Mario Molina

(1943–2020)

Ozone-hole Nobel winner, Montreal Protocol advocate, presidents' adviser.

In the mid-1970s, Mario Molina helped to predict that global emissions of chlorofluorocarbons (CFCs) could deplete stratospheric ozone. A decade later, scientists at the British Antarctic Survey reported that a vast hole had appeared in the ozone layer over the South Pole. Molina's tireless advocacy and scientific diplomacy helped to bring about the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, an international agreement to phase out CFCs and other ozone-depleting chemicals. Molina shared the 1995 Nobel Prize in Chemistry with his former adviser F. Sherwood Rowland and the Dutch chemist Paul Crutzen for their work on stratospheric chemistry. He died on 7 October, aged 77.

The Montreal Protocol, the first United Nations treaty to achieve universal ratification, reduced stratospheric chlorine and bromine, and the ozone hole has begun to recover. In 2003, former UN secretary-general Kofi Annan described the treaty as "perhaps the single most successful international agreement to date". Its implementation, and Molina's later work on air quality in megacities, and on climate change, improved the quality of life for millions worldwide. A treasured public figure in the United States and Mexico, he was a trusted adviser to US president Barack Obama.

Born in Mexico City, the son of a diplomat, Molina went to boarding school in Switzerland. He studied chemical engineering at the National Autonomous University of Mexico, in his home city, and applied chemistry at the University of Freiburg, Germany. Doctoral studies in physical chemistry at the University of California (UC), Berkeley, brought him to the United States, where he built his career.

At UC Irvine, he and Rowland calculated the threat posed by CFCs to the atmosphere (see M. Molina and F. Rowland *Nature* **249**, 810–812; 1974). The chemical inertness that made CFCs valuable as refrigerants and propellants also prevents oxidation removing them from the atmosphere, where they become a Trojan horse for introducing chlorine to the stratosphere. There the gas can catalyse the destruction of ozone, allowing harmful high-energy ultraviolet (UVB) light to penetrate to Earth's surface.

Communicating this work to the media and policymakers was Molina's initiation into scientific diplomacy. These efforts created momentum for the phasing out of CFCs in aerosol cans, accelerated by the discovery of the ozone hole, and concluded with the Montreal Protocol. However, basic questions remained unanswered: why was the ozone hole localized over the South Pole, and seasonal?

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Molina found the answer in the surface chemistry of ice particles that make up the beautiful 'mother of pearl' polar stratospheric clouds (PSCs) observed during the winter over the South Pole. During the dark, cold polar winter, stratospheric chlorine is stored in the relatively inert forms of gas-phase chlorine nitrate, hypochlorous acid and hydrogen chloride.

> **"His work on air quality in megacities improved the quality of life for millions worldwide."**

Molina and his research group, then at the Jet Propulsion Laboratory in Pasadena, California, did creative experiments to mimic PSC particles: reactions between ice surfaces and chlorine compounds led to the release of chlorine. The winter build-up of the gas in the Antarctic polar vortex due to such reactions leads to intense ozone depletion when sunlight returns in the polar spring.

A mystery remained as to why ice should be such an efficient catalyst for these stratospheric processes. Calculations based on the reactions of hydrogen chloride with a crystalline ice surface predicted that chlorine activation would be much less efficient than is observed in the lab or in the environment. Molina suggested that the difference might be due to a disordered surface layer, or quasi-liquid layer, on ice. At the Massachusetts Institute of Technology (MIT) in Cambridge, his research group did experiments confirming that hydrogen chloride at low stratospheric temperatures induced such disorder, and that it played a part in activating chlorine.

While he was institute professor at MIT between 1989 and 2004, Molina and his then-wife and long-time collaborator, Luisa Tan Molina, began work on air quality in megacities (broadly, those with more than ten million inhabitants) in the global south. To steer policy, the Mexico City Project combined unprecedented large-scale field studies of atmospheric chemistry in urban neighbourhoods, involving hundreds of international scientists, with in-depth analysis and stakeholder engagement. This work improved the air quality in his beloved home city.

In 2004, Molina relocated to UC San Diego and founded the Mario Molina Center for Strategic Studies on Energy and the Environment, a think tank based in Mexico City. In his last decades, he spent increasing time in Mexico, but remained an inspirational faculty member at UC San Diego. In 2014, he spearheaded a major public-outreach initiative on climate change, 'What we know', for the American Association for the Advancement of Science.

Molina could communicate the essence of a technical issue to anyone, with gentle diplomacy and scientific credibility. He served as a scientific adviser to several presidents of Mexico, and, as a member of the Vatican's Pontifical Academy of Sciences, he advised three popes and co-authored the 2017 report 'Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change' (see go.nature.com/2hzsB1). In his final months, he advocated passionately for mask-wearing to reduce the transmission of SARS-CoV-2 in Mexico.

V. Faye McNeill is a professor in the departments of chemical engineering and environmental science at Columbia University, New York. Molina was her PhD adviser at MIT from 2000 to 2004. She co-organized a symposium in his honour in 2014, and in 2015 co-edited his Festschrift special issue in *The Journal of Physical Chemistry A*.
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