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What Launch Life Cycle Assessment Should Count for Starship-Scale Fleets: Ozone Health Damage Factors and a Failed Warming Potential

Jiawei Jing

jiawei.jing@mkhr.co.jp

Makuhari Development Corporation https://orcid.org/0009-0000-8365-367X

Research Article

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Abstract

Purpose

Life cycle assessments (LCA) of spaceflight count launch mainly through CO_2 and report black carbon only as mass, with one untested high-altitude warming potential as the alternative. As Starship-class vehicles could raise the propellant burned each year by orders of magnitude, this study asks what launch LCA should count: which pathways can be characterized at the endpoint, and which should stay out.

Methods

We built human health damage factors (disability-adjusted life years per kilogram, DALY/kg) for black carbon (BC), chlorine, and nitrogen oxides in stated altitude layers, each from one traceable source, with public model output recomputed using area weighting. A health chain converts column ozone loss to skin cancer and cataract burden. We applied the factors to Starship and Falcon 9, per launch and per tonne of payload capacity, compared fleet emissions with simulated doses, and tested the only high-altitude global warming potential (GWP) we found.

Results and discussion

If the heating-driven ozone response to BC holds, one Starship launch's exhaust causes 11 DALY of UV damage at 5 g BC per kg propellant and 48 DALY at 22 g/kg, or 2.9–13 times the damage from its combustion CO_2 over 100 year and 0.65–2.8 times over 500 year. A surface-ozone co-benefit offsets about 75% of this on central assumptions, leaving the net sign undetermined. Methane-engine BC, never measured in flight, decides whether Starship does less UV damage than Falcon 9 per tonne of payload capacity. At 3,000 launches a year, BC in the 15–70 km layer reaches simulated doses. The GWP implies about seven times the simulated instantaneous forcing, and 0.61 K at 10 Gg/yr where an interactive-ocean simulation shows no detectable change.

Conclusions

Launch LCA should count stratospheric ozone loss, show results with and without a dedicated BC line, and report the surface-ozone co-benefit separately. It should not add a BC climate term from the available GWP. Re-entry, stratospheric water vapor, and the BC climate term cannot yet be characterized, so totals that omit them should say so. Measuring BC from methane engines at altitude is the most useful next step.

1 Introduction

Starship burns about ten times the propellant of Falcon 9, environmental reviews already cover 145 launches a year (Department of the Air Force 2025; Federal Aviation Administration 2025, 2026), and SpaceX describes a future of "thousands of launches per year" to place compute in orbit (Space Exploration Technologies Corp. 2026). The exhaust enters the atmosphere at altitudes that no other human source reaches. Black carbon (BC, or soot) from hydrocarbon engines, nitrogen oxides (NOx), and chlorine from solid motors alter stratospheric ozone and the radiative budget (Barker et al. 2026; Maloney et al. 2022; Revell et al. 2025; Vliex et al. 2026).

Life cycle assessment (LCA) does not yet capture this. Assessments of spaceflight count rockets mainly as a CO_2 source (Kukreja et al. 2026). The space-sector handbook adds ozone depletion in CFC-11 equivalents from steady-

state ozone depletion potentials and lists soot only as a mass flow (ESA LCA Working Group 2025). Endpoint methods convert emissions into disability-adjusted life years (DALY), but their ozone factors assume release near the ground (Hayashi and Itsubo 2023), and the Global Life Cycle Impact Assessment Method (GLAM) lists ozone depletion as a future category (Fantke et al. 2026). We found no study that carries launch emissions, by altitude, to health. The closest work covers single links (Oh et al. 2026; Xu et al. 2026).

A practitioner who wants to count BC meets two problems. The first is ozone: chemistry–climate models lose substantial ozone when BC heats the stratosphere (Maloney et al. 2022; Tsigaridis et al. 2024), but only at far higher emissions than present fleets produce, so any factor applied to them is a long extrapolation. Offline chemistry calculations that omit the heating find little loss (Vliex et al. 2026).

The second is climate: BC absorbs sunlight strongly, yet large injections cool the surface in climate simulations (Jones et al. 2016; Robock et al. 2007). The only high-altitude warming potential we found is a sensitivity case of Dominguez Calabuig et al. (2024): a 100-yr global warming potential (GWP) of 1.60×10^6, which with similar factors for water and alumina raises launch climate impacts by up to about 1,000 times. Its authors caution that the approach should rest on forcing after stratospheric adjustment, that a GWP does not translate directly into surface temperature, and that climate simulations should validate it. To reach the endpoint, LCA multiplies a GWP by a CO_2 damage factor, and that step assumes the translation. The validation has not been done.

We therefore ask what launch LCA should count, with Starship as the main case. We build damage factors from published simulations and public model output, apply them per launch and per tonne of payload capacity, and compare fleet emissions with simulated doses. Finally, we test the GWP and sort every pathway into what to count, what to report separately, and what cannot yet be characterized.

2 Methods

2.1 Damage Factors and Scope

An ozone damage factor, the endpoint characterization factor, is the steady-state column ozone response to sustained emission, divided by the emission rate, multiplied by damage per Dobson unit-year (DU·yr; Fig. 1). Under linearity this equals the total damage of a pulse. Because the responses are averaged across simulated emission rates (doses), these are average, not marginal, factors. Mass is counted in layers: 15–70 km for BC, 15–50 km for chlorine species (Cly, as Cl), and at or above 15 km for NOx (as NO_2).

The functional unit is one tonne of payload capacity to low Earth orbit; results per launch are reference flows and do not compare vehicles of different capacity. The boundary is launch exhaust, without propellant production, vehicle manufacture, or re-entry. Re-entry, emissions below 15 km, and BC above 70 km are sized in Section 4. Population and baseline disease are held at 2015, and the background atmosphere is that of each simulation. Results are committed damage and are not discounted.

2.2 Emissions

Primary emission indices (pEI) come from Barker et al. (2024) and the Launch Emission Assessment Tool (LEAT; Fischer et al. 2026). BC is 22 g/kg for RP-1 kerosene and 16 g/kg for solid motors. Methane engines have no flight measurement, so we carry 5 g/kg (Barker et al. 2024) and the RP-1 value of 22 g/kg as an upper bound. Afterburning, BC oxidation in the hot plume, follows Barker et al. (2024):

$$\mathrm{EI}_{\mathrm{BC}}(h) = \mathrm{pEI} \times \max\left[0.04,\ \min\left(1,\ 0.04\, e^{0.12(h-15)}\right)\right],$$

1

with h in km. Burn profiles come from LEAT: Starship with 4,658 t of propellant, the V2 flight IFT-8; Falcon 9 with 456.6 t; and Ariane 62 with 489.2 t. On this profile one Starship launch puts 3.8 t of BC in the 15–70 km layer at 5 g/kg and 17 t at 22 g/kg (Table 1). For payload capacity we use 100 t for Starship, the V3 design value (Space Exploration Technologies Corp. 2026), and 17.5 t for Falcon 9 (Ohs et al. 2025). The 2022 fleet uses the database of Barker et al. (2024), and our inventory matches it within 6% (Text S1 in Supplementary File 1).

Table 1
Emissions by Layer per Tonne of Propellant

Propellant	BC pEI (g/kg)	BC, 15–70 km (kg/t)	Cly as Cl, 15–50 km (kg/t)	NOx as NO_2, ≥ 15 km (kg/t)	CO_2 (kg/t)
RP-1	22	4.42	0	0.044	967
Methane	5	0.809	0	0.0383	528
Methane	22	3.56	0	0.0383	528
Liquid hydrogen	0	0	0	0.0139	0
Solid motors	16	4.48	89.9	0.0568	456
UDMH	16	3.38	0	9.85	222

Note. UDMH, unsymmetrical dimethylhydrazine. Burn profiles are LEAT trajectories, except UDMH, which uses the 2022 launch database. Other vehicles need their own burn profile (Text S3 in Supplementary File 1).

2.3 Ozone Responses

Each factor rests on one traceable source. BC uses CESM2-WACCM6 at 10, 30, and 100 Gg/yr (Maloney et al. 2022), recomputed from its public output. Cly uses the three scenarios of Li et al. (2026), and NOx uses Larson et al. (2017). Two other models serve as checks on BC and do not enter the factor: GISS ModelE at 8.4 and 84 Gg/yr (Tsigaridis et al. 2024) and SOCOLv4, an atmosphere–ocean chemistry–climate model, at 4.25 Gg/yr (Revell et al. 2025; Revell and Sukhodolov 2024). Table S1 in Supplementary File 1 lists each case.

The tabulated global values of Maloney et al. (2022) appear to omit area weighting: latitude means without it reproduce them, including a control net top-of-atmosphere flux of − 29 W/m^2 that becomes + 1.5 W/m^2 with weighting (Table S3 in Supplementary File 1). Area weighting shrinks the column ozone change from − 3.5, − 9.05, and − 20 DU to − 2.2, − 5.5, and − 12.9 DU at 10, 30, and 100 Gg/yr, all significant, a loss of 0.22, 0.18, and 0.13 DU per Gg/yr. Uncertainties are 2 standard errors of annual means with lag-1 autocorrelation, from a single realization. We exclude 2034–2038 from ΔT, when a seam in the interactive-ocean files of Maloney et al. (2022) drops the BC burden anomaly near zero (Text S4 in Supplementary File 1). ΔT is the area-weighted change in air temperature at the lowest usable level.

2.4 From Ozone to Health

The health chain converts column ozone loss by latitude band to a UV change, and then to a change in disease burden, the UV damage, with the radiation and biological amplification factors of each disease (Madronich et al. 2021; UNEP 1998). Baseline disease burden is the World Health Organization estimate for melanoma, non-melanoma

skin cancer, and cataract (WHO 2026). Skin cancer burden is divided among regions by DALY share (Zhang et al. 2021), and only lighter-skinned regions respond (Text S2 in Supplementary File 1). For a uniform column loss this chain gives 11,248 DALY/(DU·yr), with a Monte Carlo 5th–95th percentile range of 8,825–12,794. Cataract contributes 51%, squamous cell carcinoma 32%, and melanoma 17%.

On CFC-11 the chain gives 6.3×10^{-4} DALY/kg. Hayashi and Itsubo (2023) give 9.2×10^{-4} for 2015, and ReCiPe 2016, which builds on the same line of work, gives 1.3×10^{-3} for its egalitarian perspective, the one with an infinite horizon and cataract (Huijbregts et al. 2016). These totals hide two offsets: our ozone loss per kilogram of CFC-11, which agrees with a scenario estimate from WMO (2022), is about 3.4 times that of Hayashi and Itsubo, and our damage per DU·yr, mainly through cataract, is about one-fifth (Text S2 and Fig. S1 in Supplementary File 1). Only the second reaches the BC factor (Section 4.2).

BC ozone loss concentrates north of 30°N, where most of the responding population lives. We therefore multiply BC UV damage by a shape factor computed from the zonal output, 1.5–1.6 across doses. Cly and NOx stay at uniform DU.

Less stratospheric ozone also lowers surface ozone and respiratory mortality. We take this co-benefit from Eastham et al. (2018) as published: 83 fewer deaths per 10^9 person-years per DU, or − 11,790 DALY/(DU·yr) with the Jerrett et al. (2009) concentration–response function. It counts years of life lost only. For combustion CO_2 we use the GLAM factors of 1.5×10^{-6} DALY/kg over 100 year and 6.8×10^{-6} DALY/kg over 500 year (Fantke et al. 2026).

2.5 Testing the Warming Potential and Sorting Pathways

To test the GWP without any health assumption, we compare the forcing it implies with the simulated forcing and with the sunlight BC can absorb. We then convert it to the ΔT it implies under sustained emission, using the impulse and two-box temperature responses of the Sixth Assessment Report (Forster et al. 2021), and compare that ΔT with the simulated value at the same dose (Text S4 in Supplementary File 1). We apply the same temperature test to the three-dimensional instantaneous radiative forcing (IRF) and the stratospherically adjusted forcing of Barker et al. (2026).

We sort each pathway by two questions. Is the response settled in size and sign where it has been simulated? Is there an established route from that response to health? A pathway that passes both is counted, one that passes conditionally is shown on its own line, and any other is reported as mass.

2.6 Uncertainty

Per-launch and fleet distributions come from a joint Monte Carlo ($n = 2^{20}$) in which the cases of each species carry equal weight (Text S3 in Supplementary File 1). P50 and P5–P95 denote the median and the 5th–95th percentiles. These ranges cover parameters and model cases. Section 4.2 lists what they do not cover.

2.7 Use of AI Tools

Claude (Anthropic, Claude Opus 5.5, accessed through Claude Code) was used to write and run analysis code, extract values from the cited literature, draft and edit the text, and produce the figures. The author specified the research design and reviewed the code, data, and text, and takes responsibility for the content.

3 Results

3.1 Damage per Kilogram

Per kilogram, UV damage from BC at 15–70 km is about 1,900 times that of CO_2 over 100 year (Table 2). The Cly factor is about 1/12 of the BC factor, and the NOx factor about 1/82.

Table 2
Human Health Damage Factors by Species and Emission Layer, for Launch Emissions

Species, layer	Ozone loss, case range (DU·yr/kg)	Ozone loss relative to CFC-11, case range (kg CFC-11 eq/kg)	UV damage, P50 (P5–P95) (DALY/kg)	Surface-ozone co-benefit, P50 (P5–P95) (DALY/kg)
BC, 15–70 km, after afterburning	1.3×10^{-7} to 2.2×10^{-7}	2.4–4.1	2.9×10^{-3} (1.9×10^{-3} to 4.7×10^{-3}), conditional	-2.2×10^{-3} (-4.5×10^{-3} to -7.4×10^{-4})
Cly as Cl, 15–50 km	2.2×10^{-8} to 2.3×10^{-8}	0.51–0.54	2.4×10^{-4} (1.9×10^{-4} to 3.0×10^{-4})	-2.9×10^{-4} (-5.1×10^{-4} to -1.0×10^{-4})
NOx as NO_2, ≥ 15 km	3.6×10^{-9}	0.067	3.5×10^{-5} (2.5×10^{-5} to 4.4×10^{-5})	-4.1×10^{-5} (-7.4×10^{-5} to -1.4×10^{-5})

Note. UV damage and co-benefit come from the joint mixture of model cases and are not products of the other columns. BC UV damage carries the shape factor (1.5–1.6), and the BC factor averages 10–100 Gg/yr. CFC-11 at steady state is 5.3×10^{-8} DU·yr/kg globally and 4.3×10^{-8} for 60°S–60°N, the domain of the Cly cases. Mass is that of the emitted species in each layer. For comparison, CO_2 is 1.5×10^{-6} DALY/kg over 100 year and 6.8×10^{-6} over 500 year. Negative values are avoided damage. Do not add these factors to ozone depletion potential-based or surface-release factors for the same emission (Text S3 in Supplementary File 1).

The three species rest on different evidence. Cly and NOx destroy ozone through catalytic cycles, and the Cly response is nearly linear across doses. BC acts indirectly: it heats the stratosphere, and the loss comes through circulation change and chemistry altered by the warming (Maloney et al. 2022; Revell et al. 2025). Offline calculations omit this response and obtain far less loss (Vliex et al. 2026). We use chemistry–climate models because only they include the heating, but no observation decides between the two, so the BC factor holds only if the heating-driven response holds.

Surface ozone works the other way. The co-benefit offsets about 75% of BC UV damage (the shape factor applies to UV damage only) and all of Cly UV damage. Its net with UV damage, the net ozone damage, is not a robust number: the P5–P95 range spans zero for one Starship launch, − 4.1 to 9.0 DALY at 5 g/kg, and other concentration–response functions move the BC net ozone damage from − 17,000 to about + 10,000 DALY/(DU·yr) (Text S5 in Supplementary File 1). We therefore recommend a separate indicator and no net value.

3.2 One Starship Launch

The exhaust of one Starship launch causes 11 DALY of UV damage at 5 g/kg and 48 DALY at 22 g/kg, against 3.7 DALY for its combustion CO_2 over 100 year and 17 DALY over 500 year (Table 3). Almost all of this is BC, since NOx at or above 15 km gives under 0.01 DALY. UV damage exceeds 100-yr CO_2 at any Starship BC above about 1.7 g/kg, and 500-yr CO_2 only at the higher of our two values.

Table 3
UV Damage, Combustion CO_2, and Co-Benefit per Launch, and UV Damage per Tonne of Payload Capacity

Vehicle	UV damage, P50 (P5–P95) (DALY)	CO_2, 100 year; 500 year (DALY)	UV ÷ CO_2, 100 year; 500 yr	Surface-ozone co-benefit, P50 (DALY)	UV damage per tonne of payload capacity (DALY/t)
Starship, BC 5 g/kg	11 (7.0 to 18)	3.7; 17	2.9; 0.65	−8.1	0.11–0.16
Starship, BC 22 g/kg	48 (31 to 78)	3.7; 17	13; 2.8	−36	0.48–0.69
Falcon 9	5.8 (3.8 to 9.5)	0.67; 3.0	8.6; 1.9	−4.4	0.33

Note. Payload capacity is 100 t for Starship and 17.5 t for Falcon 9, whose BC is held at the RP-1 value. Per-launch values use 4,658 t of propellant; the per-tonne range scales the same burn profile linearly to 6,750 t (1.45 times). Table S7 in Supplementary File 1 gives other vehicles and fleets.

Per tonne of payload capacity, methane-engine BC decides which vehicle does more UV damage. The 100 t is a V3 design value and the 4,658 t is the ascent burn of the V2 flight IFT-8 in LEAT, so we bracket Starship between that burn and the 6,750 t propellant load in environmental reviews, scaling the same burn profile linearly at an unchanged 100 t. Falcon 9 then does 2.1–3.1 times the UV damage of Starship at 5 g/kg, and Starship 1.4–2.1 times that of Falcon 9 at 22 g/kg, with parity at 11–15 g/kg, and its combustion CO_2 per tonne is 0.037–0.054 against 0.039 DALY/t over 100 year. The two vehicles share the BC factor, so its size cancels if the response is linear in mass and independent of release altitude.

3.3 Starship Fleets Reach Simulated Doses

The 2022 fleet, and Starship at the 145 launches a year covered by environmental reviews, lie below every dose simulated for BC alone, so the BC factor extrapolates there. It gives 1,020 DALY of UV damage for the launches of 2022, 14 times their 100-yr CO_2 (Table S7 in Supplementary File 1); for solid motors, Cly dominates and does not depend on the BC response.

Large fleets reach those doses (Fig. 2). The lowest CESM2-WACCM6 dose, 10 Gg/yr, is reached at about 600 launches a year at 22 g/kg and 2,700 at 5 g/kg. Three thousand launches a year put 11–50 Gg/yr of BC in the layer and, with dose-specific responses, commit about 41,000–140,000 DALY of UV damage per year of launches, against 11,000 for their 100-yr CO_2.

Two other models give similar loss per unit emission, although their loss per unit BC burden differs by up to fivefold (0.022–0.11 DU/Gg; Text S5 in Supplementary File 1). GISS ModelE, at 1,000 and 10,000 launches a year of a methane heavy lifter with an 80 t payload at 7.5 g/kg, the case closest to a Starship fleet, reports 2 and 13 DU, or 0.24 and 0.15 DU per Gg/yr, without uncertainties or a stated area weighting (Tsigaridis et al. 2024). Through our health chain these are 35 and 23 DALY per launch, on 8.4 t of BC per launch. SOCOLv4 gives a loss of 0.66 ± 0.91 DU at 4.25 Gg/yr, or 0.16 DU per Gg/yr, with an interval that includes zero (Table S4 in Supplementary File 1). Agreement per unit emission therefore extends across the doses a large fleet would reach and weakens below them.

The overlap of fleet and simulated doses is in layer mass, which removes a long extrapolation but does not prove the same response: CESM2-WACCM6 ends afterburning at 15 km and GISS ModelE by the tropopause, so they release BC lower than Eq. 1 and, on that accounting, reach 10 Gg/yr at about 310 launches a year at 22 g/kg and 1,400 at 5 g/kg.

3.4 The High-Altitude Warming Potential Fails Its Test

The GWP first fails on physical grounds. The integrated forcing of a pulse equals the steady forcing per unit of sustained emission for any lifetime well under 100 year, and the GWP implies 142 mW/m^2 per Gg/yr. The three-dimensional IRF of Barker et al. (2026), scaled to steady state, gives about 20, and the all-sky shortwave change at the top of the atmosphere in the runs of CESM2-WACCM6 with fixed sea surface temperatures (fixed-SST), which includes rapid adjustments and omits the longwave, is 21–23. With the 4-yr lifetime used in deriving it, the GWP also implies about 18 MW/kg, which exceeds the 6.6–13 MW/kg of sunlight that BC can absorb (Text S4 in Supplementary File 1).

It also fails against interactive-ocean simulations (Fig. 3). Treated as CO_2-equivalent, it implies 0.61 K at 10 Gg/yr and 6.1 K at 100 Gg/yr, where CESM2-WACCM6 simulates − 0.03 ± 0.07 K and − 0.11 ± 0.07 K, and 0.26 K at 4.25 Gg/yr, where SOCOLv4 gives 0.00 ± 0.09 K (Table S4 in Supplementary File 1). At 1,000 Starship launches a year it would imply 0.23–1.0 K.

No alternative rescues the approach. The three-dimensional IRF implies 0.30 and 1.0 K at 30 and 100 Gg/yr. The stratospherically adjusted forcing of Barker et al. (2026), the form that Dominguez Calabuig et al. (2024) say the approach should use, has the right sign, but used in the same way it implies − 0.65 K at 100 Gg/yr, about 6 times the simulated cooling. The aviation-analog GWP of 1,166 used as a baseline by Dominguez Calabuig et al. (2024) implies only 0.0004 K at 10 Gg/yr, which this test cannot reject, but it has no stratospheric basis.

The sign of ΔT at fleet doses stays open: the only significant change is the − 0.11 K at 100 Gg/yr, in one realization, and a WACCM6 preprint at 30 Gg/yr reports positive all-sky forcing that depends on launch latitude (Wongprapinkul et al. 2026). Whatever the sign, the simulated values stay far from those the GWP implies, and it should not be used.

4 Discussion

4.1 What Launch LCA Should Count

Table 4 and Fig. 4 set out what we recommend, with Starship as the worked case, by the two questions of Section 2.5.

Table 4
What Launch LCA Should Count, With Sizes for One Starship Launch

Pathway	DALY per launch	Response settled?	Route to health?	Recommendation
CO_2	3.7 (100 year); 17 (500 year)	Yes	Yes, GLAM factor	Count
UV damage, Cly and NOx	Under 0.01	Yes for Cly; NOx rests on one case	Yes, health chain	Count in an ozone depletion category
Emissions below 15 km	About 1–10	Near the ground; rough aloft	Yes, air quality factors	Count in air quality categories
UV damage, BC	11 to 48	Conditionally: in chemistry–climate models at 10–100 Gg/yr, absent offline; an extrapolation below	Yes, health chain	Count on its own line; show results with and without it
Surface-ozone co-benefit	−8.1 to − 36	Conditionally: follows the UV damage rows; size depends on the concentration–response function and the altitude of loss	Yes, in another category	Report as a separate indicator
BC climate term	Not characterized	Cooling at 100 Gg/yr only; sign open below	No: needs the pattern of ΔT	Do not use a GWP; report BC mass in the layer
Water vapor, 15–50 km	Not characterized (590 t)	No: direct injection is small beside BC-driven moistening (Tsigaridis et al. 2024)	No	Report mass
Re-entry NOx	0.031 to 7.8 per 100 t re-entering, indicative	No: published estimates differ by about 40–250 times	Yes, health chain	Report mass
Re-entry Al_2O_3	Not characterized	No: regional estimates only; sign differs by hemisphere (Maloney et al. 2025)	Not without a global change	Report mass

Note. Starship at 5 and 22 g/kg of BC. Re-entering mass per launch depends on recovery and payload (Text S5 in Supplementary File 1).

Among non-CO_2 pathways with a usable estimate, BC ozone loss is the largest, and LCA omits it. Because this line rests on the heating-driven response and on unmeasured BC, an assessment should show its results both with and without it. Practitioners who report ozone depletion at the midpoint, as the space-sector handbook does (ESA LCA Working Group 2025), can use the relative ozone loss in Table 2 and keep BC on its own line.

We keep UV damage from BC but omit its climate term, although both come from the same simulations. The first difference is in the response: ozone loss is significant at all three CESM2-WACCM6 doses, and cooling only at the highest. The larger difference is the step to health. A column ozone change has an established exposure metric and existing endpoint factors, even though BC itself alters how column ozone maps to UV (Section 4.2). A temperature change from BC at 15–70 km has no such route. Heat-related mortality needs the spatial pattern of ΔT, and the GLAM factor was not built for stratospheric heating with surface dimming and reduced precipitation (Jones et al. 2016; Xia et al. 2022). This is a judgment, and the term could be large: at the highest dose it could exceed UV damage (Text S5 in Supplementary File 1). Comparisons of UV damage with CO_2 are therefore not totals, and a total that omits the uncharacterized rows should say so.

4.2 What Could Change These Numbers

Table 5 lists what the percentile ranges leave out. For Starship the distinctive one is the large upper-stage burn above 70 km.

Table 5
Conditions Outside the Reported Ranges

Condition	Effect on BC UV damage	Evidence
BC above 70 km	×1.22 with 70–100 km mass; ×3.45 with all mass above 70 km (Falcon 9: ×1.08, ×2.40)	Upper-stage burn is absent from CESM2-WACCM6 and GISS ModelE; fate above 100 km unknown
Afterburning	×1.9 if none above 15 km; ×0.50 if BC retention rises more slowly with altitude	No data above about 40 km; one in-plume sampling near 16 km
Model structure (BC burden and sensitivity)	×0.42 to ×2.0, or ×2.5 to ×4.5 with GISS ModelE BC burdens	Loss per unit BC burden and lifetime compensate across models (Text S5 in Supplementary File 1)
UV-B absorbed directly by BC aloft	−14% to − 28%	First-order estimate, no scattering or clouds
Damage per DU·yr	×0.72 with the WHO cataract fraction to ×5.3 with the prevalence cataract route (Text S2 in Supplementary File 1); Table S6 in Supplementary File 1 gives responding regions	Upper value implies about 6 times the WHO cataract burden; the value implied by Hayashi and Itsubo (2023) lies within this range
Release altitude, launch latitude, and background state	Not bounded	Simulations release lower than Eq. 1; one site near 30°N in CESM2-WACCM6; backgrounds of 2000, 2030, and 2050 across models
CO_2 damage factor	Ratio only, at 5 and 22 g/kg: 2.9; 13 with GLAM, 0.35; 1.5 with ReCiPe egalitarian, 4.7; 21 with hierarchist	Only the CO_2 factor changes; the hierarchist ozone factor itself omits cataract

4.3 What to Measure and Simulate Next

The most useful measurement is BC from methane engines at altitude. It sets the 4.4-fold range in Starship UV damage and decides the comparison with Falcon 9. Afterburning above about 40 km comes next: it has no data, it affects every hydrocarbon propellant, and it governs what an upper-stage burn leaves behind. Low-dose ensembles with a common emission profile would settle whether the BC response persists at near-term fleet doses, and a common set of NOx and Al_2O_3 experiments would do the same for re-entry.

5 Conclusions

Launch LCA should count stratospheric ozone loss, show results with and without a dedicated BC line, and report the surface-ozone co-benefit separately. We give factors by species for stated layers of launch emissions. If the heating-driven response holds, UV damage from one Starship launch is 11–48 DALY, or 2.9–13 times the damage from combustion CO_2 over 100 year and 0.65–2.8 times over 500 year, with a co-benefit of − 8.1 to − 36 DALY that leaves the net sign undetermined. Methane-engine BC sets this range and decides whether Starship does less or more UV damage than Falcon 9 per tonne of payload capacity. At thousands of launches a year, BC in the 15–70 km layer reaches simulated doses. Launch LCA should not add a BC climate term from the available GWP, which implies about seven times the simulated instantaneous forcing and warming that interactive-ocean simulations do not show. Re-

entry, stratospheric water vapor, and the BC climate term remain uncharacterized, so these comparisons are not totals.

Declarations

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Consent for publication Not applicable.

Author contributions The sole author designed the study, carried out the analysis, and wrote the manuscript.

Data and code availability The derived tables, figure source data, and analysis code are provided as Supplementary File 2 and will be archived with a DOI on Zenodo at publication under CC BY 4.0 (data) and MIT (code). Third-party inputs are available from their sources: model output of Maloney et al. (2022) at https://csl.noaa.gov/groups/csl8/modeldata/data/Maloney_etal_2021/ and of Revell et al. (2025) from Revell and Sukhodolov (2024); emission indices and burn profiles from Barker (2024) and Fischer (2026); launch rates and payload capacity from public filings (Department of the Air Force 2025; Federal Aviation Administration 2025, 2026; Space Exploration Technologies Corp. 2026); burden estimates from WHO (2026); and total ozone from the NASA SBUV Merged Ozone Data Set (NASA Goddard Space Flight Center n.d.).

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Figures

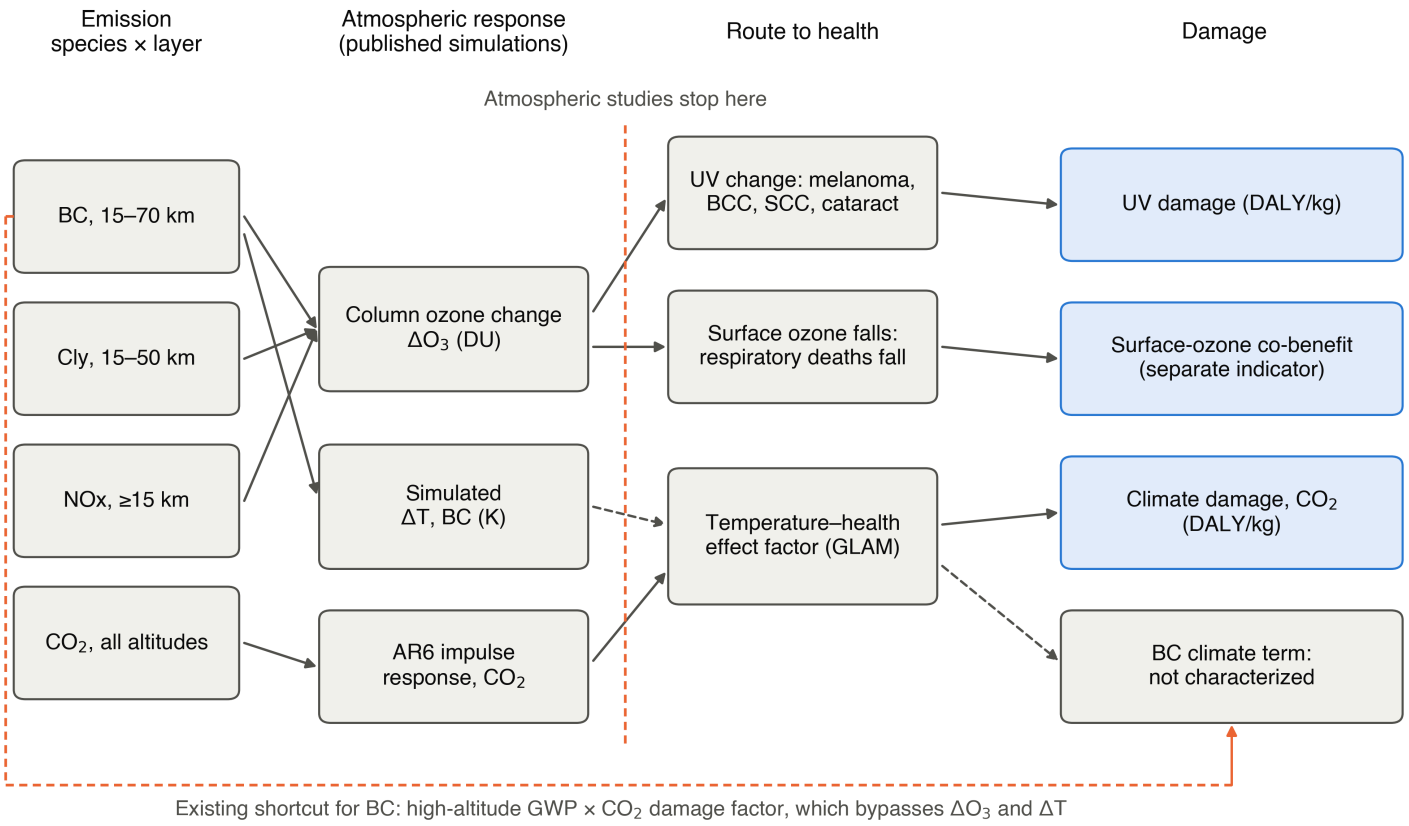


Figure 1

Calculation path from emissions by layer to damage. The dashed vertical line marks where atmospheric studies stop. The dashed path along the bottom is the existing shortcut for BC, which this study tests and does not recommend. BCC, basal cell carcinoma; SCC, squamous cell carcinoma

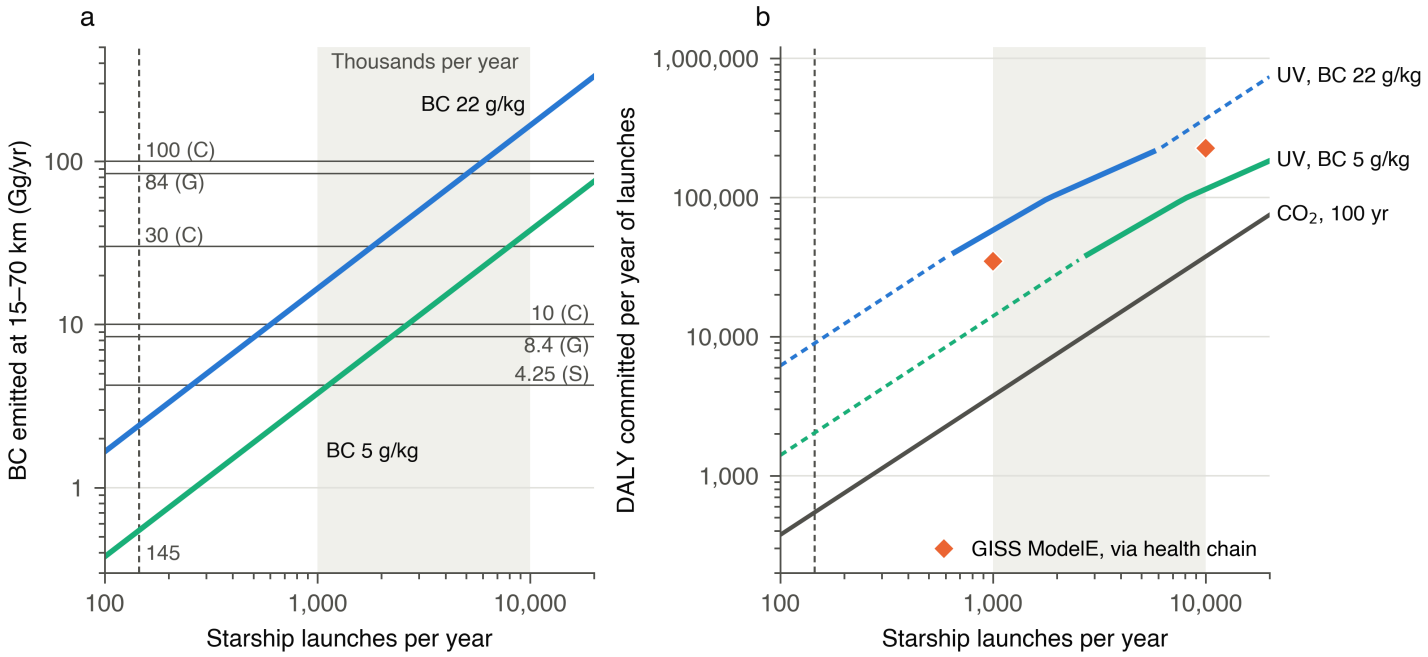


Figure 2

Starship launch rate against simulated doses. (a) BC emitted at 15–70 km, with simulated doses as horizontal lines (C, CESM2-WACCM6; G, GISS ModelE; S, SOCOLv4). (b) UV damage read at the CESM2-WACCM6 doses, dotted outside them, and CO_2 per year of launches. Diamonds are the GISS ModelE cases at their stated launch rates, passed through our health chain. In both panels the dashed vertical line marks 145 launches a year and the shaded band marks 1,000–10,000

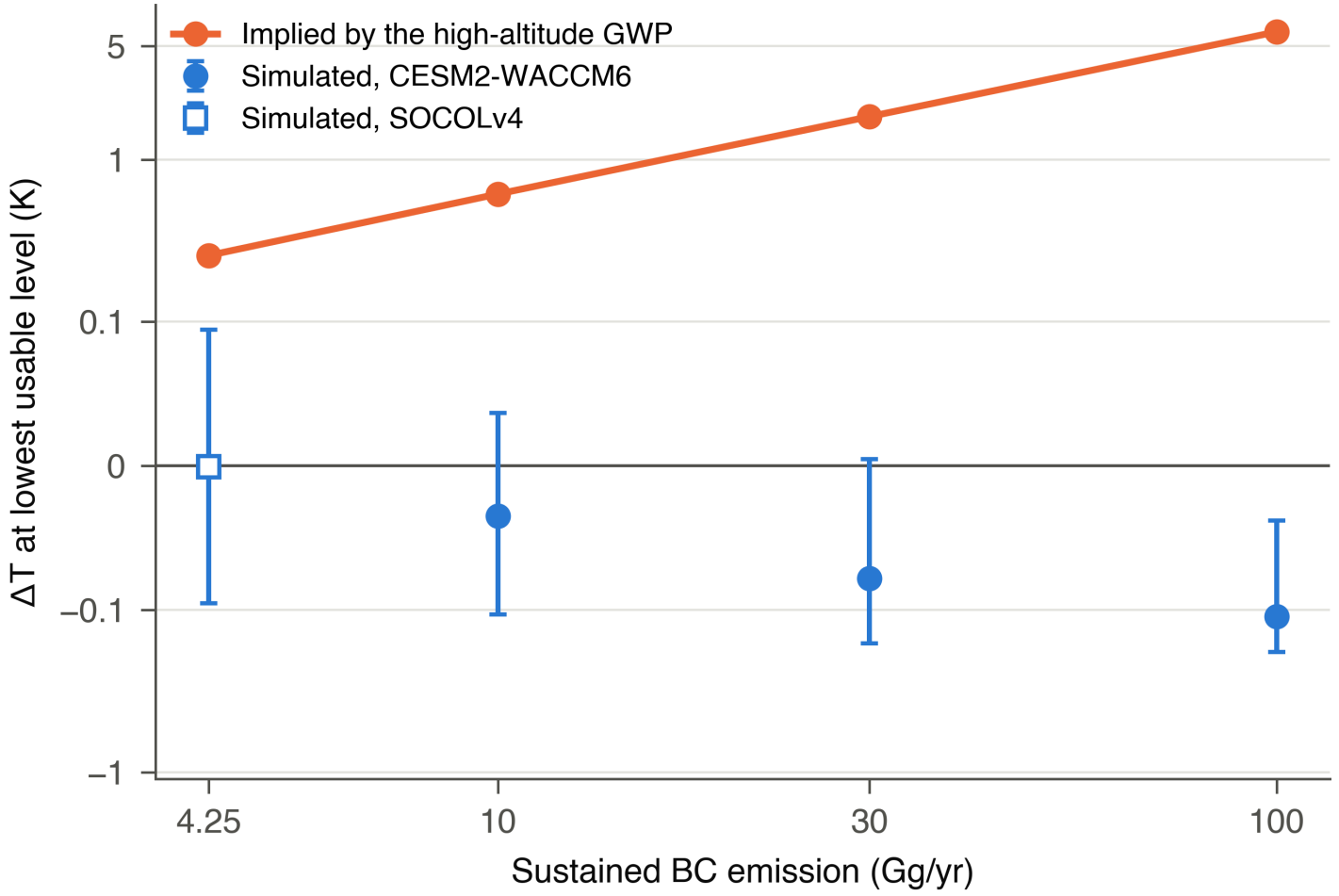


Figure 3

ΔT implied by the high-altitude GWP (orange) and simulated in interactive-ocean runs (blue), with ±2 standard errors, against sustained BC emission. The vertical axis is linear between ±0.1 K and logarithmic beyond

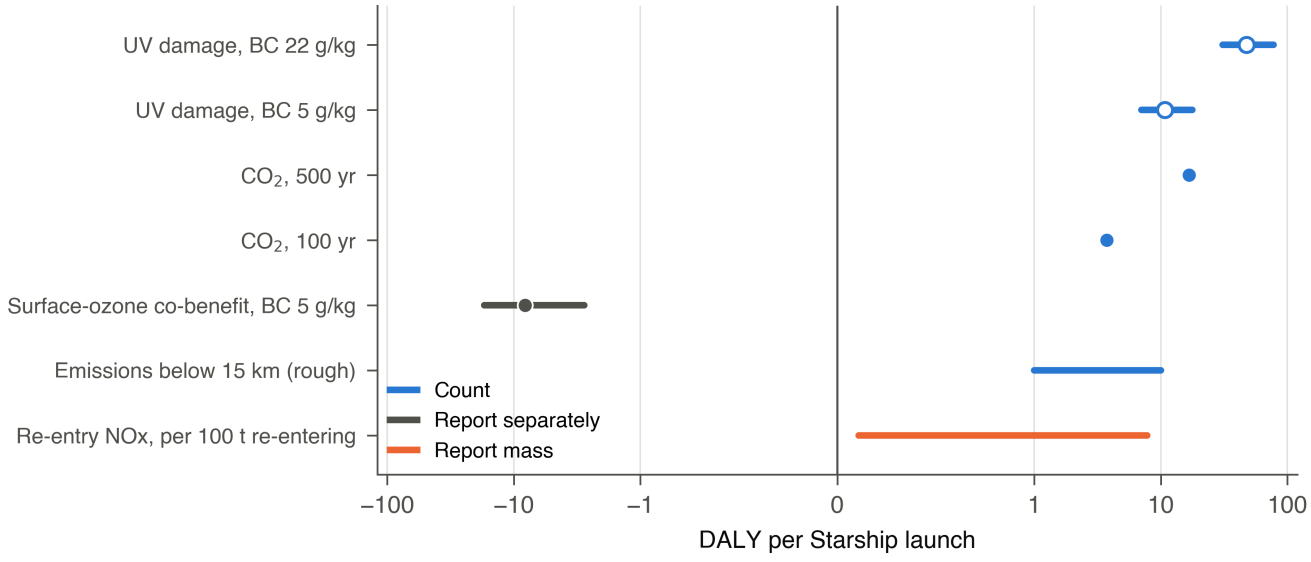


Figure 4

Pathways with a numerical estimate for one Starship launch, on a symmetric logarithmic axis. Open dots mark the conditional BC line. Lines are P5–P95 where a distribution exists, a rough range for emissions below 15 km, and the range of published estimates for re-entry NOx, per 100 t re-entering. Cly and NOx UV damage is too small to show. The BC climate term, stratospheric water vapor, and re-entry Al_2O_3 are not characterized and are not shown

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