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1. Foreward

The year 2017 marked the celebration of the 30th anniversary of the Montreal Protocol on Substances that Deplete the Ozone Layer. Hailed as an outstanding example of international cooperation for environmental protection, the Montreal Protocol, signed on September 16th, 1987, became the first international treaty to achieve universal ratification in 2010. This Protocol has halted the destruction of the ozone layer by controlling the production and consumption of ozone-depleting substances (ODSs).

The ozone layer, located in the stratosphere and containing about 90% of atmospheric ozone molecules, is a key feature of the atmosphere, as it protects life on Earth by filtering out damaging ultraviolet radiation from the sun. Ozone abundance in the atmosphere is very small. At its peak in the tropical mid-stratosphere, it does not exceed 8 to 10 molecules per million air molecules. Despite its central role in the Earth's atmosphere, the ozone equilibrium is fragile. It is governed by complex chemical processes whose main features are production by solar radiation and losses from atmospheric compounds – some of which are several orders of magnitude less abundant than ozone. The concern that human activities could harm the ozone layer dates back to the 1970s, when the threat was linked to increased levels of chlorine compounds in the stratosphere due to emissions of industrial products (Molina and Rowland, 1974). Since then, ozone research has played a pioneering role in alerting the general public and policy makers to the impact of human activities on the global environment, promoting a direct link between science and policy action.

The Vienna Convention for the Protection of the Ozone Layer was signed by 20 nations in 1985. It identified the need to protect the ozone layer, and it sought to promote cooperation and information exchange on the effects of human activities on atmospheric ozone. The Vienna Convention further continued work on a protocol to address strategies to control ODSs. At the same period, British researchers reported unexpected significant decreases of ozone total content above Antarctica during the Austral springtime (Farman et al., 1985). Satellite measurements showed that ozone depletion, which reached more than 40% in October, had an extension comparable to the area of the Antarctic continent. In situ balloon ozone soundings (Chubachi, 1984) revealed a near-complete disappearance of ozone molecules between 16 and 20 km, an altitude range where ozone concentration is maximum over Antarctica. This phenomenon, which would be popularized as "Ozone Hole", was far greater than the natural year-to-year variation observed so far in monthly averaged total ozone. While the cause was unknown in 1985, it rightfully raised global concern about the fate of the protective ozone layer.

The processes causing the Ozone Hole were uncovered only a few years after its discovery. They involve human-produced chlorine and bromine compounds whose abundance had dramatically increased in the stratosphere due to their rapidly growing emissions. The industrially produced source gases, chlorofluorocarbons (CFCs) and halons, are transported by winds into the stratosphere in the tropical regions. The stratospheric circulation carries these compounds into the upper stratosphere, where the intense solar radiation breaks them down into moderately active halogen forms. The circulation in the upper stratosphere carries these southward and downward into the Antarctic lower stratosphere. During winter, these moderately active halogen species are converted to highly reactive forms by chemical reactions that take place on the surfaces of polar stratospheric cloud particles. These clouds form in the extremely low temperature conditions of the polar lower stratosphere in winter. When solar light reappears above the pole at the end of August, very efficient catalytic chemical reaction cycles involving these compounds destroy ozone at a rate of few per cent per day,

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leading to the complete destruction of ozone molecules in the lower stratosphere. These findings radically changed the understanding of chemical processes affecting ozone, which were previously thought to occur through gas phase reactions only (Solomon, 1999).

In the Arctic, similar processes occur, but seasonal ozone losses are much smaller, due to higher temperature conditions in the wintertime Arctic stratosphere. At global scale, evidence was also made of a thinning of the stratospheric ozone layer due to elevated ODS abundance. Ozone decrease was observed up to the end of the 1990s in the lower and higher stratosphere. Current average total ozone levels are about 2.2% lower than those measured before 1980 over the 60 °S to 60 °N latitude range (WMO Scientific Assessment of Ozone Depletion, 2018).

The Montreal Protocol on Substances that Deplete the Ozone Layer was signed in 1987. It entered into force in January 1989, following sufficient country ratification. Since then, it has undergone nine revisions, in 1990 (London), 1991 (Nairobi), 1992 (Copenhagen), 1993 (Bangkok), 1995 (Vienna), 1997 (Montreal), 1999 (Beijing), 2007 (Montreal), and 2016 (Kigali). The Protocol establishes legally binding controls for developed and developing nations on the production and consumption of halogen source gases known to cause ozone depletion and referred to as "ozone-depleting substances". Under the Montreal Protocol, developed countries had to act first and developing countries (defined as Article 5 Parties of the Protocol) followed, with financial assistance from the developed countries through a multilateral fund. Montreal Protocol's controls are based on the relative ODS effectiveness in depleting ozone and the availability of suitable substitutes for domestic and industrial use. Controlled compounds include chlorofluorocarbons CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2), carbon tetrachloride (CCl_4), halon 1211 (CF_2BrCl), halon 1301 (CF_3Br), and methyl bromine (CH_3Br). These gases have been used as refrigerants, solvents, blowing agents for plastic foam manufacture, and fire extinguishers. Their production was phased out in 1996 in developed countries and in 2010 in Article 5 (developing) countries.

The chemical industry initially replaced CFCs and halons with the "transitional" hydrochlorofluorocarbons (HCFC). Since HCFC molecules have a hydrogen atom, they are mostly oxidized in the troposphere and a smaller fraction reaches the stratosphere, leading to less ozone depletion than from CFCs. Despite their lower ozone depletion potentials, the production and consumption of HCFCs have also been controlled by the Montreal Protocol. They are now gradually being replaced by the hydrofluorocarbons (HFC), a second generation of substitutes, which do not contain chlorine and are therefore relatively harmless for the ozone layer.

The Montreal Protocol played a pioneering role in involving scientific actors in its governance since the Parties of the Protocol rely on science to form their decisions. The Montreal Protocol mandates quadrennial reports on ozone depletion and ODSs based upon current scientific, environmental, and technical knowledge. Advances in understanding on these topics have been assessed since 1989 in a series of reports elaborated by worldwide experts and available through the United Nations Ozone Secretariat website (http://ozone.unep.org/).

Thanks to controls by the Montreal Protocol and its amendments, the ODS abundances in the atmosphere are now decreasing and the ozone layer is expected to slowly recover in the course of the 21st century. An increase of seriously harmful surface UV radiation has been prevented. According to some studies, the number of additional skin cancers prevented by the Montreal Protocol is estimated at around 2 million per year by 2030 (Van Dijk et al., 2013).

The Montreal Protocol has also substantially contributed to climate protection, as CFC and halons are potent greenhouse gases (Ramanathan, 1975). The global warming potential (GWP) of CFC-12 is 8450 times that of CO_2. Reductions in atmospheric ODS levels due to the Montreal Protocol have benefitted the global climate: in the absence of regulation, radiative forcing from ODSs could have reached about 0.6 W/m^2 in 2010. Total avoided net annual ODS emissions weighted by their GWP were estimated to be equivalent to the emissions of about 10 Gt CO_2/year, corresponding to about five times the annual reduction target of the Kyoto Protocol (Velders et al., 2007). Yet, this climate benefit from ODS reduction could have been lost if emissions of substitutes with high GWPs, such as long-lived HFCs, were to substantially increase. The Montreal Protocol's Kigali amendment was signed in 2016 in order to control the emission of HFCs, despite their innocuity with respect to the ozone layer. Implementation of this amendment is expected to prevent up to 0.4 °C increase of global temperature by the end of the 21st century, thus contributing to the objectives of the Paris Agreement (Velders et al., 2012).

In order to celebrate the 30th Anniversary of the Montreal Protocol, an international symposium was organized at the Del Duca Foundation in Paris, on September 19–20, 2017, bringing together the various actors working for the success of the Protocol. It was organized by the Observatory of Versailles – Saint-Quentin-en-Yvelines (OVSQ), the French Academy of Sciences, and the International Ozone Commission (IO_3C). More information on the Symposium can be found on the following website: http://www.montreal30.io3c.org/. This thematic issue of *Comptes rendus Geoscience* assembles several major contributions to the Symposium.

Historical aspects of ozone layer studies are addressed in two articles. Bhartia explains why the discovery of the Ozone Hole was first made by ground-based measurements in the Antarctic station of Halley Bay and not on satellite observations, which started in 1979. These observations, however, made it possible to assess the extent of ozone destruction over the Antarctic, the visualization of which lead to the 'Ozone Hole' expression whose media fortune is well known. Satellite observations are now crucial for the assessment of the state of the ozone layer at global scales. Field campaigns were also instrumental for unraveling the causes of polar ozone loss. On this subject, Kurylo revisits two decades of polar ozone research based on airborne assets of the US National Aeronautics and Space Administration (NASA).

Four articles are devoted to current issues in the study of the stratospheric ozone layer. Pommereau et al. discuss interannual winter/spring ozone depletion in the Arctic. Staehelin et al. stress the value of ground-based measurement networks in the long-term monitoring of ozone evolution and associated parameters, while Steinbrecht et al. raise the question of the detection of the recovery of the ozone layer following the application of the Montreal Protocol. Since 2000, the ozone layer has indeed stopped thinning worldwide, and the first signs of an increase are now starting to emerge, mainly in the upper stratosphere and in Antarctica in early spring. Finally, Rosenlof discusses the influence of atmospheric compounds such as water vapor and aerosols on the evolution of stratospheric ozone.

Ozone slow recovery is explained by the ODS atmospheric lifetimes, some of which exceed 50 years. Reimann et al. provide an overview of ODS monitoring by the current observing networks. They show that these networks play a crucial role in the assessment of the evolution of ODS atmospheric abundance and in the critical evaluation of the emissions of the different generation of substitutes. Their maintenance is thus essential in order to assess the enforcement of the Montreal Protocol at global scale.

Regarding the environmental effects of ozone depletion, Fountoulakis et al. review the impact of the Montreal Protocol on the evolution of surface ultraviolet radiation from 25 years of spectral UV measurements in Canada, Europe and Japan. Trends in UV-B (280–315 nm) are evaluated, and effects from changes in ozone and other parameters that affect UV radiation, such as aerosols, clouds, and surface reflectivity, are assessed.

The ozone layer's future will be affected by climate change. This issue is addressed by Langematz. Based on projections of chemistry – climate models, the author summarizes the effects of future greenhouse gases emissions on stratospheric ozone evolution in various regions of the stratosphere. The specific impact of future increases in nitrous oxide and methane, greenhouse gases also involved in chemical processes affecting ozone, is discussed.

Four articles of this issue are dedicated to technological, sociological, and institutional aspects of the Montreal Protocol. As the chemical industry played a prominent role in the success of the Montreal Protocol, Andersen et al. detail how the various actors in this sector developed, commercialized and implemented alternatives to ODSs that are also safer for climate. An endeavor such as the Montreal Protocol would not be possible without strong coordination. Birmpili, the executive secretary of the Ozone Secretariat, draws lessons from 30 years of Montreal Protocol governance and more specifically from the negotiations that led to the Kigali amendment in 2016 on HFC regulation. The solid, yet flexible foundation of the Montreal Protocol made it possible to implement an amendment whose primary target is climate change and not the depletion of the ozone layer. Jucks provides an institutional point of view to describe current NASA contributions to ozone research and monitoring. The issues of climate change and ozone depletion wear many similarities. Both are global environmental issues that threaten human societies. Indeed, the case of ozone science and the Montreal Protocol has been viewed as a potential model for the climate regime. Grundmann provides a cross-look on both questions and details the difference between them. Conclusions of this thematic issue are then drawn by Newman, who discusses next challenges in the study of the ozone layer and the application of the Montreal Protocol.

Finally, we would express our gratitude to Marie-Lise Chanin, corresponding member of the "Académie des sciences", who suggested to publish these contributions to the celebration of the 30th anniversary of the Montreal Protocol in the journal *C. R. Geoscience* of the Academy. She had been involved in the study of the impact of ozone depletion on the stratosphere since the early time and co-created and directed the stratospheric and troposphere processes and their role on climate (SPARC) component of the World Climate Research Programme (WCRP) designed to take into account the impact of stratospheric processes on climate.

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