

ISSUES NOTE[1,2]

United Nations
Office for Outer Space Affairs

UN environment programme

Safeguarding Space

Environmental issues, risks and responsibilities

Executive summary

The space sector is growing exponentially, with over 12,000 spacecraft deployed in the past decade and many more planned as the world embraces the benefits provided by satellite services. This growth presents significant environmental challenges at all layers of the atmosphere. These include air pollution from launch emissions, spacecraft emissions in the stratosphere, spacecraft demise, orbital debris (legacy and new) and increased risk of collision creating more debris; with the potential to alter atmospheric chemistry and dynamics, climate change and deplete stratospheric ozone. Objects that do not disintegrate on re-entry into Earth's atmosphere pose threats to ground safety and marine ecosystems. The increase in space objects in orbit is also affecting the darkness and quietness of the sky and Earth-based astronomical observations.

Monitoring of upper-atmosphere impacts remains limited. There is a lack of high-altitude observations, in-situ measurements and systematic tracking of re-entry emissions or resulting chemical changes. Weak coordination among actors (space agencies, scientists, engineers, industry) further hinders a full understanding of the scale, nature and significance of these potential risks. While space agencies, regulators and launching states have started implementing sustainability measures and standards to reduce impacts, the rapid increase in space activity highlights the urgent need for sustainable practices to manage potential orbital congestion and environmental impacts to all layers of the atmosphere. A multilateral, interdisciplinary approach is needed to better understand the risks and impacts and how to balance them with the essential daily services and benefits that space activity brings to humanity.

1 This Issues Note provides a review of the latest literature on specific topics that are of relevance to UNEP's mandate. It also presents a set of agreed approaches and recommendations regarding UNEP's communication of the subject matter. It is meant to ensure consistency in messaging across the organization on this topic.

2 This note was developed by UNEP and UNOOSA with expert advice from participants of a joint workshop organized in Vienna May 2025.

1. **Space activities are related to the advancement of scientific knowledge, research and exploration, and they also contribute to daily activities on Earth such as earth observation, communications, positioning, navigation and timing, which provides a wealth of monitoring data about the Earth that is essential for advancing the Sustainable Development Goals.** While there is no universally agreed definition of the altitude where space begins, spacecraft deployment ultimately affects all layers of Earth's atmosphere (Figure 1). Space activities—including design, development and manufacturing of hardware (spacecraft and rockets), spacecraft launch and operations, related activities in outer space including rendezvous and proximity operations, and end-of-life disposal—pose diverse environmental impacts of varying significance and understanding.

2. **In the past six years, satellite launches and commercial space flights have surpassed those of the previous six decades** (Karacalioglu and Stupl 2016; Christensen *et al*. 2018; Boley and Byers 2021; Rao and Letizia 2022). Most recent spacecraft deployments have been in low earth orbit (LEO), with a large increase in spacecraft from so-called large constellations (built by rapid deployment of hundreds to thousands of satellites with five-year lifetimes) in 2024—increasing the number of objects expected to re-enter the atmosphere soon (Barker *et al*. 2024; Ferreira and Wang 2025). There are two key issues: the ascent of launchers through the troposphere, stratosphere and into the mesosphere, and re-entry of spacecraft in the mesosphere with associated material ablation as they descend to Earth.

3. **Atmospheric ablation (or "burn up") is the removal of spacecraft surface material under intense heat and friction during re-entry, through processes such as vaporisation, melting and chipping.** Similar effects are seen with meteorites: most burn up, but some fragments reach Earth. A key concern is the volume, composition and total mass of space debris and spacecraft re-entering the atmosphere at the end-of-life, since not all objects are expected to fully ablate—as evidenced by space debris that has landed on Earth (*The Independent 2025*). Re-entry mass can be tracked via mass conservation (Atmospheric Composition and Air Quality Group n.d.). There is also non-ablative re-entry producing oxides of nitrogen (NOx) from heating of the surrounding atmosphere (Zhang *et al*. 2023). As of 31 December 2024, approximately 23,000 objects had been placed in orbit with over 30,000 legacy objects in space, with the total launched mass expected to triple over the next century (European Space Agency [ESA] Space Debris Office 2025).

4. **This expansion, coupled with a reduction in satellite orbital decay lifetimes from 25 to 5 years** (Federal Communications Commission 2022; ESA 2024c) **to deal with congestion in LEO and reduce collisions, creates environmental impacts. With launch frequency rising, the urgency for action grows** especially as the global space economy is forecasted to reach US$ 3.7 trillion by 2040 (Brown *et al*. 2023).

5. **A number of organizations and researchers have highlighted the issue of the rapid increase in the launch of spacecraft globally and that emissions could impact atmospheric chemistry and stratospheric ozone specifically** (Park *et al*. 2021; Clormann and Klimburg-Witjes 2022; Ryan *et al*. 2022; Maggi *et al*. 2023; United Nations Environment Programme [UNEP] 2023; Ferreira *et al*. 2024; Maloney *et al*. 2024; Sharma 2024; UNEP 2024; Maloney *et al*. 2025). The Scientific Advisory Panel to the Montreal Protocol (UNEP 2023), and other researchers (Murphy *et al*. 2023), have highlighted concerns over aerosols released during and after re-entry and their potential impacts on stratospheric chemistry. Emissions may also generate unknown by-products in the upper atmosphere with uncertain effects. Additional issues include black carbon, NOx, thermal pollution and water vapour—the latter influencing cloud formations and aurora activity (Ryan *et al*. 2022; Murphy et al. 2023).

6. **Research has shown that re-entry of spacecraft, whether satellites or other objects, results in emissions of metals such as aluminium, lithium or copper and other compounds/**

elements within the atmosphere (Beck *et al*. 2019; Murphy *et al*. 2023; NOAA Chemical Sciences Laboratory 2023). Aluminium is widely used, and its anthropogenic contribution to the atmosphere is comparable with that coming from meteoroids (Boley and Byers 2021; Schulz and Glassmeier 2021). Estimates show that the anthropogenic contributions of Aluminium have surpassed that from natural sources in 2024 (Ferreira and Wang 2025). Between 800 to 5000 metric tons of rocket bodies and spacecraft are due to re-enter the atmosphere each year (Organski *et al*. 2020; (Organski *et al*. 2020; Schulz and Glassmeier 2021). It should be noted that most satellites, at least those in the LEO, are designed to demise in the atmosphere to ensure human safety on Earth, with only a small proportion—and only in higher geostationary orbit (GEO)—having been refuelled to date.

7. **The National Oceanic and Atmospheric Administration (NOAA) has matched the metal ratios in atmospheric dust with those of spacecraft objects, confirming their source** (NOAA 2023). NASA flights have found that at ~19km altitude, 20 per cent of sampled particles contained spacecraft-specific elements, estimating that 10 per cent of stratospheric particles originate from spacecraft ablation (Murphy *et al*. 2023). Trace metals—even at low concentrations—and particle size, are critical factors for atmospheric chemistry and radiative processes (Murphy *et al*. 2023). These particles may act as nuclei for cloud formation in the stratosphere and mesosphere. A small fraction may alter the occurrence and properties of polar stratospheric clouds by triggering ice or Nitric Acid Trihydrate formation (Kalicinsky *et al*. 2021). Potential impacts on the ionosphere remain uncertain (Pedatella and Liu 2025), underscoring the need for systematic research and monitoring as a basis for international guidelines on re-entry emissions.

8. **Nearly 130 million pieces of orbital debris—from fragmentation events (explosions and collisions), abandoned spacecraft, satellites and rocket stages, mission-related operational debris and intentional destruction such as anti-satellite weapon tests—pose escalating risks to space activities** (ESA Space Debris Office 2025). Additional debris has a potentially compounding effect where more debris means more debris strikes, shorter lifetimes, more launches to replace satellites and also more pollution.

9. **Elements from ablation are known to accumulate in polar regions due to the circulation pattern in the upper atmosphere that sends particles from the Equator, where most objects re-enter, to the poles** (Ross *et al*. 2009). Modelling concentration and where such materials would be found is increasingly important. While current atmospheric metal concentrations are assumed to be negligible, their accumulation is projected to rise with intensifying space activity and environmental change mobilizing pollutants.

10. **Annual collision losses are estimated between US$ 86 million to US$ 103 million (Johnson *et al*. 2023), underscoring the urgency of mitigation.** While technical solutions for debris removal are emerging, international rules, regulatory, licensing and market incentives are essentially absent (McKnight *et al*. 2021). Efforts to remove legacy debris, including the 50 most concerning derelict objects (McKnight *et al*. 2021), could raise international legal concerns if undertaken unilaterally but would also remove debris-generating potential in the LEO by 62 per cent (Environmental Science Services Administration [ESSA] 2024). NASA's 2024 cost-benefit analysis highlights the high expense and limited national capacity to act alone, with many states lacking clear space sustainability measures. Some studies propose in-space recycling or disposal to avoid re-entry and ablation impacts, but these early-stage solutions are currently insufficient to match the rising satellite count (ESA 2022a).

11. **Concerns have been raised about the potential negative impact on marine ecosystems when objects fall into the ocean as they can introduce toxic substances, physically damage or smother seabed organisms, disturb habitats and increase underwater noise** (International Maritime Organization [IMO] 2019a; IMO 2024). The London Convention and Protocol Scientific

Groups raised these issues in 2018 calling for a formal assessment of both environmental impacts and governance, including whether existing treaties cover such issues (IMO 2019b). Concerns also persist about the rising complexity and cost of potential recovery efforts.

12. **The rise in satellites, orbital debris emissions and dust is increasing light pollution and radio-frequency spectrum interference, disrupting astronomical research and altering the sky worldwide** (International Astronomical Union 2022). Satellites and debris reflect sunlight when illuminated, producing numerous rapidly moving objects in the sky (Barentine *et al*. 2023), and flares and glints add variability and flashes of light. Radio-frequency emissions from satellites—both intentional and unintentional—can interfere with astronomical observations and create broad radio-frequency interference, especially without coordination between operators and observatories (Di Vruno *et al*. 2023). Space debris forms a diffuse dust cloud around Earth that scatters light, raising the global night sky brightness—already estimated to be about 10 per cent brighter than the International Astronomical Union (IAU) limit for brightness (Kocifaj *et al*. 2021). Additional concerns include atmospheric metal layers altering natural sky glow, and proposals to place bright objects in the atmosphere, such as advertising (Schwarz 2003) and space mirrors to redirect sunlight (Baum *et al*. 2022; Jang and Woo 2025), which could have profound effects on the sky.

13. **Fuel, energy and water use, as well as waste production, are substantial environmental issues throughout the production lifecycle of spacecraft. Both launchers and the materials in spacecraft become waste unless they can be recycled or re-purposed (such as space capsules or reusable launchers) with such technology in early development.** Increasing space activity globally will increase the consumption of resources needed to manufacture spacecraft and launchers, including the need for rare earth elements. Some proponents advocate space mining, suggesting resources from space could help meet demand, but the idea remains speculative and controversial. It should be noted that Member States are presently negotiating a first draft set of initial principles around the legal aspects of space resource activities within the corresponding Working Group of the Committee on the Peaceful Uses of Outer Space (COPUOS).

14. **Space agencies and private actors are starting to consider sustainability such as exploring alternative fuels to lower launch emissions, limiting and managing debris, and adopting responsible disposal and satellite operations** (Martinez 2021). Although no launch is impact-free, advances in cleaner technologies, reusability and full life-cycle management represent progress while noting that environmental trade-offs are also evident3[1] (Dallas 2020; Miraux *et al*. 2022; Miraux 2025). ESA has committed to cutting its own direct emissions by 46 per cent and indirect emissions (including those of suppliers) by 28 per cent by 2030. It relies on life cycle assessment to identify hotspots and eco-design to implement technologies and processes to reduce impacts (ESA 2019; ESA 2024b). ESA has launched the Zero Debris Charter to achieve debris neutrality from 2030 onwards. A proposed EU Space Act would further promote sustainability and standardize life cycle assessment across the sector. Other nations currently use or are developing reusable launch systems and investigating lower-impact fuels. France's recent carbon footprint assessment and decarbonization roadmap are specific national-level examples (Centre National d'Études Spatiales [CNES] 2025).

15. **Efforts to advance circularity in the space sector include developing in-orbit servicing technologies, enabling on-orbit refuelling and designing methods for the safe removal of debris.** Agencies are assessing the feasibility and sustainability implications of emerging in-space propulsion and space-based solar power technologies, recognizing their potential benefits as well as their environmental and safety challenges (ESA 2022b). Key concerns include fuel types,

3 European Space Agency. The ESA Green Agenda. Retrieved from https://www.esa.int/About_Us/Climate_and_Sustainability/The_ESA_Green_Agenda

development of alternative fuels in space and plans for nuclear energy use in space, which could raise nuclear proliferation risks (Paek *et al*. 2025). Any implications can only be hypothesized at this point.

16. **Understanding of upper-atmosphere environmental impacts from spacecraft re-entry is constrained by limited observations and capacity, relying mainly on remote sensing, sparse in-situ measurements, small-scale experiments and modelling.** Groups are developing emissions inventories (Rumpf and Neubert 2023; Barker *et al*. 2024), but there are limitations in launch and re-entry data, and emissions factors do not necessarily reflect those of current day activities (Barker *et al*. 2024). High-altitude observations are scarce, with minimal systematic monitoring of which chemical species are injected, in what quantities and with what effects. Aircraft-mounted spectroscopic tools at ~20 km altitude can identify species but not precise concentrations (Murphy *et al*. 2023), limiting accurate modelling of impacts on stratospheric chemistry, radiative forcing and ozone dynamics. Data from uncontrolled debris re-entry are rare, and compositional information remains insufficient to assess long-term consequences or inform regulation (Bekki *et al*. 2021a; Maloney *et al*. 2024).

17. **Existing international space governance is largely based on a set of United Nations (UN) treaties**, including the Outer Space Treaty (1967), the Rescue Agreement (1968), the Liability Convention (1972), the Registration Convention (1975) and the Moon Agreement (1984). While the UN treaties on outer space do not establish a comprehensive environmental regime, Article IX of the Outer Space Treaty imposes a duty to avoid harmful contamination of outer space and adverse changes to the Earth's environment, while the Guidelines of the Committee on the Peaceful Uses of Outer Space for the Long-term Sustainability of Outer Space Activities (UNOOSA 2021) address environmental risks across launch, on-orbit operations and re-entry. International instruments outside of the UN treaty system, such as the Artemis Accords, contain more specific provisions on discrete areas (e.g. managing orbital debris) but do not include robust provisions on environmental protection or sustainability. The International Telecommunication Union (ITU) has required the disposal of Geostationary Orbit satellites (GSO) via ITU-R S.1003 (ITA 2000).

18. **National governments regulate and license launches and satellite deployment within a global co-ordination framework, but no overarching framework exists for in-orbit servicing or active debris removal.** The Pact for the Future (2024) commits Member States to strengthen cooperation on peaceful space use and to consider new frameworks for space traffic, debris and resources through COPUOS—though environmental sustainability focuses mainly on debris. Current national regulations govern materials, manufacturing, licensing, market access, insurance and spectrum allocation, but no entity yet oversees space tourism. COPUOS formed an expert group involving governments, space agencies and industry to address the need for global space traffic coordination as Member States acknowledge its urgency. Some countries have begun to define environmental damage to include outer space (Loyens and Loeff 2024), and some apply non-binding national standards (ESA 2023) that could become binding through licensing, procurement and market access requirements. However, protection of areas beyond national jurisdiction remains unclear. Nevertheless, principles of intergenerational law—equity, polluter pays and the duty to cooperate—apply to the Outer Space Treaty and should shape any future governance.

19. **The decisions made now will affect current and future generations, especially vulnerable groups like women and children who are more susceptible to environmental degradation and who have limited opportunities to engage in this sector, and who are often absent from discussions and activities relating to space** (Bekki *et al*. 2021b; Di Pippo and Vruno 2023). The Youth 20 (Y20) acknowledges the environmental impacts of space activities and calls for formally recognizing Earth's orbital zones as an integral part of the planetary environment. It also proposes a UN-led working group to advance interdisciplinary research on space's environmental aspects. The

Y20 recommend that the outcomes of this work be presented to the annual G20 Space Economy Leaders Meeting and considered for future integration into the Intergovernmental Panel on Climate Change assessment cycles, ensuring that space sustainability is systematically embedded within global environmental governance frameworks (G20 Space Economy Leaders Meeting 2021; Y20 Communiqué 2021).

20. **UNEP and UNOOSA recommend creating a dedicated UN interdisciplinary expert working group to review the status of knowledge** to facilitate (i) information-sharing among researchers, industry and governments for better decision making, and (ii) the organization of next steps and actions concerning the environmental impact of space activities. Once technical aspects are clear, these will become questions of governance for COPUOS to consider as the UN body responsible for maintaining the peaceful, safe and sustainable use of space.

The following actions would strengthen the understanding of the environmental impacts of space:

- **Enhanced and harmonized databases on the composition, trajectories and re-entry timelines of orbital objects.** This provides a critical foundation for impact assessment and informing international cooperation, while acknowledging the technical and operational challenges involved. Understanding evolving technologies—fuel types, propulsion systems, materials and re-entry behaviour of space hardware—will support informed policy and sustainable space operations.

- **Further development and expansion of inventories on the composition of materials used for spacecraft and related hardware, and breakdown of chemical products following ablation.** This will support modelling of atmospheric changes and assess impact, and support recommendations for the safest manufacturing materials to reduce emissions affecting the atmosphere.

- **Enhanced in-situ measurements and experimental studies**, including opportunistic data collection from commercial and tourist vehicles, detailed analysis of launch plumes and data specifically on ablation. This will help better understand the concentration, speciation and size distribution of re-entry metals and their oxides and other compounds on stratospheric ozone.

- **Continue the use of life cycle assessment approaches and apply more broadly to facilitate decision-making** with protocols for the best environmental outcomes in design, the choice of materials, manufacturing, operations and end-of-life (demise).

- **Improve data, assumptions and observations** to support atmospheric change modelling and enable model validation.

- **Assess the potential risks to human health** and property from the re-entry of large and heavy space objects that make landfall, including warning and mitigation activities.

- **Pursue resource efficiency and circularity as a priority.**

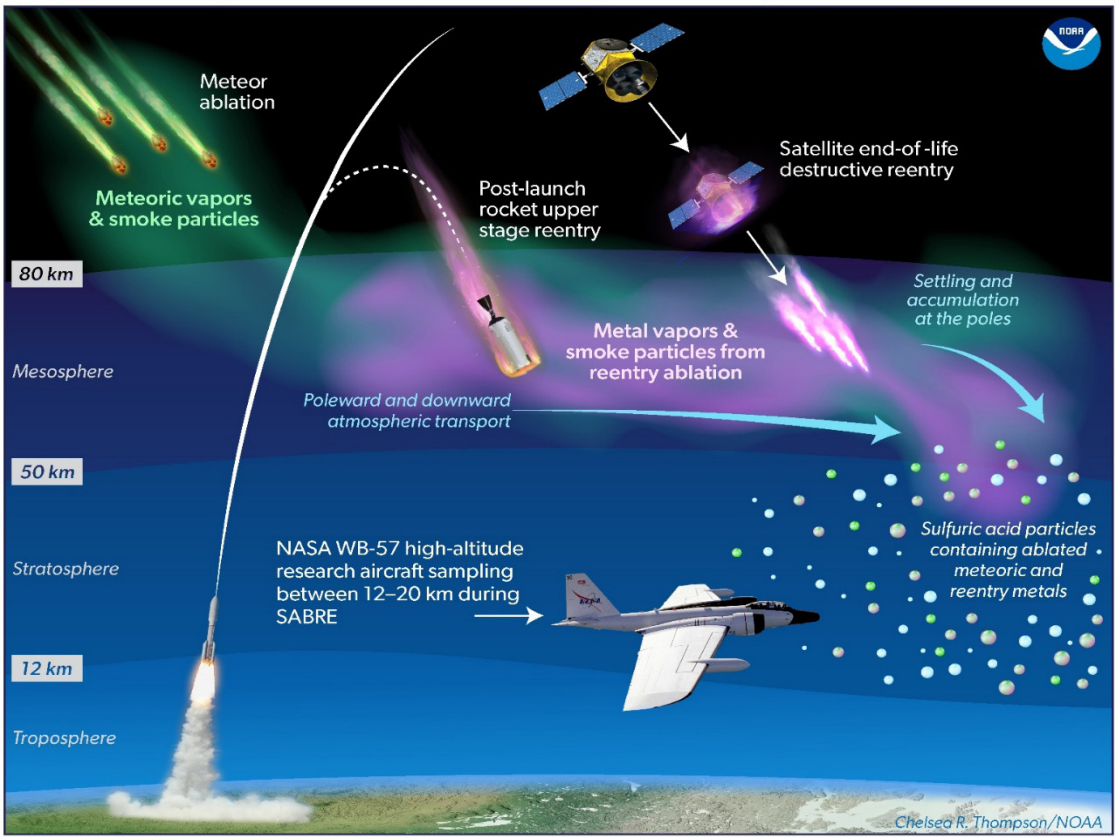
- **Monitor sky brightness and factors affecting dark** and radio quiet skies for retention of astronomical observation.

- **Develop and consolidate guidelines to implement sustainability measures, best practices, and standards** including in licensing and procurement. These should be accessible to all states. including emerging space-faring states and should consider environmental and cultural aspects.

- Given the nature of potential global impacts, **gender-responsive education and capacity-building in atmospheric science and environmental monitoring** could empower more women and underrepresented groups to contribute to understanding and mitigation efforts.

- **Review mechanisms for global collaboration, co-ordination and resource sharing**, considering gender balance, diversity and inclusion under the banner of Sustainable Space, to strengthen these efforts.

Figure 1: Incorporation of metals from re-entry into stratospheric particles



Source: Chelsea Thompson, NOAA

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