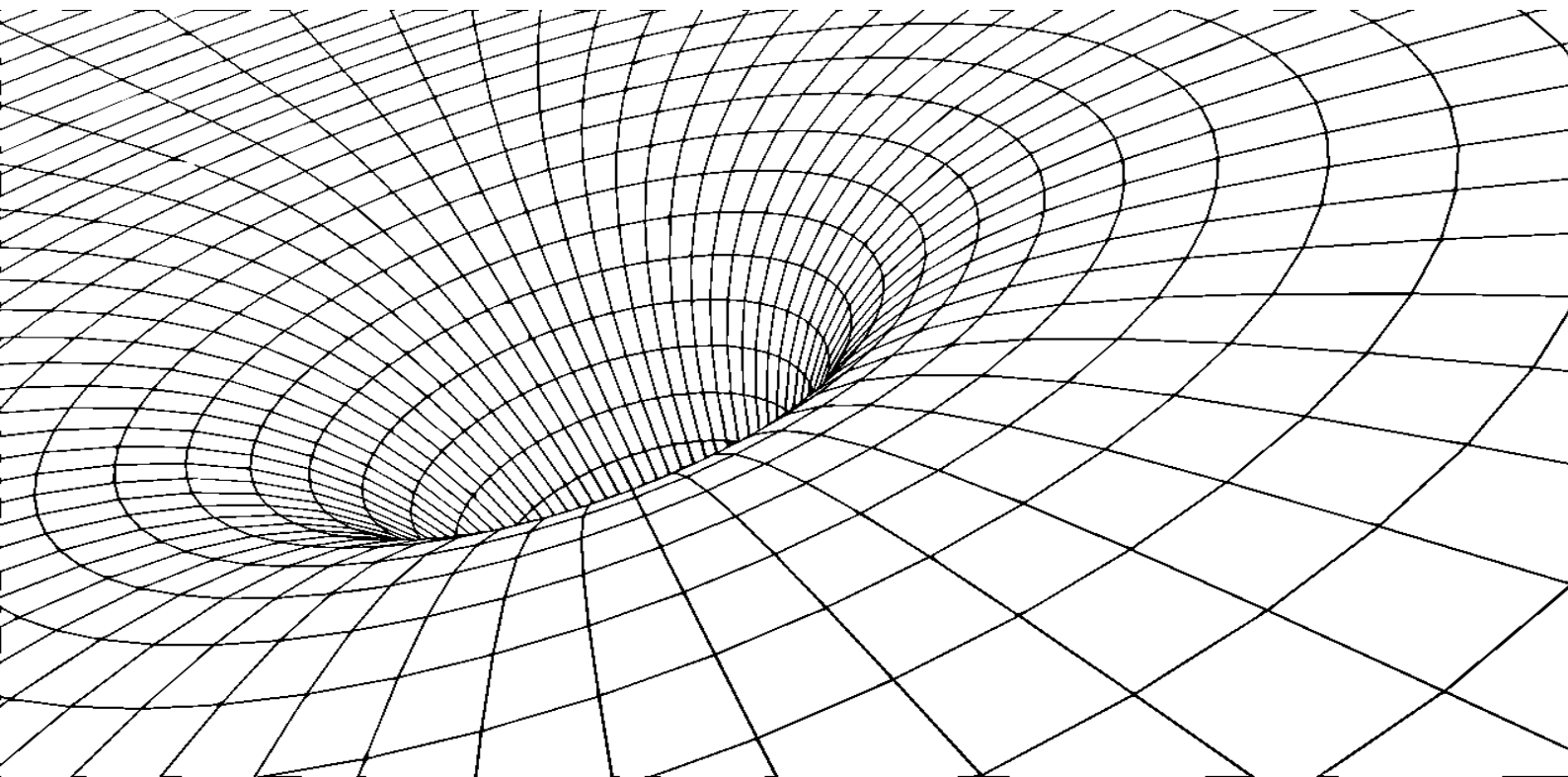


ORBITAL DEBRIS, RE-ENTRIES, AND THE STRATOSPHERIC ENVIRONMENT

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SPACE ECONOMICS

Working Paper n. 09/2026

Orbital Debris, Re-entries, and the Stratospheric Environment*

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Abstract

One approach to mitigating the risks posed by large orbital debris objects, i.e., derelict satellites and rocket bodies, is their deliberate deorbiting into Earth's atmosphere. During atmospheric reentry, a substantial fraction of an object's mass is ablated and burned, while the remaining material may survive and reach the surface. Controlled deorbiting of intact objects is therefore included among the mitigation strategies recommended in international orbital debris guidelines. However, this practice also has environmental implications for Earth's atmosphere. The ablation of spacecraft during reentry releases combustion by-products into the mesosphere, which can subsequently be transported into the stratosphere. These by-products consist primarily of metal vapors, particularly aluminum, and aluminum oxide particles. Such emissions may contribute to chemical processes that affect stratospheric ozone. This paper presents projections of future atmospheric reentries under different activity scenarios and evaluates the associated emissions of aluminum oxide released into the mesosphere and stratosphere, along with their potential impact on ozone depletion. Over a 100-year period, the modeled ozone depletion due to reentries is estimated at approximately -0.4 Dobson Units per year, corresponding to about 0.1% of the total ozone column.

Keywords: Orbital debris; Re-entries; Ozone depletion; Integrated Assessment Model.

JEL Classification: D62; E21; E22; Q53; Q58.

*Corresponding author: Anelí Bongers. E-mail: abongers@uma.es. The authors acknowledge the financial support from the Spanish Ministry of Science, Innovation and Universities through grant PID2023-152748OB-I00, and Regional Government of Andalusia through Research Project PPRO-SEJ122-G-2023. The authors declare that they have no conflict of interest or financial interests to disclose. Full replication code in GAMS is available from the authors upon request.

1. Introduction

Human activity in space generates a range of negative externalities affecting both the orbital environment and the Earth system. A major environmental negative externality arises from the generation of orbital debris. As a result of space operations, a growing population of artificial non-functional objects has accumulated in orbit, including upper stages of rocket bodies and defunct satellites.

Since the beginning of the space age, launch activities have relied predominantly on multi-stage rockets to place payloads into orbit. While the lower stages typically reenter the atmosphere shortly after launch and fall back to Earth, upper stages are often left in orbit and may remain there for extended periods if no end-of-life disposal strategy, such as controlled atmospheric reentry, is implemented. Similarly, spacecraft become orbital debris once they reach the end of their operational life and are abandoned in orbit. Some of these derelict satellites eventually reenter the atmosphere due to orbital decay driven by atmospheric drag, while others can be intentionally deorbited through controlled reentry procedures.

Derelict satellites and spent rocket bodies constitute a class of intact orbital debris that poses a significant threat to ongoing and future space activities, as first highlighted by Kessler and Cour-Palais (1978). In addition to these large intact objects, orbital debris fragments are continuously generated through satellite launches, routine operations, accidental breakups, and in-orbit collisions. The resulting fragments span a wide size distribution, from large trackable objects to sub-centimeter particles. Despite their small size, even centimeter-scale debris can cause severe damage due to hypervelocity impacts, potentially leading to catastrophic failures of operational spacecraft. This self-reinforcing process of debris generation, often referred to as collisional cascading (Kessler, 1991), raises concerns about the long-term sustainability of the near-Earth orbital environment.

The literature has estimated the cost of orbital debris using alternative approaches (Adilov et al., 2022, Nozawa et al., 2023, Bongers et al., 2025), primarily focusing on damages within the space environment. Nevertheless, orbital debris can also have consequences for the Earth’s atmosphere. While the risks associated with orbital debris are most commonly framed in terms of space safety and mission reliability, their impacts are not confined to space. Orbital debris also interacts with the Earth’s atmosphere through the process of reentry. Objects in low Earth orbit (LEO) gradually lose altitude due to atmospheric drag and ultimately reenter the atmosphere. In some cases, deorbiting is performed intentionally at the end of a satellite’s operational life, in accordance with international debris mitiga-

tion policies; in others, it occurs passively over time. These reentering objects, often large and massive, such as satellites and upper-stage rocket bodies, undergo intense heating and ablation as they pass through the upper atmosphere.

During reentry, a significant fraction of the object’s mass is vaporized and chemically transformed. In particular, aluminum, which is widely used in spacecraft structures, oxidizes to form aluminum oxide (Al_2O_3). These byproducts are injected into the mesosphere and can subsequently be transported into the stratosphere. There, they contribute to the growing burden of anthropogenic aerosols in the upper atmosphere. Unlike natural meteoritic inputs, which have long been part of the atmospheric system, these human-derived materials may differ in both composition and spatial distribution (Larson et al., 2017; Ryan et al., 2022).

The accumulation of such particles has implications for the stratospheric environment (Spencer, 1996). In particular, aluminum oxide particles can act as surfaces for heterogeneous chemical reactions that influence ozone chemistry. By facilitating the activation of chlorine and nitrogen species, these particles may contribute to catalytic cycles that deplete ozone. Although current estimates suggest that the global impact remains relatively small (Schulz and Glassmeier, 2021; Ryan et al., 2022; Ferreira et al., 2023; Maloney et al., 2025), the rapid increase in satellite deployments, especially with the emergence of large constellations, raises concerns about the future magnitude of these effects.

In this context, orbital debris should be understood not only as a space sustainability issue but also as an emerging component of Earth’s atmospheric system. The coupling between space activities and atmospheric chemistry highlights the need for integrated assessments that account for both orbital dynamics and environmental impacts on Earth. These interactions raise concerns about the continued effectiveness of the Montreal Protocol in the evolving space era, which has successfully limited emissions of ozone-depleting substances. The growing contribution of reentry-derived aerosols represents a novel and unregulated source of stratospheric perturbation that may partially offset expected ozone recovery.

This paper contributes to the literature by studying the implications of de-orbiting defunct satellites and rocket bodies and their burn-up in the upper atmosphere. To this end, we use a general equilibrium Integrated Assessment Model (IAM) that captures the interactions between the economy, orbital debris dynamics, and the stratospheric environment. The model produces trajectories for the relevant variables, including satellites, launches, different types of orbital debris, reentries, and emissions of aluminum oxide and their impact on ozone depletion. We compute trajectories for a centralized economy, in which a social planner maximizes global welfare (a first-best world).

The results indicate that the number of reentries will increase over time, leading to higher emissions of aluminum into the mesosphere and the stratosphere. As a consequence of increasing space activity and reentries, the anthropogenic stock of aluminum oxide will accumulate over time. However, we find that the effects on ozone by space activity are limited. Over the next 100 years, ozone depletion is relatively small, at approximately -0.4 Dobson Units (DU) per year, which corresponds to approximately a decline of about 0.1% of the total ozone column. The cumulative ozone depletion over the next 100 years due to re-entries is estimated in about 18 DU over the entire period, equivalent to roughly a 6% reduction in total ozone column.¹

The remainder of the paper is organized as follows. Section 2 describes the relationship between reentries and the stratospheric environment. Section 3 presents a general equilibrium integrated assessment model for evaluating the impact of space activity on ozone depletion in a first-best world. Section 4 presents the calibration of the model’s parameters. Section 5 presents the projections for the relevant variables. Finally, Section 6 provides concluding remarks.

2. Reentries and the stratospheric environment

The rapid expansion of space activity in low Earth orbit has established a new and increasingly significant link between the orbital environment and Earth’s atmosphere. In particular, the reentry of satellites and orbital debris provides a pathway for human-made materials to enter the upper atmosphere, with potential implications for the stratospheric environment. Understanding this connection requires integrating the physical processes of reentry with atmospheric chemistry and long-term environmental dynamics.

As satellites and debris reenter the atmosphere, they experience intense aerodynamic heating that leads to ablation and fragmentation. Most objects begin to disintegrate in the mesosphere, typically between 50 and 90 kilometers in altitude. During this process, structural materials, especially aluminum, are vaporized and chemically transformed. A substantial portion of this material oxidizes to form aluminum oxide (Al_2O_3), which condenses into fine particles. These particles are initially injected into the mesosphere but gradually descend into the stratosphere through atmospheric mixing and gravitational settling.

The presence of Al_2O_3 particles in the stratosphere is important because they act as surfaces for heterogeneous chemical reactions. These reactions do not directly destroy ozone

¹The change in ozone is measured in Dobson units (DU). DU measures the total column of ozone in the atmosphere, from surface to space. One DU is 2.69×10^{20} ozone molecules per m^2 (WMO, 2022).

but facilitate the activation of chemical species that do. In particular, particles provide surfaces on which relatively inert “reservoir” compounds containing chlorine and nitrogen are converted into reactive forms. These reactive species can then participate in catalytic cycles that break down ozone molecules. The result is a reduction in the total column of ozone, typically measured in Dobson Unit (DU), which represents the integrated amount of ozone in a vertical column of the atmosphere (WMO, 2022).

The magnitude of this effect depends on several factors, including the total mass of material reentering the atmosphere, the fraction converted into Al_2O_3 and the residence time of these particles. Current research suggests that roughly 10-12% of the mass of a reentering satellite may be converted into Al_2O_3 . Once formed, these particles can persist in the stratosphere for several years, with a characteristic lifetime on the order of 4 to 5 years. This persistence implies that the environmental impact is cumulative: even if annual injections are modest, repeated reentries over time can build up a stock of particles that enhances their chemical influence.

Although the global impact on ozone is currently small, it is not negligible. Present-day reentries contribute tens of tons of Al_2O_3 per year, although leading to very small changes in global ozone levels. However, projections for the future suggest more significant impacts. The deployment of large satellite constellations, such as Starlink by SpaceX, entails a steady and potentially large flux of satellites reentering the atmosphere at the end of their operational lifetimes. Under such scenarios, annual injections of hundreds of tons of Al_2O_3 are plausible. Over a decade, this could result in a persistent atmospheric burden of thousands of tons of particles, causing measurable, though still relatively minor, reductions in global ozone.

Beyond ozone depletion, Al_2O_3 particles may also influence the stratosphere’s radiative balance. As aerosols, they can scatter and absorb radiation, potentially altering temperature profiles and atmospheric circulation patterns. While these effects are less well understood than their chemical impacts, they represent an additional pathway through which orbital debris reentries could affect the climate system.

An important aspect of this issue is the comparison with natural sources. Micrometeorites continuously enter Earth’s atmosphere, delivering metals such as iron, magnesium, and some aluminum. However, the magnitude and composition of anthropogenic inputs are changing. In some future scenarios, aluminum injection from satellite reentries could exceed natural sources, introducing a qualitatively different aerosol into the stratosphere.

Schulz and Glassmeier (2021) show that currently the anthropogenic material influx is a

small fraction of the natural injection, but that large satellite constellations will disproportionately increase the anthropogenic injection of aerosols. Boley and Byers (2021) indicate that satellite reentries from the Starlink mega-constellation alone could deposit more aluminum into Earth’s upper atmosphere than is delivered by meteoroids, and that satellites could become the dominant source of high-altitude alumina. Although the mass of satellites is small compared to the ≈ 54 tons of meteoroid mass daily, the aluminum content differs significantly (less than 1% of meteoroids mass), whereas aluminum is the primary component of satellites and rocket bodies.

Ryan et al. (2022) use a radiative transfer model to determine the influence on stratospheric ozone, finding a small decline (0.01%) in global ozone for the year 2019, but up to 0.15% in the upper stratosphere. They show that upon the re-entry of orbital debris emissions of pollutants occur in high quantities, primarily NO_x , followed by Al_2O_3 . Murphy et al. (2023) indicate that when rocket bodies and defunct satellites reenter the atmosphere, they produce metal vapors that condense into aerosol particles, and that about 10% of the aerosol particles in the stratosphere contain aluminum and other metals from the burn-up of satellites and rocket bodies during reentry.

Ferreira et al. (2024) pointed out that a typical 250 kg satellite can generate around 30 kg of aluminum oxide nanoparticles, which may endure for decades in the atmosphere. They estimate that for the entire satellite population reentering the atmosphere in 2022, is around 17 metric tons (a 29.5% increase of aluminum in the atmosphere above the natural level). Scenarios involving mega-constellations reaches 360 metric tons of aluminum oxide compounds per year, which could provoke significant ozone depletion as aluminum oxide nanoparticles may remain in the atmosphere for decades. Shareefdeen and Al-Najjar (2024) offer a description of the type of pollutants from spacecraft combustion due to re-entry that lead to global warming and ozone layer depletion. Maloney et al. (2025) investigate the radiative impact of satellite reentry. During reentry, satellite emits vaporization, releasing aluminum oxide, and estimate a 1.5 K-temperature anomaly in the mesosphere and the stratosphere at Southern Hemisphere high latitudes, based on a estimated yearly emissions of 10,000 metric tons of alumina from reentering orbital debris. Finally, Wing et al. (2026) measured upper-atmospheric pollution caused by lithium atoms from a Falcon 9 re-entry. Their findings highlight that, although environmental concerns about re-entering space debris have primarily focused on the effects of aluminum and other metals on the stratospheric ozone layer, detecting and quantifying such pollutants in that region remains technically challenging and costly.

3. The model

This section describes the general equilibrium IAM for the space-economy that integrated by three blocks: an economy block, an orbital debris dynamics block, and a stratospheric environmental block. Whereas the first two blocks are interconnected, the third block is a by-product of the first two with no feedback.

3.1. The economy model

The general equilibrium integrated space-economy model is based on the optimal neo-classical growth model of Ramsey (1928), extended to account for human activity in space. Time is discrete and extends over an infinity horizon. The model includes a negative environmental externality in space resulting from the accumulation of orbital debris. It is assumed a centralized economy, where a social planner maximizes social welfare.

3.1.1. Preferences

The economy is populated by a large number of identical households, represented by a single representative household with instantaneous utility $U(\hat{c}_t, N_t)$, defined over per capita consumption $\hat{c}_t$, and where N_t is population. The aggregate consumption, c_t , is defined as $c_t = \hat{c}_t N_t$. The function $U(\hat{c}_t, N_t)$ represents the flow of utility and assumed to reflect overall social welfare. The function $U(\hat{c}_t)$ is assumed to be concave and twice continuously differentiable, CRRA-type.

$$U(\hat{c}_t) = \frac{\hat{c}_t^{1-\sigma}}{1-\sigma} \quad (1)$$

The problem to be solved by the social planner consists in maximizing the sum of discounted utility,

$$\max_{\{\hat{c}_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t \frac{\hat{c}_t^{1-\sigma}}{1-\sigma} N_t \quad (2)$$

where $\rho > 0$ is the subjective intertemporal preference parameter or the pure rate of social time preference. The discount factor, $0 < \beta < 1$, is defined as $\beta = 1/(1+\rho)$.

Households satisfy the following budget constraint which coincides with the feasibility constraint in the final-good sector:

$$c_t + i_t^k + i_t^s = y_t \quad (3)$$

where i_t^k is investment in physical capital other than satellites (Earth capital), i_t^s is investment in satellites (space capital), which includes all costs insert satellites into orbit, and y_t is final output. All prices are defined in output units and are normalized to one.

3.1.2. Launch cost

To place a service-providing satellite into orbit, a launch vehicle must be used. Launch vehicles, typically multi-stage rockets, account for a substantial portion of the total cost of satellite deployment. To reflect this, investment in space capital is divided into two components:

$$i_t^s = h_t + l_t \quad (4)$$

where h_t is the satellites hardware cost, and l_t is the launch cost. The launch cost is interpreted as an installation cost required to build up the satellite stock. It is modeled as a fixed adjustment cost per unit of investment, reflecting that launch prices are typically charged per kilogram of satellite mass, although they may vary depending on the target orbit. Alternatively, the launch cost can be viewed as a markup or premium over the purchase price of space capital.

The installation cost function for satellites is defined as:

$$l_t = m_t M_t H_t \quad (5)$$

where m_t is the launch cost per kilogram, M_t is the mass of the representative satellite, and H_t is the number of new satellites launched. This cost captures the notion that adjusting the capital stock is not frictionless, that is, spacefaring firms cannot install or reallocate space capital instantaneously or without incurring in launch costs.

3.1.3. The technology

We assume that all firms have access to the same technology; therefore, the analysis is conducted using a representative firm and a representative aggregate production function. Output is assumed to be a function of aggregate productivity, the stock of physical capital on the Earth, k_t , the stock of satellites, s_t , and labor, N_t . Given that most services provided by satellites can also be provided in the Earth (for example, internet access by terrestrial networks or Earth observation by gloves), but other services are exclusive (for example, global positioning), we assume a Cobb-Douglas technology,

$$y_t = a_t k_t^{\alpha_1} s_t^{\alpha_2} N_t^{1-\alpha_1-\alpha_2} \quad (6)$$

where a_t is the Total Factor Productivity (TFP), representing Hicks-neutral technological change, and $0 < \alpha_1, \alpha_2 < 1$, $\alpha_1 + \alpha_2 < 1$, where α_1 is the elasticity of output to Earth capital, and α_2 is the elasticity of output to space capital. Labor is assumed to be equal to population, and therefore, the growth rate of labor is equal to the population growth rate.

The accumulation of physical capital other than satellites follows the standard capital accumulation equation:

$$k_{t+1} = (1 - \delta_k)k_t + i_t^k \quad (7)$$

where $0 < \delta_k < 1$ is the capital depreciation rate.

The stock of satellites, measured in final output units as an equipment asset, is denoted by s_t , and is given by the following process,

$$s_{t+1} = (1 - \Lambda_t)[(1 - \delta_s - \varepsilon_s)s_t + q_t h_t] \quad (8)$$

where $0 < \delta_s < 1$ is the depreciation rate for satellites, ε_s is the fraction of operational satellites breakups due to design failures, and Λ_t is the damage function representing the fraction of operational satellites destroyed by collisions. This accumulation process establishes the link between the space environment and the accumulation of space capital. Damage results in the destruction of satellites, the reduction of space capital stock used in production, and the reduction of the final output. The stock of satellites law of motion incorporates an investment-specific technological change (ISTC), denoted by q_t , (see Greenwood et al., 1997). For simplicity, it is assumed that ISTC occurs only in the space sector.

3.1.4. Exogenous growth sources

The model incorporates three exogenous sources of growth: aggregate neutral technological change, investment-specific technological change for satellites, and aggregate labor growth. Aggregate productivity technological progress is characterized as,

$$a_{t+1} = \exp(g_{a,t})a_t \quad (9)$$

where $g_{a,t}$ is the growth rate of TFP defined as,

$$g_{a,t} = g_{a,0} \exp(-\delta_a t) \quad (10)$$

where δ_a is the decay rate in the TFP growth rate.

We assume a similar specification for the satellite investment-specific technological progress,

$$q_{t+1} = \exp(g_{q,t})q_t \quad (11)$$

where $g_{q,t}$ is the growth rate of ISTC defined as,

$$g_{q,t} = g_{q,0} \exp(-\delta_q t) \quad (12)$$

where δ_q is the decay rate in ISTC for satellites.

Finally, labor is assumed to equal population. Following the specification by Hassell (1975), population dynamics are defined as,

$$N_{t+1} = N_t \left(\frac{N^*}{N_t} \right)^\varsigma \quad (13)$$

where N^* is the asymptotic population at the end of the simulation period and ς is a population growth parameter.

3.2. The space model

We next describe the physical space component of the model. This block consists of three core elements: (i) the damage function, (ii) the emission (debris generation) function, and (iii) the laws of motion governing the stocks of the three debris species. Any human-made object that is no longer functional and remains in Earth orbit is classified as space debris. Traveling at very high velocities, such objects pose significant collision risks and can severely damage or destroy operational spacecraft.

3.2.1. The stock of pollution

Pollution in Earth's orbit takes the form of orbital debris. The stock of debris, D_t can be defined as:

$$D_t = W_t + Z_t + F_t \quad (14)$$

where W_t is the stock of derelict satellites abandoned in orbit, Z_t is the number of final-stage rocket bodies, and F_t are fragments larger than 1 cm.

Debris comes from different sources: launches (including derelict final-stage rockets and fuel deposit bodies), derelict satellites not removed from orbit, accidental explosions and breakups, collisions, and intentional debris creation through military activities, such as destroying a satellite using an anti-satellite missile.

3.2.2. Damages

Human activities in outer space produce pollution in the form of orbital debris, which travels at high speeds (on average of 36,000 km/h, or approximately 10 kilometer per second in LEO). This debris can collide with operational satellites and other spacecraft, leading to the loss of valuable space assets. While it is true that some uncontrolled, large mass debris in low orbit can re-enter the Earth's atmosphere and potentially cause harm to life or property, the probability of such an event is very low.

Following Farinella and Cordelli (1991), the number of satellites destroyed each period due to collision with debris is modeled as a function of both the stock of debris and the

number of operational satellites. Additionally, the probability of collision is very sensitive to the collision avoidance capabilities of operational satellites.

The damage function is defined as,

$$\Lambda_t = \theta[(1 - v_{w,t})W_t + (1 - v_{z,t})Z_t + (1 - v_{f,t})F_t] \quad (15)$$

where $\theta > 0$ is a parameter representing the collision probability capturing factors such as cross-section, relative velocity, and orbital overlap, $v_{w,t}$ represents the collision avoidance capability of satellites to derelict satellites, $v_{z,t}$ is collision avoidance against rocket bodies, and $v_{f,t}$ is collision avoidance against debris fragments. The probability of collision can be reduced through the use collision avoidance systems, which rely on tracking data and maneuver capabilities to prevent high-risk encounters.

Therefore, the number of operational satellites destroyed by collisions, X_t , can be defined as,

$$X_t = \theta[(1 - v_{w,t})W_t + (1 - v_{z,t})Z_t + (1 - v_{f,t})F_t][(1 - \delta_s - \varepsilon_s)S_t + H_t] \quad (16)$$

3.2.3. Derelict satellites

First, we account for the dynamics of derelict satellites. This type of debris are end-of-life satellites that are no longer operational (typically due to fuel depletion) and are not de-orbited but instead abandoned in orbit. In each period, the number of end-of-life satellites is $\delta_s S_t$, and a fraction χ of these are abandoned in orbit.

The law of motion of derelict satellites is given by,

$$W_{t+1} = (1 - \delta_w - \varepsilon_w)W_t - \theta(Z_t + F_t + (1 - v_{w,t})S_t)W_t - \frac{\theta W_t^2}{2} + \chi \delta_s S_t \quad (17)$$

where δ_w is the natural decay rate of derelict satellites, and ε_w is the fraction of derelict satellites that explode in each period. In case of explosions, the number of debris fragments generated is $\phi_w \varepsilon_w W_t$, where ϕ_w is the number of fragments per exploding derelict satellite. The term $\theta(D_t + (1 - v_{w,t})S_t)W_t$ represents the number of derelict satellites fragmented by collisions.

3.2.4. Rocket bodies

The second source of debris arises from the final stages of launch vehicles, which often remain in orbit after payload insertion. These rocket bodies are large objects that pose a significant risk of breakup. We assume the number of rocket bodies produced per launch is given by φL_t , where $0 < \varphi < 1$ represents the fraction of launches that generate this type

of debris. This fraction is strictly less than one to account for the use of reusable launch vehicles. Rocket bodies accumulate over time in a stock of large debris objects in orbit.

Second, the stock of body rockets can be defined as

$$Z_{t+1} = (1 - \delta_z - \varepsilon_z)Z_t - \theta(W_t + F_t + (1 - v_{z,t})S_t)Z_t - \frac{\theta Z_t^2}{2} + \varphi L_t \quad (18)$$

where δ_z is the natural decay rate of body rockets bodies, ε_z is the fraction of body rockets that breakup each period. The number of debris fragments produced by the breakup of a large rocket body is given by $\phi_z \varepsilon_z Z_t$. The term $\theta(D_t + (1 - v_{z,t})S_t)Z_t$ represents the number of rocket bodies fragmented by collisions.

3.2.5. Fragments

The third type of debris considered are fragments. The stock of fragments increases due to the following sources: debris from launches (mission-related objects), breakups of derelict satellites and body rockets, and collisions between debris and operational satellites.

The first source of debris is mission-related objects (MROs), which are directly linked to the number of launches. We represent this debris generation process as ωL_t , where ω denotes the number of debris items created per launch at the time of launch. This type of debris is classified as fragment and includes protective fairings, covers, adapters, bolts, cables, and similar components.

The fourth source of debris arises from fragmentation events caused by the explosion or breakup of derelict satellites and rocket bodies. These events may be either unintentional or deliberate. Unintentional fragmentation typically results from the breakup of satellites, upper-stage rocket bodies, or engines. A primary cause of in-orbit explosions is residual fuel remaining in tanks or fuel lines after mission completion. Over time, the harsh space environment degrades structural materials and internal components, potentially leading to leaks, mixing of propellant components, and spontaneous ignition. Batteries may also fail explosively. When such failures occur, the original object is destroyed and its mass is dispersed into numerous fragments of varying sizes and velocities.

A final source of debris is fragmentation due to collisions. The model accounts for collisions between operational satellites and debris, as well as collisions involving derelict satellites, rocket bodies, and existing fragments. Taking all these mechanisms into account, we next specify the laws of motion governing the three categories of orbital debris.

Formally, the law of motion of fragments is given by,

$$\begin{aligned}
F_{t+1} = & (1 - \delta_f)F_t + (1 + \Gamma)\omega L_t + (1 + \Gamma)\gamma_s X_t + (1 + \Gamma)\phi_w \varepsilon_w \theta W_t \\
& + (1 + \Gamma)\phi_z \varepsilon_z Z_t + (1 + \Gamma)\gamma_w \theta (Z_t + F_t)W_t + (1 + \Gamma)\gamma_w \theta \frac{W_t^2}{2} \\
& + (1 + \Gamma)\gamma_z \theta (W_t + F_t)Z_t + (1 + \Gamma)\gamma_z \theta \frac{Z_t^2}{2}
\end{aligned} \tag{19}$$

where δ_f is the natural decay of fragments, γ_s is the number of tracked debris fragments created by a collision that destroys an operational satellite, and ω is the number of tracked fragments produced per launch. We exclude the possibility that operational satellites can breakup due to design failure. The number of tracked fragments produced by the collisions of derelict satellites with other debris is denoted by γ_w , and γ_z represents the number of tracked fragments produced by the collision of rocket bodies with other debris. The parameter Γ is a scaling factor that converts the number of fragments larger than 10 cm into fragments larger than 1 cm.

3.3. The stratosphere environmental model

The last block of the model is a simplified representation of the mesosphere and stratosphere environment related to the re-entry of big orbital debris.

3.3.1. Re-entries

It is assumed that the number of reentries of controlled rocket bodies depends directly on the number of launches. Let L_t denote the number of launches at time t and let φ represent the fraction of launches whose rocket bodies are successfully recovered or reused. Then, the number of reentries from controlled rockets is given by $(1 - \varphi)L_t$. For uncontrolled rocket bodies, reentries are instead determined by the existing stock of objects in orbit, Z_t , with δ_z representing the fraction of these bodies that naturally reenter during the period. This approach distinguishes between reentries driven by new launches and those resulting from the accumulated orbital stock, providing a clear framework for quantifying the sources of reentering objects. Combining these sources, the total number of rocket body reentries can be expressed as:

$$Z_t^d = \delta_z Z_t + (1 - \varphi)L_t \tag{20}$$

A similar framework applies to derelict satellites. Let S_t denote the number of newly launched satellites, δ_s the fraction of these satellites that eventually reenter, and χ the fraction that remain in orbit. Let W_t represent the stock of existing derelict satellites and

δ_w the fraction of these that reenter naturally. The total number of derelict satellite reentries is then,

$$W_t^d = \delta_w W_t + (1 - \chi)\delta_s S_t \quad (21)$$

3.3.2. Emissions of aluminum oxide

Emissions of aluminum oxide depend on the fraction of aluminum of each type of objects and on the fraction of aluminum that transforms in aluminum oxide. The associated emissions of aluminum oxide (Al_2O_3) in the mesosphere are given by:

$$E_t = v[\tau_w M_w W_t^d + \tau_z M_z Z_t^d] \quad (22)$$

where M_w denotes the average mass of derelict satellites, M_z denotes the average mass of rocket bodies, τ_j denotes the fraction of aluminum content in each type of object $j \in \{W, Z\}$, and v represents the fraction of material that oxidizes during atmospheric reentry due to ablation. Emissions are measured in gigagrams (1 Gg=10⁶ kg).

We consider two separate atmospheric processes. The first, is the injection layer corresponding to the mesosphere (50-80 km), where reentries occurs and where aluminum oxide is initially produced. The second layer is the stratosphere (15-50 km) where ozone chemistry occurs.

The law of motion of the stock of mesospheric (Al_2O_3) is given by:

$$G_{t+1} = (1 - \delta_g - \psi)G_t + E_t \quad (23)$$

where δ_g is the decay rate of aluminum oxide in the mesosphere, and ψ is the fraction moving from mesosphere to stratosphere.

The law of motion of the stock of stratospheric (Al_2O_3) is given by:

$$B_{t+1} = (1 - \delta_B)B_t + \psi G_t \quad (24)$$

where δ_B represents the rate of stratospheric sedimentation (see Ryan et al., 2022). Ozone depletion is measured in Dobson Units,

$$\Delta\Omega_t = -\varepsilon_o B_t \quad (25)$$

where ε_o denotes the ozone depletion efficiency of stratospheric aluminum oxide (DU per Gg).

4. Initial data and calibration

Initial data corresponds to the year 2025. Table 1 summarizes initial values for the key variables of the model, including the initial stock of Al_2O_3 in the mesosphere and in the stratosphere. These stock have been calculated using data from re-entries of rocket bodies and derelict satellites for the period 1967-2025, calculating the emissions of aluminum oxide and computing their accumulation processes in both the mesosphere and the stratosphere. We use reentry data from the ESA’s DISCOS database to estimate the annual mass of the reentries during the period. The resulting stock of anthropogenic aluminum oxide for the year 2025 is 2.49 Gg (gigagrams) in the mesosphere and 0.52 Gg in the stratosphere.²

Tables 2 and 3 present the calibrated parameters of the model. For a detailed description of the calibration of both economic and space parameters see Bongers and Torres (2025).

Table 1: Initial values for the year 2025

Variable	Value	Units	Source
World GDP	206.878	Trillions international US\$	IMF
Earth Capital stock	549.345	Trillions international US\$	Internal
Space capital stock	1.0385	Trillions international US\$	Internal
World Population	8,200	Millions inhabitants	United Nations
Operational satellites	12,900	Units	ESA
Number of launches	321	Units	NASA
Derelict satellites	2,950	Units	ESA
Rocket bodies	2,136	Units	NASA
Orbital debris > 10 cm	41,100	Units	NASA/ESA
Orbital debris > 1 cm	1,241,100	Units	NASA/ESA
Stock of Al_2O_3 in mesosphere	2.49	Gigagrams	Internal
Stock of Al_2O_3 in stratosphere	0.52	Gigagrams	Internal

Table 4 shows the calibration of the parameters of the stratosphere environmental model. While vertical transport rates from the mesosphere to the stratosphere are constrained by observational and modeling studies (e.g., Plane et al., 2021), the fraction of particles removed prior to reaching the stratosphere is not directly observed. We therefore introduce a mesosphere removal parameter, δ_g , which captures unresolved loss processes and calibrate it to match plausible residence times. Aluminum oxide are chemically very stable, are refractory (don’t easily react or evaporate), and exist as very small particles (nanometer–micron scale). Therefore, particles can remain suspended for many years, vertical transport is very slow and removal is dominated by gradual processes.

²A gigagram is equivalent to 1,000 tonnes.

Table 2: Baseline calibration of economic parameters

Parameter	Definition	Value	Source
ρ	Pure preferences parameter	0.015	Nordhaus (2008)
σ	Risk aversion parameter	1.500	Nordhaus (2008)
α_1	Capital share	0.3479	BEA
α_2	Satellite share	0.0021	BEA
δ_k	Capital depreciation rate	0.07	Standard
δ_s	Satellite depreciation rate	0.15	NASA
g_a	TFP growth rate	0.015	Assumption
g_q	Satellite ISTC growth rate	0.030	Assumption
δ_a	TFP growth decay rate	0.001	Assumption
δ_q	ISTC growth decay rate	0.005	Assumption
ς	Population growth parameter	0.05	United Nations
μ	Conversion parameter	4,942	Internal

Table 3: Baseline calibration of space parameters

Parameter	Definition	Value	Source
η	Satellites per launch	10	NASA
θ	Collision risk parameter	1.25×10^{-10}	ESA
χ	Fraction of abandoned satellites	0.40	ESA
δ_f	Fragment natural decay rate	0.01	NASA
δ_w	Derelict satellites natural decay rate	0.00015	Lafleur (2011)
δ_z	Rocket bodies natural decay rate	0.00015	Lafleur (2011)
ε_w	Fraction of dead satellites breakups	0.0012	NASA
ε_z	Fraction of body rocket breakups	0.0012	ESA
φ	Body rockets per launch	0.40	ESA
ω	Fragments > 10 cm per launch	4	ESA
ϕ_w	Fragments > 10 cm per derelict satellite breakup	44.6	ESA
ϕ_z	Fragments > 10 cm per rocket body breakup	100.2	NASA/ESA
γ_s	Fragments > 10 cm per operational satellite collision	70	NASA/ESA
γ_w	Fragments > 10 cm per derelict satellite collision	70	NASA/ESA
γ_z	Fragments > 10 cm per rocket body collision	70	NASA/ESA
Γ	Proportion parameter fragments 10 cm to 1 cm	33.4	ESA

Table 4: Chemical parameters

Parameter	Definition	Value	Source
δ_g	Al ₂ O ₃ mesospheric decay rate	0.05	Assumption
ψ	Transfer rate of Al ₂ O ₃	0.05	Hervig et al. (2021)
δ_b	Al ₂ O ₃ stratospheric decay rate	0.20	Toohey et al. (2025)
M_w	Mass of derelict satellites (kg)	500	ESA
M_z	Mass of rocket bodies (kg)	3,000	ESA
τ_w	Aluminum percentage in derelict satellites	0.30	Ferreira et al. (2023)
τ_z	Aluminum percentage in rocket bodies	0.50	Ferreira et al. (2023)
ν	Conversion fraction to oxide	0.90	Plane et al. (2021)
ε_o	Ozone depletion parameter	0.05	Ryan et al. (2022)

The removal rate of aluminum oxide in the mesosphere is not directly observed and is therefore calibrated based on estimates of vertical transport and residence times of meteoric smoke particles. Observational and modeling studies suggest that metal-containing aerosols injected in the mesosphere can take on the order of 10-30 years to descend into the stratosphere (Hervig et al., 2021). Consistent with this timescale, we assume a mesosphere removal rate $\delta_g = 0.05$, corresponding to an average residence time of approximately 20 years.

To our knowledge, direct estimates of the residence time of aluminum oxide in the stratosphere are not available. We therefore rely on the literature on stratospheric aerosols, which indicates decay timescales on the order of 1-2 years for volcanic sulfate particles (Toohey et al., 2025). Given differences in particle properties and the continuous injection of material from the mesosphere, we adopt a more persistent effective lifetime of approximately five years, corresponding to a decay rate $\delta_b = 0.2$.

During atmospheric reentry, aluminum is efficiently oxidized under high-temperature conditions, forming aluminum oxide particles. Modeling and observational studies suggest that a large fraction of ablated aluminum is converted into Al₂O₃, with effective conversion rates on the order of 70-100% (Plane et al., 2021). Given typical satellite compositions, this corresponds to approximately 10-12% of total satellite mass being converted into Al₂O₃.

Rocket bodies are typically constructed from aluminum alloys, comprising roughly 50% of their dry mass. We use data from Ferreira et al. (2023), and use a 30% of aluminum percentage for derelict satellites and a 50% for rocket bodies. Combined with efficient oxidation during reentry, this implies that a large fraction of the mass can be converted into aluminum oxide aerosols.

The parameter ε_o can be interpreted as a reduced-form representation of the heterogeneous chemical processes occurring on Al₂O₃ aerosol surfaces. From a microphysical per-

spective, injected Al_2O_3 generates substantial reactive surface area, which facilitates catalytic ozone destruction through chlorine activation. Chemistry-climate model simulations indicate that the associated efficiency lies in the range of 0.01-0.1 DU per Gg of injected material. In line with these estimates, we adopt a central value of $\varepsilon_o = 0.05 \text{ DU/Gg}$.

5. Results

The model is simulated for a centralized economy in which a social planner maximizes social welfare and determines the optimal trajectories of the key variables, taking into account the on-orbit damages caused by orbital debris, namely, collision risk. However, it is assumed that the social planner does not internalize the effects of ozone depletion on economic activity, either on Earth or in space. The model is simulated over a 150-year horizon, with the final 50 years discarded to avoid contamination of the results by terminal conditions.

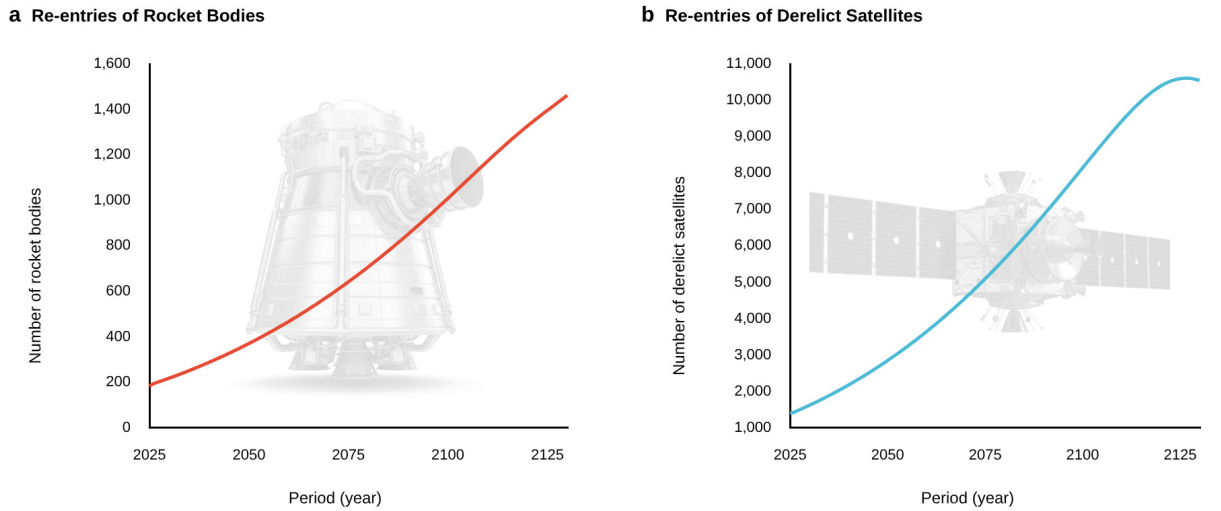


Figure 1 | Projected atmospheric re-entries over a 100-year horizon. Estimated annual re-entries of **a**, rocket bodies and **b**, derelict satellites from 2025 to 2130. Both metrics exhibit a steady growth driven by the accumulation of existing orbital debris and the implementation of controlled de-orbiting mitigation strategies under a centralized space economy model.

Figure 1 presents the projected trajectories of atmospheric reentries, distinguishing between derelict satellites and rocket bodies. Although other types of orbital debris also reenter the atmosphere, their mass is relatively small compared to that of rocket bodies and derelict satellites. The projections indicate that reentries of these objects will grow steadily over the next century, although the rocket bodies stabilized at the end of the simulation horizon due the increasing number of collisions of operational satellites with orbital debris, which

reduces the optimal number of satellites in orbit. The estimated number of rocket body reentries in the base year (2025) predicted by the model is approximately 200, and increases to about 700 over the 100-year horizon. A fraction of these correspond to controlled reentries immediately following launch, while the remainder are uncontrolled reentries of upper-stage rocket bodies that have been abandoned in orbit since 1957. A similar pattern is observed for derelict satellites: some reentries are controlled at the end of operational life, while others result from satellites abandoned in previous periods. Predicted number of derelict satellites re-entries for the initial year is large due mainly to the short operational life of Starlink satellites, scalating to above 10,500 for the year 2125.

Figure 2 plots the trajectory of anthropogenic emissions of aluminum oxide into the mesosphere resulting from atmospheric reentries. These emissions depend on the mass of both rocket bodies and derelict satellites, and assuming that the metal composition of both intact debris objects remains without changes over the simulation horizon. They are estimated to start at around 0.5 gigagrams in 2025 and increase steadily to over 3.5 gigagrams over a 100-year period.

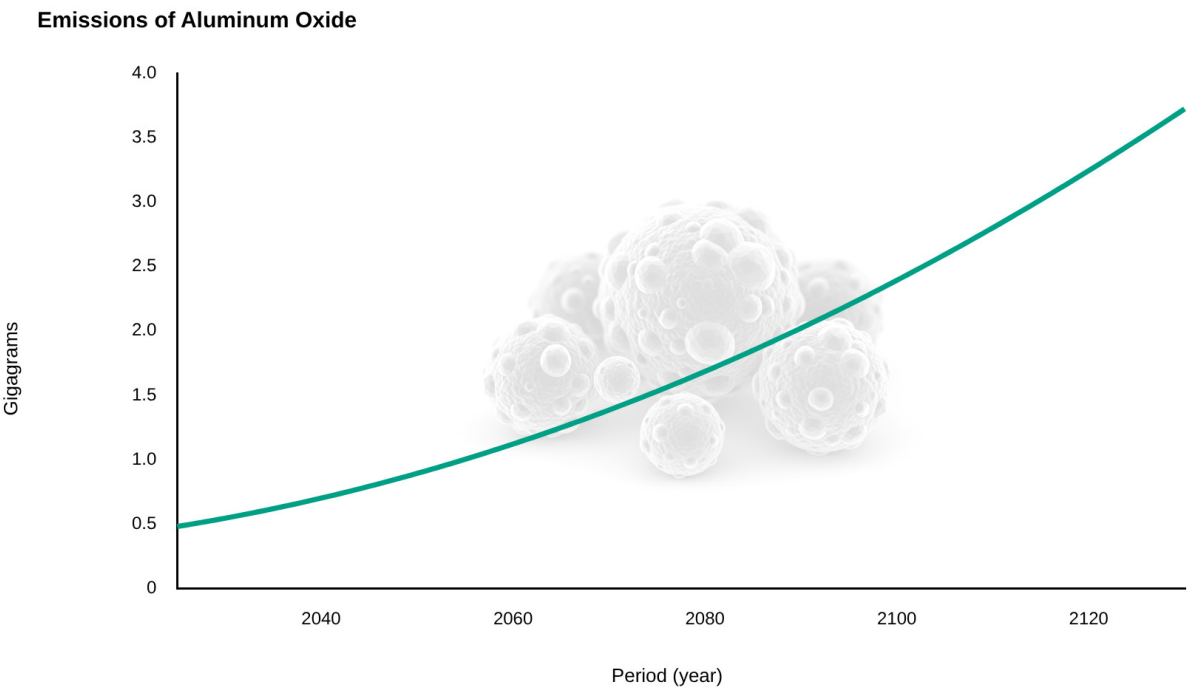


Figure 2 | Anthropogenic emissions of Aluminum Oxide from re-entries. Estimated annual emissions of aluminum oxide into the mesosphere resulting from atmospheric re-entries of rocket bodies and derelict satellites over the simulation horizon. The values start at around 0.5 gigagrams in 2025 and increase steadily to over 3.5 gigagrams over a 100-year period.

Figure 3 plots the trajectory of the anthropogenic stock of aluminum oxide in the stratosphere. Starting from an initial stock of 0.52 gigagrams in 2005, the stock increases steadily to approximately 8 gigagrams over a 100-year period.

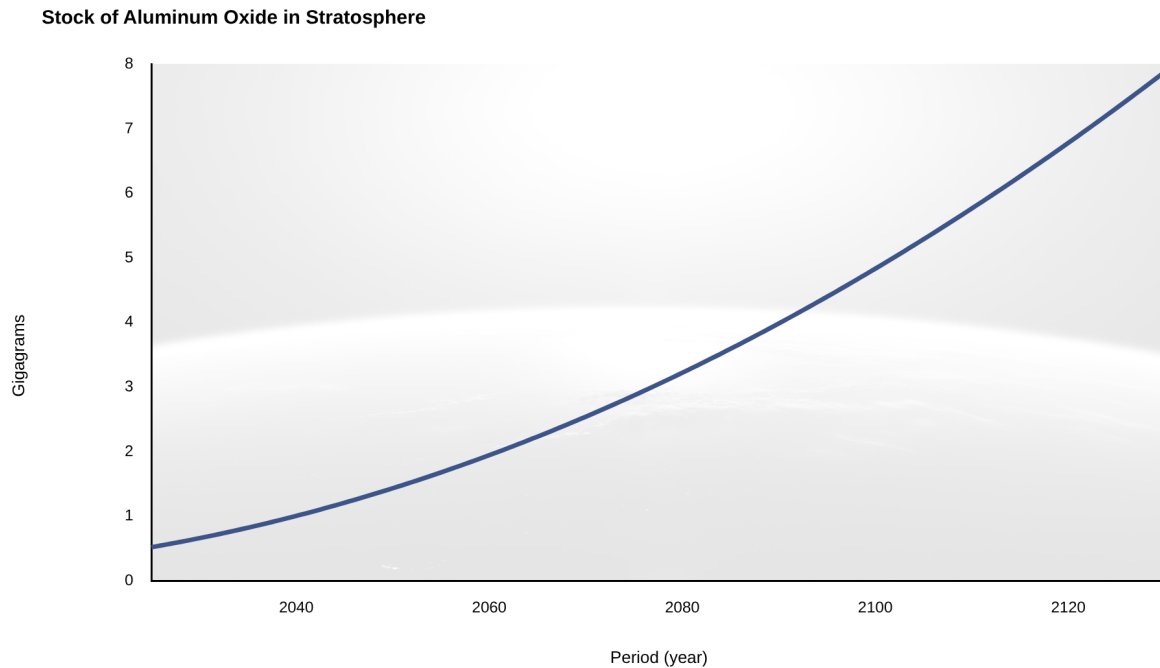


Figure 3 | Anthropogenic stratospheric stock of Aluminum Oxide. Trajectory of the accumulated stock of aluminum oxide particles in the stratosphere (15–50 km) over the 100-year simulation horizon. In accordance with the model projections, the stock increases from an initial 0.52 gigagrams in 2025 to approximately 8 gigagrams by 2130, reflecting the long-term accumulation of re-entry by-products in the upper atmosphere.

Figure 4 plots ozone depletion resulting from the reentries of rocket bodies and derelict satellites over the next 100 years. Changes in ozone are expressed in percentage terms relative to a baseline column of 300 DU, implying that a reduction of 1 DU corresponds to approximately a 0.33% decrease in total column ozone. The estimated ozone depletion values are moderate. In the initial year, ozone depletion is about 0.026 DU. As space activity increases, ozone depletion rises accordingly, reaching approximately 0.4 DU by the year 2125. Throughout the simulation horizon, annual ozone depletion remains within moderate levels. However, the cumulative ozone depletion over the 100-year period amounts to 17.98 DU, which corresponds to an approximate reduction of 5.93% of the total column ozone.

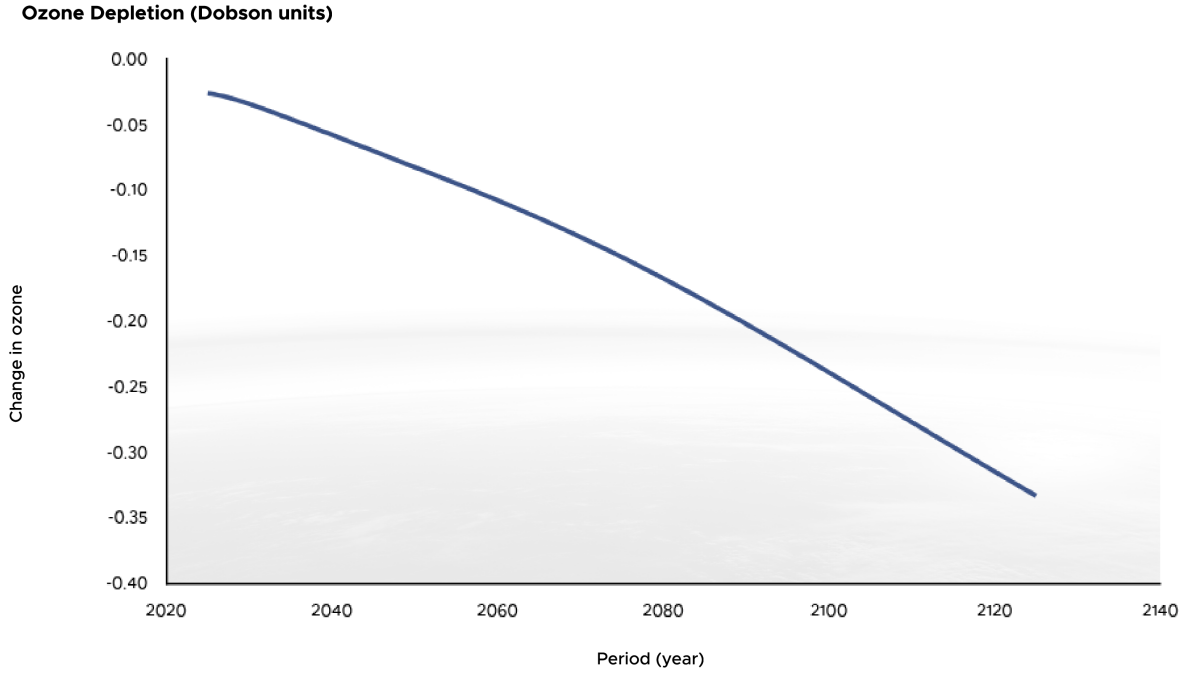


Figure 4 | Projected change in total column ozone due to re-entries. Trajectory of the estimated annual depletion of stratospheric ozone (in Dobson Units) resulting from Al_2O_3 particle accumulation. The depletion reaches approximately 0.4 DU by 2125. In accordance with the model results, the cumulative depletion amounts to 17.98 DU over the simulation horizon, representing a reduction of roughly 6% in total column ozone relative to the 300 DU baseline.

6. Conclusions

This paper estimates the impact of space object reentries on stratospheric ozone. Reentries are driven by human activity in space: some are controlled as a mitigation strategy to reduce the stock of non-functional objects in orbit, while others occur naturally due to atmospheric drag acting on orbital debris. We develop a general equilibrium integrated assessment model (IAM) composed of three interconnected blocks: an economic module, a debris dynamics module, and an environmental (stratospheric) module. The model is calibrated and solved for a centralized economy to derive optimal trajectories of the key variables over a 100-year horizon.

Using the mass of reentering rocket bodies and derelict satellites, we estimate emissions of aluminum oxide into the mesosphere. These emissions accumulate and are partially transported into the stratosphere, increasing the stock of aluminum oxide and contributing to ozone depletion. Our results indicate that ozone depletion rises from an initial level of 0.026 DU in 2025 to approximately 0.4 DU by 2125, with a cumulative depletion of about

18 DU over the entire period, equivalent to roughly a 6% reduction in total column ozone. Although the annual impacts appear moderate, the results highlight that the removal of large intact debris through atmospheric reentry is not environmentally neutral, as it constitutes a non-negligible source of ozone depletion.

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