Environmental Impact of Propellants

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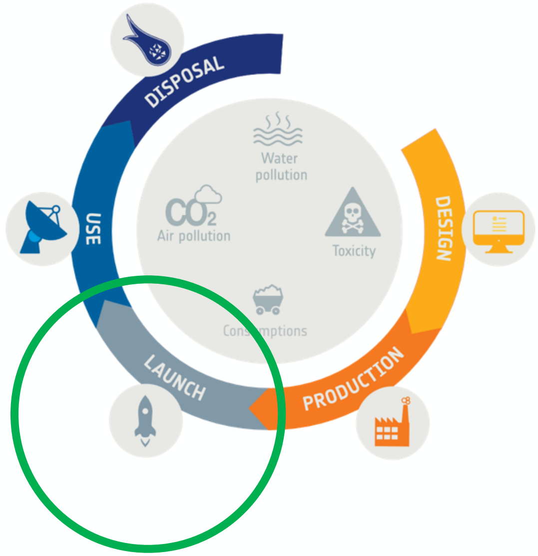
Agenda

1. Introduction to propellants' LCA
2. Manufacturing
   - Raw material
   - Production
3. Transportation and storage
   - Transport
   - Storage
4. Atmospheric Impact
   - Global Warming
   - Ozone Depletion
5. Conclusion

1. Introduction to propellants' LCA

Introduction to propellants’ LCA

Propellants in launch systems, have an impact on the environment through all their life cycle. Considerably, they “pollute” the most during the **launch event, the production, transport and storage.**



The launch event is the only human activity to “pollute” directly in **all the atmospheric layers**.

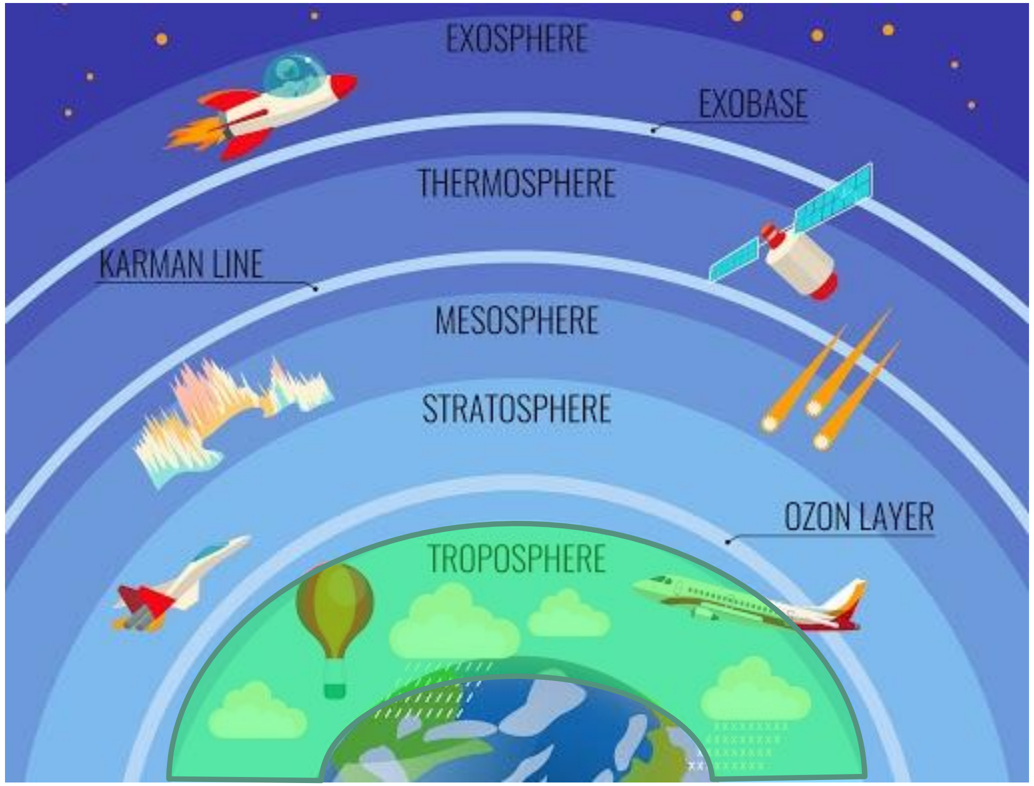
Introduction to propellants' LCA

Tropospheric Impact:

The impact on the troposphere is evaluated with the same methodology and models as for many other industries (e.g. aviation).

All the life cycle phases have an indirect impact on the troposphere, especially the release of GHG. During the launch phase, **emissions** in troposphere are less than the in stratosphere, but **not negligible**.

Local short-term perturbation are considerable for **air acidification** and **human toxicity** (presented after).



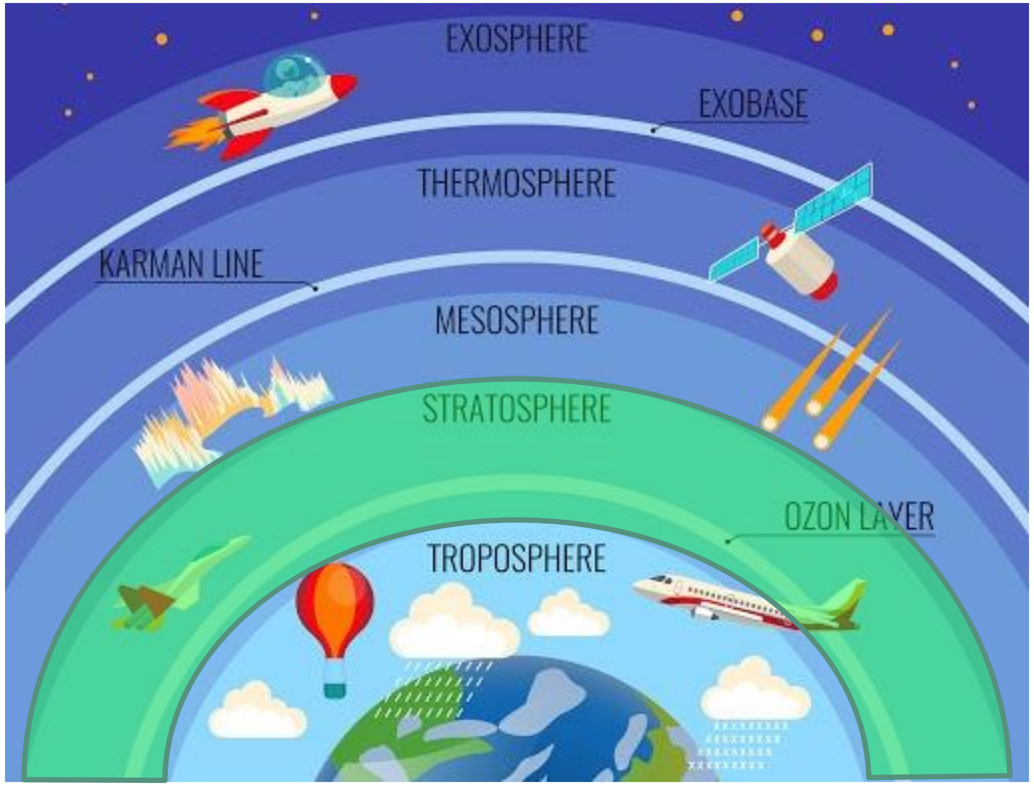
Introduction to propellants' LCA

Stratospheric Impact:

Stratospheric impact is the hot-topic of launcher's emissions. **Most of the propellant's mass** is released in this layer (about 2/3 of the total mass of propellant)

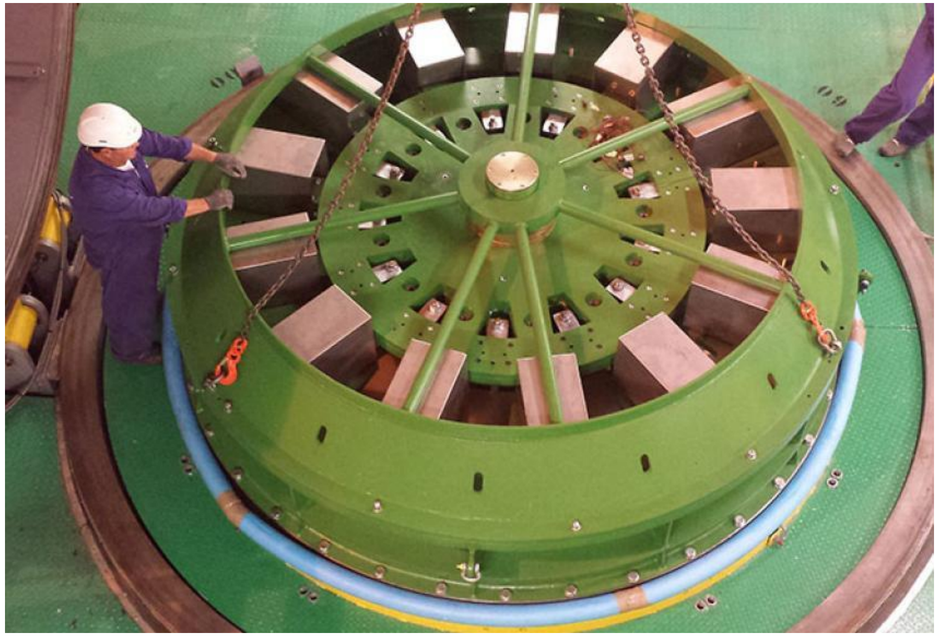
Here, particles can **accumulate** and decay into lower layers after 3-4 years. The effects in the stratospheric layer are impacting more in the long-term and globally.

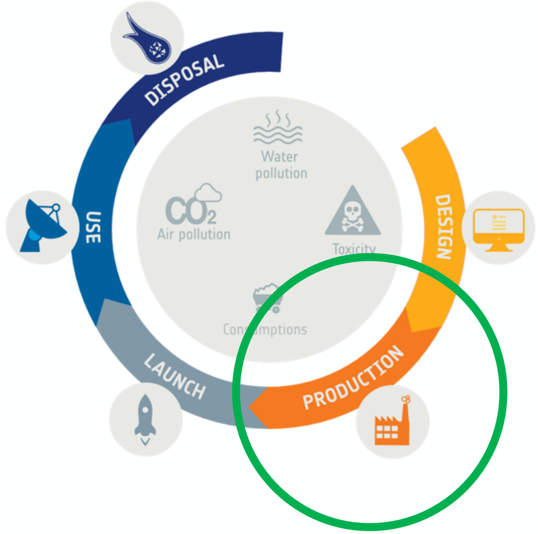
The main impacts are **climate change** and **ozone depletion** (presented after).



Introduction to propellants' LCA

Propellants "pollute" not only during the launch phase, but also the **production of the propellant** itself has an impact. Especially, considering the energy consumed and the materials/chemicals used.

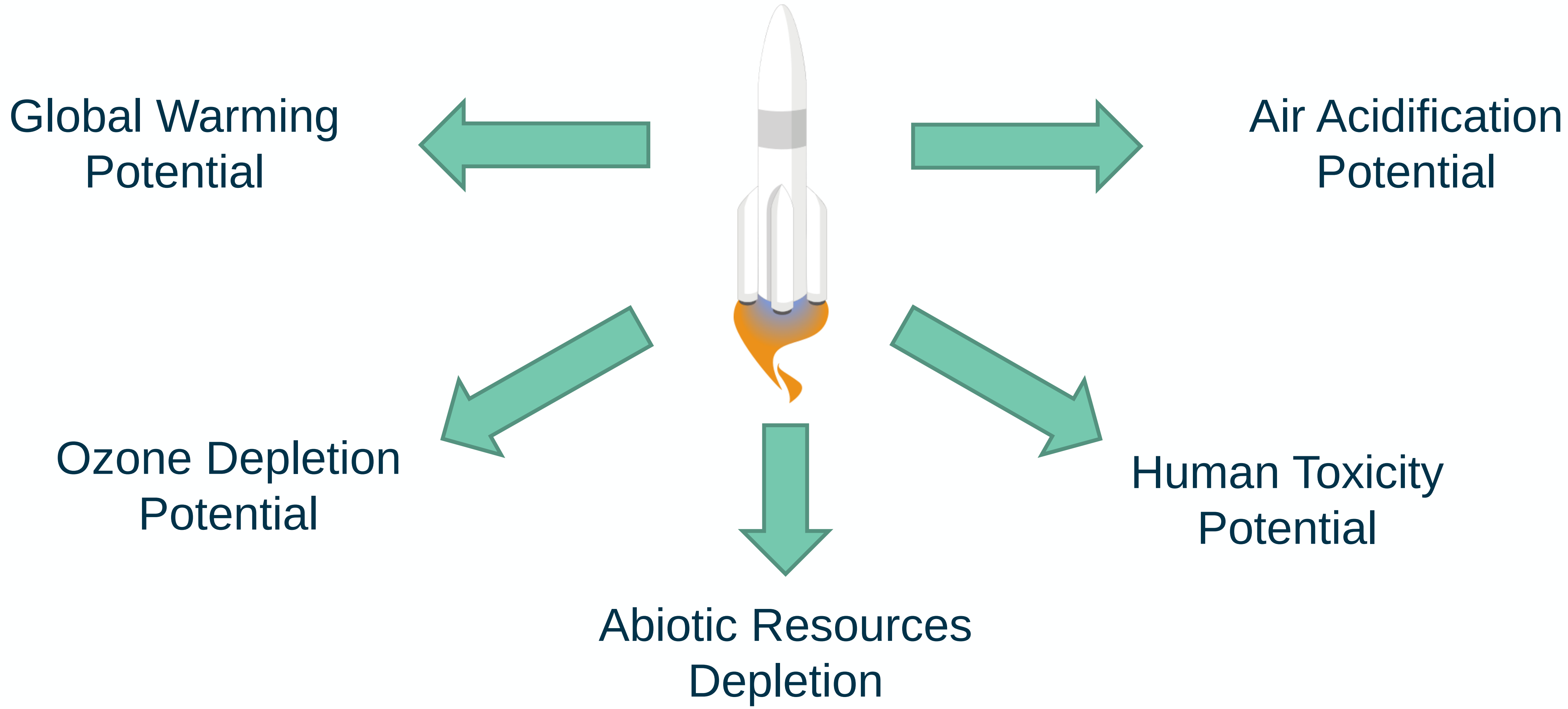




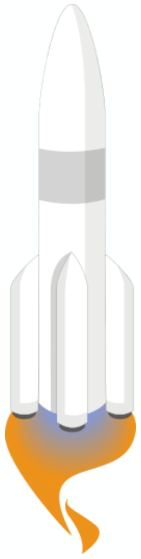
Primary energy consumption impacts mostly on the **Global Warming Potential** (also called Climate Change).

The important amount of different raw material used impacts on the **Abiotic Resources Depletion** (presented after).

Impact Categories (Highlighted for propellants)



Impact Categories



Emissions

Physical phenomena impacting the atmosphere

Global Warming Potential

Ozone Depletion Potential

Air Acidification Potential

2. Manufacturing

Raw Materials

The mass of propellants account for the biggest contributor in a launch vehicle. **Abiotic resource depletion** is impacted significantly.

Hydrocarbons **extraction has leakages of GHGs**, which impact directly the atmosphere and the **climate change**. For example, direct emission of CH_4 or H_2 behave as GHG.

Bio-based propellant usually requires vast land-areas for cultivation (unless agricultural waste is available). It impacts the **water consumption** and land-use and consequently the **carbon sink capacity** is reduced. Consequently, also impact categories less common to space LCAs might be affected.

Production

The production of the propellants could require a significant amount of energy consumption, which will have implication in **climate change**.

Depending on the propellant type, the **production process is different**. Solid propellants are usually casted, liquid propellants derives from industrial processes and bio-propellants are produced through biological processes.

Limited study have been conducted to the impact of the production phase of propellants.

Remark: more propellant than required is usually produced.

3. Transportation and storage

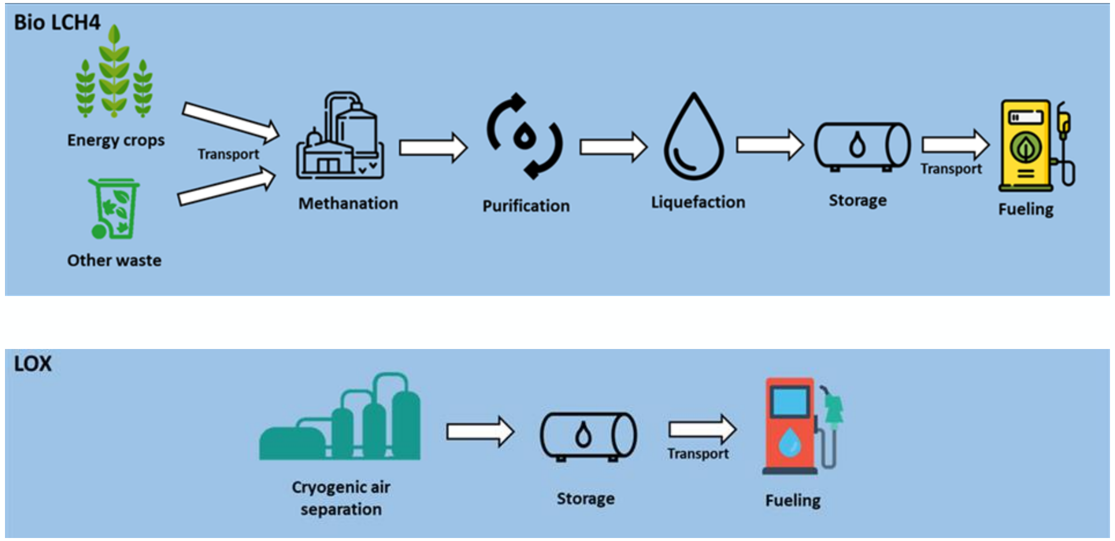
Transport

Examples of production cycle are illustrated on the right. Respectively for:

- **BioMethane**
- **LOx**

White arrows represent **transportation** and **pipelines**. Each one has intrinsic waste/leakage. Those waste/emissions shall be considered in complete LCA studies on propellants.

Transportation for solid and liquid propellants requires energy. **Climate change** is impacted.



Credits: Loïs Miraux (MaiaSpace)

Storage

To keep cryogenic propellants at their temperature:

- Partial evaporation (**atmospheric emission**), or
- Cooling (**energy consumption**)

Solid propellant can be stocked at atmospheric temperature, but in a humidity controlled environment (**energy consumption**).

If the production happens directly before the launch the storage impact is reduced. In case of early disposal the **flaring or atmospheric disposal** shall be considered.

Example: CH4 and H2 are GHGs. It is suggested to implement boil-off gas minimization and recovery strategies before flaring or venting.

4. Atmospheric impact

Atmospheric Emissions

In order to study the atmospheric impact, the chemical species released shall be known. Hitherto, **emissions' models are low-fidelity** (concentrations and particles' size are estimated).

The table on the right reports the most common propellants and their emissions:

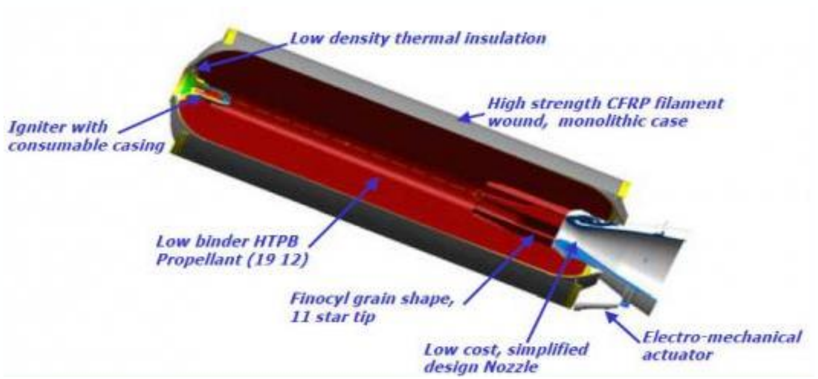
1. At nozzle's exit condition (before afterburning)
2. At the chemical equilibrium with the atmosphere (afterburning)

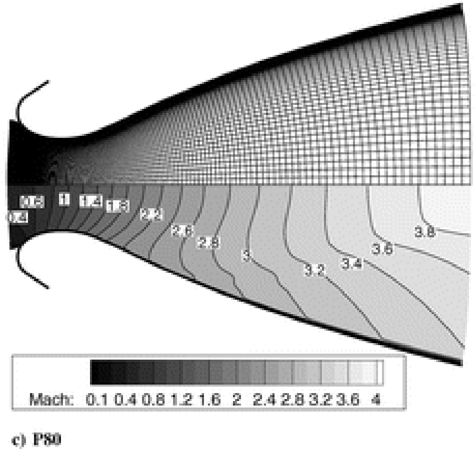
	Propellant	afterburning	before afterburning
Liquid	H_2/LOX	H_2O, NO_x	H_2O, H_2, OH
	RP-1/LOX	CO_2, H_2O, NO_x	CO_2, CO, H_2O, OH, UHCs, soot
	CH_4/LOX	CO_2, H_2O, NO_x	CO_2, CO, H_2O, OH, soot
	N_2H_4/NTO	H_2O, N_2, NO_x	H_2O, OH, N_2, NO_x
	UDMH/NTO	CO_2, H_2O, N_2, NO_x	CO_2, CO, H_2O, OH, N_2, NO_x, soot
	MMH/NTO	CO_2, H_2O, N_2, NO_x	CO_2, CO, H_2O, OH, N_2, NO_x, soot
	H_2O_2	H_2O, NO_x	H_2O, O_2, H_2, OH
Solid	NH_4ClO_4/HTPB /Aluminium	CO_2, H_2O, HCl, Al_2O_3, N_2, NO_x	CO_2, CO, H_2O, H_2, OH, Al_2O_3, HCl, N_2, NO_x, UHCs, soot
Hybrid	HTPB-Paraffin/ NTO	CO_2, H_2O, NO_x	CO_2, CO, H_2O, OH, N_2, NO_x, UHCs, soot

Credits: MT-Aerospace

Afterburning: Chemical equilibrium of the hot exhaust gases with the surrounding atmosphere. As a remark, in the troposphere and stratosphere the air mixture remains unchanged. Density, pressure and temperature change.

Atmospheric Emissions





Combustion Chamber:

- Uncertainties on combustion mechanisms
- Uncertainties on CFD

Nozzle:

- Uncertainties on boundaries thermal exchange
- Uncertainties on CFD

Rocket Plume:

- Uncertainties on reactions with atmosphere
- Uncertainties on atmospheric models (composition, transport and diffusion)

Current **emissions' estimation** are low-fidelity

→ In-situ tests to characterize the particles are needed.
→ In flight and on-ground (i.e. during static firing tests/qualification)

Particles **Morphology** and **Emission Model**

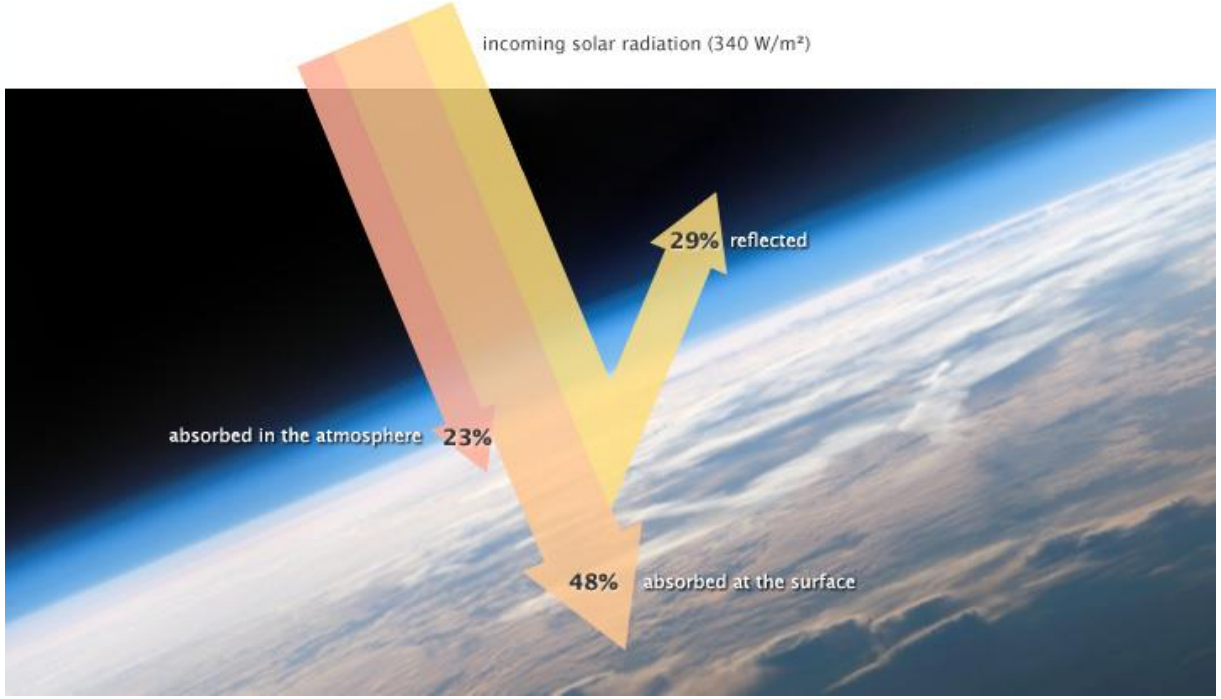
Global Warming Potential

Global Warming Potential is the **equivalent number of kilograms of CO_2** needed to have the same radiative forcing (RF) power.

Direct emissions of **soot** (black carbon), **Al_2O_3**, **H_2O**, **CO_2** and **primary energy consumption** for the production can have a significant impact, uncertainties are still present in characterizing he impact. Other molecules' impact is not modelled.

➔ The current **characterization factors** do not allow to have a good estimation of the impacts on GWP

➔ Not enough knowledge on **models to predict the impact** (depending on altitude, particles' size, …).



Note:
- Loss of ozone layer can also have impacts on Global Warming, which is not yet considered.
- Emissions of soot estimated to the major impact, while its modelling is still uncertain.

Global Warming (actors)

Direct effects are the ones related to direct injection of mass into the atmosphere (mainly stratosphere):

- Black carbon emissions
- Al_2O_3
- H_2O
- NO_x
- CO_2
- CH_4
- H_2

(CH_4, H_2): Direct emission with leakages or afterburning (O/F usually is slightly fuel-rich)

Indirect effects

- Ozone depletion (presented after)

Black Carbon

Stratospheric black carbon (BC or soot) is estimated to be the **greatest contributor** to global warming during the launch event. While aging it acquires a sulphate coating which enhance heterogeneous chemistry. It also contributes to direct ozone depletion in a mixed propellant plume. IPCC reported estimation of tropospheric BC GWP in AR5 (2018) Table 8.A.6:

Table 8.A.6 | GWP and GTP from the literature for BC and OC for time horizons of 20 and 100 years. For the reference gas CO_2, RE and IRF from AR4 are used in the calculations. The GWP_{100} and GTP_{100} values can be scaled by 0.94 and 0.92, respectively, to account for updated values for the reference gas CO_2. For 20 years the changes are negligible.

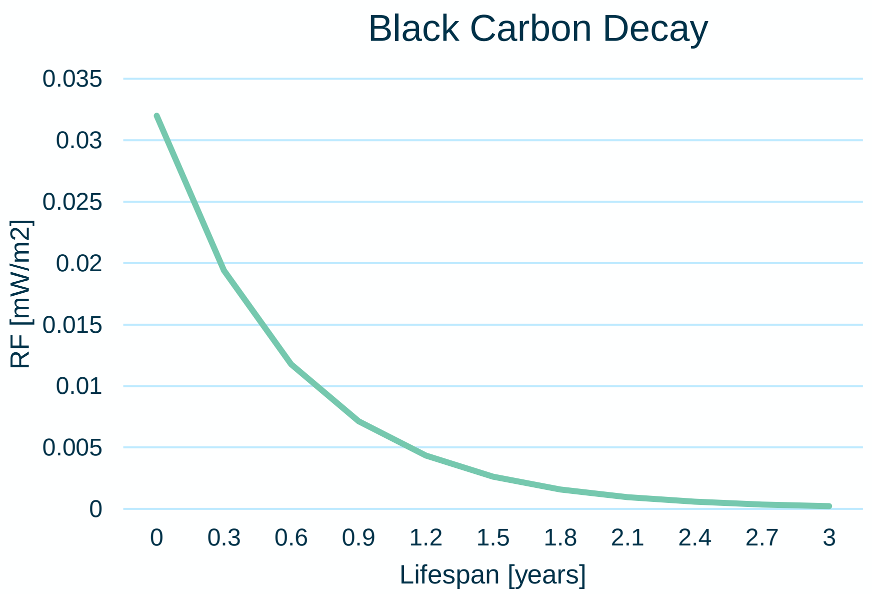
	GWP		GTP	
	H = 20	H = 100	H = 20	H = 100
BC total, global[c]	3200 (270 to 6200)	900 (100 to 1700)	920 (95 to 2400)	130 (5 to 340)
BC (four regions)[d]	1200 ± 720	345 ± 207	420 ± 190	56 ± 25
BC global[a]	1600	460	470	64
BC aerosol–radiation interaction +albedo, global[b]	2900 ± 1500	830 ± 440		
OC global[a]	–240	–69	–71	–10
OC global[b]	–160 (–60 to –320)	–46 (–18 to –19)		
OC (4 regions)[d]	–160 ± 68	–46 ± 20	–55 ± 16	–7.3±2.1

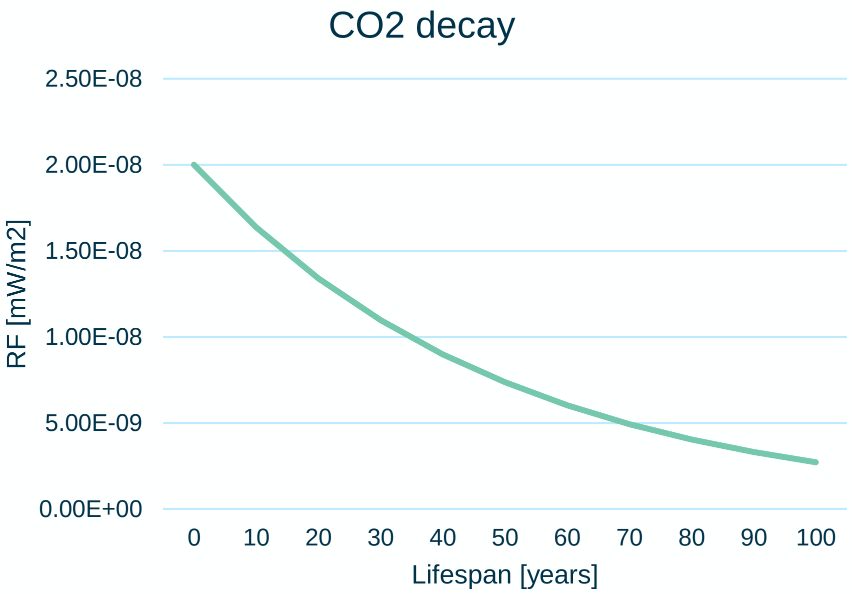
Stratospheric BC is estimated to have a longer lifetime [3-4 years] than in troposphere [3-8 days], potentially increasing the total radiative balance. Consequently, the GWP for **stratospheric black carbon is expected to be two order of magnitude more impacting**.

Black Carbon

Internal estimation based on literature: **GWP-100 years = 23.000**

- Based on literature study (uncertain data)
- Comparable to strongest GHG
- Short-term effect need to be accounted
- FURTHER STUDIES/MEASUREMENTS WILL BE NEEDED





Timescale for GWP

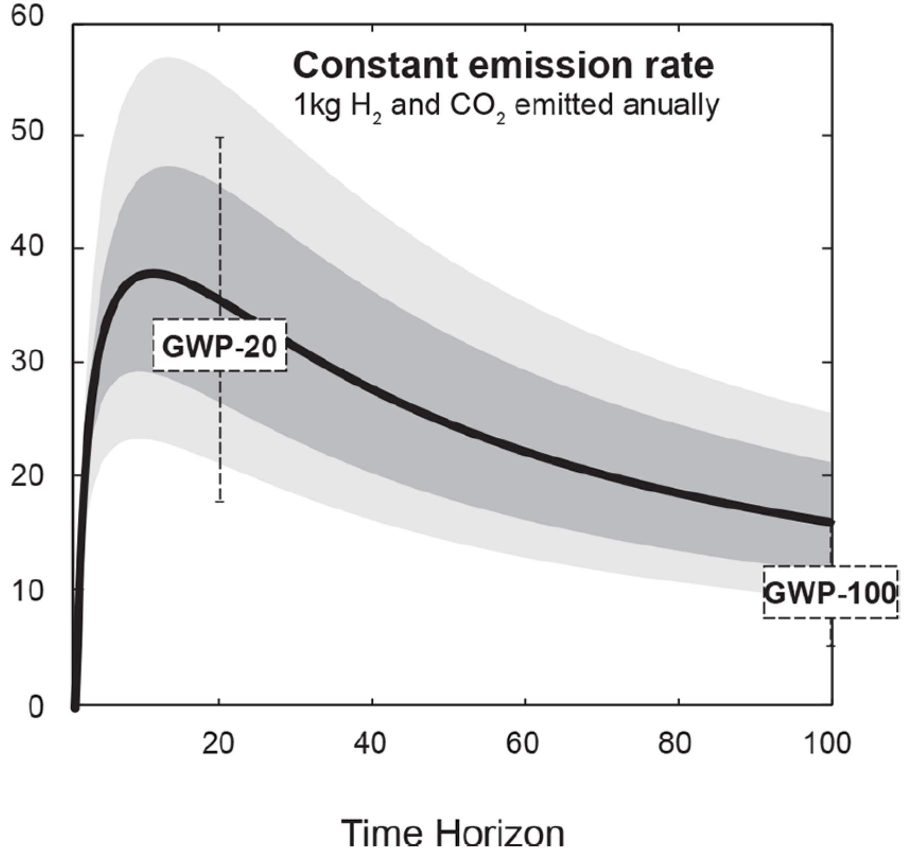
Selection of a longer timescale for the Global Warming Potential indicator could hide the importance of short-term warming.

Stratospheric emissions are estimated to have a a lifespan of 3 to 5 years in average. GWP100 might be not the best suitable indicator. While GWP20 could be enhancing stratospheric emissions rather than long term effects.

From:

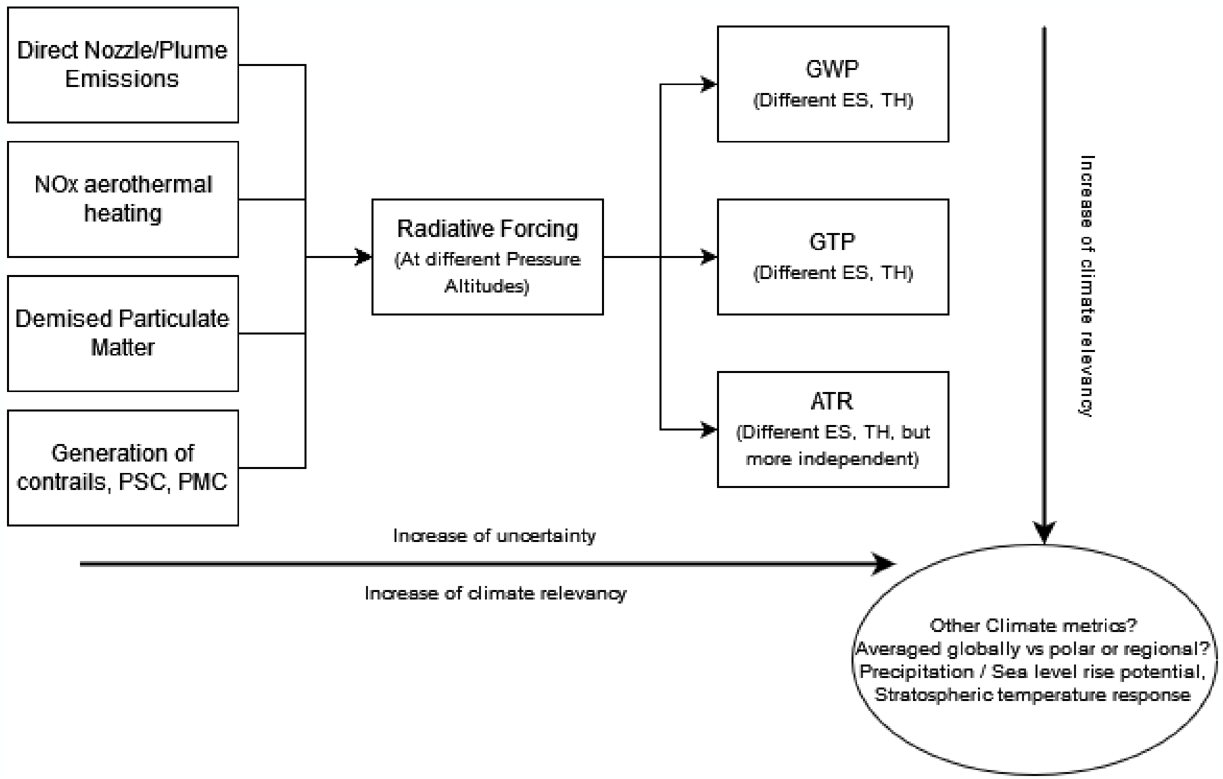
Climate consequences of hydrogen emissions

Ilissa B. Ocko and Steven P. Hamburg



Other Climate Impact Metrics

- **Global Warming Potential (GWP)** depends on:
  - Emission scenario: pulse, sustained, forecasted emission scenario
  - Time horizon (eg. 5-20 for short term, 50-100-500 for medium-long term)
  - Emission pressure-altitude
- **Global Thermal Potential (GTP):** Temperature change at the end of a given period caused by an emission w.t.r. CO_2. Same dependencies as GWP
- **Average Temperature Response (ATR):** Derivative of GTP, combines integrated temperature changes for scenarios and time horizons. Different climate change functions have been derived for aviation for each agent.



Curiosity: Polar Mesospheric Clouds (PMCs)

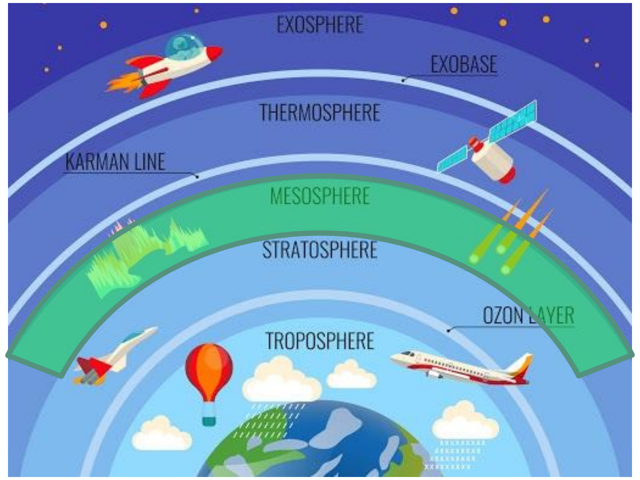
Also called “noctilucent clouds” as they are visible at night.

The phenomenon is caused by **direct H_2O emissions into the mesosphere**.

Due to very low temperatures, water **freezes** into ice crystals. Eventually, those will absorb more **radiative power** and **liquefy** forming clouds.

It is **not clear** how PMCs can influence radiative forcing and atmosphere in general.

Methane, h2 and water emissions have a significant effect.

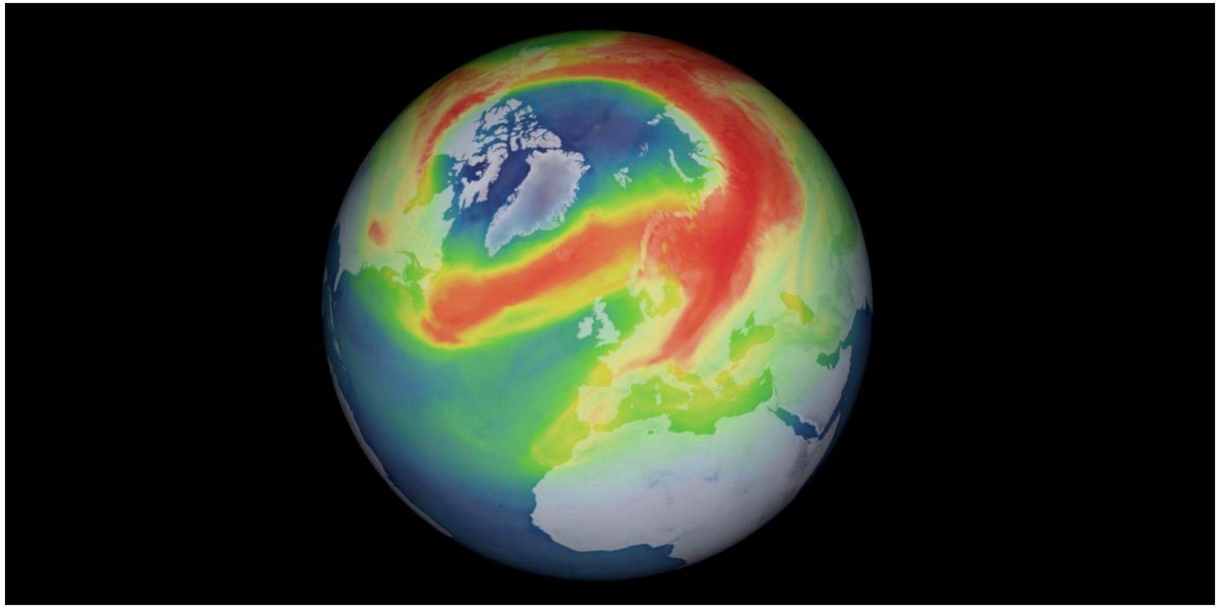


Ozone Depletion Potential

The ozone depletion potential is the **relative degradation w.r.t. trichlorofluoromethane** (CFC-11).

Chlorine depletes O_3 and **Al_2O_3 enhances** the Cl-activated. Research estimated that **NO_x due to re-entry** heating and ablation have a contribution comparable to Cl emissions.

H_2O contributes to the depletion and the formation of polar stratospheric clouds. A small contribution is also due to CO and CO_2.



ATILA project studied the impact of Al_2O_3, leaving **data gaps on the size of particles** which fundamental for the ozone layer depletion.

Ozone depletion (actors)

Emissions:

Chlorine in solid propellant

Bromine in solid propellant

Reaction with atmosphere's nitrogen*

Water vapour

→

Damaging substances:

Reactive chlorine ClO_x

Reactive bromine BrO_x

Reactive nitrogen NO_x

Hydrogen radicals HO_x

Enhancing:

- Al_2O_3 coating on alumina particles act as catalyst → particles' morphology
- Black Carbon in mixed propellant hot-plume
- Increase of atmospheric temperature due to global warming

Catalytic effect on Al_2O_3 particles:

$O_3 \rightarrow 1.5\ O_2$

$ClONO_2 + HCl \rightarrow Cl_2 + HNO_3$

*Afterburning, aerothermal heating during re-entry and demise of materials

Alumina

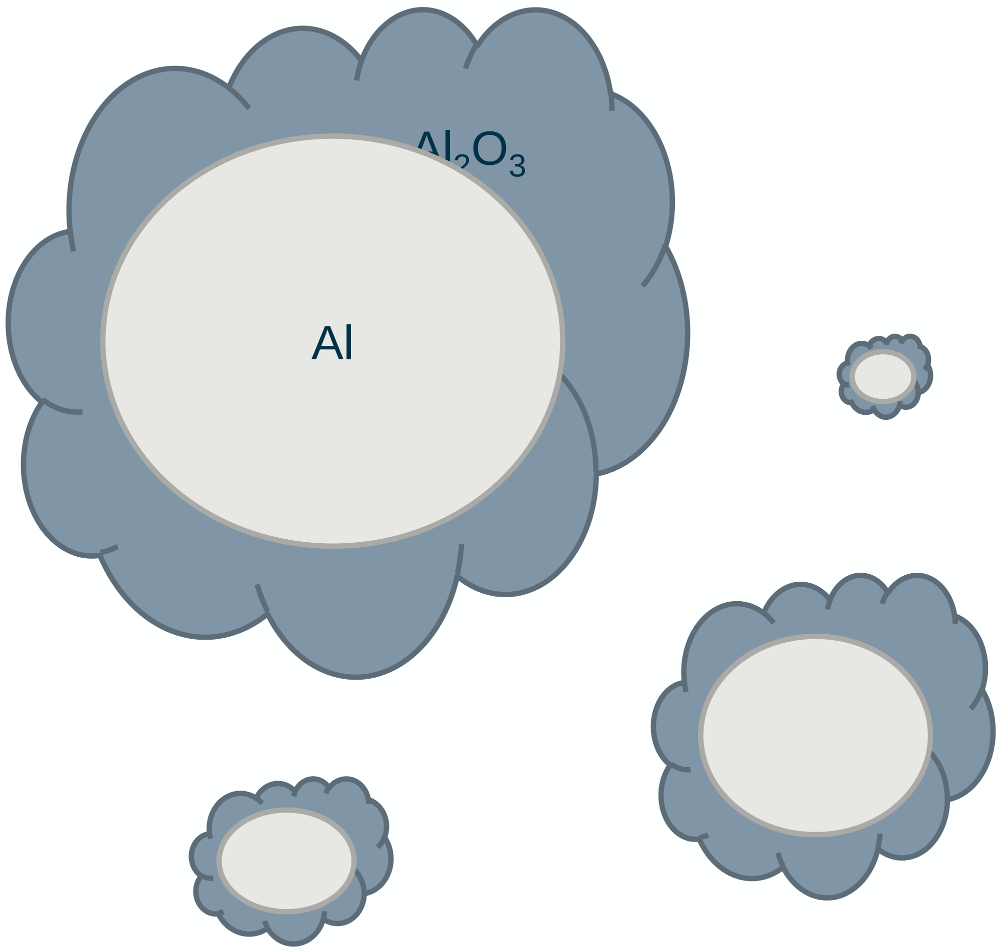
Alumina covers aluminium particles

↓

Alumina coated surface enhance ozone depletion

↓

The diameter is necessary to estimate the surface and so evaluate the magnitude of ozone depletion



Curiosity: Polar Stratospheric Clouds (PSCs)

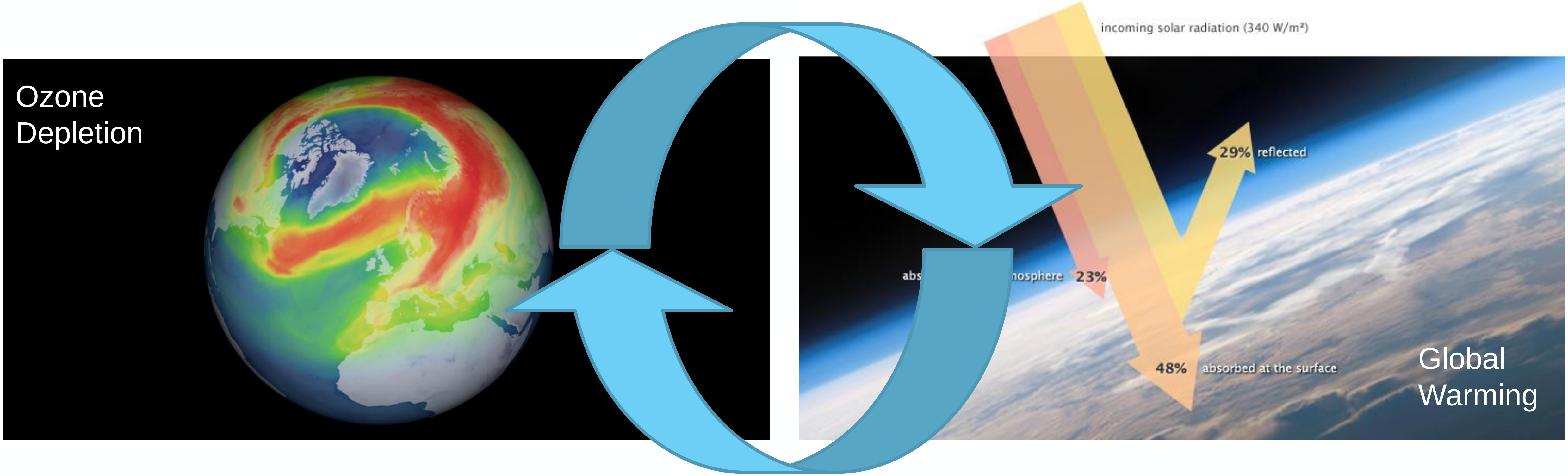
PSCs play an important role in **Antarctic ozone destruction**. They are occurring with increasing frequency in the Arctic.

PSCs impact the ozone layer by **converting** benign forms of **chlorine into reactive forms** and by removing nitrogen compounds that moderate the destructive impact of chlorine.

Radiative forcing and ozone changes from polar stratospheric clouds is estimated to be **small compared to** the impact of **NO_x** on O_3, and **black carbon** on forcing.

GWP and OZDP

Interaction



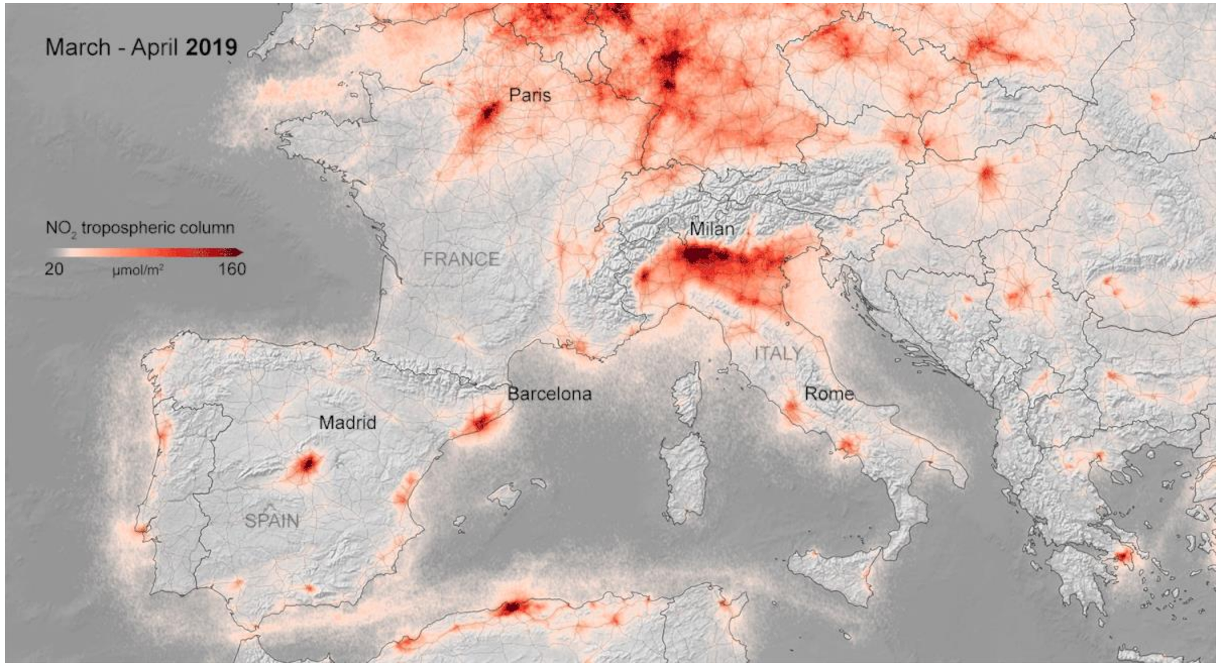
Air Acidification Potential

Atmospheric emissions of acidifying substances such as sulphur dioxide (**SO_2**) and nitrogen oxides (**NO_x**).

They can persist in the and undergo chemical conversion into acids (sulphuric and nitric).

The primary pollutants sulphur dioxide, **nitrogen dioxide** and **ammonia** (NH3).

Even non-nitrated propellants contribute to acidification due to the **afterburning** reactions into the atmosphere (where nitrogen is naturally present).

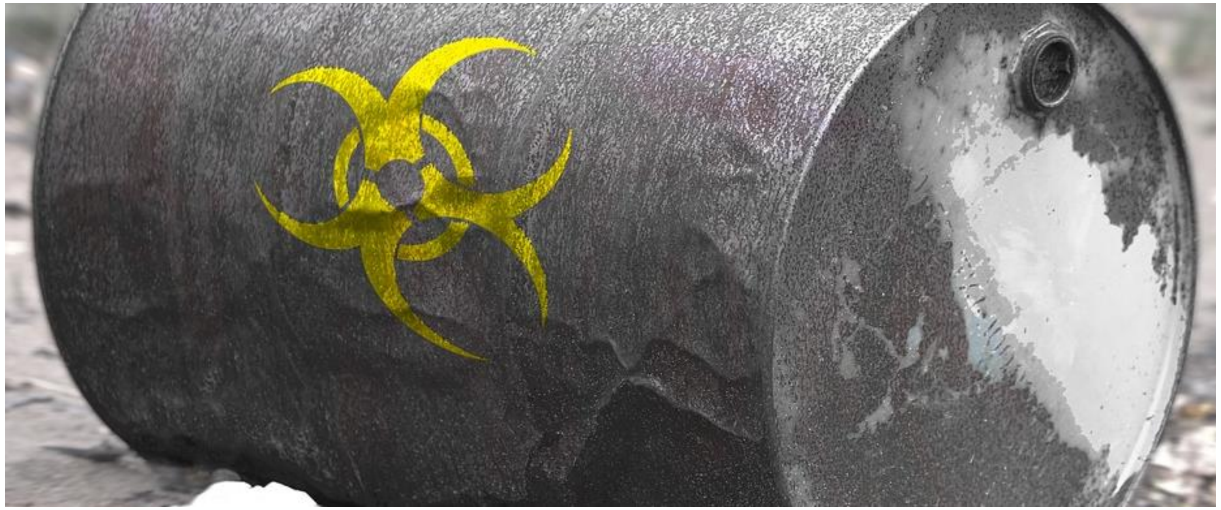


Human Toxicity Potential

The human toxicity potential is an index that reflects the potential harm of a unit of chemical released into the environment.

Certain propellants (e.g. **Hydrazine**) are extremely toxic for humans already in their state before combustion (or expulsion).

Others, can produce toxic substances after the combustion process. E.g. solid propellants with perchlorate (**ClO_4-**) form hydrogen chloride (**HCl**), which is toxic for humans.



5. Conclusion

Various Considerations

Usually, **firing test of new engines** is a short process and as a consequence a **negligible** amount of propellant mass is burned.

Ground firing **test on full-scale shall be considered** in the LCA. However, its impact shall be considered only for **tropospheric** emissions.

Moreover, if a space mission’s launch mission is not nominal (eventual **failures**) the amount of propellant burned is a multiple of the single nominal launch.

General consideration on methane

Preliminary Assessment:

- Methane's production impact depends on the used source (Biomethane requires vast areas for land-use, extraction affects abiotic resource depletion and industrial processes consumes significant amount of energy).
- Methane is a GHG. Any leakages could be potential harmful to the climate change effect.
- It is not clear yet whether the soot's formation during the propellant's burning is greater or not than solid propellants.
- Methane seems promising in reducing the ozone layer depletion and avoiding local toxic emissions with respect to solid rocket motors.
- **Further studies are needed**. Propellants' life cycles are complex and focusing only on a small portion of it could be misleading.

Conclusion

Hitherto, full LCA studies on launch vehicles contain knowledge gaps and need to be extended: atmospheric impact needs further studies, and other typologies of propellants need to be studied.

Needs:

- **Full LCA studies** (e.g. include complete atmospheric impact)
- **Scientific studies** on unknown and uncertain phenomena (e.g. black carbon) and how to include them into environmental impact categories

For the moment, it is difficult to assess which propellants are “green” without a full LCA study

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