

Atmospheric science

The discovery of the Antarctic ozone hole

Susan Solomon

The unexpected discovery of a hole in the atmospheric ozone layer over the Antarctic revolutionized science – and helped to establish one of the most successful global environmental policies of the twentieth century.

In 1985, Joe Farman, Brian Gardiner and Jonathan Shanklin reported¹ unanticipated and large decreases in stratospheric ozone levels over the Antarctic stations of Halley and Faraday. Their data showed that, after about 20 years of fairly steady values, ozone levels began dropping in the austral spring months around the late 1970s (Fig. 1). By 1984, the stratospheric ozone layer over Halley in October was only about two-thirds as thick as that seen in earlier decades – a phenomenon that became known as the Antarctic ozone hole. Farman *et al.* boldly suggested a link to human use of compounds called chlorofluorocarbons (CFCs), often used in aerosol cans and cooling devices such as fridges. Their findings transformed the fields of atmospheric science and chemical kinetics, and led to global changes in environmental policy.

The stability of the stratospheric ozone layer has attracted the interest of scientists, the public and policymakers for more than 50 years because this layer protects life on Earth's surface from biologically damaging ultraviolet

radiation. The potential for pollutants known as nitrogen oxides to deplete global ozone prompted much research² on the influence of aviation on the ozone layer³. A study⁴ in 1974 suggested that chlorine monoxide (ClO) produced from CFCs might similarly deplete ozone. By the early 1980s, the best projections from stratospheric models indicated that continuing production of CFCs at then-current amounts risked the destruction of only about 2–4% of the ozone layer by the end of the twenty-first century³. There was no suggestion that ozone at polar latitudes would be especially sensitive.

The expected depletion was relatively small and far in the future, but posed serious threats, including increased incidence of skin cancers and ecological damage. International policymakers therefore concluded that a cautious ozone-protection strategy was needed, and, in March 1985, the United Nations Vienna Convention for the Protection of the Ozone Layer was signed. It called for more ozone research, but contained no legally

binding goals for CFC reductions⁵.

Farman and colleagues' report of a loss of one-third of the springtime ozone layer over Antarctica was published a few months later. The paper's strengths were the authors' careful analysis of the seasonal character of the change, and the fact that changes were detected using two different instruments. The authors suggested that Antarctica's extremely cold temperatures during winter and spring made the region "uniquely sensitive to growth of inorganic chlorine" produced in the atmosphere from CFCs, although the chemical mechanism they proposed was incorrect. The careers of hundreds of scientists and dozens of diplomats worldwide were abruptly transformed by this single paper.

At that time, the atmospheric chemistry of the Antarctic was *terra incognita*. Measurements needed to be made both at ground level and from aircraft to understand whether CFCs had a role in producing the ozone hole. Scientists were energized and excited to attack the challenge.

I was fortunate to be among a group of scientists who went to the US station at McMurdo in 1986, where the first Antarctic measurements of ClO (ref. 6) and of another CFC-derived ozone-depleting compound, chlorine dioxide (OCIO) (ref. 7), were obtained. These compounds were roughly 100-fold more abundant than elsewhere. The 'smoking gun' for the role of CFCs in ozone depletion came from aircraft measurements taken in 1987. They revealed⁸ a dramatic enhancement in ClO levels (comparable to those at McMurdo) and a co-located decrease in ozone concentrations as the plane flew south from Chile into the Antarctic.

These independently obtained data sets indicated that the Antarctic was indeed uniquely sensitive to chlorine compounds⁹, as Farman *et al.* had suggested. Unusual changes in atmospheric abundances of related chemicals were also measured¹⁰. Moreover, satellite monitoring confirmed that depletion extended over a vast region (typically up to about 20 million square kilometres; see ref. 10, for example).

The response of policymakers to Farman and colleagues' paper was initially cool. In my view, this was because they did not want to upset the apple cart of the delicate diplomacy embarked on with the Vienna convention until it was clear that the science was correct. Nevertheless, they argued that precautionary principles were part of the convention, and – even as the research planes were flying from Chile – signed the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. This was an agreement to freeze production and consumption of ozone-depleting substances at then-current rates, and to meet over time to consider whether to decrease production.

But the signing of global environmental

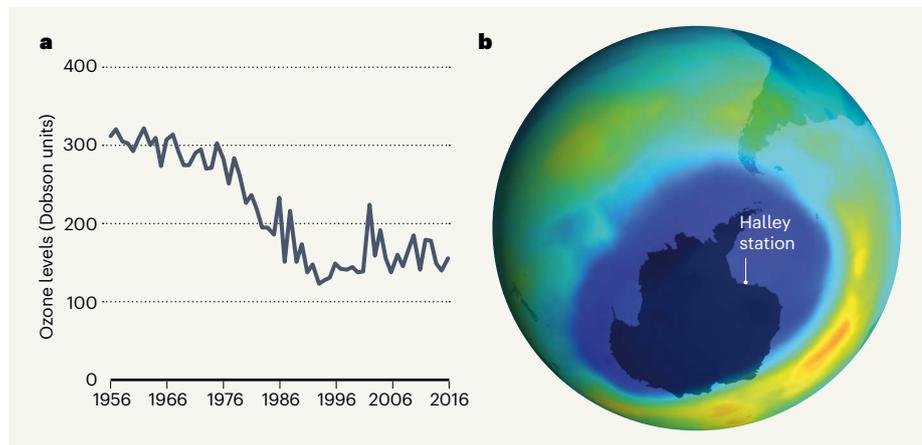


Figure 1 | Ozone over Antarctica. **a**, In 1985, Farman *et al.*¹ reported that stratospheric ozone levels over the Halley and Faraday stations in Antarctica during the austral spring had declined greatly from previously steady values. The graph shows the Halley times series, extended to 2016. **b**, Subsequent satellite monitoring revealed that the area of ozone depletion – the ozone hole – extended over a vast region. This map shows a satellite ozone map for 10 September 2000, when ozone depletion was close to its maximum: blue indicates low ozone levels; red, high levels. The position of the Halley station is indicated.

agreements is only a ceremonial first step; they must subsequently be ratified and strengthened over time⁵. I believe that Farman and colleagues' paper led to the remarkably fast ratification of the protocol in 1989, and to later amendments (beginning with the London Amendment in 1990) that included ever-tightening restrictions on the global production and consumption of ozone-depleting substances.

So why was the ozone hole not seen in computational simulations of the stratosphere? It turned out that the models lacked a key ingredient: by considering only gas-phase atmospheric chemistry, they overlooked the activation of ozone-destroying chlorine species that occurs on and within polar stratospheric cloud particles at extremely low temperatures^{11,12}. The discovery of the missing ingredient drew physical chemists in increasing numbers to study the surface chemistry involved¹³. Previously unknown gas-phase reactions associated with ozone depletion were also identified, particularly those involving a ClO dimer (see ref. 10, for example). Laboratory and field studies were carried out, and microphysical models were developed (see ref. 14, for example), to determine what polar stratospheric clouds are made of: ice, nitric acid hydrates or supercooled liquids. The answer was that they could be all three, depending on temperature and the histories of the sampled air parcels.

Ground-based and airborne missions to understand Arctic ozone chemistry¹⁵ were also inspired by Farman and colleagues' paper and related studies. It emerged that ozone loss in the Arctic is generally much less severe than in the Antarctic, broadly because temperatures in the region are warmer as a result of meteorological differences between the two regions. The coupling of chlorine-containing species with bromine-containing ones was found to be a key ingredient in polar ozone depletion, especially in the Arctic¹⁶.

Atmospheric modelling also progressed to simulate the newly discovered processes, evolving from two dimensions (latitude–altitude) to three (latitude–altitude–longitude), to better represent global stratospheric temperatures, winds and circulation¹⁷. Dynamical studies have shown that the ozone hole influences Antarctic winds and temperatures not just in the stratosphere, but also in the underlying troposphere, and there is evidence for climate connections at other latitudes¹⁸. Modern global climate models therefore include increasingly detailed representations of stratospheric chemistry and dynamics. The ozone hole has thus inspired a new generation of scientists to probe climate–chemistry interactions, forging connections between previously separate disciplines.

The Montreal Protocol led to global CFC production and consumption phase-outs

by 2010, and now the Antarctic ozone hole is slowly healing¹⁰. The protocol thus prevented the ozone layer from collapsing¹⁹ and is a signature success story for global environmental policy. Because CFCs have atmospheric lifetimes of 50 years or more, the atmosphere will not fully recover until after 2050, even in the absence of further emissions.

However, recent work²⁰ provides strong evidence of the continuing production and release of one type of CFC (trichlorofluoromethane). The source is not large enough to reverse the healing of the ozone hole, but it is slowing recovery and shows that there is still a need for scrutiny in this field. Research into, and policy to protect, the stratosphere will thus continue to be inspired by Farman and colleagues' research – and will probably do so until the ozone hole finally closes.

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Immunology

The advent and rise of monoclonal antibodies

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A 1975 *Nature* paper reported how cell lines could be made that produce an antibody of known specificity. This discovery led to major biological insights and clinical successes in treating autoimmunity and cancer.

In their 1975 *Nature* paper¹, the immunologists Georges Köhler and César Milstein described the production of monoclonal antibodies of predetermined specificity, each made by a continuously growing cell line that had been generated by the fusion of an antibody-producing cell from an immunized mouse with an immortal cancer cell specialized for antibody secretion. Hearing from César about this work before it was published, on the way to an obscure meeting in San Remo in Italy, I knew immediately that our research field had reached a turning point.

Antibodies were discovered in 1890 by the physiologist Emil von Behring and the microbiologist Shibasaburo Kitasato as protective antitoxins in the blood of animals exposed to diphtheria or tetanus toxin². Ever since, antibodies have been a major research subject, given their key role in adaptive immunity (specific immune responses against, for example, invading disease-causing agents) and

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their wide range of specificities, essentially covering the universe of chemical structures. This had stood out from early on as a major genetic puzzle. How can our limited genome encode a seemingly limitless repertoire of specificities? And in medical (and industrial) practice, antibodies have been used ever since their discovery as the basis for serum therapy (the treatment of infectious diseases using blood serum from immunized animals), as diagnostic tools to monitor infectious disease, and in innumerable other contexts.

But antibodies specific for any given molecule (called an antigen in the context of an antibody response) came, with a few notable exceptions, as mixtures of antibodies, produced by thousands of antibody-producing cells in an immunized animal or infected person. Each of these cells produced an antibody of its own kind, so that 'antibody specificity' usually referred to the properties of antibody populations rather than those