

SPACE-BASED DATA CENTERS ROADMAP: THE CASE FOR CAUTION

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CHAPTER 2.3:

Stratospheric Ozone Depleation

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MAIN MESSAGES

- Space based-data centers (SBDCs) pose significant risks to the stratospheric ozone layer due to chemical reactions during their launch and demise.
- Mitigation strategies include sending satellites into higher orbits at the end of their useful lives, extending satellite lifetimes and using alternative materials for satellite components.
- Data and scientific understanding on these topics are limited.
- Regulatory authorities should delay large-scale deployment of SBDCs until risks related to stratospheric ozone depletion are better understood and mitigation strategies have been adopted as needed.

The stratospheric ozone layer is located roughly 15–30 km (9–18 miles) above the Earth's surface. Ozone at this altitude absorbs harmful radiation, including ultraviolet rays that cause skin cancer, cataracts and damage to crops and marine life.[1-5] During the middle of the 20th century, chemicals in widespread use began to deplete the stratospheric ozone layer. Growing quantities of these chemicals (including chlorofluorocarbons (CFCs), which were used in refrigerants, aerosol propellants and solvents) rose to the stratosphere, where their chlorine atoms reacted with and consumed ozone molecules. Scientists found that a single chlorine atom in the stratosphere could consume as many as 100,000 ozone molecules.[1]

In the early 1980s, scientists confirmed a hole in the stratospheric ozone layer above Antarctica. This led to adoption of the Vienna Convention for the Protection of the Ozone Layer in 1985 and the Montreal Protocol in 1987. Thanks largely to the binding controls imposed under the Montreal Protocol, more than 98% of ozone-depleting substances have been phased out and the stratospheric ozone layer is slowly recovering.[6]



Figure 1. *The ozone layer and ozone hole. Source: Wikimedia Commons. CC BY-SA 4.0*

Space-based data centers (SBDCs) could threaten this achievement. Rocket launch

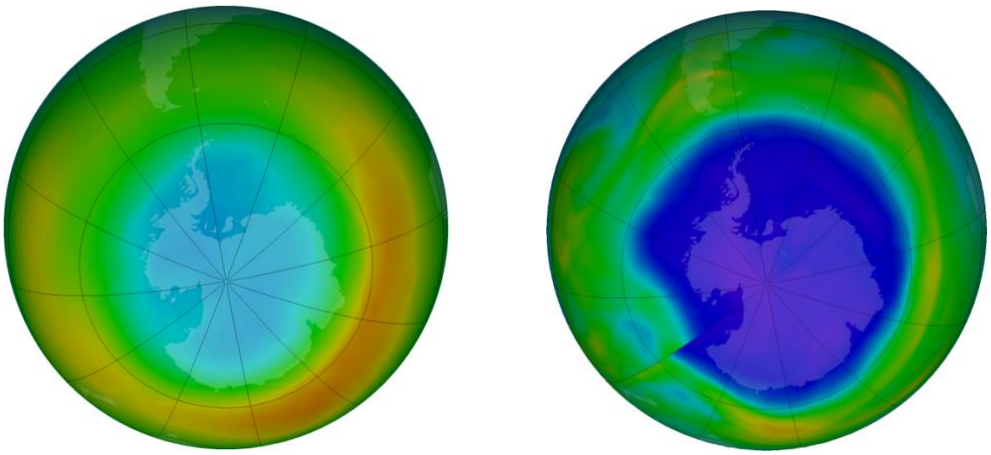


Figure 2. *The ozone hole in Sept. 1981 vs Sept. 2026. The more purple, the lesser the ozone. Source: NASA Ozone Watch*

emissions can release chlorine and black carbon into the stratosphere, leading to ozone depletion. Likely more serious, SBDCs re-entering the stratosphere at the end of their useful lives will burn up, releasing aluminum oxides (Al_2O_3) and generating nitrogen oxides (NOx), both of which deplete the ozone layer.

The extent of ozone depletion from SBDC constellations could be anywhere from small to very significant. This chapter explains the mechanisms that lead to this ozone depletion, discusses knowledge gaps and considers mitigation strategies. We recommend delaying large-scale deployment of SBDCs until risks related to stratospheric ozone depletion are better understood and mitigation strategies, if necessary, are implemented.

A. Launch Emissions

Launch emissions raise the first concern, with potential releases of chlorine and black carbon as rockets climb through the stratosphere after launch.[7,8]

Solid rocket motors release chlorine in the stratosphere during the launch phase, destroying ozone molecules. However, SBDCs are unlikely to be launched from solid rocket motors for cost reasons.[9] All current SBDC proposals envision using reusable liquid-fueled rockets. Except perhaps if reusable liquid-fueled rockets become unavailable or capacity-constrained, the use of solid rocket motors for SBDCs is unlikely.

Black carbon (soot) is another concern. Combustion of propellants during rocket launches releases black carbon in the stratosphere. Black carbon releases can deplete stratospheric ozone through several mechanisms that are not fully understood.[7,10] The amount of black carbon released varies by propellant, with kerosene propellants releasing the most black carbon. Liquid natural gas (LNG) propellants release less black carbon than kerosene, although data are limited and the topic requires significant additional research.[11-13] SpaceX and other SBDC companies mainly plan to use LNG propellants.

B. Re-Entry Emissions

SBDCs pose risks to the stratospheric ozone layer on re-entry for two distinct reasons.

i. Aluminum Oxides

Aluminum is a dominant material in satellites, typically making up roughly 35–40% of total satellite mass.[14] When a satellite re-enters the atmosphere at the end of its useful life, most of its aluminum burns up (ablates) and becomes Al_2O_3 nanoparticles. Al_2O_3 particles can catalyze reactions that convert chlorine into forms that destroy ozone. Al_2O_3 is not consumed in these reactions, so each particle can continue depleting ozone for decades. The extent of ozone depletion likely to result from greater quantities of Al_2O_3 in the stratosphere is uncertain and requires significant additional research.[15]

Satellite re-entries have begun changing the composition of the upper atmosphere, and far greater changes are possible. In 2016, satellite demise added roughly 2 tonnes of Al_2O_3 to the atmosphere. In 2022, this figure reached almost 17 tonnes. Ferreira et al. (2024) estimated that mega-constellations in planning could raise annual emissions of Al_2O_3 to 360 tonnes—more than 600% above natural levels.[15] This projection predates recent proposals for SBDC mega-constellations from SpaceX and others.



Figure 3. *Artist's rendition of satellite re-entering the atmosphere. Source: © ESA/David Ducross*

Al_2O_3 particles may take up to 30 years to drift down from the altitude where satellites ablate (roughly 60–80 km above the Earth) to the stratospheric ozone layer (at roughly 15–30 km).[16] Satellites launched today will continue creating ozone depletion risks for decades to come.

Our Reference 1-GW SBDC constellation has 10,000 satellites and assumes a 5-year satellite lifetime. (See Chapter 2.) Once the constellation is fully deployed, at least 2000 of its satellites would re-enter the Earth's atmosphere each year. Each of these satellites would carry roughly 1 tonne of aluminum. Estimates of the amount of Al_2O_3 created by the demise of a satellite vary. Ferreira et al. (2024) found that a single 250-kg satellite generates roughly 30 kg of these particles.[15] Based on this assumption, we find that our Reference 1-GW SBDC constellation would produce roughly 600 tonnes of Al_2O_3 per year.[a]

[a] Our reference satellite weighs 2.5 tons—10x the satellite in Ferreira et al. (2024). A 10x increase in Ferreira et al.'s estimate of 30 kg Al_2O_3 per satellite = 300 kg Al_2O_3 per satellite. Multiplying this by 2000 satellites demising per year = 600,000 kg of Al_2O_3 per year = 600 tonnes of Al_2O_3 per year.

Ross and Sheaffer (2014) estimate a stratospheric Al_2O_3 burden of roughly 2400 tonnes.[17]b Maloney et al. (2023) modeled the lifetime of Al_2O_3 in the stratosphere with a source of 10,000 tonnes per year, consistent with their projections of satellite mega-constellation size in 2040. They found this would result in a steady-state burden of 20,000–40,000 tonnes of Al_2O_3 in the stratosphere—vastly in excess of background levels.[18]

The rate of ozone depletion from additional quantities of Al_2O_3 in the stratosphere has not been established. The risks are unknown but potentially large.[15]

ii. Nitrogen Oxides

NOx created upon satellites' demise also threatens the ozone layer. The reaction starts when spacecraft re-entering the atmosphere create strong three-dimensional shock waves known as bow shocks. These bow shocks cause collisional heating, which causes nitrogen (N_2) and oxygen (O_2) in the air to react. This reaction principally creates nitric oxide (NO), which can convert to nitrogen dioxide (NO_2). Together these compounds are referred to as NOx, which destroys ozone (O_3) in the stratosphere

Estimates of NOx produced during satellite re-entry vary and are based on modeling results, not measurements of actual re-entries. Barker et al. (2024) estimate that NOx equal to roughly 40% of a re-entering satellite's mass is created.[12] Vliex et al. (2026) estimate a higher yield, with NOx roughly equal in mass to the re-entering object itself.[19] Applying this range to our Reference 1-GW SBDC, which has 2000 satellites with roughly 5000 total tonnes of mass re-entering each year, yields an estimate of between 2000 and 5000 tonnes of NOx.

The ozone loss from NOx created by a single constellation is hard to isolate, but Vliex et al. (2026) offers a useful real-world benchmark. They modeled the full inventory of 2022 global launch and re-entry activity, which totaled roughly 5000 tonnes of re-entering mass across 472 objects. They found that this activity caused an annual global ozone column loss of roughly 0.03% of the atmosphere's ozone column, with nearly 88% of this loss driven by NOx from re-entering objects.[19]

If a constellation with 1 million 2.5-tonne SBDCs with 5-year lives returned 200,000 satellites per year to Earth, this would imply (based on the figures in Vliex et al.) a loss of roughly 2.5–3% of the atmosphere's ozone column annually from nitrogen oxides alone. This would quickly reverse gains since 1985 in restoring the ozone layer and would deplete the ozone layer further, potentially to dangerous new levels.[20]

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[b] See Section 5.1: "In any case, the current submicron alumina stratospheric burden M_A is about 1.2 kt (with an additional burden of the same order in the concentrated but dispersing plumes from recent launches)..."[17]

C. Mitigation Strategies

Several mitigation strategies are possible, but all involve significant tradeoffs, cost or scientific uncertainty.



Figure 4. *ULA's Vulcan Centaur. Source: NASA/Ben Smegelsky*

For launch emissions, using LNG propellants instead of kerosene reduces black carbon releases into the stratosphere, though not to zero, and avoiding solid rocket motors eliminates chlorine emissions entirely. LNG propellants are the default choice in current SBDC proposals for cost reasons, although a capacity-constrained launch market could push some SBDC providers toward solid-boosted vehicles, such as United Launch Alliance's (ULA's) Vulcan Centaur or Europe's Ariane 6.[21] Black carbon releases from LNG propellants could be further reduced with modifications to fuel mixing or engine design.

For re-entry issues, there are several options:

1. Send satellites into higher orbits or toward the Sun at the end of their useful lives instead of letting gravity and atmospheric drag bring them back down toward the Earth. This would require significant additional propellant on board each satellite, adding cost and mass to every satellite in a constellation.

2. Extend satellite operational lifetimes, which reduces how often a constellation of a given size must be replenished and, correspondingly, how much Al_2O_3 and NOx it generates each year. Researchers who track anthropogenic material injected into the atmosphere have specifically recommended sharing space infrastructure and increasing satellite lifetimes as ways to reduce the atmospheric burden of large constellations.[14] On-orbit servicing and refueling, still an emerging capability, could extend satellite lifetimes further without requiring new spacecraft designs. For SBDCs, in particular, the useful service life of the on-board compute may be limited to roughly 3–5 years due to obsolescence, given how rapidly AI compute chip technology is evolving. On-orbit servicing to replace aging chips could therefore be an important mitigation strategy, if the capability could be reliably implemented.



Figure 5. *Artist's rendition of Ariane 6. Source: © ESA/David Ducross*

3. Adjust re-entry trajectories and timing. Because satellite re-entries are currently concentrated near the equator, NOx-driven ozone loss is concentrated as a result. Steering re-entries toward less sensitive

latitudes or seasons could reduce localized damage, although without reducing total emissions.[22]

4. Use alternative, non-aluminum materials for satellite components. In 2024, Japan's space agency, JAXA, launched several wooden satellites from the International Space Station (ISS). The satellites were designed to incinerate into fine ash upon re-entry without the metallic byproducts associated with conventional aluminum satellites.[23] Carbon composites are lightweight, although expensive, and could perhaps substitute for some portion of the aluminum on a spacecraft. Research on aluminum alternatives remains nascent.

Regulatory action and research investment could accelerate progress on each of these fronts. National regulatory authorities could also require atmospheric chemistry assessments before issuing launch permits.

D. Recommendations

In light of the foregoing, we offer the following four recommendations.

1. Regulatory authorities should delay large-scale deployment of SBDCs until risks related to stratospheric ozone depletion are better understood through direct measurement of re-entry plumes and related atmospheric modeling.

2. Government science agencies, as well as companies deploying SBDCs, should invest now in research and development (R&D) on strategies for mitigating the risk to the stratospheric ozone layer from SBDC constellations.[8] National regulators should require stratospheric ozone impact disclosures in satellite launch and re-entry licensing.

3. The Parties to the Vienna Convention should establish a standing study program focused on the space sector, including SBDCs. This program should quantify Al_2O_3, chlorine, black carbon and NOx fluxes across a range of SBDC deployment pathways and fund sampling of the stratosphere to reduce the uncertainties in current models.

4. If further research suggests threats to SBDCs and other space activities could present significant threats to the stratospheric ozone layer, the Parties to the Vienna Convention should amend the Montreal Protocol or adopt a new protocol to address these issues.

E. Conclusion

SBDCs pose a real risk to the stratospheric ozone layer, although the uncertainties on this topic are enormous.

Ozone depletion from large SBDC constellations could, over time, rival the magnitude of the ozone depletion that the Montreal Protocol has spent decades repairing. At the same time, the ozone depletion impacts of individual SBDCs could be small. The black carbon output of LNG engines remains uncertain, the chemistry of Al_2O_3 in the stratosphere has not been directly measured, and the cumulative effect of a large SBDC fleet has not been modeled. A robust research agenda to better understand the impacts of SBDCs on the stratosphere is essential.[8]

Several mitigation strategies could reduce risks. These strategies include cleaner propellants, better fuel mixes, improved engine designs, longer satellite lifetimes, alternative materials and smarter re-entry trajectories. Most or all of these strategies involve tradeoffs in cost, safety or feasibility, and none eliminates the risk entirely.

F. References

1 U.S. Environmental Protection Agency (EPA). Basic Ozone Layer Science; U.S. EPA, Washington, D.C., https://www.epa.gov/ozone-layer-protection/basic-ozone-layer-science (Accessed August 2026).

2 University Corporation for Atmospheric Research Center for Science Education (UCAR SciEd). The Stratosphere; UCAR SciEd, Boulder, Colorado, https://scied.ucar.edu/learning-zone/atmosphere/stratosphere (Accessed August 2026).

3 U.S. Environmental Protection Agency (EPA). Health and Environmental Effects of Ozone Layer Depletion; EPA, Washington, D.C., https://www.epa.gov/ozone-layer-protection/health-and-environmental-effects-ozone-layer-depletion (Accessed August 2026).

4 Craig S. Gilman & Karen N. Kähler. Decline of the ozone layer; EBSCO Information Services (EBSCO), Inc., Ipswich, Massachusetts, https://www.ebsco.com/research-starters/earth-and-atmospheric-sciences/decline-ozone-layer (2013).

5 Frank de Gruijl & Jan Leun. Environment and health: 3. Ozone depletion and ultraviolet radiation. Canadian Medical Association Journal 163, 851-855 (2000). https://www.cmaj.ca/content/163/7/851.

6 United Nations Environment Programme (UNEP). About Montreal Protocol; UNEP, Nairobi, Kenya, https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol (Accessed August 2026).

7 Laura E. Revell, Michele T. Bannister, Tyler F. M. Brown, Timofei Sukhodolov, Sandro Vattioni, John Dykema, David J. Frame, John Cater, Gabriel Chiodo & Eugene Rozanov. Near-future rocket launches could slow ozone recovery. npj Climate and Atmospheric Science 8, 212 (2025). https://doi.org/10.1038/s41612-025-01098-6.

8 Surendra P Sharma. Impact of Spaceflight on Earth's Atmosphere: Climate, Ozone, and the Upper Atmosphere; National Aeronautics and Space Administration (NASA) Technical Reports Server (NTRS), National Aeronautics and Space Administration (NASA) Technical Reports Server (NTRS), https://ntrs.nasa.gov/citations/20240013276 (2024).

9 SpaceNexus Research. How Much Does It Cost to Launch a Satellite? Falcon 9 at $74M, Every Rocket's 2026 Price; SpaceNexus LLC, Houston, Texas, https://spacenexus.us/guide/space-launch-cost-comparison (Accessed August 2026).

10 Sandro Vattioni & Timofei Sukhodolov. Rising rocket launches linked to ozone layer thinning; Phys.org, Douglas, Isle of Man, https://phys.org/news/2025-07-rocket-linked-ozone-layer-thinning.html (2025).

11 Selena Astroway. Why Methalox Engines Are Revolutionizing Modern Rockets; Orbital Exploration, Kent Town, Australia, https://orbitalxploration.com/why-methalox-engines-are-revolutionizing-modern-rockets (2025).

12 Connor R. Barker, Eloise A. Marais & Jonathan C. McDowell. Global 3D rocket launch and re-entry air pollutant and CO2 emissions at the onset of the megaconstellation era. Scientific Data 11, 1079 (2024). 10.1038/s41597-024-03910-z.

13 Christopher M Maloney, Robert W Portmann, Martin N Ross & Karen H Rosenlof. The Climate and Ozone Impacts of Black Carbon Emissions From Global Rocket Launches. Journal of Geophysical Research: Atmospheres 127, e2021JD036373 (2022). https://doi.org/10.1029/2021JD036373.

14 Leonard Schulz, Karl-Heinz Glassmeier, Moritz Herberhold, Adam Mitchell, Daniel M. Murphy, John M. C. Plane & Ferdinand Plaschke. Space waste: An update of the anthropogenic matter injection into Earth atmosphere. arXiv:2510.21328 (2025). https://doi.org/10.48550/arXiv.2510.21328.

15 José P. Ferreira, Ziyu Huang, Ken-ichi Nomura & Joseph Wang. Potential Ozone Depletion From Satellite Demise During Atmospheric Reentry in the Era of Mega-Constellations. Geophysical Research Letters 51, e2024GL109280 (2024). https://doi.org/10.1029/2024GL109280.

16 American Geophysical Union. Satellite 'megaconstellations' may jeopardize recovery of ozone hole; Phys.org, Douglas, Isle of Man, https://phys.org/news/2024-06-satellite-megaconstellations-jeopardize-recovery-ozone.html (2024).

17 Martin N. Ross & Patti M. Sheaffer. Radiative forcing caused by rocket engine emissions. Earth's Future 2, 177-196 (2014). https://doi.org/10.1002/2013EF000160.

18 Christopher M. Maloney, Robert W. Portmann, Martin N. Ross & Karen H. Rosenlof. Investigating the Potential Atmospheric Accumulation and Radiative Impact of the Coming Increase in Satellite Reentry Frequency. Journal of Geophysical Research: Atmospheres 130, e2024JD042442 (2025). https://doi.org/10.1029/2024JD042442.

19 Yvar S. W. Vliex, Jurriaan A. van 't Hoff & Irene C. Dedoussi. The Role of Propellant Type, Re-Entry, and Plume Reactions in the Atmospheric Impacts of Spaceflight. Earth's Future 14, e2025EF007795 (2026). https://doi.org/10.1029/2025EF007795.

20 Ross J. Salawitch (Lead Author), Laura A. McBride, Chelsea R. Thompson, Eric L. Fleming, Richard L. McKenzie, Karen H. Rosenlof, Sarah J. Doherty & David W. Fahey. Twenty Questions and Answers About the Ozone Layer: 2022 Update; World Meteorological Organization, Geneva, Switzerland, https://csl.noaa.gov/assessments/ozone/2022/twentyquestions/ (2023).

21 Jeff Foust. New Glenn failure worsens constrained launch market; SpaceNews, Alexandria, Virginia, https://spacenews.com/new-glenn-failure-worsens-constrained-launch-market/ (2026).

22 Connor R. Barker, Eloise A. Marais, Eric Y. P. Tan, Sebastian D. Eastham, Glenn S. Diskin, Joshua P. DiGangi, Yonghoon Choi, Andrew W. Rollins, Eleanor Waxman, T. Paul Bui, Charles K. Gatebe, Jonathan Dean-Day & Rajesh Poudyal. Radiative Forcing and Ozone Depletion of a Decade of Satellite Megaconstellation Missions. Earth's Future 14, e2025EF007229 (2026). https://doi.org/10.1029/2025EF007229.

23 Andrea Lloyd. JAXA’s First Wooden Satellite Deploys from Space Station; National Aeronautics and Space Administration (NASA), Washington, D.C., https://www.nasa.gov/image-article/jaxas-first-wooden-satellite-deploys-from-space-station/ (2025).