RETROSPECTIVE

Paul Josef Crutzen: Ingeniousness and innocence

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On January 28, 2021, the world lost a scholar, who won a Nobel Prize, who shaped our thinking about planet Earth, and whose fight for the protection of the global environment will be remembered forever. Paul Josef Crutzen was born in Amsterdam in 1933 and embarked on a cosmopolitan journey in 1957, when he left The Netherlands for Sweden. Looking back at that journey, we can state that he arrived at a triad of accomplishments that few intellectuals obtain: the disruptive advancement of science, the inspiring communication of science, and the responsible operationalization of science.

Paul was trained as a civil engineer for the construction sector, which he abandoned for becoming a computer programmer at the Meteorology Institute of Stockholm University (MISU). The university housed the world's fastest computers at that time, and the institute, founded by the great Gustav Rossby, was at the forefront of atmospheric research. When Paul arrived, MISU was headed by another giant of meteorology, Bert Bolin, who later became the chair of the Intergovernmental Panel on Climate Change. Paul had always longed for an academic career due to his interest and talent in mathematics and physics, yet was denied access to university education in The Netherlands by an unfortunate episode of illness. So, while helping develop numerical weather forecasting models for various projects, he also took lecture courses at Stockholm University, was graduated there, and eventually received a doctorate in meteorology in 1968.

When he in turn became a member of the MISU faculty, Paul did not join the mainstream then preoccupied with "acid rain." Instead, he jumped to stratospheric chemistry out of sheer curiosity, which was ignited by his accidental involvement in a previous project, illustrating once more the general observation that greatness tends to be approached via narrow and tortuous side paths.

Later in his career, Paul held positions in the United States (National Center for Atmospheric Research, Boulder, 1977 to 1980) and Germany (Max Planck Institute for Chemistry, Mainz, from 1980 onwards), while also teaching as a visiting professor in various other locations around the globe. Yet it was in Stockholm where he pursued his epochal work on the photochemistry of the stratosphere in general, and the stability of the ozone layer in particular. The latter, mainly found between 15 and 35 km above ground, protects life on Earth since it absorbs up to 99% of the Sun's medium-frequency UV light. It is a rather brittle shield, though, that can be damaged by human interference in amazingly intricate ways: for example, by reactions that involve nitrogen oxides originating from agricultural fertilizers and possibly also from high-flying supersonic airplanes. Paul discovered and unraveled a specific catalytic cycle in the middle atmosphere that can act as a powerful destroyer of ozone (1).

Paul J. Crutzen. Image credit: Carsten Costard Photography.

A few years later, in pursuit of a completely independent path toward understanding civilization's imprint on the composition of the stratosphere, Sherwood (Sherry) Rowland and Mario Molina performed experimental and

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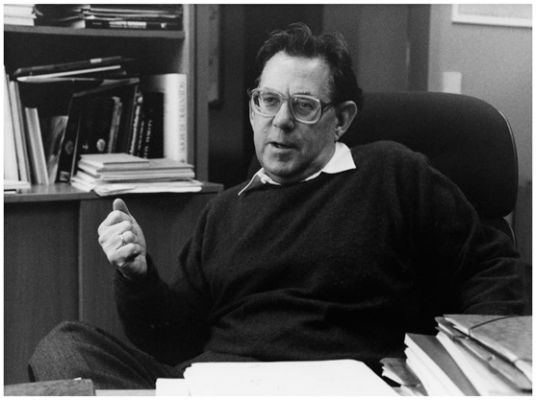

Paul J. Crutzen at work. Image credit: Archives of the Max Planck Society.

theoretical studies at the University of California, Irvine, and summarized them in a landmark paper (2). They argued that chlorine-containing industrial compounds—as widely used for propellants, solvents, and refrigerants at that time—could deplete our planet's ozone layer under certain photochemical and meteorological conditions. Immediately after their discovery, they sounded the alarm by informing colleagues, decision makers, and the general public about that insidious threat to humanity's life support systems. Thereby, the scientific work of Crutzen, Molina, and Rowland—who were later rewarded by the Nobel Prize in chemistry in 1995—helped initiate international negotiations on the protection of the stratosphere. The entire world took notice of this challenge when scientists from the British Antarctic Service made the shocking observation of a huge annual "ozone hole" over the South Pole (3). As a consequence, the celebrated Montreal Protocol was signed by 46 countries on August 26, 1987, prescribing a phase-out strategy for ozone-harming substances. There is now compelling evidence that this treaty did and still does work.

The complex scientific narrative that enabled such an unprecedented political achievement is exquisitely told in Paul Crutzen's Nobel Lecture, entitled (tongue-in-cheek) "My Life with O_3, NO_X, and Other YZO_Xs" (4). The section subtitled "And Things Could Have Been Much Worse" actually makes you shiver: Paul argues that a planetary catastrophe could have happened if either the pertinent industrial production had been based on bromine (instead of chlorine) chemistry, or if chlorine activation for ozone destruction would be possible also under less specific conditions than those prevailing high above Antarctica. Humankind had a narrow escape in this case, but there is no guarantee that the much bigger story of anthropogenic global warming (AGW) will have such a happy ending, too.

In fact, I personally became acquainted with Paul in the climate context in 1991. He was a member of a German Parliamentary Commission that screened appropriate political measures for reducing greenhouse-gas emissions nationally and worldwide, and I shared first insights from a federal research program on the coastal impacts of AGW with the body. Ever since, we kept in touch, exchanging thoughts about major scientific advances and the environmental risks associated with purely profit-driven economic growth. When I was asked by *Nature* magazine to write a "millennium essay" on the emerging field of Earth system science (5), Paul pointed me to the potential bromine calamity mentioned above.

We also became partners in mind within the framework of the International Geosphere-Biosphere Program, one of the most successful multilateral research initiatives of all times. I recall several exciting steering-committee meetings in places far away from the conventional academic temples, but the encounter in Cuernavaca (Mexico) in the year 2000 stood out: In a small conference room without air conditioning, in the late afternoon of an exhausting day, Paul eventually threw the term "Anthropocene" into the debate (see ref. 6). He did it in an almost coy way, as if the notion had spontaneously crossed his mind and he expected to be turned down immediately by his peers. And yet in that very moment, a word went viral, which epitomizes like no other the contemporary and precarious relationship between humankind and nature (7).

Paul's scientific and public contributions to the understanding of issues of critical importance are too many to be paraded here. Let me just add his intervention on geoengineering: that is, his rather desperate suggestion in 2006 to consider solar radiation management by deliberate sulfur injection into the stratosphere (8). Paul sent me the preprint then, arguing that this was an *ultima ratio* pitch against AGW. I responded in a quite skeptical way, yet we remained friends.

We frequently met at the Vatican's Pontifical Academy of Sciences that helped to prepare Pope Francis' groundbreaking encyclical on integral ecology, *Laudato si'* (9). There were several other members of that venerable academy who argued that the Catholic Church needs to take more responsibility in the global effort to preserve our common environment, most notably Veerabhadran Ramanathan (Paul's close collaborator on air-pollution and climate-change topics), Peter Raven, and Mario Molina, who sadly passed away last year (see ref. 10).

Paul and Mario had many things in common and shared a similar attitude toward science and society. What struck me most when I truly got to know the human beings behind the Nobel façade was a spirit of innocence, which they both seemed to have preserved from childhood: a combination of curiosity, passion, humor, and empathy, untainted by the vagaries and tragedies of life. Throughout their careers, Paul and Mario have shown us that kindness and ingeniousness can make a perfect blend.

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