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The Importance of Fundamental Science for Society: The Success Story of Ozone Research

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Key Points:
- Ozone research provides a concrete example of the importance of the scientific method to address geophysical problems of societal importance
- Science has become a global enterprise supported by the development of international teams
- Freedom of thought and independence of research need to be preserved; imagination and selfless fundamental investigations should be more effectively rewarded

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Abstract The successful story of ozone research from the discovery of this gas in the laboratory in 1839 to the protection of the stratospheric ozone layer by the Montreal Protocol in 1987 highlights the role and importance of fundamental research. None of the scientists who discovered the chemical nature and properties of ozone, and established its presence in the atmosphere, suspected that humans would be able to destroy a protective stratospheric layer that is essential for life on Earth. None of them had anticipated either that the emissions of pollutants associated with industrial activity and road transportation in urban areas would generate summertime ozone *smog* events with detrimental health effects and premature mortality. Scientific research has provided the knowledge needed to convince governments to take effective legislation to ban the industrial production of stratospheric ozone depleting agents and reduce the emissions of ozone precursors in the troposphere. This perspective paper calls for enhanced support of a strong fundamental research activity that rewards imagination and protects the scientific community from tight administrative and financial constraints. It highlights the need for scientists to keep a free and independent mind that leads to progress and innovation.

Plain Language Summary Ozone protects the terrestrial biosphere including humans from the detrimental action of solar ultraviolet radiation. With the sustained release into the atmosphere of industrially manufactured chlorofluorocarbons, the ozone layer could have been severely damaged with severe and long-term consequences for the biosphere and for human health. Further, the emissions of nitrogen oxides and volatile organic compounds by automobiles and industrial facilities produced during the twentieth century an increase in surface ozone during summertime, particularly in densely populated areas with detrimental effects on human health and crop production. The story of ozone research provides vibrant examples of how fundamental research was able to address important questions facing humanity and led to effective legislation to protect the biosphere including human kind. In spite of controversies and diverging interests expressed by different groups in society, scientific arguments eventually prevailed and the ozone layer was saved. It is therefore important to support a scientific community ready to address new intellectual challenges and to share knowledge through dialogs with key actors in society.

1. Introduction

Since its discovery in the laboratory in 1839 (Schönbein, 1840), ozone has received a great deal of attention from scientists, particularly throughout the nineteenth century (Brasseur, 2020). It is the detection of a peculiar odor produced during the electrolysis of acidulated water that led Schönbein at the University of Basel in Switzerland to postulate that a gas was released during this laboratory experiment. The chemical nature of this gas remained unknown for about 25 years: Soret (1865) in Geneva showed that ozone is a molecule made up of three oxygen atoms. The disinfecting properties of ozone were quickly established and around 1870, it was suggested to disseminate ozone in public buildings and in theaters to maintain the purity of the air (Fox, 1873). Ozone, whose presence in the atmosphere as a permanent substance was established by Houzeau (1858), quickly attracted the curiosity of atmospheric specialists. Albert Levy, for example, made continuous measurements of its surface concentration at the Parc Montsouris Observatory in the outskirts of Paris from 1876 to 1907 (Levy et al., 1905). During the 1920s, Dobson deployed several spectrometers around the world to observe the behavior of this atmospheric gas at different latitudes and for different seasons. And at the first conference on ozone held in Paris in 1929, Chapman (1930) suggested that ozone is formed in the stratosphere from the photodissociation of molecular oxygen. It took another 20 years to explain the presence of ozone in the troposphere, first in urban areas like Los Angeles.

10.1029/2020CN000136

None of the scientists at the time suspected that one day the ozone problem would raise an essential environmental question and that humans would be able to alter and perhaps destroy an atmospheric layer, which is essential for the maintenance of life on Earth. However, after 1970, the ozone question became intimately linked to the protection of the global environment and the discovery of a hole in the ozone layer above Antarctica in 1984 (Farman et al., 1985) demonstrated that, by its daily actions, the industrial society was able to put its own existence in danger. The Montreal Protocol, signed in 1987 and ratified by all member countries of the United Nations, saved the ozone layer. This international agreement would not have been established without the intensive work carried out for decades by the scientific community, in particular without the results brought by curiosity-driven research conducted since 1839 by a few motivated and independent scientists.

2. The Ozone Wars

At the beginning of the 1970s, when I received my degree in physical engineering at the Free University of Brussels, the scientific community asked itself a question: Are the emissions by a fleet of supersonic aircraft to be in operation in the following years likely to destroy the ozone layer that protects the Earth's biosphere from the harmful action of solar ultraviolet (UV) radiation? Already in the 1960s, it had been indicated that the water vapor emitted by the engines of these future airplanes would alter the ozone layer and hence increase the incidence of skin cancers for humans (McDonald, 1971). Harold Johnston showed in 1971 that the danger came less from water vapor than from the nitrogen oxides, also present in the aircraft exhausts. In a resounding article published by *Science*, Johnston (1971) wrote: “The projected increase in stratospheric oxides of nitrogen could reduce the ozone shield by about a factor 2.” A year earlier Paul Crutzen had shown that the most important natural process responsible for the destruction of ozone in the stratosphere is a catalytic cycle involving nitrogen oxides (Crutzen, 1970), if these were present even in very tiny quantity in this layer of the atmosphere. At that time, nitrogen oxide had never been detected in the stratosphere. However, nitric acid had been observed by a group at the University of Denver (Murcray et al., 1968), which suggested that nitrogen oxides must also be present around 15 to 30 km altitude. It therefore immediately appeared that our fundamental understanding of the photochemical processes in the stratosphere was very limited. A new field of research was to be developed.

It was in this context that I decided to prepare a doctoral thesis. I contacted Marcel Nicolet, Director of the Belgian Institute for Space Aeronomy, who suggested that I develop and use a mathematical model to estimate the impact on stratospheric ozone of a hypothetical fleet of supersonic aircraft. Nicolet was unconvinced by Johnston's argument, which he thought was overstated. It is true that the article in *Science* had raised strong controversies between scientists. Meteorologists pointed out that aircraft exhaust disperses rapidly into the atmosphere under the effect of turbulence and that the concentration of these effluents is therefore too low to destroy appreciable quantities of ozone. This view was not shared by a large number of chemists who knew that ozone is vulnerable to nitrogen oxides, even in very small quantities. There were other tensions over the issue of the supersonic aircraft. Europe, which was developing the Anglo-French supersonic Concorde, judged this discussion to be an attempt by the United States to undermine a major industrial project which would give the old continent a considerable advance in the field of civil aviation. A first “ozone war” was declared.

Stratospheric research was organized around an American program set up by the United States Department of Transportation (DOT) under the name of “Climatic Impact Assessment Program (CIAP)” and two smaller European programs supervised by the “Comité pour l'Étude des Vols Stratosphériques” (COVOS) in France and the “Committee on the Meteorological Effects of Supersonic Aircraft” (COMESA) in the United Kingdom. As a contribution to these initiatives, the Belgian Institute for Space Aeronomy in Brussels developed a crash research program on the stratosphere. Accurate measurements of the solar spectrum in the UV (Simon, 1981) and of atmospheric spectra in the infrared (Ackerman & Muller, 1973) were made from large high-altitude balloons launched from the French station of Aire-sur-l'Adour. The UV measurements provided data needed to calculate the photolysis of several atmospheric molecules, and the observed infrared spectra allowed for the retrieval of the vertical distribution in the atmosphere of radiatively active molecules. These data were essential for the development of the mathematical models of stratospheric photochemistry (Brasseur & Solomon, 2005).

The one-dimensional model that I had developed at the Aeronomy Institute was first used to determine whether the nitrogen oxides produced in the mesosphere (80–100 km) by ionospheric processes are transported to the lower layers of the atmosphere and destroy ozone molecules there. It was established that, since nitric oxide (NO) was completely dissociated by solar UV light above 60 km altitude, it cannot reach the stratosphere (Brasseur & Nicolet, 1973) and therefore cannot influence the ozone layer below 50 km altitude. Thus, the major natural source of nitric oxide in the stratosphere was provided by the mechanisms suggested by Crutzen (1971) and also noted by Nicolet (1971): the oxidation of nitrous oxide (N_2O), a molecule produced by bacteria in soils and transported upward in the atmosphere. Nicolet (1975) also showed that the deposition of cosmic radiation in the lower stratosphere resulting in the dissociation of molecular nitrogen constitutes an important source of NO, but only at polar latitudes, and that this source is variable with solar activity. Aircraft sources of NO had to be compared with the identified natural sources of this molecule.

It quickly appeared that the one-dimensional model that we had developed did not properly account for the complexity of the stratospheric dynamics and the latitudinal and seasonal variations in the photochemical effects. I decided therefore to develop a two-dimensional model (latitude-altitude) that led us to partially review our earlier conclusions about the influence of the upper atmosphere on the chemistry of the stratosphere. This new model showed that the nitrogen oxides produced in the mesosphere can in fact be transported to lower altitudes, but only in the polar regions and during the winter season (Brasseur, 1984). This mechanism leads to an appreciable destruction of ozone in the stratosphere, mainly in the spring at the time where photochemistry is re-initiated by the return of the Sun at high latitudes. Similar conclusions were reached by Susan Solomon who worked with Paul Crutzen and Ray Roble at the National Center for Atmospheric Research (NCAR) in Boulder, CO (Solomon et al., 1982), and were confirmed a few years later by space observations (Randall et al., 2005, 2006).

This fundamental work provided a framework for an estimate of the impact of supersonic aircraft on the ozone layer. Our models were used in the CIAP and COVOS programs to estimate the likely impact of a fleet of aircraft flying at an altitude of 16 or 20 km. What struck me over the years was the multiple and sometimes confrontational debates that developed during the course of the program. Science certainly made rapid progress, perhaps in a salutary way, but the process was accompanied by lively debates in international conferences and sometimes sharp disagreements between scientists. The final report produced by CIAP (1974) and presented by the DOT that was supposed to represent a consensus view was immediately disputed by a part of the scientific community as being too favorable to the views of DOT. The official COVOS report in France was printed (Comité d'Études sur les conséquences des vols stratosphériques (COVOS), 1976) but never officially published: The French government, which strongly supported Concorde, argued that releasing publicly such a document would be an implicit recognition that the supersonic aircraft could potentially alter the ozone layer. The project to develop an American supersonic aircraft was abandoned in 1971 because funding was cut by the U.S. Congress. The service provided by Concorde lasted 27 years but was eventually interrupted because the operations were judged unprofitable.

A second "ozone war" started in 1974 when Molina and Rowland reported that the injection of chlorine in the stratosphere produced by the photolysis of chlorofluorocarbons may destroy significant amounts of ozone in the stratosphere (Molina & Rowland, 1974). Chlorofluorocarbons, which have a long lifetime in the atmosphere, were produced in large quantities by the chemical industry and used in many commercial applications. Wofsy et al. (1973) added that bromine may catalyze the ozone recombination even more efficiently than either nitric oxide or chlorine molecules. Immediately, a group of deniers, often politically motivated retired scientists, challenged the community by stating that the research conducted on ozone lacked objectivity and that the conclusions were incorrect (Oreskes & Conway, 2010). Rather than proposing alternative explanations based on established facts and observations, they choose to concentrate their efforts on the publication of articles in mainstream newspapers, on multiple interviews and on repeated participations in parliamentary hearings. The industry also responded vigorously and was supported by several governments, notably European (Benedick, 1998). I remember attending a press dinner organized in the vineyards of northern Italy by a CFC-producing company. The President of the company stated to the journalists that the information produced by the scientific community was incorrect: "it emanated from groups of researchers who have no knowledge about industrial realities but are motivated by a political ideology." The industry, he added, will soon restore the scientific truth. He then turned to me and, a little embarrassed by his attack on scientists, said to me in Italian: "Mi scusi, professore." I first thought that, for policy makers,

Figure 1. Photo taken in Paris at the occasion of the thirtieth anniversary of the Montreal Protocol for the protection of the ozone layer with several colleagues involved in ozone research. From left to right: Paul Newman, (NASA), Susan Solomon (MIT), Michael Kurylo, (formerly at NASA), Richard Stolarski, (John Hopkins University), Sophie Godin, (CNRS/LATMOS), Guy Brasseur (MPI-M and NCAR), and Irina Petropavlovskikh (NOAA).

the point of view of industry leaders had more weight than that of researchers. However, at the end of a long process of negotiations that involved governments and industry, the point of view of scientists eventually prevailed, and in 1987, 197 states signed in Montreal a protocol for the protection of the ozone layer. Scientists played a key role in providing the fundamental knowledge on which the protocol was based (Figure 1).

A few years earlier, in 1984, British researchers, under the leadership of Joe Farman from the British Antarctic Survey in Cambridge, UK, expressed concerns about a very significant decrease in the stratospheric ozone concentration that they had observed at the Antarctic Base of Halley Bay during the month of October (Farman et al., 1985). The cause of this rapid decrease was not established, and several theories were proposed. Here, too, disagreements led to intense debates and professional controversies that were resolved two years later following two scientific expeditions that took place in the austral polar region. It became clear that the culprit was the industrially produced chlorofluorocarbons. The measurements made in 1986 and 1987 from the Antarctic station of McMurdo and in 1987 from the NASA ER-2 aircraft flying in the lower stratosphere (Anderson et al., 1989) confirmed the theory introduced a couple of years earlier by Susan Solomon and her colleagues (Solomon, 1999; Solomon et al., 1986): the destruction of ozone resulted from the activation of chlorine on polar stratospheric cloud particles. This finding concluded the second "ozone war."

Although they took into account the presence of chlorine compounds in the stratosphere, atmospheric models had never predicted the possible formation of an ozone hole over the Antarctic continent because, at that time, the importance of heterogeneous chemistry on the surface of the particles contained in polar clouds had not been highlighted. Farman's observations came therefore as a real surprise for all members of the scientific community. This was also a lesson for all of us. Even when a long-standing problem is believed be solved, surprises can arise. It was the case for ozone, but it could also be the case tomorrow for climate change or for other geophysical issues. Society needs to keep a strong intellectual capital and to support a community of researchers able to promptly address difficult scientific questions that arise unexpectedly.

A surprise came up already in June 1991, when Mt. Pinatubo (Philippines) erupted and injected about 20 Tg of sulfur in the lower tropical stratosphere. The sulfate particles that were formed above the tropopause offered for the next couple of years additional surface sites on which chlorine could be activated and potentially destroy ozone. Together with Claire Granier, we predicted from our models that the Northern Hemisphere ozone column would be reduced by up to 10% in the winter of 1992–1993 and up to 6% during the following summer (Brasseur & Granier, 1992), with the largest effects occurring at the edge of the polar regions. An ozone depletion of about 6% was observed at mid-latitudes (30°N and 60°N) by the TOMS space instrument in January 1993 and of about 4% in June 1993 (Aquila et al., 2013).

3. Ozone in the Troposphere

In 1988, I began a new phase of my career as I was joining the NCAR in Boulder, Colorado. I was hired by Ralph Cicerone who I replaced as Director of the Atmospheric Chemistry Division in 1990. At the time, the scientific community was actively interested in the problem of tropospheric ozone. Measurements made in different regions of the world had highlighted a significant increase in the ozone concentration, not only at the surface in urban areas such as Los Angeles during summer but also in the remote free atmosphere. As the presence of ozone, a powerful oxidant that irritates the respiratory system, can increase the frequency of asthma attacks and cause chronic pulmonary obstructions (Landrigan et al., 2018; Lelieveld et al., 2015), it was important to understand the chemical processes that lead to its photochemical formation and destruction. Tropospheric ozone became therefore a major research topic for the NCAR Division and global change research had become a priority for the NCAR Division.

As early as 1950, it was suggested by Haagen-Smit (1952) that the very high ozone concentrations recorded during summertime *smog* episodes in Los Angeles and responsible for the destruction of plant leaves resulted from the combined photochemical effect of hydrocarbons and nitrogen oxides emitted by automobiles and industrial facilities in the city. This claim generated a strong response from different lobbies promoting automobiles, but the conclusions of the scientific studies became gradually accepted: Air pollution regulations were established and the automobile industry adapted to the new situation. As a result, the level of summertime ozone was considerably reduced in Los Angeles and other major urban areas with positive impacts on human health.

An important question remained. Does the ozone in the remote troposphere originate only from the injection of ozone-rich stratospheric air, as has been thought for a long time, or is this molecule photochemically produced in the lower layers of the atmosphere? Paul Crutzen, as early as 1972, had developed a model of tropospheric ozone, but no one paid sufficient attention to this work because researchers at the time were primarily interested in the possible depletion of stratospheric ozone. Chameides and Walker (1973) made an important contribution; they showed that the photooxidation of methane leads to the production of ozone. With his collaborators Jack Fishman and Susan Solomon, Paul Crutzen, then at NCAR, developed in 1979 by a more detailed model and showed that the concentration level of ozone in the remote atmosphere is controlled primarily by the atmospheric level of nitrogen oxides (Fishman et al., 1979).

In the late 1980s, a new scientific problem was posed in the context of the Global Change Program: What are the chemical and biological processes that determine the oxidizing capacity of the atmosphere? And how does human activity modify this quantity that determines how rapidly air pollutants and certain greenhouse gases are eliminated from the atmosphere? The chemical species that controls the oxidizing capacity of the atmosphere and is often called the "detergent" of the atmosphere was believed to be the hydroxyl radical (OH). At that time, the atmospheric concentration of OH had never been systematically measured in the atmosphere and its spatial and temporal distributions were unknown. We knew from Hiram Levy's work (Levy, 1971) that the OH radical is produced by photochemical reactions that involve the presence of ozone and water vapor. In addition, this radical is influenced by the presence in the atmosphere of nitrogen oxides (NOx), carbon monoxide (CO), and other volatile organic compounds (VOCs). The major source of atmospheric VOCs remained, however, a matter of debate for some time since it became clear that large amounts of organic compounds such as isoprene are emitted by the vegetation. To a large extent however, VOCs and NOx are of anthropogenic origin and are emitted in the atmosphere in the most populated areas. Legislations to reduce NOx and VOC emissions were therefore introduced, and, as a result, air quality improved locally and regionally (Trainer et al., 1987). However, since the influence of pollutants can be far reaching, air pollution is not just an urban or regional problem; it has should be viewed as a global issue.

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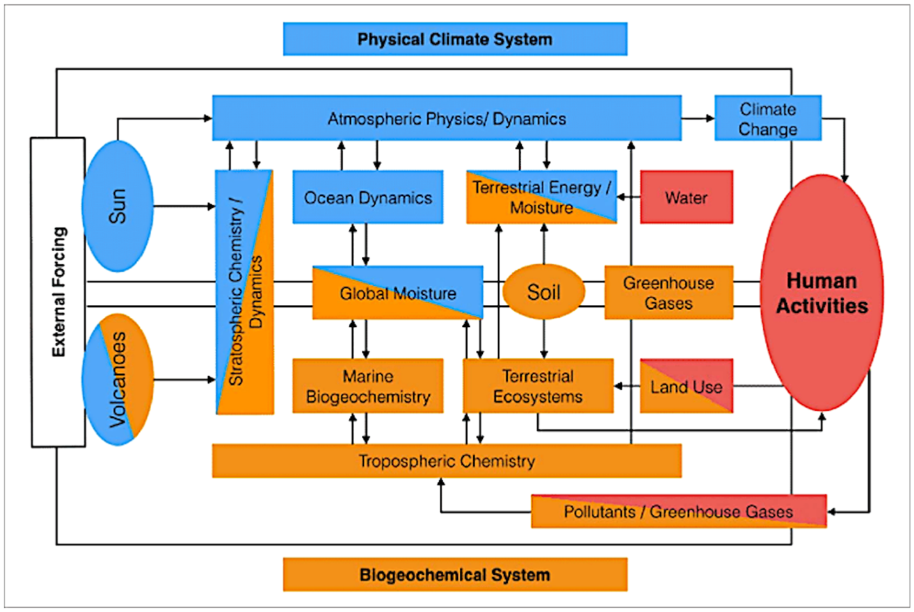

Figure 2. The Bretherton-Moore diagram: A conceptual representation of the different components of the Earth system and their mutual interactions. This diagram provided the strategic foundation for the International Geosphere-Biosphere Programme (IGBP) and was a guide for international research on "Global Change."

The question of global air pollution was immediately perceived as essential and the United States, in particular the National Science Foundation with the active support of Jarvis Moyers defined a vast research program under the name of "Global Tropospheric Chemistry Program (GTCP)." An international extension, the "International Global Atmospheric Chemistry (IGAC) Project, was quickly established and linked to the "International Geosphere-Biosphere Program (IGBP)." I enjoyed very much to chair between 2002 and 2005 the Steering Committee of IGBP and to work closely together with the IGBP Director Will Steffen. Together, we promoted the concept of Earth System Science and the need for global and regional climate models to become more integrative and include coupled chemical and biological processes as well as their interactions with the human system (Figure 2). The program has provided guidance to international research initiatives on global change and has released science-based information to governments who wished to develop smart and sustained approaches for the long-term development of their country (Figure 3).

At NCAR, with a software engineer, Stacy Walters, and several colleagues including Didier Hauglustaine, Larry Horowitz, Jean-François Müller and later with Jean-François Lamarque, Louisa Emmons, Gabriele Pfister, Douglas Kinnison, XueXi Tie, and others, we developed a global chemical transport model focusing on the problem of tropospheric ozone (Brasseur et al., 1998; Emmons et al., 2010; Horowitz et al., 2003; Kinnison et al., 2007). This model, called MOZART (Model for Ozone and Related Tracers), was soon adopted by several groups around the world, as was the GEOS-Chem model developed at Harvard by Daniel Jacob and his students and post-docs (Bey et al., 2001). The chemical mechanism developed for MOZART has now been included in the more advanced Community Earth System Model (CESM) including the Whole Atmosphere Community Climate Model (WACCM).

The Atmospheric Chemistry Division, which hosted talented experimenters including Brian Ridley, Fred Eisele, Elliot Atlas, Alex Guenther, and several others, developed a measurement program to observe in the same air mass a number of rapidly interacting chemical species and to characterize the fundamental processes that govern the oxidizing processes in the atmosphere. The priority set up by this team was to observe chemical processes in remote regions (little affected by air pollution) with the difficult challenge of measuring key species at very low concentrations. Several field campaigns took place including the 1-year-long Mauna Loa Photochemical Experiment (MLOPEX) in the middle of the Pacific Ocean, which investigated the chemical system above the atmospheric boundary layer in Hawaii (Atlas & Ridley, 1996; Ridley

Figure 3. Discussion during the 2003 meeting of the IGBP Steering Committee in Punta Arenas with Chilean President Ricardo Lagos (left) next to Eric Goles, Head of the Chilean Science and Technology Commission, with Paul Crutzen (right) next to Guy Brasseur. The President of Chile was very worried about the effects of the ozone hole in the most southern regions of his country. He asked IGBP to formulate guidance about how Chile should respond to global change issues, generated in large part by human activities in the Northern Hemisphere.

et al., 1992). The Atmospheric Chemistry Division also participated in numerous airborne expeditions organized in different regions of the world by NASA under the leadership of Joe McNeal.

All these studies highlighted the complexity of the tropospheric chemical system and the heterogeneity in the chemical regimes encountered in different regions. They also showed the importance of natural processes including the emissions of chemical species by the biosphere, by wildfires, and by the ocean in addition to human-induced perturbations associated with energy production, industrial and residential activities, transportation, and so forth. Very few remote regions have not been significantly disturbed by human activities. Air pollution has indeed become a global problem.

These multiple studies also show the essential role played by the OH radical, the concentration of which, like that of ozone, strongly depends on the level of nitrogen oxides. A detailed understanding of the processes involving nitrogen compounds is therefore essential. The important role for the atmospheric oxidizing capacity of the biogenic and anthropogenic emissions of organic compounds (hydrocarbons) was highlighted and supported, for example, by the flux measurements made in different ecosystems of the world by Alex Guenther and his team at NCAR (Guenther et al., 1995, 2006). In other words, reducing ozone pollution requires a complex strategy that varies depending on location and time of the year and must be adjusted according to the long-term evolution in human-generated emissions.

Today, according to the World Health Organization, nearly 4 million people die prematurely from diseases caused or exacerbated by outdoor air pollution. The problem is particularly acute in several parts of the world such as Asia, South America, and Africa. Almost 90% of the world's population has no access to clean air, particularly in India and China and increasingly in Africa (https://www.who.int/). Ozone is not solely

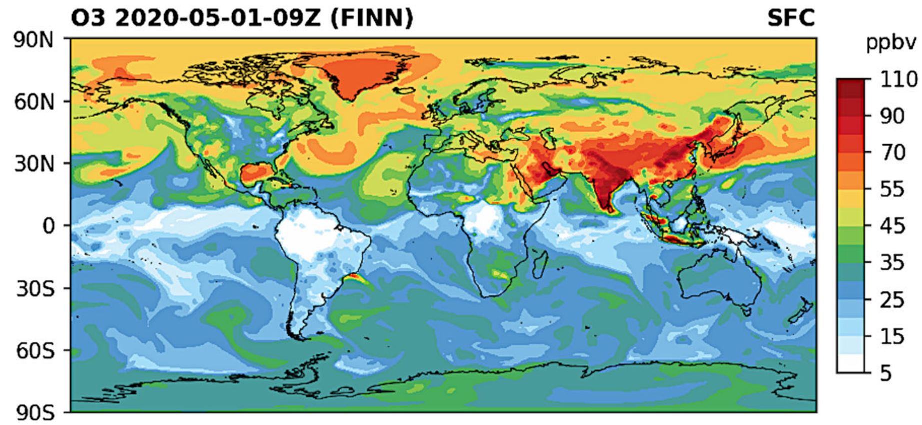

Figure 4. Global forecast of the ozone surface mixing ratio (ppbv) for 1 May 2020 produced by the MOZART Chemical mechanism embedded into the NCAR Whole Atmosphere Community Climate Model (WACCM) model. The higher concentrations in the Northern Hemisphere, specifically in Asia, are associated with human activities. One notes the intercontinental ozone plumes between Asia and North America and between the United States and Europe and the very low concentrations in the tropics (from www.acom.ucar.edu).

responsible for this situation; the presence of fine particles, particularly sulfates, nitrates, organic aerosols, and soot contributes significantly to this public health problem. Relative to ozone, particulate matter is a higher source of premature mortality in the world. However, the high concentrations of aerosols result to a large extent from the oxidation of primary pollutants by hydroxyl radicals and ozone. Here, too, basic research is producing the knowledge necessary to implement the policies that will solve a problem that affects the majority of people on Earth.

With the fundamental knowledge gained in the previous decades, we became able to provide reliable global and regional forecasts of air quality of direct interest to economic stakeholders and to citizens and to evaluate these forecasts. In 2003–2004, I worked together with Anthony Hollingsworth at the European Center for Medium-Range Weather Forecasts (ECMWF) in Reading, UK, to develop a global Earth System monitoring and prediction system using space and in situ observational data. The project called GEMS (Hollingsworth et al., 2008), supported by the European Union, has evolved over the years and has now become the very successful Copernicus Atmospheric Monitoring System (CAMS) that operationally produce daily global and regional air quality forecasts. Several more regional initiatives that involve local scientists were developed such as, for example, the joint European-Chinese MarcoPolo-Panda prototype system for the forecast of air quality in the 28 largest cities of China (Brasseur et al., 2019). Developing a worldwide coordinated system for regional and local air pollution monitoring, forecasts and attribution should be viewed as an urgent priority (Kumar et al., 2018). Capacity building is an important aspect of such a program that needs to attract, in particular, scientists and environmental officers from low- and middle-income countries.

4. Ozone and Climate

In the early 2000s, as I was joining the Max Planck Institute for Meteorology in Hamburg, Germany, one of the research centers of the Max Planck Society, the scientific community was perceiving the importance of the complex nonlinear interactions and feedbacks in the multi-scale evolution of the climate system. Traditional climate models were therefore extended to become more comprehensive Earth system models that couple the biogeochemical system to the physical climate system and account in particular for atmospheric chemical and the ocean biogeochemical processes. Ozone is a greenhouse gas and increasing concentrations since the pre-industrial era have therefore contributed to global warming. It also influences other greenhouse gases including methane. Atmospheric chemistry modeling (Figure 4) now takes into consideration the complex mass exchanges with the continental biosphere and with the ocean. At the same time, the chemical mechanisms that are adopted in these models have become considerably more detailed and include an improved representation of an increasing number of organic compounds. Chemical models also include a detailed representation of the chemical and microphysical processes that describe the formation and fate of organic and inorganic atmospheric aerosols.

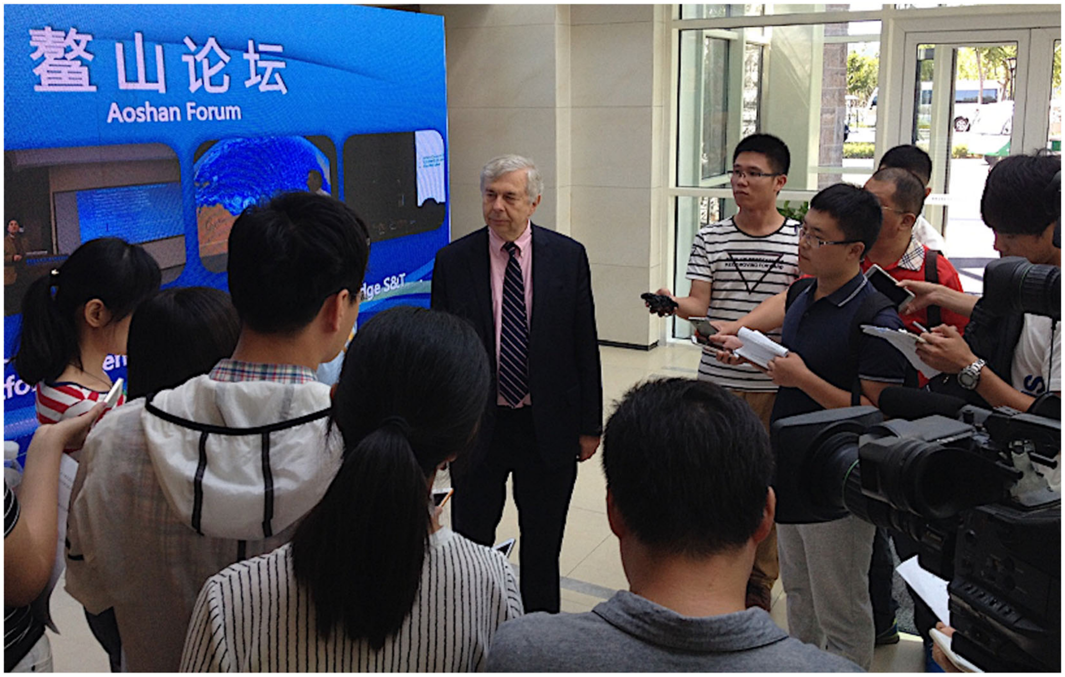

Figure 5. Discussions on climate change issues with Chinese journalists during the 2013 WCRP/CLIVAR conference in Qingdao.

Today, Earth system models have become so complex and detailed that they need to be developed and supported by large interdisciplinary teams that include a strong software engineering component. Stratospheric and tropospheric ozone related processes are now included in these models. I was very privileged to chair from 2015 to 2018 the World Climate Research Programme (WCRP) that did an outstanding job in supporting the development of these models since the program was established 40 years ago. WCRP was able to coordinate the research conducted on all continents, develop a real worldwide climate community, and organize large scientific conferences to communicate new findings (Figure 5). The Intergovernmental Panel for Climate Change (IPCC) has greatly benefited from this work that led to societally important information about the projected future of the earth climate at the global and regional scales.

All these activities led us to realize the importance of two-way communication with different stakeholders and with the public in general. Communicating has become a key responsibility for scientists. Characterizing the process that led to the Montreal Protocol, U.S. Ambassador Benedick (1998) wrote: "Science has become the driving force behind ozone policy, but it was not sufficient for scientists merely to publish their findings. In order for the theories to be taken seriously into account, scientists had to interact closely with government policy makers and diplomatic negotiators. This meant that they had to leave the familiar atmosphere of their laboratories and assumed an unaccustomed shared responsibility for the policy implications of their research."

To support communication of knowledge, I was asked by the German government to return to Europe and develop in 2010 the German "Climate Service Center" in Hamburg. The purpose of this center is to provide scientifically credible and actionable climate information to decision makers. The task was fascinating but at the same time extremely difficult because it required appropriate engagement with users and two-way interactions. It offered also a unique opportunity to develop a transdisciplinary vision with the participation of natural and social scientists as well as representatives from industry, government and municipalities. Even in this case, a lot of fundamental research questions remain to be answered, in particular about the type of business model required to make climate services successful and about new approaches to communication and partnerships with different types of actors in society (Brasseur & Gallardo, 2016).

5. Some Personal Considerations

In the last decade, funding agencies in most countries have increasingly emphasized the importance of applied research to address important societal problems, sometimes at the expense of fundamental research. Clearly, the role of scientists is to work with different stakeholders to tackle societally important questions and to respond to urgent challenges such as ozone depletion or climate change. At the same time, there will be no sustained applied science without an upstream input of knowledge provided by fundamental research. Today, there is an urgent need to support long-term research initiatives and maintain a strong intellectual capacity able to respond to surprises facing our planet. Perhaps the scientific community should show more convincingly how unselfish research is a prerequisite for the development of innovation and is therefore essential for our economic, social and cultural development.

Research on the ozone problem is an interesting example of how science has evolved for almost two centuries (Brasseur, 2020) and has addressed a problem of highest importance for the future of humanity. The discovery in the laboratory of a peculiar odor produced by the formation of an unknown chemical species, which was not identified until more than 20 years later, did not result from a planned research initiative. The progress which followed was the work of a few independent scholars who communicated with each other, often by letters, and who presented their results in journals published by their national academies. Not all the ideas put forward were immediately accepted; some were dismissed after much discussion and debates between colleagues. However, all of these pioneers in ozone research were free thinkers and motivated minds who displayed great intellectual independence and selflessness. None of them probably, while they were conducting their research, suspected that the stratospheric ozone question would one day become a quasi-political issue.

Since the Second World War, science has evolved considerably. Rather, rudimentary measurement techniques have been replaced by modern instrumentation resulting from unprecedented technological development, and individual research has given way to team research. Satellite launches have made it possible to observe dynamical, physical and chemical processes in our atmosphere like never before. Mathematical models have benefited from the increasing power of the most advanced supercomputers (Brasseur & Jacob, 2017).

At the same time, research has become a global enterprise. Scientists work together across the borders and develop international strategic partnerships. It is therefore important, in particular for junior scientists, to become part of these international networks and spend time in foreign laboratories where the scientific culture may be different and an internship very rewarding. International groups of early career scientists, specifically in the area of Earth science, are thinking about a "new way" to do science and about more sustained approaches to communicate and exchange ideas across the globe. The rapid development of social media and video conferencing systems provides interesting opportunities for a new type of communication, perhaps at the expense of face-to-face meetings, which remain important in the development of a career.

The nature of scientific work has changed dramatically: Strategic planning often receives more attention from funding agencies than intellectual curiosity and individual imagination by the scientists themselves. Following the concept of market economy, the system increasingly favors competition over collaboration, immediate results over long-term (in-depth) investigations, publication quantity over quality, and the need to meet stated and agreed upon objectives over individual initiatives. Today, the publication of scientific results has shifted from academies or professional societies to large multi-national commercial publishers. In fact, in many cases, the administrative constraints placed on research activities pursue the hidden goal of removing from the scientists the control and ownership of their research.

It is therefore important for scientists, especially those starting their careers, to constantly address the big questions and therefore fight for the maintenance of research initiatives that are free and selfless. Imagination and curiosity-driven research remain important. And perhaps we should listen to what James Lovelock said in an interview to the BBC (4 August 2020) at the occasion of his 101st birthday: "Treat science as an art; don't expect to make a living from it. Enjoy it."

The search for societally important solutions and, more generally, for developing a sustainable world is by no way incompatible with fundamental research programs. A strong scientific community ready to address new intellectual challenges must therefore be preserved and supported. And as French mathematician Henri Poincaré (1910) stated more than a century ago: "La pensée ne doit jamais se soumettre [...] parce pour elle, se soumettre, c'est cesser d'exister." (Thought must never submit [...] because, for thought, submission would mean ceasing to be.")

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