Ozone Depletion: The need to prevent a global catastrophe, even after the Montreal Protocol

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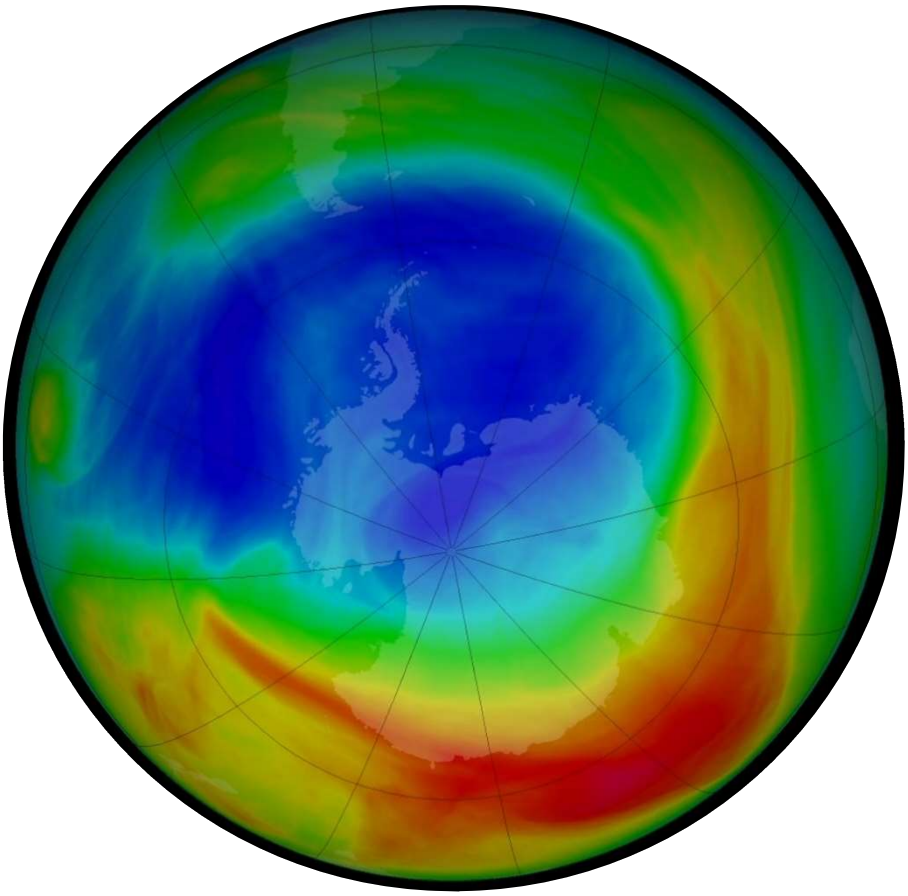

Representation of Earth Ozone Layer (NASA 2019)

Ozone Depletion: The need to prevent a global catastrophe, even after the Montreal Protocol

Executive Summary

Ozone depletion has been identified as a tipping point for planetary health, a problem that needs to be addressed to ensure life on earth continues. Ozone acts as a natural barrier to harmful radiation wavelengths, as well as providing ecological niches for species survival. The last 50 years have seen developments in understanding ozone and depletion caused by anthropogenic action, including the implementation of the Montreal Protocol as a landmark agreement of international cooperation. Yet, recent discoveries have shown that there are still problems surrounding ozone depletion and action must be taken to avoid transgressing a boundary for planetary survival. Oceans, which have often been considered as stores of harmful ozone-depleting substances, are now becoming emitters that threaten to overwhelm a system that has only recently started repairing with the introduction of regulatory policy. In order to mitigate the possible problems, recommendations include a wider emissions ban, including HCFC's; policy action on climate change and ocean acidification, following the previous work of Kyoto and the Paris Climate Agreement; phase out schemes and comprehensive research investments for alternatives; changes to current climate change proposals, specifically geoengineering; focusing solutions on land emissions rather than on oceanic stores; acting quickly to implement policies based on the precautionary principle to minimise further damage and constructing and enforcing an appropriate monitoring and sanctioning scheme for compliance on existing agreements.

Foundational Science

Ozone, O_3, makes up 0.00006% of the atmosphere[1] and is responsible for atmospheric screening of the ultraviolet spectrum, creating an ecological niche that supports life on the Earth[2]. The causes and consequences of ozone depletion have been widely identified since the discovery of the Antarctic ozone hole in 1985[3], creating a public desire and planetary need to address ozone depletion. The "hole" was caused by increased ozone depletion due

[1] NASA Ozone Watch, 2018
[2] Ashmore & Bell, 1991, pg.39
[3] Stolarski, 1988; Kuttippurath & Nair, 2017; Anwar et al. 2016

to anthropogenic interruption of natural ozone cycles, through the release of ozone-depleting substances such as chlorofluorocarbons (CFCs).[4] Whilst the ozone hole is now decreasing, it has yet to stabilise at pre-ozone depletion levels[5].

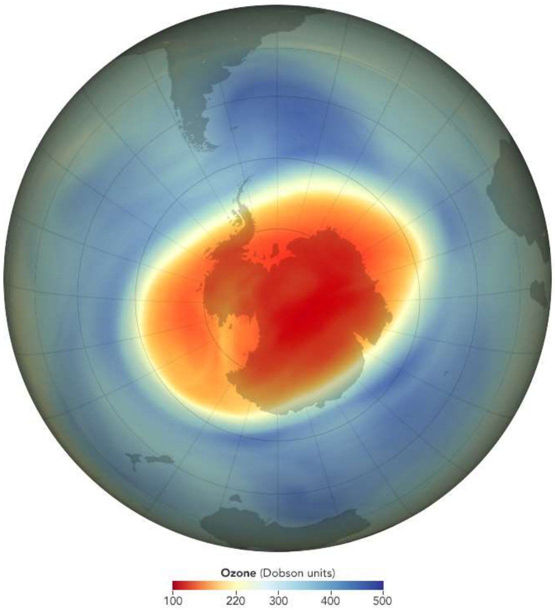

Figure 1- Extent of the ozone hole at its largest point on September 20th 2020 (NASA Earth Observatory 2020)

When ozone is exposed to ultraviolet radiation, it begins the process of breaking down and reforming[6]. This naturally occurs by ozone, O_3, breaking down into oxygen, O_2, and a singular oxygen atom, O[7]. This is a reversible reaction, meaning ozone is constantly being destroyed and created to maintain an equilibrium[8]. The introduction of ozone-depleting substances interrupts the natural balance[9], as ozone reacts with the chemicals, creating new compounds. In the case of chlorofluorocarbons, the chlorine acts as a catalyst for ozone breakdown[10], reacting to create oxygen and an individual chlorine molecule that can continue the breakdown with other ozone molecules.[11]

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[4] Solomon, 1998, pg.131; Newman et al. 2006: Wang et al., 2021
[5] Newman et al. 2006; World Meteorological Organization 2021; Dhomse et al. 2019
[6] Ozone Hole, 2019
[7] NASA Earth Observatory, 1999
[8] Belikovich et al., 2017, pg. 246
[9] NASA Ozone Watch, 2018
[10] NASA Earth Observatory 1999
[11] United States Environmental Protection Agency, 2018

Whilst anthropogenic emissions have decreased, there are causes for concern from other sources including the ocean. Similar to carbon dioxide, oceans can sequester and store CFCs, yet are reaching a critical limit that may turn them from stores to emitters[12]. With rising ocean temperatures and acidification, the timescale for this is expected to increase, meaning by 2100 the oceans become a significant contributor to CFC emissions in the atmosphere.[13] There is a high level of uncertainty in information about the oceans, as the storage capacity is largely unknown[14], as is the consequences of passing the storage threshold. However, there is significant evidence to show that the capacity is being reached, such as in the increased emissions from the oceans[15], and experts conclude that this represents a tipping point, causing major changes to life on Earth[16].

Ozone is essential to maintaining life on Earth, as it regulates the amount of radiation able to reach the Earth's surface[17]. Natural ozone screens out UV-C, the most powerful and potentially harmful type of ultraviolet radiation, as well as UV-B; both of which are linked to cancer and eye damage[18]. Through ozone depletion, humanity places itself at risk of medical concerns that could threaten the entire species. Outside of purely human concerns, the entire planetary ecosystem is designed to live in certain niche conditions, that can be provided by the ozone layer[19]. Depletion creates changes to the ecological niches[20], leading to species endangerment and potential extinction, which would have a profound impact on humanity.

Even the alternatives used to reduce dependency on CFCs carry problems for ozone depletion even if they are less severe. Hydrochlorofluorocarbons (HCFCs) were implemented as an alternative, yet they are still known depleting substances of stratospheric ozone, being identified as Class II ozone-depleting substances[21]. They are also greenhouse gases, with some having a global warming potential 23,000 times larger than

[12] Hossain, 2019, pg. 139
[13] Wang et al., 2021
[14] Khatiwala et al., 2013; DeVries 2014
[15] Wang et al., 2021
[16] Heinze et al. 2020
[17] Ashmore & Bell 1991
[18] Sheedy & Edlich, 2004
[19] Helaouët & Beaugrand, 2009
[20] Wynn-Willaims & Edwards, 2002
[21] United States Environmental Protection Agency, 2020

carbon dioxide[22]. Natural refrigerants have been suggested as an alternative, with abundant companies such as ammonia, water or carbon dioxide being proposed, since their ozone-depleting potential is 0[23]. However, these have yet to reach large-scale commercial introduction, and each comes with problems, including safety and storage[24], hence continued HCFC use.

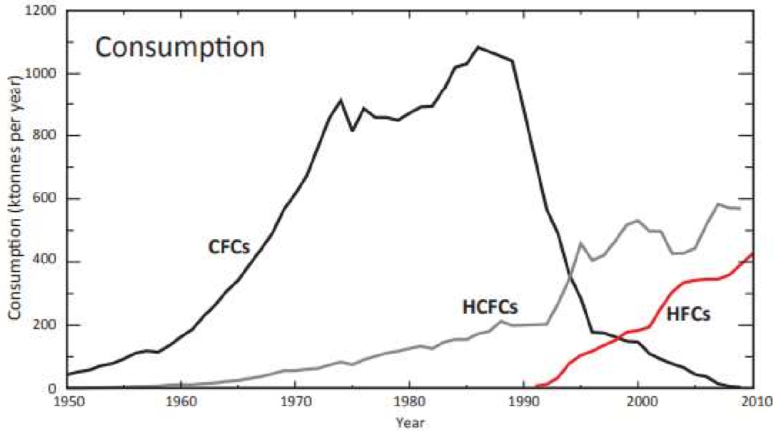

Figure 2- Global consumption of CFCs and HCFCs from 1950 to 2010, indicating greatly increased HCFC usage and CFC decline from ~1990 (Ravishankara et al. 2011, pg. 9)

Existing Governance

Created in 1987, the Montreal Protocol has been the main source of governance on ozone depletion, acting as a landmark in achieving international cooperation on environmental concerns.[25] Widespread adoption of the agreement, focus on solutions rather than blame and early adoption to address the growing problem has led to the popular success of the initiative but failed to comprehend some of the shortcomings it could face[26]. Designed upon the precautionary principle, the agreement was created and instated on the basis that the science was confident that ozone depletion was a global problem but there was uncertainty surrounding the details, such as the extent of the impacts and the implications for the future[27].

[22] European Environment Agency, 2020
[23] Bolaji & Huan, 2013, pg. 51
[24] Bolaji & Huan, 2013; Palm, 2008
[25] Velders et al., 2007
[26] Green, 2009, pg.259
[27] Jacobs, 2014

Whilst originally setting out a comprehensive list of ozone-depleting substances, subsequent additions have not always received the same attention or been achieved by every country[28]. A lack of monitoring and sanctioning has allowed countries to break the rules; China increased CFC emissions from 2013 to 2019 with no obvious repercussions, potentially encouraging other countries to follow their example, especially those in economic hardship[29].

Whilst the original agreement was designed to be flexible, to follow developments in science, very few changes have occurred to the fundamental basis of the agreement, maintaining the balance between science and political interests[30]. Much of the fundamental science around how ozone is depleted and the implications have remained unchanged[31], only expanded on in subsequent scientific discoveries[32]. However, advancements have been made in understanding climate change[33], which has led to a recognition that alternatives to ozone-depleting substances are actually environmentally harmful as greenhouse gases[34]. Yet amendments have failed to comprehend this problem, and still encourage hydrofluorocarbons as suitable alternatives.

Additionally, subsequent international agreements, most recently the Paris Climate Agreement[35], have neglected to mention ozone depletion, regarding the issue as being solved and concluded within the Montreal Protocol. Continued investigation and monitoring are proving that ozone depletion has only been addressed in the short-term and longer-term problems have been neglected.

[28] Weiss, 2009, pg. 3
[29] Park et al., 2021 pg.433
[30] Weiss, 2009, pg.2
[31] Rowland, 1991; Solomon, 1999
[32] Rowland, 2009
[33] National Research Council, 2010
[34] European Environment Agency, 2020
[35] United Nations, 2015

Figure 3- Summary of key points of the Paris Climate Agreement, with emphasis on climate change and no mention of ozone depletion (UNFCCC, 2018)

There is increasing recognition that the problems of ozone depletion are demonstrated at a global level, resulting in the creation of a multilateral fund to aid in decreasing ozone depletion in less developed countries that face financial difficulties[36]. Countries with higher economic standing, who are more often historically responsible for emissions, have committed to contribute to funds that offer aid and assistance to less affluent countries[37], to allow them to phase out ozone-depleting substances. Currently, 99% of global productions have ceased[38], with the hope that the continuation of this fund will help to end all CFC production, although this remains difficult with the limited monitoring and enforcement.

<u>Policy Recommendations</u>

Whilst the Montreal Protocol has largely been a success, changing times require updated policies to reflect uncertain international relations and growing scientific developments.

1. **The introduction of an appropriate monitoring and sanctioning system**. Currently, the Montreal Protocol offers a framework for phasing out chemical usages, but relies on self-enforcement and currently offers limited sanctioning to incentivise

[36] Patlis, 1992; Ozone Secretariat United Nations Environment Programme, n.d.
[37] Ozone Secretariat United Nations Environment Programme, n.d.
[38] Andersen et al., 2018, pg. 410

participants[39]. The introduction of a regulatory force and a sanctioning system would encourage long-term compliance by using penalties and incentives to encourage compliance[40], rather than simply offering technical assistance to those not meeting standards, which is the current model of enforcement[41].

2. **Implement policies on ocean acidification and climate change.** CFC emissions from the oceans are linked to increasing temperatures and acidification[42], suggesting that mitigation depends on implementing policies that limit the extent of global warming to a maximum of 2°C and limiting carbon dioxide emissions.
3. **Implement further policies based on the precautionary principle.** Key to the success of the Montreal Protocol was the early implementation that worked on the uncertainty of the science[43]. These uncertainties still exist, meaning that any policies would have to be precautionary but early implementation can limit the harmful impacts and help protect the quality of life.
4. **Encouragement of phase-out schemes such as in the USA.** Current CFC alternatives are still causing climate change, as well as minor ozone depletion, and were only intended as temporary measures, so encouraging phase-out schemes to more sustainable long-term alternatives is the only way to protect ozone for the future, demonstrated currently in the USA[44].
5. **Research and implementation into further alternatives for CFC's.** In order to effectively phase out CFC alternatives, a new generation of chemical alternatives needs to be found, requiring extensive research. New alternatives would need to be safe, non-environmentally harmful and not be a greenhouse gas, to ensure compliance with climate change legislation, for example, ammonia or natural refrigerants[45]. Therefore, large scale investment is required to research these alternatives, which can then be implemented using similar legislation to those created for the original CFC alternatives.

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[39] Barrett, 1994
[40] Green, 2009
[41] Weiss, 2009, pg. 3
[42] Wang et al., 2021
[43] Jacobs, 2013, pg.161
[44] United States Environmental Protection Agency, 2021
[45] Bolaji & Huan, 2013

6. **Address wider emissions.** To mitigate the risks of rising ocean temperatures and climate change, it is imperative to take urgent action on greenhouse gas emissions, ensuring the best chances of keeping global temperature rise below 2°C. The transition away from petrol or diesel cars to electric or alternative fuel vehicles, including biofuels or hydrogen[46], is one example that can be introduced at a national level, allowing quicker implementation than policies requiring global consensus.
7. **Focus on land emissions and not ocean storage[47].** Over the past few decades, oceans have been regarded as an unlimited resource that can be used to mitigate anthropogenic emissions[48]. But this is no longer scientifically grounded, prompting a shift away from ocean dependency to the need for land-based management. Dependency on oceanic protection needs to be replaced by solid legislation that tackles emissions of ozone-depleting substances as well as greenhouse gases, and is supported and based on a scientific foundation that has space and flexibility to adapt as scientific advancements are made.
8. **Changes to current climate change proposals.** Whilst there are natural fluctuations in the ozone layer, proposals for climate change mitigation policies have the potential to disrupt the natural cycle. Geoengineering in terms of sulphate enhancement in the stratosphere is meant to decrease the impacts of climate change by reducing radiative force but will disrupt natural systems[49]. Therefore, these ideas need to be carefully considered and alternative propositions need to be created which are less environmentally damaging, for example, carbon capture[50].

[46] Granovskii, Dincer & Rosen, 2006
[47] Wang et al., 2021
[48] Gee, 2019
[49] Salawitch et al., 2018
[50] Wilberforce et al., 2019

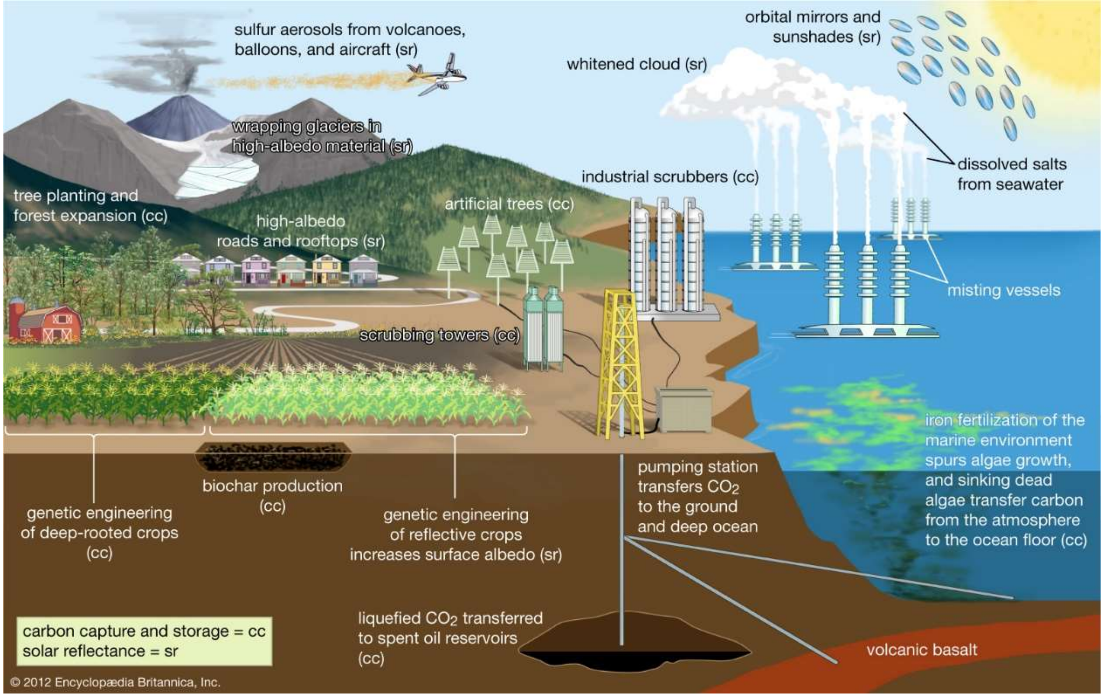

Figure 4- Summary of proposed geoengineering climate change solutions, with sr denoting solar reflectance technologies and cc for carbon capture, the preferred alternative (Boyd, 2021)

Reference list

Andersen, S., Sherman, N., Carvalho, S. & Gonzalez, M. (2018) The global search and commercialization of alternatives and substitutes for ozone-depleting substances. *Comptes Rendus Geoscience* 350 (7): 410-424

Anwar, F., Chaudhry, F., Nazeer, S., Zama, N. & Azam, S. (2016) Causes of Ozone Layer Depletion and Its Effects on Human: Review. *Atmospheric and Climate Sciences* 6 (1) Doi: http://www.scirp.org/journal/PaperInformation.aspx?PaperID=63065&#abstract

Ashmore, A. & Bell, J. (1991). The Role of Ozone in Global Change. *Annals of Botany* 67(1): 39-48

Barrett, S. (1994). Self-Enforcing International Environmental Agreements. *Oxford Economic Papers* 46: 878-894

Belikovich, M., Kulikov, M., Grygalashvyly, M., Sonnemann, G., Ermakova, T., Nechaev, A. & Feigin, A. (2017) Ozone chemical equilibrium in the extended mesopause under the nighttime conditions. *Advances in Space Research* 61: 426-432

Bolaji & Huan (2013). Ozone depletion and global warming: Case for the use of natural refrigerant – a review. *Renewable and Sustainable Energy Reviews* 18: 49-54

Boyd, P. (2021) Geoengineering. *Encyclopaedia Britannica.* Doi: geoengineering | Types & Techniques | Britannica

Devries, T. (2014) The oceanic anthropogenic CO_2 sink: Storage, air-sea fluxes, and transports over the industrial era. *Global Biogeochemical Cycles* 28: 631-647 Doi: 10.1002/2013GB004739.

Dhomse, S., Feng, W., Montzka, S., Hossaini, R., Keeble, J., Pyle, A., Daniel, J. & Chipperfield, M. (2019). Delay in recovery of the Antarctic ozone hole from unexpected CFC-11 emissions. *Nature Communications* 10 (5781) Doi: https://doi.org/10.1038/s41467-019-13717-x

European Environment Agency (2020). *Protecting the ozone layer while also preventing climate change* [online]. Available from: Protecting the ozone layer while also preventing climate change — European Environment Agency (europa.eu) (Accessed 3rd May 2021)

Green, B. A. (2009). Lessons from the Montreal protocol: Guidance for the next international climate change agreement. *Environmental Law* 39(1), 253-284.

Heinze, C., Bleckner, T., Martins, H., Rusiecka, D., Döscher, R., Gehlen, M., Gruber, N., Holland, E., Hov, O., Joos, F., Matthews, J., Rodven, R. & Wilson, S. (2020). The quiet crossing of ocean tipping points. *PNAS* 118 (9) Doi: https://doi.org/10.1073/pnas.2008478118

Helaouët, P. & Beaugrand, G. (2009). Physiology, Ecological Niches and Species Distribution. *Ecosystems* 12: 1235-1245

Hossain, F. (2019) Chapter 9- Air Pollution. In: *Sustainable Development for Mass Urbanization.* Amsterdam: Elsevier: 129-150

Gee, K. (2019) The Ocean Perspective. In: Gee, K. & Zaucha, J. *Maritime Spatial Planning.* Camden: Palgrave Macmillan: 23-46

Granovskii, M., Dincer, I. & Rosen, M. (2006). Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles. *Journal of Power Sources* 159 (2): 1186-1193

Jacobs, J. (2013) The precautionary principle as a provisional instrument in environmental policy: The Montreal Protocol case study. *Environmental Science & Policy* 37: 161-171

Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S., Graven, H., Gruber, N., McKimley, G., Murata, A., Rios, A. & Sabine, C. (2013) Global ocean storage of anthropogenic carbon. *Biogeosciences* 10: 2169-2191 Doi: [10.5194/bg-10-2169-2013](10.5194/bg-10-2169-2013)

Kuttippurath, J. & Mair, P. (2017) The signs of Antarctic ozone hole recovery. *Scientific Reports* 585 (7) Doi: https://doi.org/10.1038/s41598-017-00722-7

Ozone Secretariat, United Nations Environment Programme (n.d.) *Multilateral Fund.* [online] Available from: Multilateral Fund | Ozone Secretariat (unep.org)

Palm, B. (2008) Hydrocarbons as refrigerant in small heat pump and refrigeration systems – A review. *International Journal of Refrigeration* 31 (4) 552-563 Doi: https://0-doi-org.pugwash.lib.warwick.ac.uk/10.1016/j.ijrefrig.2007.11.016

Park, S., Western, L. Saito, T., Redington, A., Henne, S., Fang, X., Prinn, R., Manning, A., Montzka, S., Fraser, P., Ganesan, A., Harth, C., Kim, J., Krummel, P., Lia ng, Q., Mühle, J., O'Doherty, S., Park, H., Park, M., Reimann, S., Salameh, P., Weiss, R., & Rigby, M. (2021). A decline in emissions of CFC-11 and related chemicals from eastern China. *Nature* 590: 433-437

Patlis, J. (1992) The Multilateral Fund of the Montreal Protocol: A Prototype for Financial Mechanisms in Protecting the Global Environment. *Cornell International Law Journal* 25 (1): 181-230

NASA (2019). *2019 Ozone Hole is the Smallest on Record since its Discovery* [online]. Available from: 2019 Ozone Hole is the Smallest on Record Since Its Discovery | NASA (Accessed 25 March 2021)

NASA Earth Observatory (1999). *Ozone* [online]. Available from: Ozone (nasa.gov) (Accessed 1st May 2021)

NASA Earth Observatory (2020). *Large, Deep Antarctic Ozone Hole in 2020* [online]. Available from: Large, Deep Antarctic Ozone Hole in 2020 (nasa.gov) (Accessed 5th May 2021)

NASA Ozone Watch (2018). *What is Ozone?* [online]. Available from: Nasa Ozone Watch: Ozone facts (Accessed 1st May 2021)

National Research Council (2010) *Advancing the Science of Climate Change.* Washington: National Academies Press

Newman, P., Nash, E., Kawa, S., Montzka, S. & Schauffler, S. (2006). When will the Antarctic ozone hole recover? *Geophysical Research Letters* 33 (12) Available from: https://doi.org/10.1029/2005GL025232 (Accessed 21 March 2021)

Ozone Hole (2019). *The Ozone Layer* [online]. Available from: The Ozone Layer - Ozone Hole Website (ozone-hole.org.uk) (Accessed 1st May 2021)

Ravishankara, A., Velders, G., Millar, M. & Molina, M. (2011) *HCFCs: A Critical Link in Protecting Climate and the Ozone Layer.* UNEP. Available from: UNEP_HFC_Report_2011.pdf (Accessed 29th July 2021)

Rowland, S. (1991) Stratospheric Ozone Depletion. *Annual Review of Physical Chemistry* 42: 731-768 Doi: https://doi.org/10.1146/annurev.pc.42.100191.003503

Rowland, S. (2009) Stratospheric Ozone Depletion. In: Zerefors, C., Contopoulous, G. & Skalkeas, G. (eds) *Twenty Years of Ozone Decline.* Dordrecht: Springer: 23-66

Salawitch, R., Fahey, D., Hegglin, M., McBride, L., Tribett, W. & Doherty, S. (2018) *NOAA: Twenty Questions and Answers about the Ozone Layer: 2018* [online]. Available from: Q20.pdf (noaa.gov) (Accessed 4th May 2021)

Sheedy J. & Edlich, R. (2004). Ultraviolet eye radiation: the problem and solutions. *J Long Term Eff Med Implants* 14 (1) : 67-71 Doi: https://doi.org/10.1615/jlongtermeffmedimplants.v14.i1.60

Solomon, S. (1988). The Mystery of the Antarctic Ozone “Hole”. *Reviews of Geophysics* 26 (1) 131-148

Solomon, S. (1999). Stratospheric ozone depletion: A review of concepts and history. *Reviews of Geophysics* 37 (3): 275-316 Doi: https://0-doi-org.pugwash.lib.warwick.ac.uk/10.1029/1999RG900008

Stolarski, R. (1988) The Antarctic Ozone Hole. *Scientific American* 258 (1): 30-37

United Nations (2015). *Paris Agreement.* Paris: United Nations

United States Environmental Protection Agency (2018). *Basic Ozone Layer Science* [online]. Available from: Basic Ozone Layer Science | Ozone Layer Protection | US EPA (Accessed 1st May 2021)

United States Environmental Protection Agency (2020). *Phaseout of Class II Ozone-Depleting Substances* [online]. Available from: Phaseout of Class II Ozone-Depleting Substances | Phaseout of Ozone-Depleting Substances (ODS) | US EPA (Accessed 23 March 2021)

United States Environmental Protection Agency (2021). *Phaseout of Ozone-Depleting Substances (ODS)* [online]. Available from: Phaseout of Ozone-Depleting Substances (ODS) | US EPA (Accessed 4th May)

United Nations Framework Convention on Climate Change (2018). *UN Climate Change Annual Report 2017.* Bonn: UNFCCC. Available from: UN Climate Change Annual Report 2017 (unfccc.int) (Accessed 29th July 2021)

Velders, G., Andersen, S., Daniel, J., Fahey, D., & McFarland, M. (2007) The importance of the Montreal Protocol in protecting climate. *Proceedings of the National Academy of Sciences of the United States of America* 104 (12) Available from: https://doi.org/10.1073/pnas.0610328104 (Accessed 24 March 2021)

Wang, P., Scott, J., Solomon, S., Marshall, J. Babbin, A., Lickley, M., Thompson, D., DeVries, T., Liang, Q. & Prinn, R. (2021). On the effects of the ocean on atmospheric CFC-11 lifetimes and emissions. *Proceedings of the National Academy of Sciences of the United States of America* 118 (12). Available from: https://doi.org/10.1073/pnas.2021528118 (Accessed 24 March 2021)

Weiss, E. (2009) The Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol on Substances that deplete the Ozone Layer. *United Nations Audiovisual Library of International Law* [online]. Available from: Introductory Note -Edith Brown Weiss, Francis Cabell Brown Professor of International Law, Georgetown University Law Center - English (Accessed 21 March 2021)

Wilberforce, T., Baroutaji, A., Soudan, B., Hai Al-Alami, A. & Ghani Olabi, A. (2019). Outlook of carbon capture technology and challenges. *Science of The Total Environment* 657: 56-72 Doi: https://doi.org/10.1016/j.scitotenv.2018.11.424

World Meteorological Organization (2021). *Record-breaking 2020 ozone hole closes* [online]. Available from: Record-breaking 2020 ozone hole closes | World Meteorological Organization (wmo.int) (Accessed 1st May 2021)

Wynn-Williams, D. & Edwards, H. (2002) Environmental UV Radiation: Biological Strategies for Protection and Avoidance. In: Horneck, G. & Baumstark-Khan, C. *Astrobiology: The Quest for the Conditions of Life.* Berlin: Springer: 245-260