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Permalink

<https://escholarship.org/uc/item/3w84t57s>

Journal

Nature, 381(6583)

ISSN

0028-0836

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Publication Date

1996-06-01

DOI

10.1038/381551a0

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Peer reviewed

The ozone layer: the road not taken

Michael Prather, Pauline Midgley, F. Sherwood Rowland and Richard Stolarski

In evaluating the cost of phasing out chlorofluorocarbons, it pays to look not only at current damage to the ozone layer but also at what might have happened had our use of these chemicals continued unimpeded.

IMAGINE the Antarctic ozone hole bursting upon a scientific community in which concern about depletion of stratospheric ozone had faded out after the debate over supersonic aircraft in the early 1970s. What would today's atmosphere be like and what future might we expect? Does analysis of the road not taken help towards solving current or future global problems?

Estimates, with considerable uncertainty attached, of the costs of the global phase-out of chlorofluorocarbons (CFCs) and other man-made chlorocarbons are now appearing. In this Commentary we analyse the benefit side — where estimates are also uncertain — of the comparison of what might have happened had global use of these ozone-depleting chemicals continued unimpeded.

The threat to the global ozone layer posed by CFCs and related halocarbons has been dispelled because, since the early 1970s, the global community has followed a path of scientific understanding, public awareness, environmental activism and boycotts, national regulations, industry studies of CFC substitutes and, finally, an international agreement — the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. Without this sequence of events, which culminated first in restricted use of CFCs and later in a complete phase-out of these chemicals, ozone depletion would be worse than it is today and the global atmosphere would have been committed to a very different future over most of the next century.

Here we compare the path we are now following — the amended Montreal Protocol and its implied future — with the most likely path of CFC growth and ozone depletion expected had not the CFC threat to the ozone layer been identified in 1974. In particular, what if CFC use had followed a free-market growth into all sectors and countries until the observation of stratospheric ozone depletion itself were the first warning? What if the ozone hole had been discovered in 1985 (as indeed it was) but no prior suspicion had focused on chlorine from CFCs? When can we now expect to see recovery of the ozone layer as the provisions of the protocol show their effects in the global atmosphere? How much stratospheric chlorine and associated

ozone depletion would the global atmosphere have been committed to in a likely alternative scenario?

Early stratospheric science

Consider the state of stratospheric science in 1974. P. J. Crutzen had demonstrated in 1970 the importance of nitro-

longer envisaged, and stratospheric chlorine from projected Space Shuttle launches was predicted to have a negligible effect. Stratospheric science in the United States had received a great boost from the Climatic Impact Assessment Program, but no intense follow-on science was

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High returns: early balloon experiments like this allowed researchers to point quickly to CFCs as the cause of the Antarctic ozone hole on its discovery in 1985.

gen oxides from naturally occurring N_2O in the ozone balance¹, and the potential for technology to deplete stratospheric ozone on a global scale was raised by H. S. Johnston² in an assessment of the impact of a proposed fleet of supersonic aircraft (SSTs). The exhaust from these aircraft injects nitrogen oxides and water vapour directly into the stratosphere in proportion to the size and activity of the global SST fleets. The economic outlook for SSTs failed before environmental issues were fully resolved, and only a few Concordes and no 'Boeings' were built. In the late phases of the US Climatic Impact Assessment Program, initiated in 1971 to study the stratospheric problems surrounding SSTs, chlorine-catalysed loss of stratospheric ozone was discovered³ and the impact of chlorine emissions from the solid rocket motors of NASA's Space Shuttle (and also from volcanoes) was evaluated⁴.

By early 1974, concerns about threats to the stratospheric ozone layer had diminished: large fleets of SSTs were no

needed with the demise of the large-scale SST programmes. If there had been no further focus for concern about the ozone layer, stratospheric science would have continued to develop, but much more slowly through individual research efforts funded by several agencies.

Production of CFCs

For at least two decades extending into the early 1970s, the chemical industry had expanded the global markets for CFCs, continually developing new applications. Technical journals showed no abatement in proposals for new potential markets. The applications took advantage of the inertness and volatility of the CFCs; none involved their chemical alteration or permanent confinement (that is, all were intended to be eventually released into the atmosphere). The global production of CFCs showed rapid free-market growth: in 1974, the combined annual production of CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) exceeded 0.8 megatonnes and had been growing for two

decades at a rate of about 10 per cent a year — a doubling time of about 7 years. As much as three-quarters of CFC use was in rapid-turnover applications, especially as propellants for aerosol spray cans; the rest was primarily in refrigeration, air conditioning and foam blowing; and the market for CFCs as cleaning solvents had just opened up.

Although they are certainly not precise, we can adopt typical business projections for growth (Gompertz curves) leading eventually to a saturated market. Indeed, these predictions fit the growth in CFC-11 and CFC-12 very well up to 1974. The 1975 decrease in CFC production can be ascribed in part to the global recession, but the continued depression of production compared to a free market was clearly driven by the environmental concerns described below. The economics of using existing CFC industrial plants and creating new ones are very different when the product is under an environmental cloud, and plant expansion for CFC-11 and CFC-12 essentially came to a halt in the mid-1970s. (But production of CFC-113, which was not involved in aerosol propellant use, continued to rise rapidly until 1990 — aerosols were the initial focus of environmental concern.) In the free-market case considered here, growth in production of CFC-11 and CFC-12 is projected to continue from 1974 but with gradually slowing annual growth, for example declining to 5 per cent a year by 1990. Similar free-market scenarios for the other two main ozone-depleting halocarbons, methyl chloroform (MCF; CH_3CCl_3) and CFC-113 ($\text{CCl}_3\text{FCClF}_2$), were actually followed until 1990. The top right panel of the figure shows the emissions of CFC-11, -12 and -113 expected under free-market assumptions up to 2002, and compares them with those derived from expected emissions based on reported production and the amended Montreal Protocol (labelled 'Copenhagen '92'). The choice of 2002 for the end of the free market is based on considerations of scientific developments and the pace of regulatory response to them (see below).

Atmospheric build-up

The atmospheric build-up of CFCs and MCF can be reliably computed with knowledge of their emissions. Most uses of MCF and CFC-113 lead to rapid release of these compounds into the atmosphere. Three-quarters of pre-1974 use of CFC-11 and CFC-12 was also in rapid-release products such as aerosol spray cans. So in projecting the free-market case from 1974, we ignore the banking of unreleased CFCs and assume that most production would be released into the atmosphere within a year. The tropospheric chlorine loading⁵ is the sum of the concentrations of chlorine atoms delivered to the stratosphere by all halocarbons, including the natural compound methyl chloride (CH_3Cl), and so is a

benchmark of chlorine-driven ozone depletion. In the bottom right panel of the figure, the projected chlorine loading in the free-market case is compared with the actual history of atmospheric halocarbons up to 1995, appended with the projected chlorine loading under the amended Montreal Protocol ('Copenhagen '92').

The CFC threat

In 1974, the CFC threat to the ozone layer was raised by M. J. Molina and F. S. Rowland⁶. In brief, CFCs are long-lived gases that accumulate in the atmosphere, break down only in the stratosphere and release their chlorine there. Chain reactions initiated by chlorine atoms and involving ClO then act to deplete the ozone layer. In the late 1970s, CFC markets for spray can propellants were shut down in the United States, Canada, Sweden and Norway because of environmental pressure or legislation, or a combination of both. The Clean Air Act of 1977 authorized NASA to study the ozone layer and report biennially to Congress, and thus was born the Upper Atmosphere Research Program. As a result of this highly focused research programme and related efforts funded by other US federal agencies and in other countries around the world, many scientists embarked on careers to study the ozone layer, stratospheric dynamics, atmospheric chlorine and CFCs.

A better understanding of the stratospheric ozone layer arose through: (1) extensive laboratory work on the chemical reactions controlling ozone, the photochemical destruction of CFCs, and reactions of the applicable chlorine-containing chemical species; (2) instrument development and measurement campaigns directed at measuring CFCs, stratospheric chlorine and particularly ClO (ref. 7); (3) study of the data from an extensive set of ground-based ozone instruments (Dobson spectrophotometers) put in place during the 1957 International Geophysical Year and the ensuing decade; (4) the launch of TOMS/SBUV satellite instruments to measure ozone globally; and (5) the development of atmospheric chemistry models.

In the late 1970s, there were several country assessments of the potential impact of human activity on the ozone layer. In 1985, these assessments became international, and the resulting three-volume 'blue books'⁸ summarize a decade or more of intensive research on understanding and predicting ozone depletion. With incomplete knowledge of stratospheric chemistry in the early 1980s, ozone depletions of several per cent were predicted by the end of the next century if CFC production remained at 1974 levels (eventual chlorine loading of about 8 parts per billion (p.p.b.)). But when growth in CFC production resumed as in

the early 1980s, some calculations of this long-term ozone depletion exceeded 10 per cent, and control of the growth in CFC production became a more public issue.

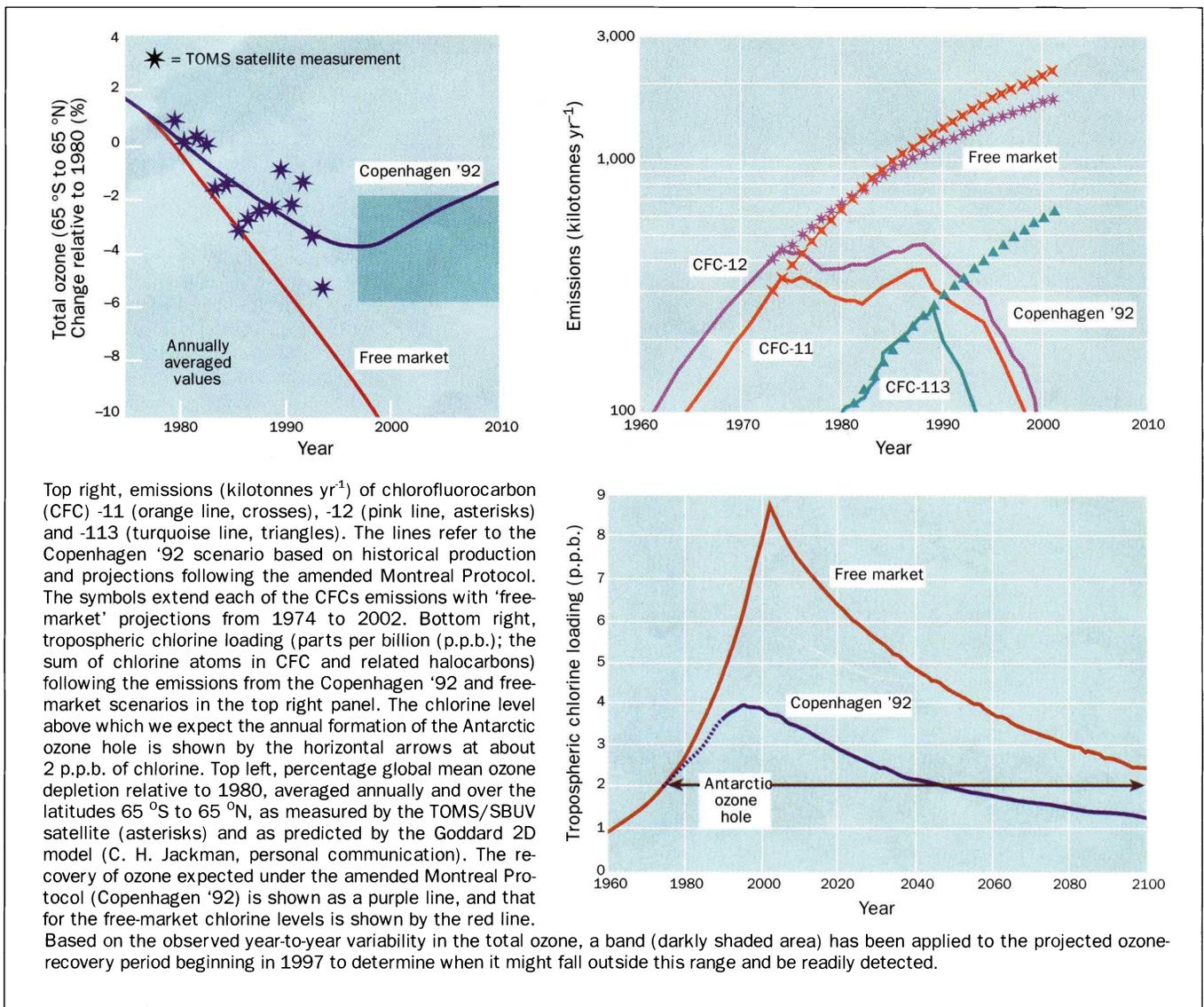
The Antarctic ozone hole

The Antarctic ozone hole came to the sudden attention of the scientific community in 1985. J. C. Farman, B. G. Gardiner and J. D. Shanklin⁹ documented the rapid springtime decrease in Antarctic ozone over their British Antarctic Survey (BAS) station at Halley Bay. Noting previous arguments for massive ozone loss at high chlorine levels, they suggested that the observed depletion was due to the rising stratospheric chlorine levels accompanying CFC growth. The BAS observations were rapidly confirmed by NASA satellite data and shown to extend over the entire Antarctic polar region¹⁰. The ozone hole has recurred every year since and has become more pronounced. None of the early 1980s' atmospheric models, all of which considered only homogeneous gas-phase chemistry, could explain the amount of ozone lost when sunlight returned to Antarctica each spring. In 1986, a novel mechanism was put forward in which chemical reactions on polar stratospheric clouds converted inactive chlorine reservoirs such as HCl into reactive ozone-destroying forms such as ClO (ref. 11). But this mechanism alone was not sufficient to explain the rapid ozone loss. Subsequent laboratory work¹² identified a new chain-reaction mechanism whereby ozone could be quickly and nearly completely removed by ClO at high concentrations. The patterns of ozone depletion expected to result from these combined mechanisms were later measured inside the Antarctic ozone hole¹³.

During this period there was open scientific debate about the cause of the ozone hole: some scientists argued for mechanisms driven by meteorological changes, solar-cycle effects or other chemical processes. Continued measurements and modelling soon eliminated these other possibilities. So fairly soon after the discovery of the Antarctic ozone hole, the scientific community had abundant evidence that the primary cause of the depletion was the increase in CFCs and related halocarbons.

Protocols and phase-outs

The Montreal Protocol was being negotiated at the time of the discovery and explanation of the Antarctic ozone hole. Its ratification and subsequently stronger amendments and adjustments were made possible only through the convincing scientific evidence of ozone depletion occurring globally, as well as over Antarctica. The complete phase-out of CFC and MCF production (as well as some other



Top right, emissions (kilotonnes yr⁻¹) of chlorofluorocarbon (CFC) -11 (orange line, crosses), -12 (pink line, asterisks) and -113 (turquoise line, triangles). The lines refer to the Copenhagen '92 scenario based on historical production and projections following the amended Montreal Protocol. The symbols extend each of the CFCs emissions with 'free-market' projections from 1974 to 2002. Bottom right, tropospheric chlorine loading (parts per billion (p.p.b.); the sum of chlorine atoms in CFC and related halocarbons) following the emissions from the Copenhagen '92 and free-market scenarios in the top right panel. The chlorine level above which we expect the annual formation of the Antarctic ozone hole is shown by the horizontal arrows at about 2 p.p.b. of chlorine. Top left, percentage global mean ozone depletion relative to 1980, averaged annually and over the latitudes 65°S to 65°N, as measured by the TOMS/SBUV satellite (asterisks) and as predicted by the Goddard 2D model (C. H. Jackman, personal communication). The recovery of ozone expected under the amended Montreal Protocol (Copenhagen '92) is shown as a purple line, and that for the free-market chlorine levels is shown by the red line.

Based on the observed year-to-year variability in the total ozone, a band (darkly shaded area) has been applied to the projected ozone-recovery period beginning in 1997 to determine when it might fall outside this range and be readily detected.

halocarbons) was agreed in London (1990) and was brought forward by four years in Copenhagen (1992), with the result that CFC production in developed countries was ended by 1 January 1996. A few months more than 8 years elapsed from the initial Montreal Protocol agreement to the complete phase-out of CFCs. Once agreement had been reached on control or elimination of CFCs, market incentives accelerated the phase-out; and the chemical industry attained the established goals ahead of time by more rapidly switching over to alternative compounds. The period 1987–1995 was required to convince all parties of the scientific and environmental needs and to develop and switch to alternative compounds. A best approximation to the historical and projected emissions of CFCs and related industrial halocarbons is a bottom-line case, here designated 'Copenhagen '92'. Emissions of CFCs are shown in the top right panel of the figure, and the resulting tropospheric chlorine loading is shown in the bottom right panel.

Without early warning

Without early warning of the causal relationship between CFCs and stratospheric ozone depletion by Molina and Rowland in 1974 — or soon after by someone else — stratospheric science would have evolved differently. Without a pressing concern such as CFCs, the overall pace of investigations of stratospheric chemistry would probably have slowed considerably over the decade 1975–1985. In 1971, when the first CFC paper appeared¹⁴, no measurements had yet been made of any chlorine-containing compound in the stratosphere, nor were the tropospheric data yet calibrated well enough for the observed growth in the tropospheric concentration of these chemicals to stimulate interest. (Even when people did become interested in their tropospheric growth rates, such calibration waited several more years.) Without direct enquiry into the atmospheric fate of CFCs, the likely triggering event would have been the observation of springtime Antarctic ozone loss by the BAS observational system. Yet without

the preceding 11 years of scientific publications on the stratospheric effects of chlorine from CFCs, Farman and colleagues almost certainly would not have pointed to chlorine or CFCs as the cause of the ozone hole, and their observations might never have made the headlines — at least not until the ozone hole as an Antarctic-wide phenomenon had been corroborated by the global maps of ozone from the TOMS satellite.

How long would it have taken to establish CFCs as the source of stratospheric chlorine, to measure ClO in the stratosphere (and inside the ozone hole), to use these observations with laboratory measurements to define the mechanism of ozone loss, and to prove beyond reasonable doubt that CFCs were the cause of the ozone hole? Clearly, a substantial time lag would have transpired while the developments in scientific knowledge we actually made during our decade 1974–1985 were discovered for the first time along this alternative path. The instruments, and even the techniques, used for measuring chlorine compounds

in the stratosphere in 1985 were simply not in existence in 1974, nor was there any particular motivation to develop them. The successful measurement of ClO from the ER-2 aircraft in 1987 had its origins in the balloon-borne instruments first proposed and funded in 1975.

Without the early warning, there would also have been no demands to phase-out CFC use in aerosols, and CFC production would have been expected to follow the free-market scenario. The elapsed time from early warning to the Montreal Protocol was 13 years, and to the full regulatory ban in the developed world it was more than 21 years. If the first alert had indeed been the BAS observations of Antarctic ozone loss in mid-1985, then one could argue that the full regulatory ban might

have been set for 1 January 2007 — that is, 21 years later. Allowing for some acceleration in our learning, assume that the 1975–1985 knowledge was gained in 8 years, that is by 1993. Optimistically, it would still take a further 2 years (1995) to adopt a protocol and another 7 years (2002) to shut down the CFC industry. This second period would be critical: we would have to continue to build convincing evidence that CFCs were responsible for the ozone loss and also find industrial alternatives that could fulfil their uses. Consider the repercussions to ozone, and even to climate forcing, of allowing CFC use to grow until 2002 or even longer, say to 2007.

Environmental consequences

If we had ignored the scientific evidence, or not had it at all, ozone depletion would be dramatically worse than that which we are controlling today. Compare the levels of atmospheric chlorine expected under the Copenhagen '92 scenario with the alternative free-market scenario that shuts down the CFC industry only after 2002. The chlorine loading in the latter situation would approach 9 p.p.b. in the first decade of the twenty-first century instead of a maximum of just under 4 p.p.b. in the 1990s. The predicted globally averaged ozone depletion relative to 1980, shown in the top left panel of the figure, would exceed –10 per cent soon after 2000, rather than just reaching –4

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Given the cold shoulder: over 21 years elapsed from the early warning about CFCs to the shutdown of the industry in them.

per cent in 1997. The cumulative impact would be even greater, because the larger ozone depletion in the free-market case would also recover more slowly, lasting well into the twenty-first century. At these levels of chlorine loading, our predictions are still scientifically sound but are more uncertain because such stratospheric conditions lie outside our range of experience.

For example, at 9 p.p.b. of chlorine, the Arctic lower stratosphere might become dominated by chlorine instead of nitrogen oxides (as now happens over Antarctica owing to denitrification), and during very cold Arctic winters the ozone loss would be more difficult to predict. If CFCs had followed free-market growth until 2002, the Antarctic ozone hole would be a permanent fixture throughout the twenty-first century, instead of disappearing by 2050 as predicted in the Copenhagen '92 scenario. Additionally, CFCs are important greenhouse gases, and for the period 1985–2000 their increases would have added more radiative forcing to the climate than that due to typical increases in carbon dioxide (+1.5 parts per million a year). (By contrast, over the same period in the Copenhagen '92 scenario, CFC increases contribute only about 40 per cent of the additional radiative forcing.) Much of this additional greenhouse forcing would, like the ozone hole, have remained throughout the next century. So the future not taken is much worse than

that expected in the Copenhagen '92 scenario, and has no easy repair.

The good news is that we, as a global community, are committed to following the amended Montreal Protocol and the phase-out of CFCs. Effectively, we are now in the second phase of our grand experiment, that of reversing our atmosphere's CFC content. Ozone depletion is expected to reverse and recover measurably in the first decades of the next century, as shown in the top left panel of the figure. This prediction is part of a causal chain whose verification is an important part of the overall scientific assessment process: production and emission of CFCs have fallen greatly; the tropospheric chlorine content has now peaked; we expect the peak in stratospheric chlorine to follow a few years later; and stratospheric ozone should recover soon after. Because of the year-to-year variability in global annual mean ozone (see top left panel of the figure), unambiguous detection of the recovery will take a decade or more. If we do not make careful measurements during that time and do not make the effort to understand and characterize this data, then we will not be able to demonstrate the recovery of the ozone as soon as possible and close the chapter on the CFC threat to the ozone layer. □

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ACKNOWLEDGEMENTS. This Commentary is based on a session at the December 1995 American Geophysical Union meeting and has benefited from comments from W. Brune, P. Fraser, C. Jackman, M. McFarland, S. Montzka and R. Prinn.

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