Environmental impacts of atmospheric emissions from spacecraft re-entry demise

Project: ATmospheric Impact of SPAcecraft Demise (ATISPADE)

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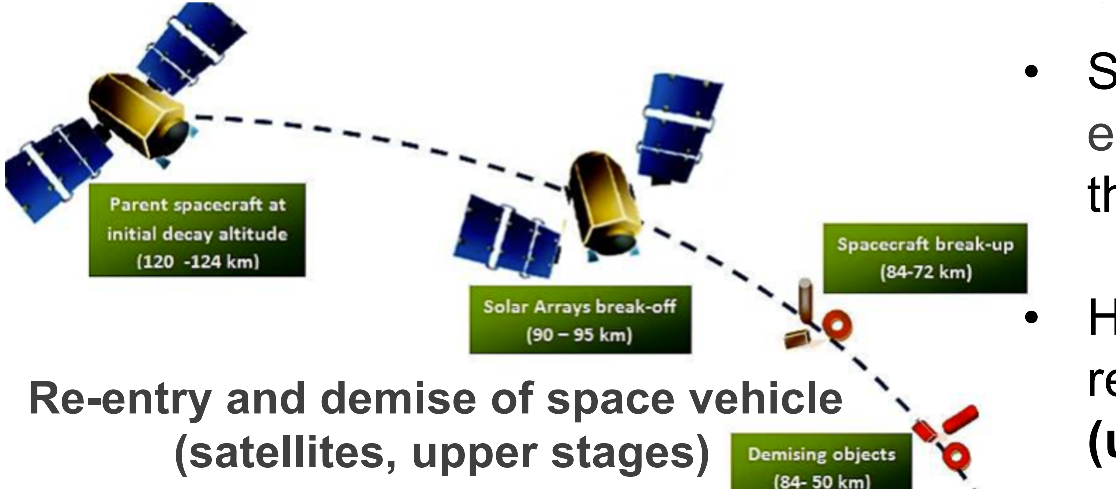
Context ESA: Eco-design/Clean Space

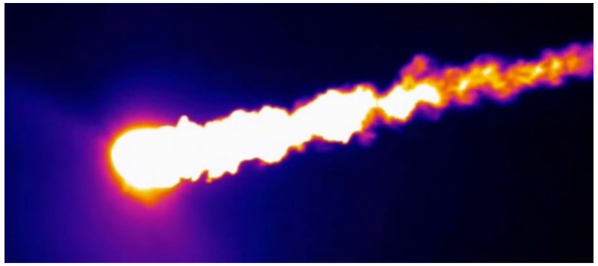
How can space industry quantify its environmental impacts (and mitigate)?

- ❑ **Standard approach**: **Life Cycle Analysis** (LCA) evaluates inputs, outputs, and potential environmental impacts throughout life cycle of products. LCA can deal successfully with most phases of space activities (R&D, infrastructure, production, assembly, in-orbit operations,...), which are common to other industries.

- ❑ Like launch, **atmospheric re-entry phase is specific to space industry**, highly specialised issues, so assessing environmental impacts is more challenging.



Re-entry and demise of space vehicle (satellites, upper stages)



Demise of a burning Falcon 9 first stage

- So far, focus on casualty risk in re-entry environmental studies (fraction of debris that can survive and reach ground).

- However, products of re-entry demise released in **middle/upper atmosphere (unique with launch)** as gases/particles:
  → Ozone depletion: particles, gases (e.g. halogens, NOx)?
  → Climate: particles, greenhouse gases?
  → Toxicity: e.g. heavy metals?

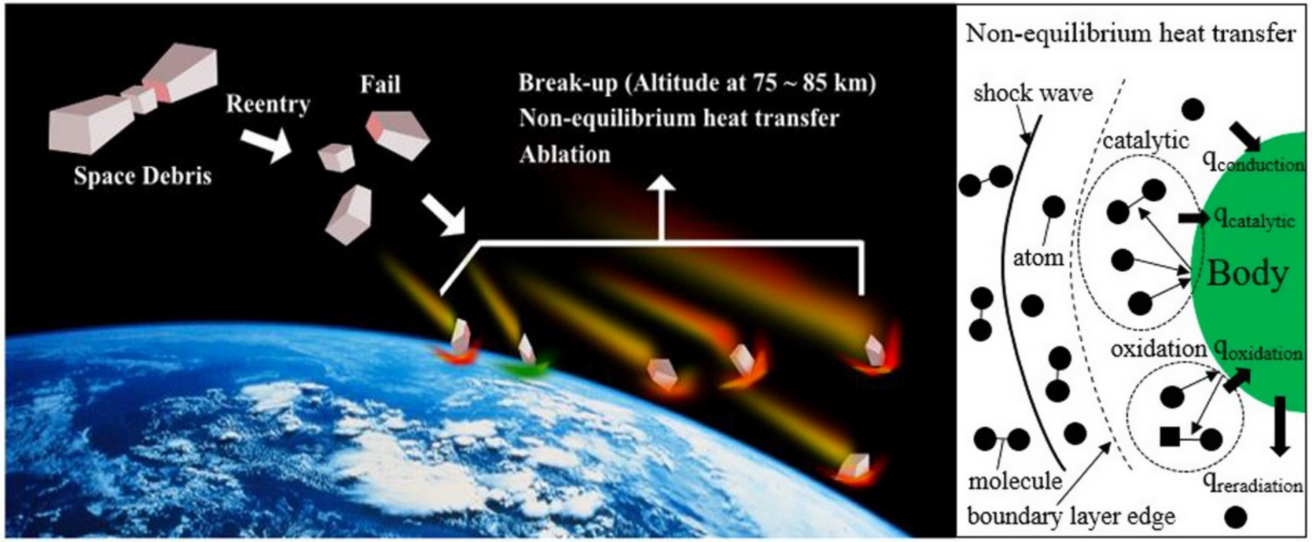
ATISPADE: ATmospheric Impact of SPAcecraft Demise

Led by Varuna UK (1 of 2 parallel ESA-funded environmental assessments)

Two phases distinguished based on physical processes & spatiotemporal scales

1. Space object demise: Destructive re-entry aerothermodynamics

Assess mass losses, physical/chemical transformations, and final re-entry products



- Complex ablation mechanisms
- Shock layer/wake: **hypersonic flow and high-T (> 1000K) chemistry**

→ gases & particles re-entry demise emissions

2. Fate and impacts of re-entry emissions: Atmospheric chemistry & dynamics

Large-scale dispersion by winds, **low-T chemistry**, and removal of re-entry emissions (up to global scale)

→ impacts re-entry emissions on ozone layer and climate

Methodology: Linking multiple physical models

1. Aerothermodynamics

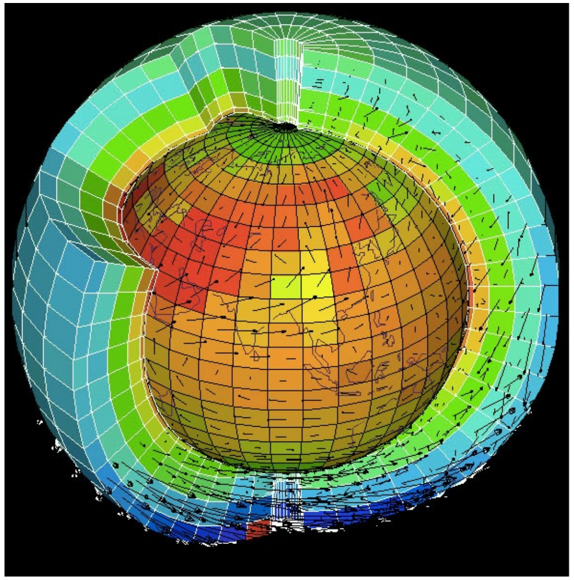
- Definition of representative U/S & S/C: construction, material composition.
- Demise assessments using **2 destructive re-entry models:** few **SCARAB** historic results, multiple new **SAM** results) → mass loss per material for range of U/S and S/C for (un)controlled re-entry.
- Hot shock layer/wake non-equilibrium chemistry with **MISTRAL**.

→ Re-entry emissions of relevant gases and particles (size, composition) 2-D mapped (alt., along-track) for range of U/S and S/C for (un)controlled re-entries.

2. Atmospheric dynamics and chemistry

- Re-entry frequency scenarios of U/S & S/C (based historical data and projections)
  → Time-evolving re-entry emissions on global scale
- Impact assessment using a **global chemistry-transport model REPROBUS** (including sub-grid scale representation of plume chemistry).

→ Ozone and climate changes.

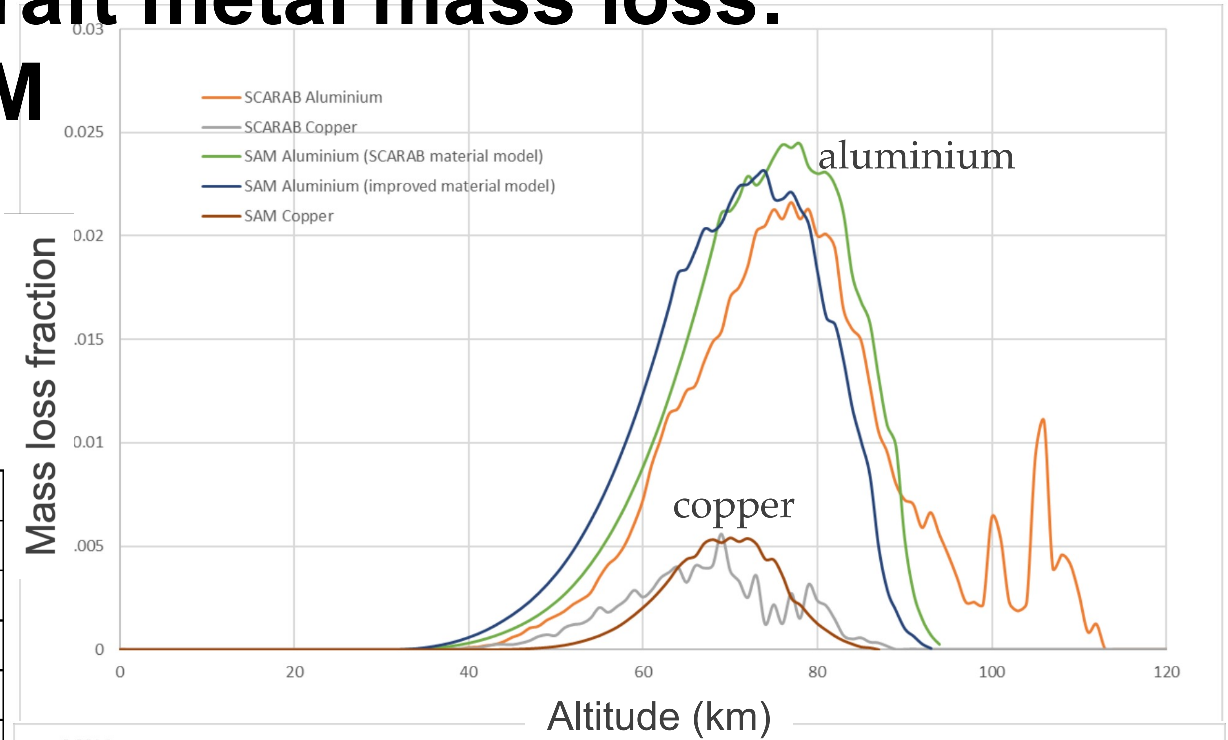


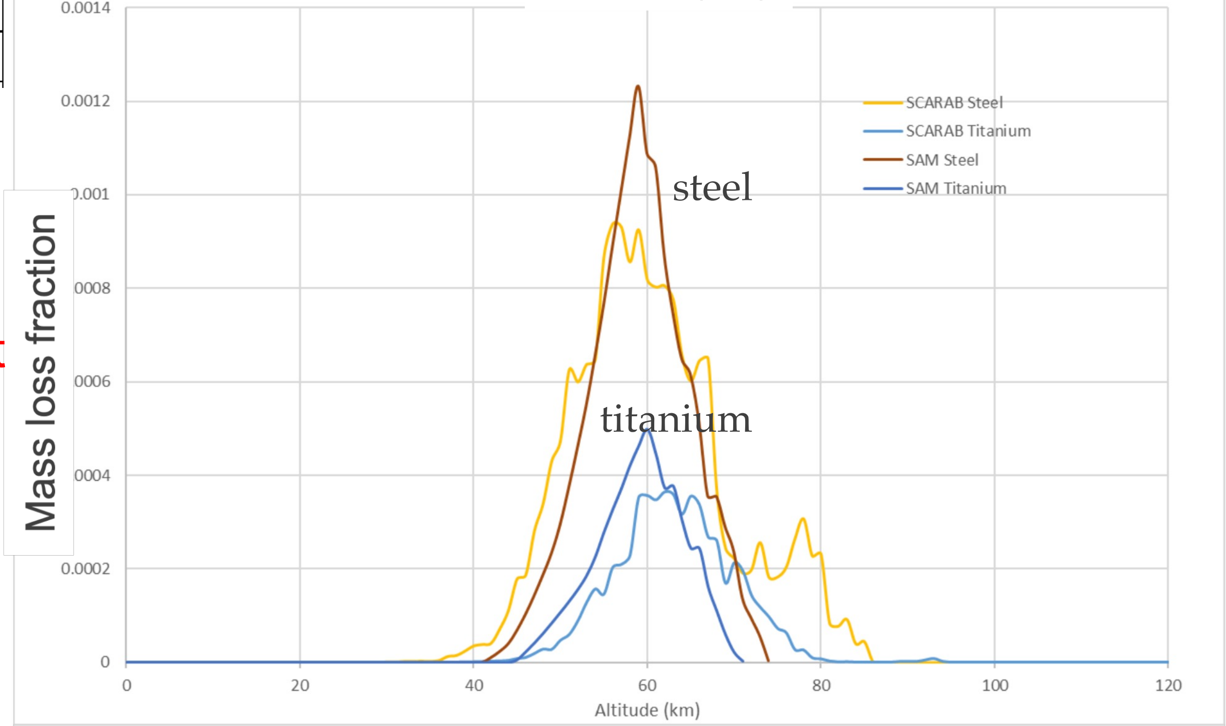
Grid of global chemistry-climate model

Examples of spacecraft metal mass loss: SCARAB versus SAM

	Spacecraft
Initial altitude (km)	120
Initial latitude (deg)	45.2
Initial longitude (deg)	10.0
Initial speed (m/s)	7800
Initial bearing (deg)	0
Initial flight path angle (deg)	-0.01

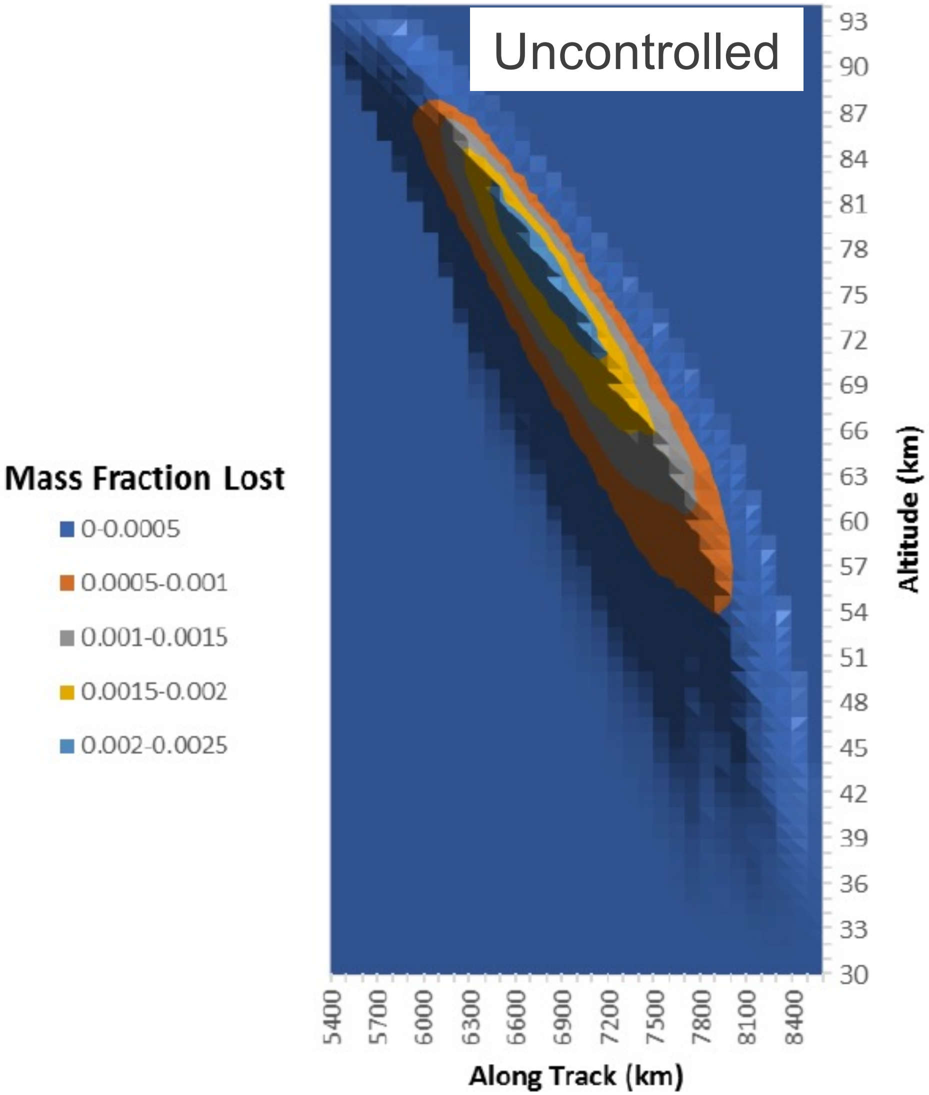
- Material model is very important
- Overall, SAM and SCARAB simulations in good agreement

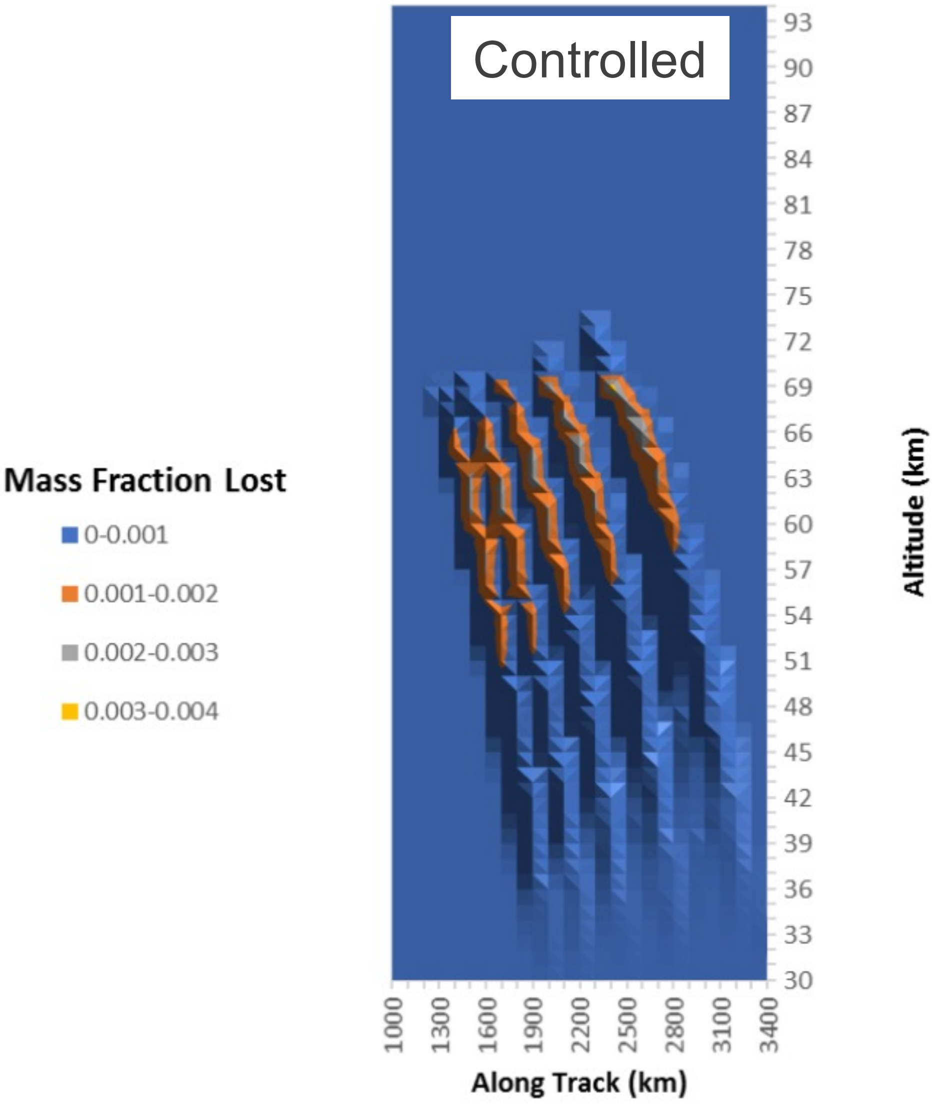




Controlled vs. uncontrolled reentry: Aluminium case

Multiple SAM simulations with varying conditions



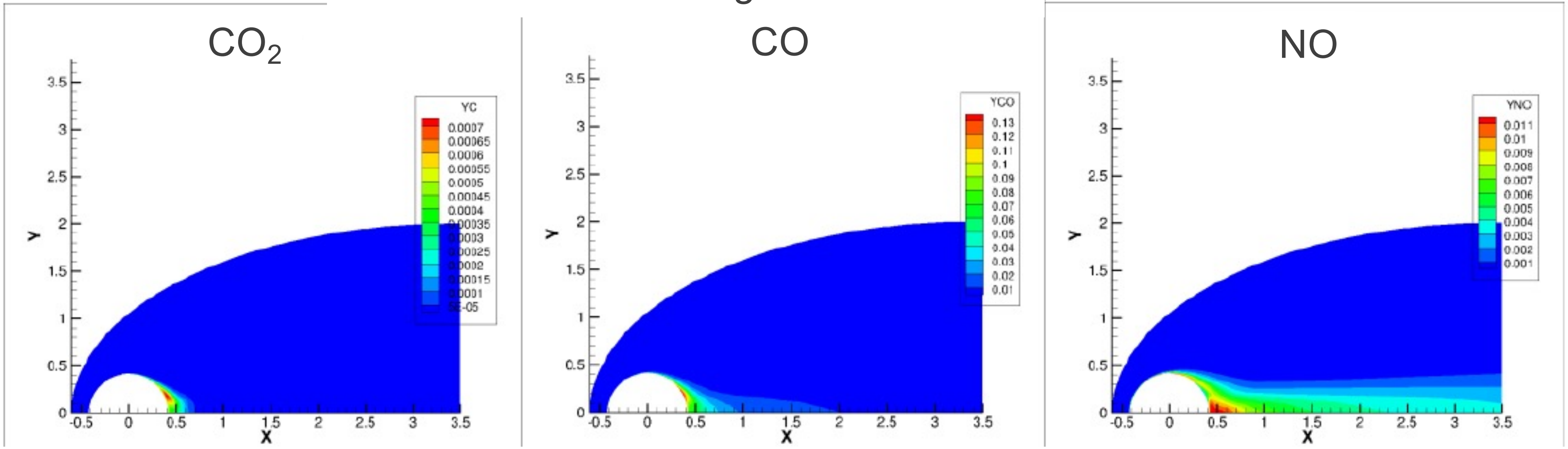


From uncontrolled to controlled re-entry : weaker and lower mass loss peak

Shock layer and wake non-equilibrium chemistry with CFD model MISTRAL

Example of results for a large spacecraft debris item (modelled as spheres).
Axisymmetric 2D grid

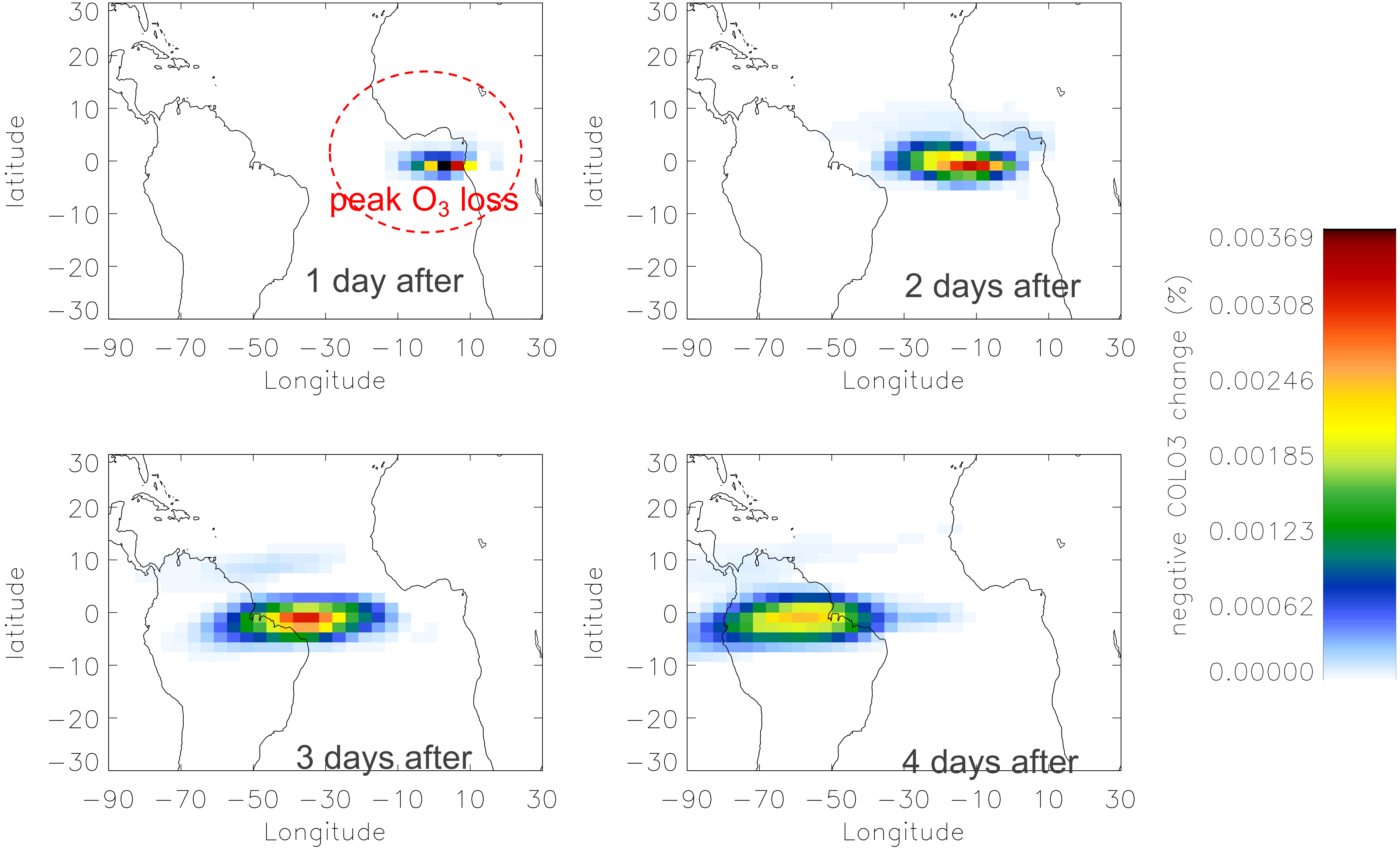
Concentration field of gases of interest



- Produced gases of interest (radicals) in very near wake (10-15 m from centreline)
- Higher production of ozone-destroying radicals (e.g. **chlorine)** at higher speeds
- **Significant NO production in shock layer**

Atmospheric chemistry-transport simulations:

Impact of single re-entry event (20 T S/C)

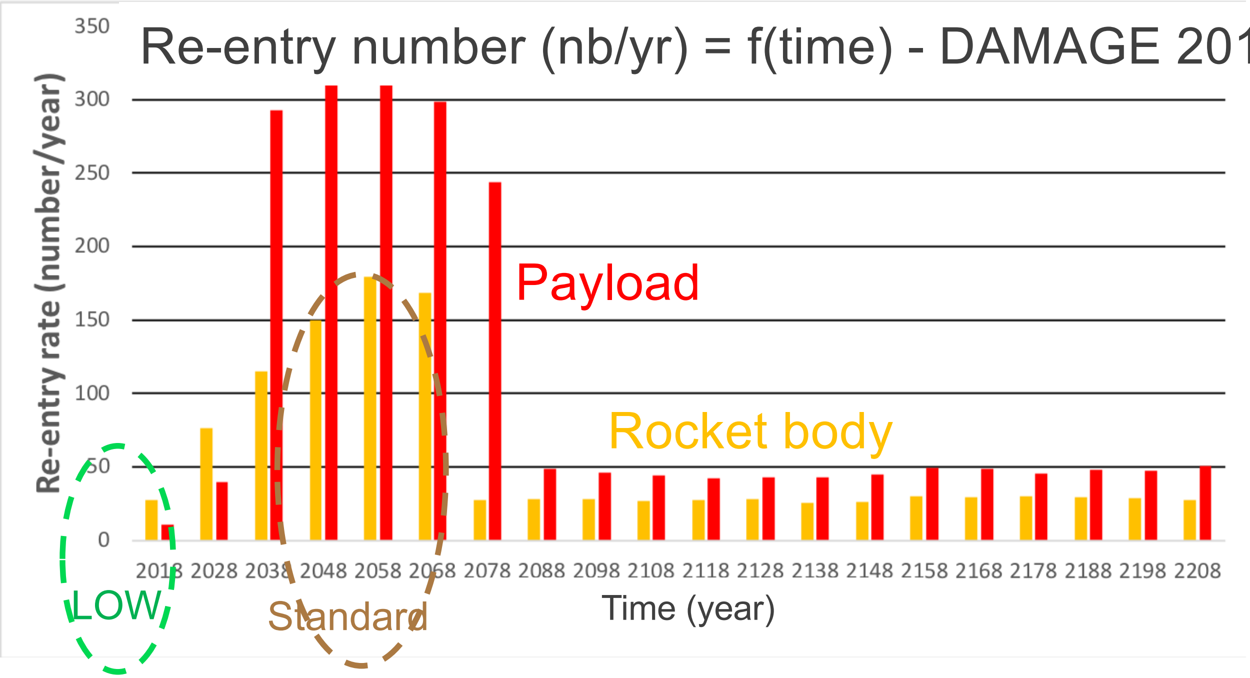


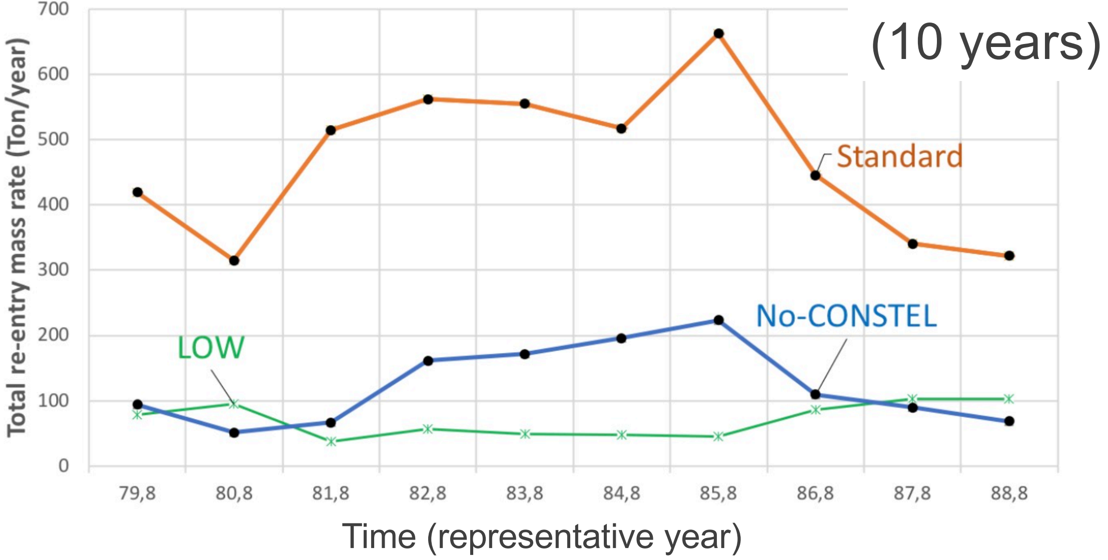
Ozone column reduction (%) [re-entry standard run – control run]

peak O_3 loss

Global O_3 column loss levels off after a week

Atmospheric chemistry-transport simulations:
Long-term impact


Re-entry number (nb/yr) = f(time) - DAMAGE 2013-2213 projection


Re-entry mass (T/yr) = f(time) for different scenarios (10 years)

Multiple simulations

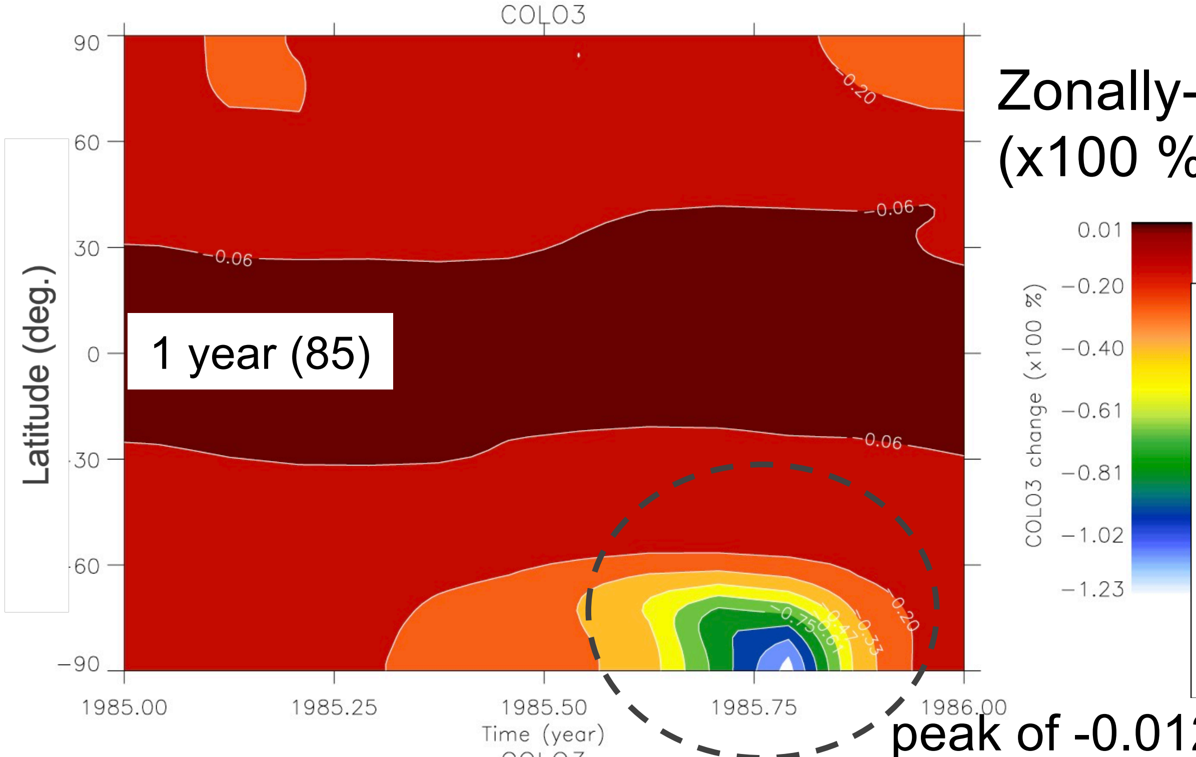
=

Gas & particles emissions for U/S and S/C (different conditions)

+

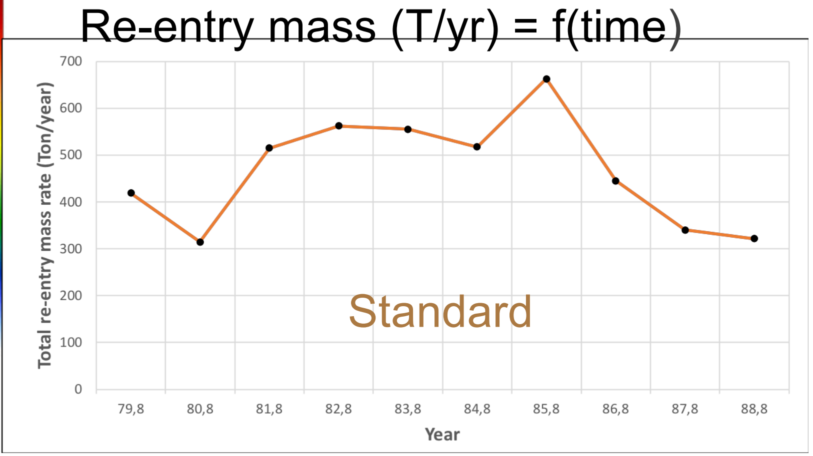
Re-entry frequency scenario (Standard, Low, No-constellation, sensitivity...)

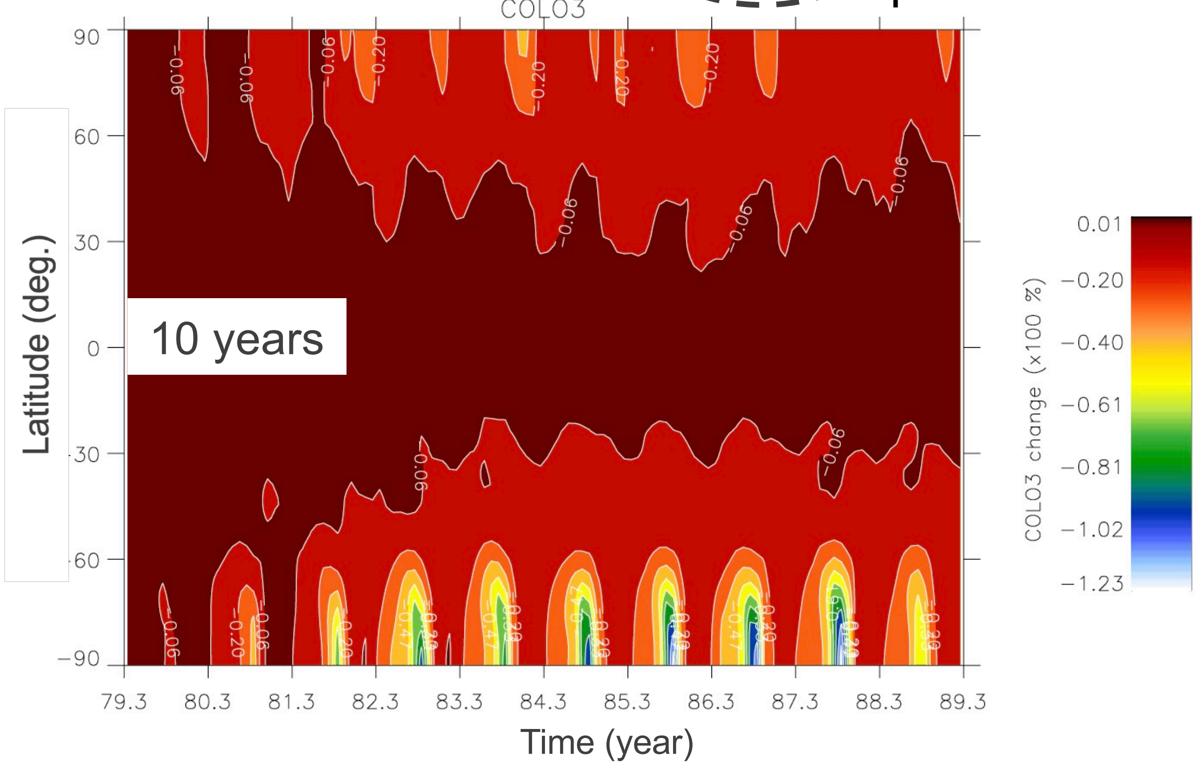
Zonally-averaged O_3 column changes (x100 %) = f(time) [standard scenario]



peak of -0.012%

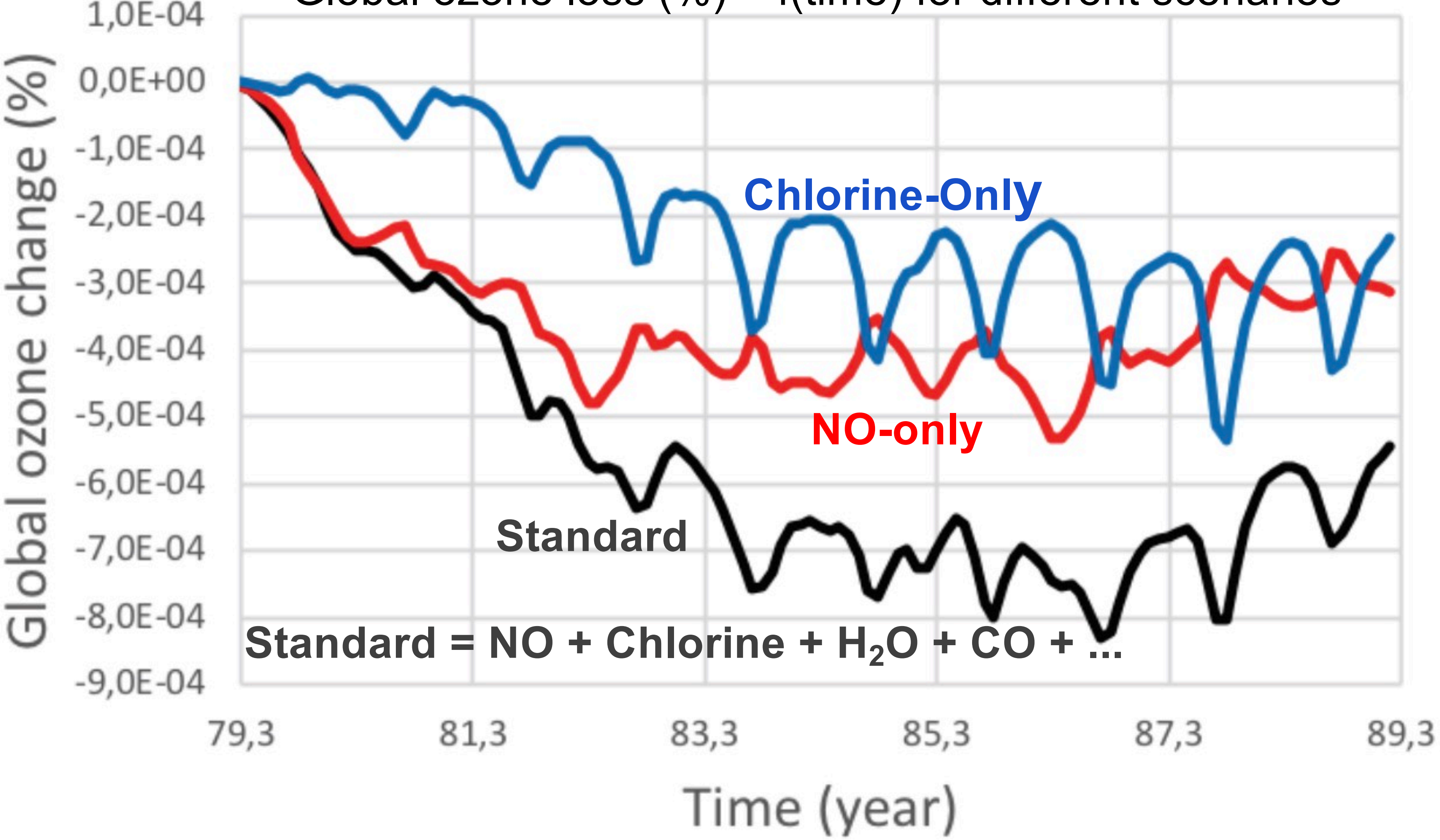
Re-entry mass (T/yr) = f(time)





After ~5 years of re-entry emissions, O_3 loss somewhat levels.
Then, a large interannual variability in O_3 response, linked to the interannual variability of emissions and of atmospheric dynamics.

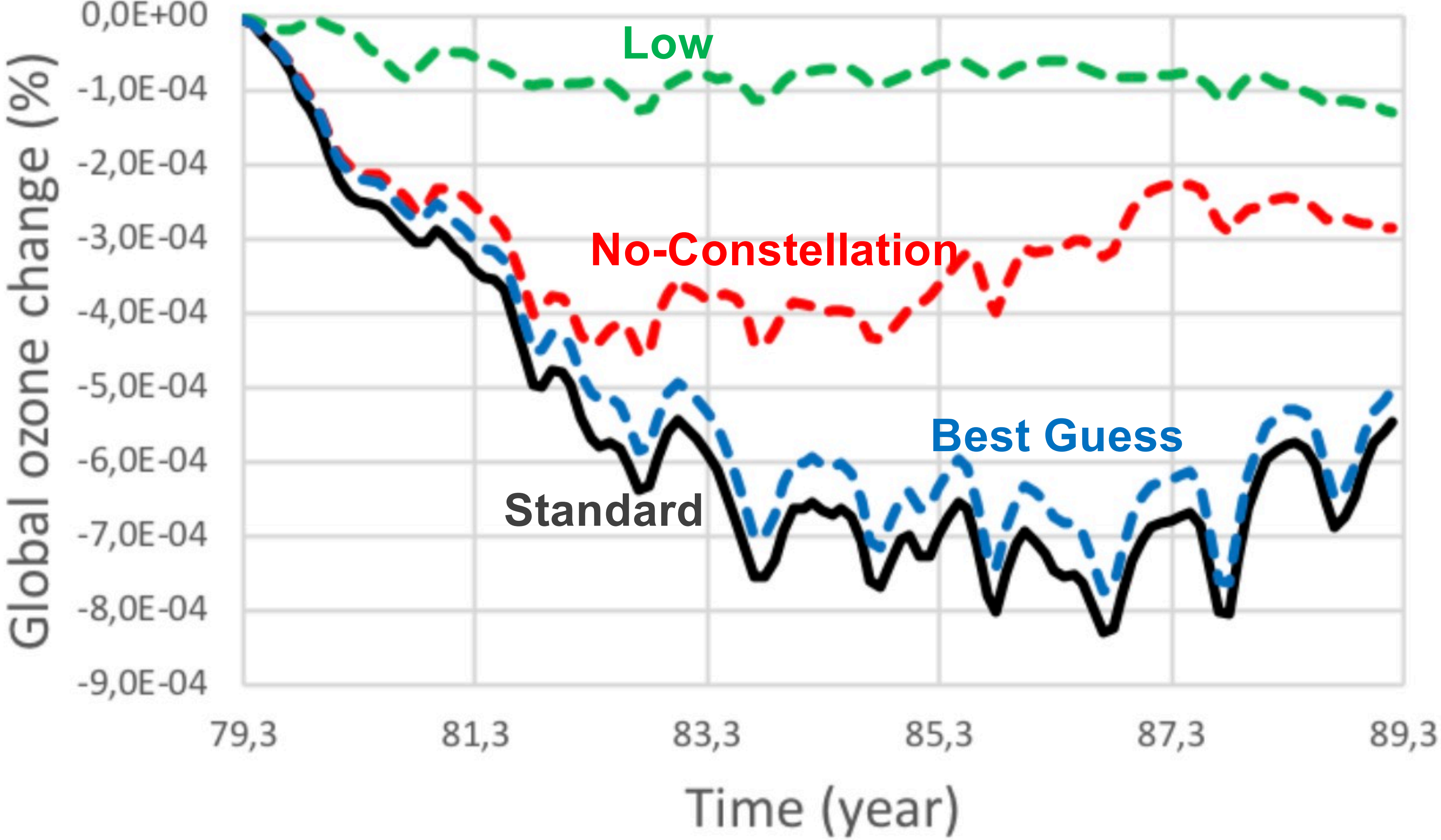
Global ozone loss (%) = f(time) for different scenarios



Standard = NO + Chlorine + H_2O + CO + …

Dominant drivers in O_3 destruction are emissions of NO and chlorine.
Other re-entry elements play a negligible role.

Global ozone loss (%) = f(time) for different scenarios



Global ozone loss scales more or less with re-entry mass
(unchanged material composition of S/C and U/S)

Key findings

☐ Ozone is found to be mostly destroyed at high latitudes, especially over Antarctic continent.
In the case of the standard (conservative) scenario:
- Antarctic local O_3 concentration reduced by up to ~0.05% at 40 km.
- Antarctic O_3 column reduced by up to ~0.012 % during austral spring ("ozone hole" period)
- Global mean annual O_3 loss varies between 0.0006 and 0.0008 %.

☐ Dominant drivers in re-entry destruction are NO (nitrogen oxides) and chlorine emissions. Other re-entry elements play a negligible role.

☐ The globally averaged ozone direct climate radiative forcing resulting from re-entry estimated to be ~-5 (-30 to +10) $\mu W.m^{-2.}$. The magnitude of re-entry CO_2 climate forcing (generated by 20 years of re-entry) can be comparable to the estimated ozone direct climate forcing.

☐ Other re-entry elements generate RFs appear to play a marginal role in climate forcing.