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Montreal Protocol on Substances that Deplete the Ozone Layer

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Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer
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Item 3 (a) of the provisional agenda*

The 2022 quadrennial assessment of the Montreal Protocol (decision XXXI/2): Presentations and discussion on issues arising from the 2022 quadrennial assessment and synthesis reports of the Scientific Assessment Panel, the Environmental Effects Assessment Panel and the Technology and Economic Assessment Panel

Synthesis of the 2022 assessment reports of the Scientific Assessment Panel, the Environmental Effects Assessment Panel and the Technology and Economic Assessment Panel

Note by the Secretariat

1. The annex to the present note contains a synthesis report that highlights the main findings of the following three 2022 quadrennial assessment reports prepared pursuant to Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer:

- *Scientific Assessment of Ozone Depletion: 2022,* prepared by the Scientific Assessment Panel
- *Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change: 2022 Assessment Report,* prepared by the Environmental Effects Assessment Panel
- *Technology and Economic Assessment Panel: 2022 Assessment Report*, prepared by the Technology and Economic Assessment Panel

2. The synthesis report has been prepared by the co-chairs of the assessment panels. The individual assessment reports are posted on the portals of the respective panels of the website of the Ozone Secretariat[1] and on the web portal of the Open-ended Working Group of the Parties to the Montreal Protocol for consideration by the parties.[2] The Secretariat would like to express its sincere gratitude to the three assessment panels for their work.

* UNEP/OzL.Pro.WG.1/45/1/Rev.2.

[1] https://ozone.unep.org/science/assessment/sap;
https://ozone.unep.org/science/assessment/eeap;
https://ozone.unep.org/science/assessment/teap.

[2] https://ozone.unep.org/meetings/45th-meeting-open-ended-working-group-parties/pre-session-documents

Annex

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Synthesis of the 2022 Assessment reports of the Scientific Assessment Panel, the Environmental Effects Assessment Panel and the Technology and Economic Assessment Panel**

Introduction

1. The Scientific Assessment Panel, the Environmental Effects Assessment Panel and the Technology and Economic Assessment Panel are charged with providing periodic assessments within their areas of expertise to the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. This report provides a high-level synthesis of the 2022 assessment reports of the three panels. The scientific and technological issues associated with the Montreal Protocol, along with the climate and environmental benefits of the Protocol, are highlighted herein and discussed in detail in the individual assessment reports of these panels:

Scientific Assessment Panel
(https://ozone.unep.org/science/assessment/sap)

Environmental Effects Assessment Panel
(https://ozone.unep.org/science/assessment/eeap)

Technology and Economic Assessment Panel
(https://ozone.unep.org/science/assessment/teap).

2. This report provides updated information highlighting the success of the Montreal Protocol in limiting the growth in the atmospheric abundances of ozone-depleting substances (ODSs) and hydrofluorocarbons (HFCs), thereby reducing stratospheric ozone depletion, avoiding additional contributions to climate change and protecting the environment. The indications that those actions are leading to ozone recovery are increasingly clear, especially for ozone in the upper stratosphere and over the Antarctic region. With the implementation of the 2016 Kigali Amendment to the Montreal Protocol to phase-down HFCs, a significant amount of future climate warming will be avoided, adding to that avoided due to the decline in ODS production and consumption under the Protocol.

3. Significant impacts on human health, and the environment caused by stratospheric ozone depletion and the resulting increases in ultraviolet (UV) radiation have been avoided because of the Montreal Protocol. Since full recovery of the ozone layer will take several decades, long-term monitoring of ODSs, HFCs, ozone and UV radiation continues to be essential.

Key findings

I. Actions taken under the Montreal Protocol have continued to decrease atmospheric abundances of controlled ozone-depleting substances and advance the recovery of the stratospheric ozone layer.

4. The atmospheric abundances of both total tropospheric chlorine and total tropospheric bromine from long-lived ODSs have declined since the 2018 Assessment. The observed rates of decline in tropospheric chlorine and tropospheric bromine in substances controlled under the Montreal Protocol were 15.4 ± 4.1 ppt Cl yr^{-1} and 0.18 ± 0.05 ppt Br yr^{-1} respectively, close to the Baseline scenario from the 2018 Assessment. Tropospheric chlorine from very short-lived gases, whose sources are mainly anthropogenic and which are not controlled under the Montreal Protocol, increased by 2.1 ± 0.6 ppt Cl yr^{-1}.

5. Progress on ODS phase-out continues to be made in every residential, commercial, industrial, agricultural, medical, and military sector, with the production and consumption of ozone-depleting substances having been phased out from many applications worldwide.

** The synthesis report is reproduced without formal editing.

- The phase-out of the consumption and production of hydrochlorofluorocarbon (HCFC)-22 is essentially complete in non-Article 5 parties and is progressing in Article 5 parties.
- Significant progress has been made to phase out the use of HCFCs in foams. There are alternative foam blowing agents (FBAs) in use commercially today in nearly every foam application.
- Phase-out of controlled uses of methyl bromide (MB) is virtually complete, but significant quarantine and pre-shipment (QPS) uses remain, as these are currently exempted from Montreal Protocol controls. Alternatives have nevertheless been identified, and are in use in some countries, for a good proportion of these uses.
- The phase-out of controlled substances in sterilization uses is considered complete. Technically and economically feasible alternatives are commercially available for all aerosol uses, although not all alternatives are suitable across all applications in all locations.
- Alternative low global warming potential (GWP) refrigerants are available for all refrigeration, air conditioning and heat pump (RACHP) applications, which account for the majority of all HCFC and HFC emissions. These alternatives are being widely applied in some applications and regions, but accessibility is still a major hindrance for the widescale adoption of lower GWP refrigerants and progress towards goals of the Kigali Amendment phase-down schedules.

6. Evidence for ozone recovery, consistent with these declines in ODS abundances, has strengthened.

- Total column ozone (TCO) in the Antarctic continues to recover, notwithstanding substantial interannual variability in the size, strength, and longevity of the ozone hole, which is driven by interannual variability in meteorology.
- Outside of the Antarctic region (from 90°N to 60°S), the limited evidence of TCO recovery since 1996 has low confidence.
- TCO is expected to return to 1980 values around 2066 in the Antarctic, around 2045 in the Arctic, and around 2040 for the near-global average (60°N–60°S).

7. Trends in stratospheric ozone vary with altitude as well as geographic region.

- Outside of the polar regions, observations and models are in agreement that ozone in the upper stratosphere continues to recover.
- In contrast, ozone in the lower stratosphere has not yet shown signs of recovery.
- Models simulate a small recovery in mid-latitude lower-stratospheric ozone in both hemispheres that is not seen in observations. Reconciling this discrepancy is key to ensuring a full understanding of ozone recovery.

8. As yet, there is no published evidence that lockdowns associated with the COVID-19 epidemic impacted the trends in atmospheric abundances of ODSs or their replacements or that they have impacted stratospheric ozone. Supply shortages of low-GWP alternatives in some sectors are understood to have started in 2020 due to COVID-19 related supply chain and logistics issues, raw material shortages, manufacturing issues, and severe weather, at the same time as increasing global demand. While these supply issues are less severe now, these will need careful monitoring as extended shortages in supply could delay transition away from HFCs across the various sectors of use.

II. The Montreal Protocol contributes to environmental sustainability and human health and well-being, in line with many Sustainable Development Goals

9. The Montreal Protocol continues to contribute to the implementation of many of the United Nations Sustainable Development Goals (SDGs) by protecting the stratospheric ozone layer and contributing to the mitigation of climate change. These SDGs address the areas related to climate change, air and water quality, biodiversity and ecosystems, sustainable production and consumption, food security, contaminants and materials, and human health. Thus, the Montreal Protocol has wide-ranging significance for sustainability by protecting human health and maintaining healthy, diverse ecosystems on land and in the water.

10. Surface levels of solar ultraviolet-B radiation (UV-B) would have increased world-wide without the Montreal Protocol, and these changes would have been the greatest in polar regions (e.g., the Antarctic mid-summer UV index would have increased from 3 to 33 between 1975 and 2065). Further, a modelling study with an extreme scenario estimated that the impact of large increases in UV-B radiation on terrestrial vegetation in a world without the Montreal Protocol would have drastically reduced the photosynthetic uptake of carbon dioxide by plants. This reduction in carbon sequestration would have, in turn, increased atmospheric carbon dioxide levels, resulting in an additional rise of global mean surface temperature of 0.5-1.0ºC by 2100.

11. By safeguarding the Earth from extreme UV-B radiation, the Montreal Protocol is playing a key role in protecting human health. One modelling study compared the Montreal Protocol, as amended and adjusted, with the extreme scenario of unregulated ODS emissions increasing at a rate of 3% per year throughout the 21st century. This analysis estimated that 11 million cases of melanoma, 432 million cases of basal cell and squamous cell carcinoma (keratinocyte cancers), and 63 million cases of cataracts (the leading cause of blindness globally) were avoided for people born in the United States between 1890-2100 because of the Montreal Protocol. Approximately half of these cases are avoided because of the amendments and adjustments made to the original 1987 Montreal Protocol. The Montreal Protocol has also made it possible to continue to receive the beneficial health effects (e.g., vitamin D production and improved immune system function) of moderate exposure to sunlight through spending time outdoors.

12. Solar UV radiation causes photodegradation of plastics, which ultimately results in fragmentation and the formation of micro- and nanoplastics (particles less than 5 mm and 0.1 µm in diameter, respectively). The implementation of the Montreal Protocol has likely prevented increases in the generation of microplastics in the environment, although the amount of this reduction and its biological consequences remain uncertain.

III. The significant decreases in projected HFC emissions from the provisions of the Kigali Amendment will substantially protect future climate.

13. HFCs are increasingly used as ODS alternatives in refrigeration and air conditioning, in the aerosols and foam sectors, and as fire suppression agents. While they do not contain ozone-depleting chlorine or bromine, they are greenhouse gases. The Kigali Amendment, which was adopted in 2016 and came into force in 2019, sets schedules for the phase-down of the global production and consumption of specific HFCs. Although radiative forcing from HFCs is currently small, the Kigali Amendment is designed to avoid unchecked growth in emissions and the associated warming that would have arisen from the projected increases in demand in coming decades.

14. The atmospheric abundances of most currently measured HFCs continue to increase, as was projected in the baseline scenario of the 2018 Assessment. Global emissions of HFCs, which originate from both Article 5 and non-Article 5 parties, increased by 18 per cent between 2016 and 2020 in carbon dioxide (CO_2)-equivalent units.

15. Current projected HFC emissions are lower than those projected in the 2018 Assessment. The 2020–2050 cumulative emissions in the 2022 updated Kigali Amendment scenario are 14–18 Pg CO_2-eq lower than in the corresponding scenario in the previous Assessment. The new scenario follows national controls on the consumption and production of HFCs in non-Article 5 countries, reflects lower reported consumption in China, is based on updated historical information on the use of HFCs in non-Article 5 countries, uses observed mixing ratios through 2020 as a constraint, and includes assumptions about reduced use of HFCs for commercial and industrial refrigeration. The new scenario also assumes that all countries adhere to the provisions of the Kigali Amendment.

16. Annual average surface warming from HFCs is expected to be 0.04°C in 2100 under the updated 2022 Kigali Amendment scenario, compared to 0.3–0.5°C without control measures. A more rapid phase-down of HFCs than that required by the Amendment would further limit climate change from HFCs.

17. The global HFC-23 emissions of 17.2 ± 0.8 kt yr^{-1} in 2019 derived from atmospheric observations are substantially higher than the emissions of 2.2 kt yr^{-1} in that year derived from activity-based estimates. These activity-based estimates are derived from UNFCCC emission reports, information on production and emissions abatement submitted under the Montreal Protocol, and the estimated effect of national regulations. The atmospheric HFC-23 levels are inconsistent with the substantial rise in emissions abatement reported to the UNFCCC.

18. HFC-23 emissions are expected to grow in the coming decades. HFC-23 is released as a by-product of HCFC-22 production and other processes. These other processes include production of HFC-32, the manufacture of TFE/HFP from HCFC-22 feedstock, the production processes of other fluorocarbons (e.g., for HFC-125, HFC-134a, HFC-143a), and some steps of HFO production.

19. The planned HFC phase-down under the Kigali Amendment, as well as regional regulations, are driving industry towards low-GWP HFC alternatives and innovative applications, especially with respect to refrigeration, air conditioning and foams. However, the range of new, lower GWP products creates challenges in finding the best solution for each application, taking into consideration factors such as flammability, toxicity, availability, cost, accessibility, operating conditions, and other properties.

20. Trifluoroacetic acid (TFA), is a breakdown product in the atmosphere of some HFCs, HCFCs, HFOs and HCFOs and fluoroketones (FKs). TFA formed in the atmosphere is rapidly deposited in precipitation and, on reaching the surface (soil or water), it forms salts with alkali metals (e.g., sodium, potassium, calcium). TFA salts are unreactive and have long environmental lifetimes but are easily excreted by animals and therefore do not bioaccumulate in the food chain. Like other mineral salts, TFA salts accumulate in oceans and salt-lakes. The formation of TFA in the atmosphere is expected to increase in the coming decades due to increased use of HFOs and HCFOs. While TFA continues to be found in the environment, including in remote regions, concentrations are so low that it is currently judged very unlikely to have adverse toxicological consequences for humans and ecosystems. Continued monitoring and assessment are nevertheless advised due to uncertainties in the localized deposition of TFA and its potential effects on some untested marine organisms.

IV. Improvements in energy efficiency during the HFC phase-down have the potential to accelerate and further increase the climate benefits from the Kigali Amendment

21. There is a rapidly increasing global demand for refrigeration and air conditioning. Improved energy efficiency in new refrigeration, air conditioning and heat pump (RACHP) equipment synchronously with HFC phase-down could serve to moderate energy use, potentially doubling the climate benefit from the HFC phase-down. This could make a cost-effective and near-term contribution to the path to net zero GHG emissions. Early conversion to efficient RACHP equipment containing low global warming potential (GWP) alternatives can reduce energy costs and avoid the build-up of high GWP HFC refrigerant banks.

22. Technology developments are proceeding at pace, and RACHP equipment using low and medium GWP refrigerants with increased energy efficiency is available in all sectors, but not necessarily accessible in all countries.

V. Successful actions by the Parties have reversed the upward trend of unexpected emissions observed between 2013 and 2017

23. While the 2018 Scientific Assessment found that global CFC-11 emissions unexpectedly increased in the 2013-2017 period, the 2022 Scientific Assessment concluded that global CFC-11 emissions declined after 2018. The initial CFC-11 emissions increase led to a number of scientific investigations and policy responses. Consequently, CFC-11 emissions decreased to 45 ± 10 Gg in both 2019 and 2020. This decrease suggests the elimination of most of the unexpected emissions occurring in the years after 2012.

24. A large fraction of the unexpected CFC-11 emissions originated from eastern China. This finding is based on available regional observations from several east Asia sites. The decline of CFC-11 emissions from eastern China since 2018 explains 60 ± 30% of the observed global emission decrease. While the global network of surface observation stations provides estimates of total CFC-11 emissions, the network is too geographically sparse to fully assess regional emissions.

25. Emissions from the CFC-11 banks alone could not explain the 2013-2017 unexpected increase, indicating unreported CFC-11 production and use in this period. This production was most likely used for closed-cell foams. Unreported production may also have occurred earlier, in the 2007 to 2012 period.

26. Regional observations suggest some CFC-12 emissions may have been associated with the unreported CFC-11 production. Uncertainties in emissions from banks and gaps in the observing network are too large to determine whether all unexpected CFC-12 emissions have ceased.

VI. Carbon tetrachloride abundances continue to decline at a slower rate than expected based on previous trends

27. Carbon tetrachloride (CCl_4) atmospheric abundances continued to decrease, but at slower rates than expected based on previous trends. Global CCl_4 emission estimates based on atmospheric observations averaged 44 ± 15 Gg yr^{-1} in both 2016 and 2020.

28. Regional CCl4 emissions from eastern China over the period 2013–2019 show year-to-year variability likely related to CFC-11 production. Emissions increased after 2013, reaching 11.3 ± 1.9 Gg yr^{-1} in 2016, and decreased to 6.3 ± 1.1 Gg yr^{-1} in 2019.

29. Production of CCl_4 has increased in recent years due mainly to growing demand for feedstock use for production of HFCs, HFOs/HCFOs, and perchloroethylene. Increasing CCl_4 production is likely to continue because of the increasing demand for HFO/HCFOs. Most emissions arise from CCl_4 production, handling, supply chain, and usages. Additional CCl_4 emissions likely arise from non-chloromethane production, such as the vinyl chain production process, which is identified as a new potential source of CCl_4 emissions.

VII. The atmospheric abundances of a number of minor ozone-depleting substances have been increasing; cumulatively, those substances may eventually have an impact on stratospheric ozone

30. Global abundances of the minor species CFC-13, CFC-112a, CFC-113a, CFC-114a, and CFC-115 increased from 16.0 ± 0.3 ppt in 2016 to a total of 17.2 ± 0.3 ppt Cl in 2020. Atmospheric observations confirm that eastern Asia is a substantial source region. These findings likely indicate an increase or stabilization of the emissions of these relatively low abundance compounds. Some of these unexplained emissions are likely occurring as leaks of feedstocks or by-products, and the remainder is not understood. These species have a minor impact on stratospheric chlorine loading and stratospheric ozone depletion.

31. The production and usage of short-lived chlorinated solvents are not controlled by the Montreal Protocol, and some are used in large amounts. Their impact on stratospheric ozone, and their ozone depletion potentials (ODPs), vary depending on the season and location of emissions. Emissions of these substances could grow in the future even as emissions from long-lived ODSs decline. Important examples of short-lived chemicals that are used as feedstocks are $CHCl_3$ (chloroform), CH_2Cl_2 (dichloromethane or DCM), $CHCl=CCl_2$ (trichloroethene or TCE), and $CCl_2=CCl_2$ (perchloroethene or PCE). Sustained increases in anthropogenic chlorinated very short-lived substance (VSLS) emissions, as seen for CH_2Cl_2 over the last two decades, would lead to more stratospheric ozone depletion in the future.

32. Dichloromethane (CH_2Cl_2, or DCM) (180-day lifetime) is the main component of VSLS chlorine. Its atmospheric abundance continued to increase between 2016 and 2020 with a slightly lower growth rate than prior to 2016. This increase primarily results from a growth in CH_2Cl_2 emissions in Asia. Given market trends in chemical production and DCM usage, global DCM production and atmospheric concentrations are currently not expected to increase significantly in the next few decades. DCM is used mainly as a solvent (such as in pharmaceutical manufacturing, paint stripping, adhesives) and as a foam-blowing agent, and is also used as feedstock for HFC-32 production. In recent years, there has been a decrease in solvent use in some regions (e.g., EU and US) and a substantial increase in others (e.g., in South and East Asia). DCM feedstock use for HFC-32 production is increasing globally. Future global trends are difficult to predict. With the toxicity profile of DCM, general solvent uses are being increasingly regulated. Nevertheless, there is currently increasing global capacity to produce DCM to supply solvent and feedstock uses.

33. The estimated input of chlorine from VSLSs to the stratosphere in 2020 increased by about 10 ppt since the last Assessment and amounts to 130 ± 30 ppt, contributing about 4% of the total chlorine input. Brominated VSLSs, with mainly natural sources, contribute 5 ± 2 ppt to stratospheric bromine and show no long-term changes.

34. New evidence suggests that VSLS iodine, mostly from natural sources, is transported to the stratosphere, contributing 0.3–0.9 ppt iodine in particulate or gas-phase form. No observational trend estimates exist.

VIII. Production, by-production, feedstock use and intermediates

35. Since 2002, total reported ODS production has increased by a small amount, with increased production for feedstock uses offsetting the decrease in production for controlled emissive uses. The overall increase in ODS feedstock uses through the last decade has been mostly due to the increase in HCFC feedstock uses, particularly HCFC-22, while uptake of HFOs is driving a more recent increase in carbon tetrachloride feedstock use.

36. Emissions during chemical manufacturing results from products, co-products, by-products, feedstock, or intermediates.

- By-production of controlled substances in production processes occurs through over- or under-reaction enroute to the intended product, the presence of impurities undergoing reactions, and unintended side reactions.
- Intermediates are the chemical building blocks that raw materials pass through when being chemically transformed into products. Emission rates are much lower for intermediates than for the final product.

37. Several production processes generate HFC-23 by-production and emissions, including during the production of HCFC-22 and HFC-32. Production processes of other fluorocarbons can also result in HFC-23 by-production, although at lower rates. (See also Section III above.)

38. HCFC-22 is mainly used as feedstock to produce tetrafluoroethylene (TFE) and hexafluoropropylene (HFP), which are used in fluoropolymer production. The manufacture of TFE/HFP from HCFC-22 feedstock generates by-production and emissions of HFC-23 and PFC-c-318 (c-C4F8), and both have a very high GWP. These combined emissions as CO2 equivalent, without consideration of their possible abatement, are larger than the estimated emissions of HFC-23 from HCFC-22 production.

39. The current combined GWP-weighted emissions of CFCs plus HCFCs are comparable to those of HFCs. Reductions in future emissions of CFCs and HCFCs would require addressing emissions from banks and from production, by-production, and feedstock use. Global emissions of long-lived HFC-23, largely a by-product of HCFC-22 production, are likely to grow unless abatement increases or feedstock use of HCFC-22 decreases.

IX. While halon atmospheric abundances are declining slowly, there remains a demand for halon-1301 which may not be met in the future without new production

40. Tropospheric bromine from halons has decreased from a peak of 8.5 ± 0.1 ppt in 2006 to 7.3 ± 0.1 ppt in 2020. Halon-1211, halon-2402, and halon-1202 abundances continued to decline between 2016 and 2020. The rate of change of halon-1301 remained indistinguishable from zero. In 2020, it was the most abundant halon in the atmosphere.

41. Halon-1301emissions appear to be higher than anticipated from a fixed bank of fire suppression uses suggesting other source(s) of emissions such as from its feedstock production and use. Conversely, these higher emissions could be due to a higher rate of emissions from the halon-1301 bank than anticipated. If this is the case, the bank of halon-1301 could be significantly less than that required to fill ongoing needs.

42. Demand for halons for fire-fighting uses persists and will ultimately exceed the supply from available banks without the implementation of alternatives. There are continuing long-term uses of halons (e.g., in oil and gas facilities, nuclear facilities and military installations) and growing demand from civil aviation for halon-1301 owing to the lack of replacements for engine and cargo compartment fire-fighting applications in new aircraft. The current, estimated run-out timeframe of between 2030 and 2049, when halon-1301 would be no longer available, means that the civil aviation industry (and others) must look to their own stockpiles of halon-1301 to avoid grounding aircraft because of a lack of appropriate fire protection. New designs in the military sector may only be able to use halon-1301 or high-GWP HFCs to meet stringent design/life-safety requirements.

43. HFC phase-down regulations in non-Article 5 parties are having a bigger impact on the cost and availability of HFC fire suppressants than initially anticipated owing to their high GWP and the availability of a low-GWP fluoroketone suitable for some applications. As the supply of newly produced HFCs for fire protection decreases in response to phase-down regulations, HFC recycling will become even more important to fulfill demand.

X. Quantifying ODS and HFC banks and the time-course of their continued emissions is important in determining the pace of ozone layer recovery and potential impacts on climate.

44. Monitoring the banks of controlled substances and assessing their accumulation in equipment and products is important due to the potential impact of their uncontrolled emissions on ozone depletion and climate. A bank is defined as the total amount of controlled substances contained in existing equipment, stockpiles, foams, and other products not yet released to the atmosphere. This includes the “reachable” bank, also referred to as “active” bank, which includes those controlled substances contained in equipment or products in use and thus potentially reachable or accessible for management upon entering the waste stream at its end-of-life (EOL). In contrast, the “non-reachable” or “inactive” bank denotes substances that have been landfilled or illegally dumped along with the equipment or product.

45. Effective management of active ODS and HFC banks aims to minimize the global impacts associated with the release of ODSs and HFCs by minimizing emissions, and by supporting HFC phase-down through recovering HFCs for recycling, reclamation and reuse. Environmentally sound destruction of surplus or contaminated ODSs and HFCs at EOL is encouraged by the Montreal Protocol because it avoids unnecessary emissions and protects the stratospheric ozone layer and/or the climate. ODS and HFC banks in A5 parties, particularly in the refrigeration and air conditioning and foams sectors, are growing rapidly and will dominate global bank volumes by the early 2030s, resulting from declining banks in non-Article 5 parties and the rapid uptake of HFC-containing equipment in Article 5 parties. For the refrigeration and air conditioning and foams sectors, a combined estimated total of 6,000 ktonnes of ODSs and HFCs are contained in the active bank in 2022, equaling 16 $GtCO_2$ equivalent.

XI. Atmospheric concentrations of methyl bromide have not declined since 2016

46. Methyl bromide (CH_3Br) average global atmospheric abundances have varied annually between 6.5 ppt and 6.9 ppt during 2016–2020 with no clear overall trend. Northern Hemisphere abundances are approximately 0.8 ppt higher than in the Southern Hemisphere. Phase-out of controlled, non-exempted (i.e., non-QPS) uses of methyl bromide is reported to be virtually complete. Parties report that more than 99.8% of the baseline consumption of 66,428 tonnes for these controlled uses has been phased out by 1 January 2023. This means that methyl bromide is currently used almost exclusively for QPS applications, with consumption remaining generally stable at 10,000 tonnes per year and concentrated in about 17 consuming countries.

47. Economically and technically feasible alternatives are available for QPS and could replace about 40% of current uses. Recapture and/or recycling methyl bromide could avoid about 70% of methyl bromide emissions arising from QPS use; however, this technology is costly and there is little incentive to adopt it. Reduction in emissions for all remaining uses of methyl bromide for QPS, together with identification and stopping any unreported uses, are considered important factors to returning concentrations in the atmosphere to natural levels. Owing to the relatively short lifetime of methyl bromide in the atmosphere (0.7 years), adoption of any suitable alternatives and in some cases adoption of recapture/destruction would have an immediate benefit in reducing its atmospheric concentration.

XII. The timing and extent of the recovery of stratospheric ozone depends on future concentrations of both ozone-depleting substances and greenhouse gases

48. Model simulations show that the future recovery of the ozone layer outside of the polar regions will be governed mostly by GHGs, assuming continued adherence to the Montreal Protocol. The wide range of possible future levels of CO_2, CH_4, and N_2O is an important limitation to providing accurate future projections of ozone globally and for the ozone hole, as well as in other geographic regions. Total column ozone returns to 1980 values sooner for scenarios that assume larger emissions of greenhouse gases (higher climate forcing) than scenarios with smaller greenhouse gas emissions (lower climate forcing).

49. For 60°S–60°N, simulations show that total ozone recovers to the 1980 level more rapidly under a higher climate forcing scenario because large future increases in both CO_2 and CH_4 tend to

increase ozone. Under a low climate forcing scenario, the models project that ozone over 60°S–60°N may not reach the 1980 level by the end of this century. In this low climate forcing simulation, future declines in total ozone driven by rising N_2O outweigh the small future ozone increases caused by CO_2 and CH_4. For a medium climate forcing scenario, total ozone over 60°S–60°N is projected to return to the 1980 level around year 2040.

50. In addition to changes in ODSs and GHGs concentrations, projections of future ozone levels also depend on other factors that influence atmospheric chemistry and composition.

- Future commercial supersonic or hypersonic aircraft fleets could cause stratospheric ozone depletion through their emissions of substantial amounts of water vapor and nitrogen oxides (NO_x) into the stratosphere.
- Rocket launches presently have a small effect on total stratospheric ozone (much less than 0.1%). However, rocket systems using new propellants (e.g., hydrogen and methane) and increased launch frequencies could exert a substantial influence in the future. In addition, the demise of space hardware on re-entry through the atmosphere may have implications for stratospheric chemistry and composition that would lead to effects on ozone.
- Changes in stratospheric aerosol and water vapor from explosive volcanic eruptions would lead to increased ozone depletion and changes in stratospheric circulation. Ozone will become less sensitive to volcanic injections as ODS concentrations decline in coming decades.
- The intentional injection of sulfate aerosols into the stratosphere is being studied as a possible option for reducing climate warming and associated impacts. Model simulations show that injections have the potential to produce changes in ozone from chemical and dynamical processes, with the magnitude and sign of these changes depending strongly on the injection scenario and the state of climate change from anthropogenic activities.

XIII. Stratospheric ozone depletion and climate change are linked.

51. As reported in previous Assessments, ODSs are powerful greenhouse gases that lead to surface warming. Ozone itself is also a greenhouse gas and its changes impact climate. Increases in CO2 and decreases in ozone both tend to cool the stratosphere (while future increases in ozone have a warming tendency); cooling of the stratosphere away from polar regions slows the rate of ozone destruction, leading to higher ozone concentrations in the stratosphere.

52. The estimated rate of long-term cooling in the global middle and upper stratosphere (0.6 K $decade^{-1}$) based on observations is similar to previous Assessments. The long-term trends are primarily driven by increasing CO_2 and stratospheric ozone. In the future, increasing GHGs and the effects of ozone recovery would have opposing effects on stratospheric temperature and circulation.

53. New evidence suggests that ozone recovery has caused changes in the observed trends of the Southern Hemisphere atmospheric circulation between the ozone depletion and recovery periods. Model simulations support the attribution of these changes to ozone recovery. These results provide evidence that Southern Hemisphere circulation trends have responded to the recovery of Antarctic ozone due to the Montreal Protocol.

54. While there are no detectable surface impacts of long-term Arctic ozone changes, new evidence shows that for individual years low springtime Arctic ozone can amplify existing stratospheric circulation anomalies and their influence on tropospheric circulation and surface climate.

55. New evidence confirms that ozone depletion is unlikely to have driven the observed high-latitude sea-surface temperature cooling and changes in Antarctic sea ice since 1979.

XIV. Compliance with Protocol provisions ensures the protection of stratospheric ozone and climate.

56. Full compliance with the Montreal Protocol provisions contributes to ozone recovery and climate protection (as noted above).

- Total column ozone (TCO) returns to 1980 values around 2066 in the Antarctic, around 2045 in the Arctic, and around 2040 for the near-global average.
- In 2020, the Montreal Protocol has led to the avoidance of 0.17 ± 0.06°C global surface warming and 0.45 ± 0.23°C of Arctic surface warming. Projections show that by mid-

century the Protocol will likely avoid 0.79 ± 0.24°C compared to a scenario with uncontrolled ODS emissions.

- The Kigali Amendment avoids 0.3–0.5°C of warming by 2100.

57. Successful collaboration of experts across the Assessment Panels on science and technology has led to coordinated research and analyses to provide answers on sources of unexpected emissions of CFC-11 that occurred from 2013 to 2017. This issue highlights the need for vigilance to sustain compliance to guarantee the recovery of the ozone layer and maximize the speed of recovery.

58. Additional options for action to hasten the recovery of the ozone layer and protect the climate include the elimination of the remaining ODSs and their emissions, such as emissions from feedstock uses, by-product emissions, methyl bromide from QPS applications, VSLSs, and banks of controlled substances. These would individually lead to small-to-modest ozone benefits; collectively, they would advance ozone recovery by a maximum of 16 years.

XV. Scientific, Technical, and Environmental Policy Considerations.

59. If ODS feedstock emissions as currently estimated were to be eliminated in future years, the return of mid-latitude equivalent effective stratospheric chlorine (EESC) to 1980 abundances could be advanced by almost 4 years, largely due to reductions in CCl_4, and simultaneously reduce total climate forcing from ODSs. Better understanding and monitoring of emissions of controlled substances from production, by-production, and feedstock use, is important given the contribution to overall global emissions.

60. In 2021, nearly all reported methyl bromide production was for QPS purposes, which is an uncontrolled use under the Montreal Protocol. Alternatives to methyl bromide are available, as are recapture technologies, that would lead to a reduction in emissions. Eliminating future emissions of methyl bromide from QPS applications currently allowed by the Montreal Protocol would accelerate the return of mid-latitude EESC to 1980 abundances by two years (as noted in previous Assessments).

61. Emissions of anthropogenic very short-lived chlorine substances, dominated by dichloromethane (DCM), continue to grow and contribute to ozone depletion. If DCM emissions continue at their current level, they would deplete approximately 1 DU of annually averaged global TCO. Elimination of these emissions would rapidly reverse this depletion.

62. Anthropogenic N_2O emissions are now the largest of the uncontrolled ODS emissions, as other larger emission sources (CFC-11, CFC-12 and CFC-113) have been phased out. A 3% reduction in anthropogenic N_2O emissions, averaged over 2023–2070, would lead to an increase in annually averaged global TCO of about 0.5 DU over the same period, and a decrease of about 0.04 Wm^{-2} in radiative forcing, averaged over 2023–2100.

63. With increasing ODS and HFC banks in Article 5 parties, particularly in the refrigeration and air conditioning and foams sectors, quantities potentially available for recovery and management are expected to increase in Article 5 parties. The refrigeration, air conditioning and heat pump (RACHP) sector dominates HFC consumption, and it is estimated to be responsible for around 95% and 80% of the consumption in Article 5 parties and globally, respectively. Timely efforts to establish and finance EOL management capacity to prevent HFC emissions could have a significant impact, given the predicted size and growth of these banks in larger Article 5 parties. Addressing the barriers to the transboundary movement of EOL ODSs and HFCs will be important in supporting preferential recovery/recycling and environmentally sound destruction of EOL ODSs and HFCs, thereby minimizing their emissions.

64. Under the Kigali Amendment, parties are progressing with national regulations to phase-down HFCs, which is spurring market demand for lower-GWP alternatives and higher efficiency equipment. Even so, the range of new, lower-GWP alternatives creates challenges in finding the best solution for each application, considering factors such as flammability, toxicity, availability, cost, accessibility, and the equipment and system operating conditions.

- Ultralow-, low-, and/or medium-GWP alternative refrigerants are available for all RACHP applications and are being widely applied in some RACHP applications and regions. Accessibility is still a major hindrance for the widescale adoption.

- Most ultralow-, low-, and medium-GWP refrigerants have different flammability classes (lower flammability, flammable, and higher flammability). As such, the RACHP sector continues to update the relevant safety standards to enable their use (e.g., increased allowable flammable refrigerant charge limits for self-contained commercial refrigeration, air-to-air air conditioning, and heating-only heat pump applications).

- Addressing active banks containing high-GWP and energy-inefficient RAC equipment can further contribute to reducing energy demand and the servicing tail of unwanted high GWP refrigerants.
- Supply shortages of low-GWP alternatives in some sectors have eased with new production capacity of HFO and HCFO alternatives, but these shortages have delayed transitions away from HFCs across the various sectors of use. Future sufficiency of supply to meet growing demand due to the HFC phase-down will need to be monitored to avoid future disruptions.
- In most Article 5 parties, but especially in low- and very low-volume consuming countries, the majority of ODS and HFC refrigerants are used for servicing, so ensuring support for proper training and servicing would reduce direct emissions of ODS and HFC refrigerants and reduce the loss in energy efficiency in RACHP equipment over the lifetime of the equipment.
- In specific foam applications some challenges remain, particularly for smaller enterprises in some Article 5 parties due to the availability, safety, and cost of some lower-GWP alternatives as well as product performance requirements.
- While global consumption of HFCs for electronics manufacturing and magnesium production is relatively small, it is increasing for electronics manufacturing, and the alternatives to HFCs currently include other fluorinated gases, many of which have higher GWPs.
- Transition away from high-GWP HFC-pressurized metered dose inhalers (pMDIs) is a major undertaking with serious potential public health risks unless it is carefully managed.

65. Atmospheric monitoring station networks provide observations of global surface concentrations of long-lived ODSs and HFCs resulting from anthropogenic emissions. However, gaps in regional atmospheric monitoring limit the scientific community’s ability to identify and quantify emissions of controlled substances from many source regions.

66. Several space-borne instruments providing vertically resolved, global measurements of ozone-related atmospheric constituents (e.g., reactive chlorine, water vapor, and long-lived transport tracers) are due to be retired within a few years. Without replacement of these instruments, the ability to monitor and explain changes in the stratospheric ozone layer in the future will be impeded.

67. The impact on the ozone layer of stratospheric aerosol injection (SAI), which has been proposed as a possible option to offset global warming, has been assessed following the terms of reference for the 2022 Scientific Assessment Panel report. Important potential consequences, such as deepening of the Antarctic ozone hole and delay in ozone recovery, were identified. Many knowledge gaps and uncertainties prevent a more robust evaluation at this time.

68. Heightened concerns about the 21st century ozone layer include impacts of:

- further increases in nitrous oxide (N_2O), methane (CH_4), and CO_2 concentrations;
- rapidly expanding ODS and HFC feedstock use and emissions;
- continued and even increased use of methyl bromide for QPS use;
- climate change on total column ozone in the tropics;
- extraordinary wildfires and volcanic eruptions;
- and the increased frequency of civilian rocket launches and the emissions of a proposed new fleet of supersonic commercial aircraft.

69. While our knowledge of the effects of UV radiation is improving, there remain many challenges in adequately assessing the interactive effects of future changes in surface solar UV radiation and climate on human health, food security, ecosystem health and biodiversity. These challenges are in part due to uncertainty of how the effects of gradual climate change and periodic extreme climate events will alter UV irradiation at the Earth’s surface and subsequently affect species’ adaptation and ecosystem structure and function in a rapidly evolving environment. There is thus a clear need to include solar UV radiation with other climate change factors in experimental and modelling studies of human health and aquatic and terrestrial ecosystems to enable a more robust assessment of the environmental effects from changes in UV radiation under different future global climate scenarios.