey of research revealed the global presence of the chlorofluorocarbons, carbon tetrachloride and methyl chloroform. In addition, I found the unexpected presence of methyl iodide, dimethyl sulphide and carbon disulphide. It now seems that the environmental significance of these sulphur emissions may be as important as is that of the CFCs.

Sherry Rowland and Mario Molina used my data in their historic *Nature* paper. They made public their concern about the potential of the CFCs to deplete stratospheric ozone. At first, I was sceptical. I did not doubt the excellence of the science. Indeed, in 1974, I took samples of stratospheric air and was able to confirm the Rowland Molina hypothesis that the stratosphere was a sink for the CFCs. What I did doubt was that the 50 ppt of F11, and the 80 ppt of F12, in the air in the mid-1970s were, at that time, a significant threat. It is normal in science for new hypotheses to have a hard time—as I well knew from the opposition to the Gaia Hypothesis, and some of my scepticism came from this cause. At the time, it seemed that monitoring, not a ban, was needed. Looking back, I realise I was wrong to oppose an early ban on the release of CFCs to the atmosphere. I underestimated the time needed for the international understanding that led to the Montreal agreement on the CFCs.

As the years went by, the need grew for comprehensive global monitoring of the CFCs. Prinn and his colleagues suggested in 1977 that the accurate global monitoring of CFCs would provide data from which their residence times in the atmosphere could be calculated. In 1978, our holiday cottage at Adrigole became the site of the first station of what was to become the GAGE global monitoring network. The success of this trial run led to the establishment of a network of five monitoring stations in Barbados, Oregon, Samoa, Tasmania and Adrigole. These have successfully monitored the atmosphere ever since. From the results, the probable atmospheric lifetimes of the CFCs have been calculated.

The monitoring of the CFCs made accurate measurements essential. But the calibration of our detectors with a gas at a concentration of a few parts per trillion is easier said than done. My personal solution to this problem was twofold. First, I calculated from first principles the number of electrons that had reacted with fluorocarbon in the detector. This provided an absolute analysis and calibration was not needed. I was fairly sure that this method would not be in error by more than 20%. It turned out later to be only 5% in error. My second step was

to move my home and laboratory to a remote country region close to the Atlantic Ocean. Here, I converted a barn into a 50-cubic-meter exponential dilution chamber. This chamber verified the standards used in the first years of global monitoring.

Liss and Slater, 1974, used the Shackleton data to estimate the flux of DMS and halocarbons from the sea to the air and vice versa. Later in the 1970s, the German scientist, Andi Andreae, made a series of careful and accurate measurements of the DMS abundance in both the air and the sea water over many parts of the world, and, indeed, most of our knowledge of the distribution of this gas now is due to this careful research.

In 1986, I was invited to spend a month at the University of Washington in Seattle. While there, I spent some time with Robert Charlson, who was interested in the significance of cloud condensation nuclei (CCN) in the atmosphere. These are, for the most part, especially over the open oceans, tiny droplets of sulphuric acid and its ammonium salts. I asked him why he was so interested in them, and his reply astonished me. Without the CCN, he said, there could be no clouds. Of course, I knew that small droplets of pure water will always have a higher equilibrium vapour pressure than larger droplets, but never had I put together in my mind the obvious fact that natural selection among cloud droplets would leave only the larger ones, which would rapidly fall out from the air as rain. In other words, without the nuclei, there could be no clouds as we now know them. At first I protested, saying, surely there are always enough sea salt and other water-soluble particles floating in the atmosphere to act as nuclei. Dr. Charlson explained to me that for the greater part of the Earth's surface, that is to say over the open oceans, the numbers of sea-salt particles are too small to account for the abundance of CCNs. There were sufficient droplets of sulphuric acid and ammonium sulphate, but there was no way that these could have come from either industrial or volcanic sources. Where did they come from? Such particles cannot travel far over the ocean, which means that they must be produced locally. It was one of those happy moments in science when truth suddenly dawns. The atmospheric oxidation of DMS could be the answer. We moved on to discuss these ideas with Andi Andreae who knew much more about the abundance of DMS in the atmosphere than we did. Our conclusions were published in a paper in *Nature* in 1987. My interest in Gaia led me to seek mechanisms for climate control. Together with Whitfield and Watson in 1983, I had proposed the pump-down of carbon dioxide from the atmosphere by biologically accelerated rock weathering as one possible mechanism. I wondered if the association between algae in the ocean, clouds and climate could provide another. At first, it did not look like a promising candidate, but there is now strong evidence for the link between algae, clouds and climate. Kump and I showed in 1995 that this is most evident in the cooler parts of the world where the sea temperature is less than 12 degrees Celsius. So complex is the connection between cloudiness and climate that it will take time to resolve. The vigour of the debate and the worldwide research interest in DMS seems to me to indicate the value of Gaia as a different way to view the world. Whether or not it is a fact seems less important.

I hope that I have shown that science can still be a vocation, not just a career. Something even that can be done at home, in the way an artist or novelist works. Doing environmental science this way and walks through the countryside and on the seashore have kept me in touch with the natural world. I have tried to show how the ECD influenced the development of the

environmental movement and how this simple detector has taken me literally around the world in search of new information. Similar journeys in the mind, especially those using the opportunities provided by the NASA space program, enabled me to see the world of Gaia from outside. I am blessed to have two able successors who will carry on my work, Tim Lenton and Stephan Harding. It is a joyful fulfillment to have your tangible recognition through the Blue Planet Prize.

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