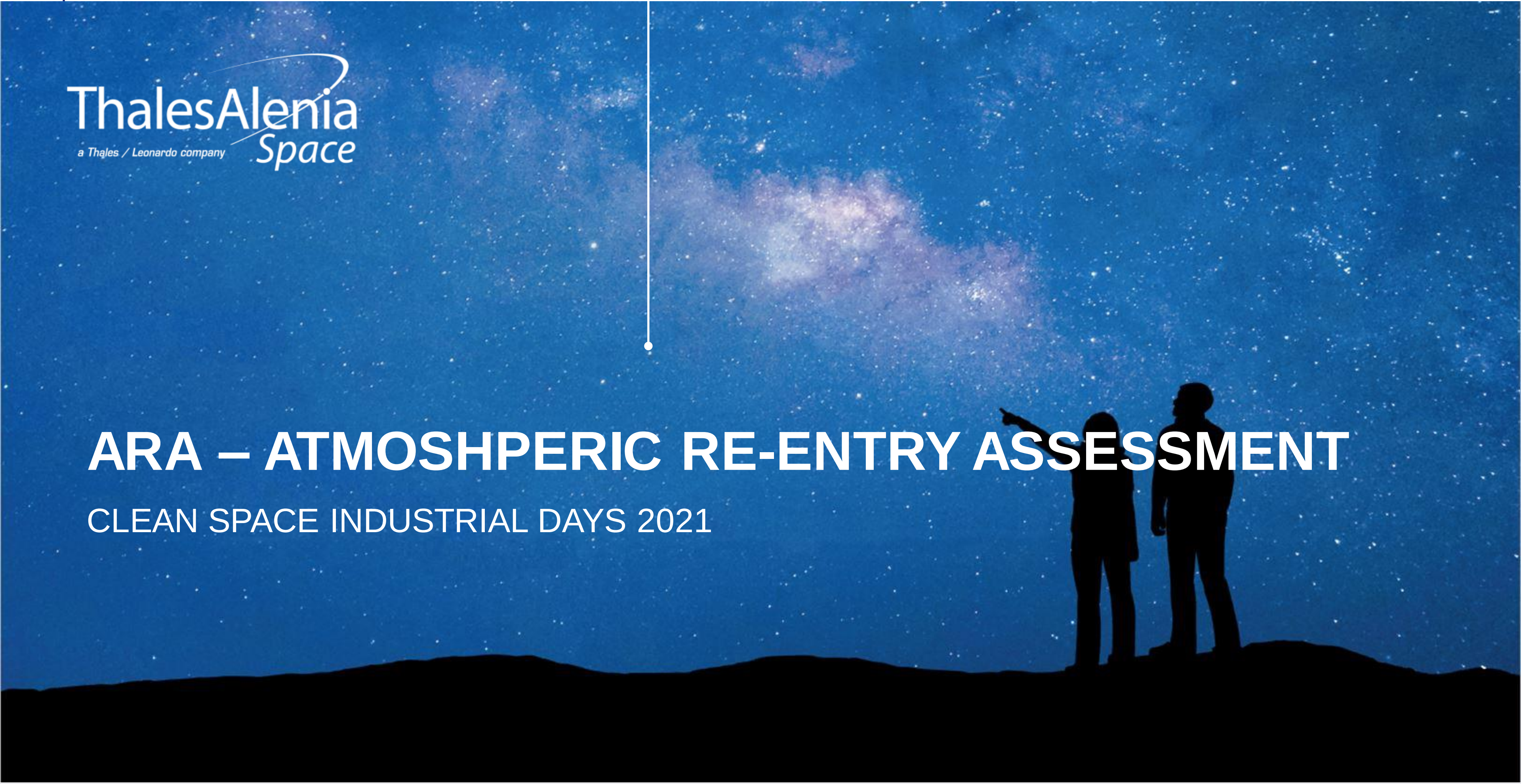

ARA – ATMOSHPERIC RE-ENTRY ASSESSMENT

CLEAN SPACE INDUSTRIAL DAYS 2021

TEAM

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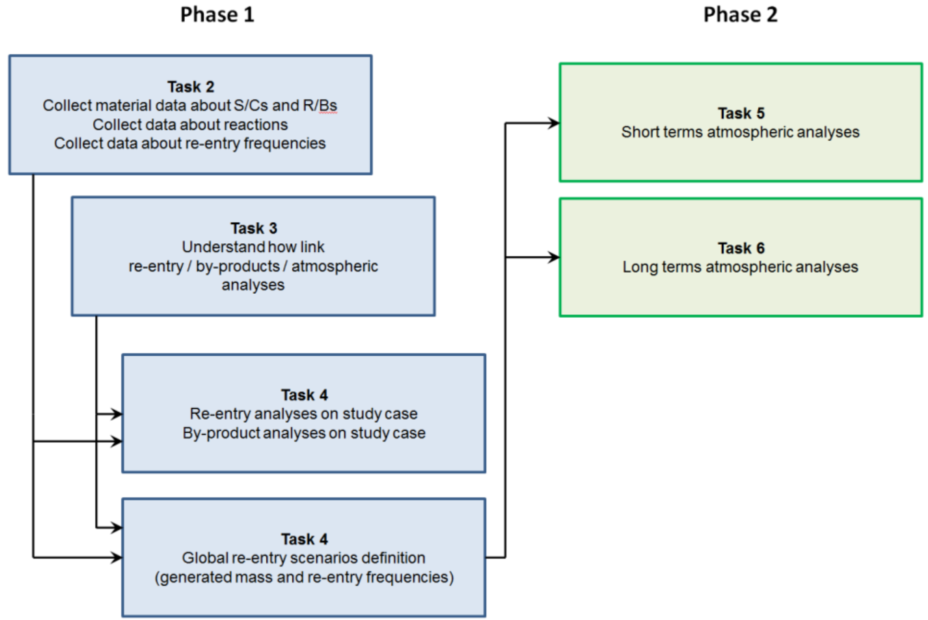
GOALS & ACTIVITY ORGANIZATION

The scope of the Study is the investigation of the potential impacts on the atmosphere and on climate, caused by gases and particles released during the re-entry of spacecrafts and rocket upper stages



Phase 1

Task 2
Collect material data about S/Cs and R/Bs
Collect data about reactions
Collect data about re-entry frequencies

Task 3
Understand how link
re-entry / by-products / atmospheric analyses

Task 4
Re-entry analyses on study case
By-product analyses on study case

Task 4
Global re-entry scenarios definition
(generated mass and re-entry frequencies)

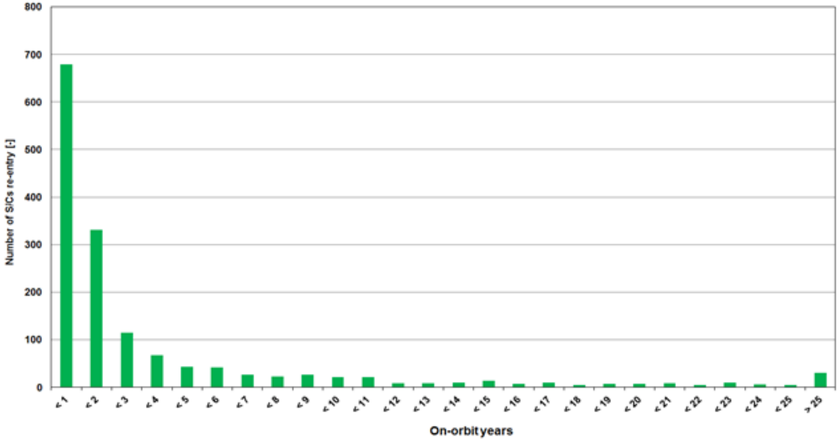
Phase 2

Task 5
Short terms atmospheric analyses

Task 6
Long terms atmospheric analyses

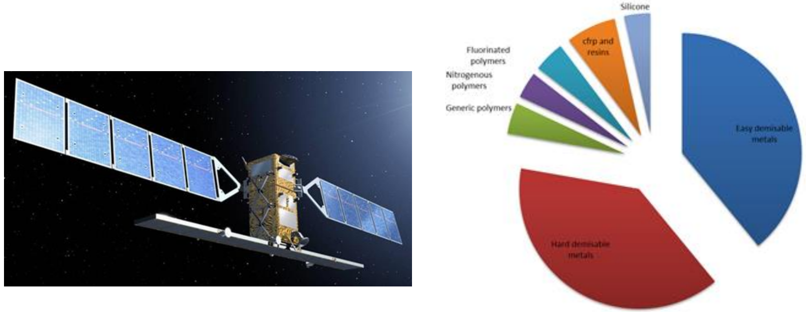
TASK 2: S/C COMPOSITION AND RE-ENTRY FREQUENCIES

- A first goal consisted in assessing the re-entry frequency (for both S/C and upper stages) to be expected over the coming decades
- This activity was carried out by collecting data about current re-entries in order to understand future trends



S/Cs on-orbit years

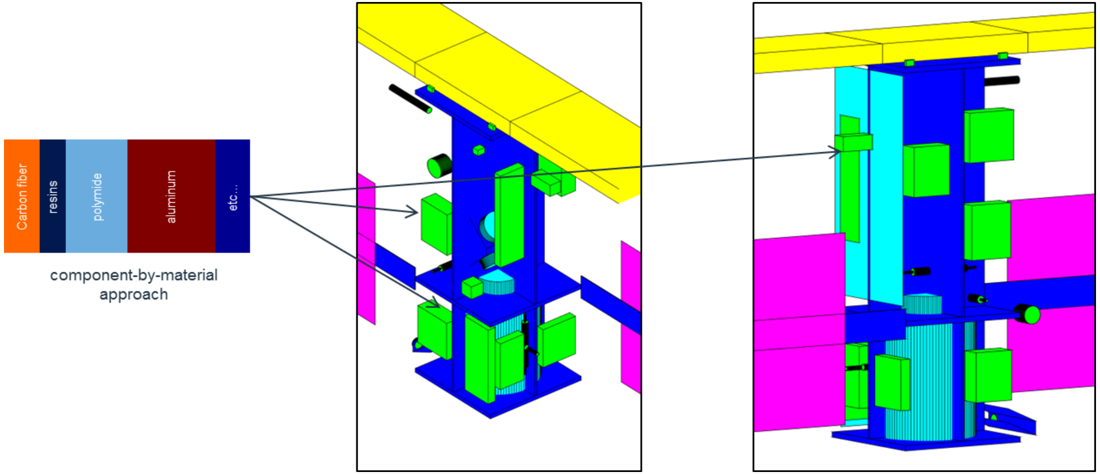
- To properly asses impact on atmosphere we need to evaluate for each material pressure, temperature, ablated mass vs altitude, time, latitude, longitude. The quantity and the altitude of the related ad material are related to the altitude of exposure of the various material exposed surface, which depends from S/C configuration and S/C progressive fragmentation. To properly evaluate the altitude of exposure we need to associate materials to components, and provide an associated material budget at component level



Sentinel-1 and example of material composition

TASK 4: RE-ENTRY SIMULATIONS

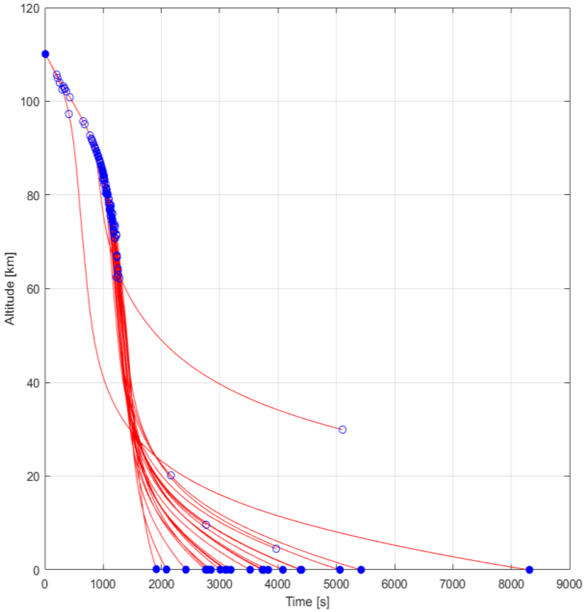
- An accurate model of the selected study case was developed in the TASinI re-entry analysis tool TADAP, taking into account the detailed material mass budget. Since TADAP is a low-fidelity code, a simplified specific routine was implement in the code to take into account the accurate data from material mass budget with the difficulty to develop a proper model for complex geometries and material assignations (e.g. inner art of electronic boxes).



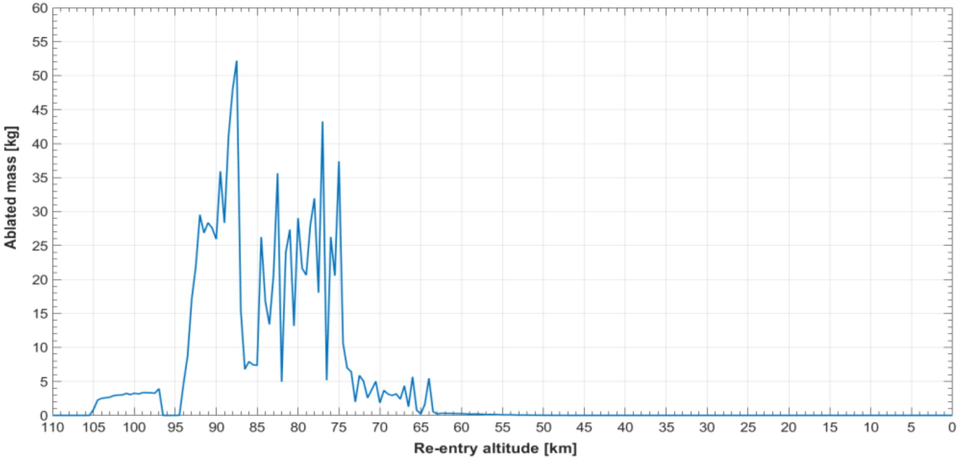
TADAP modelling of Sentinel-1

TASK 4: RE-ENTRY SIMULATIONS

/// The TADAP model allowed to develop data of the substances released in the atmosphere in terms of mass and altitude



Altitude vs time fragmentation history

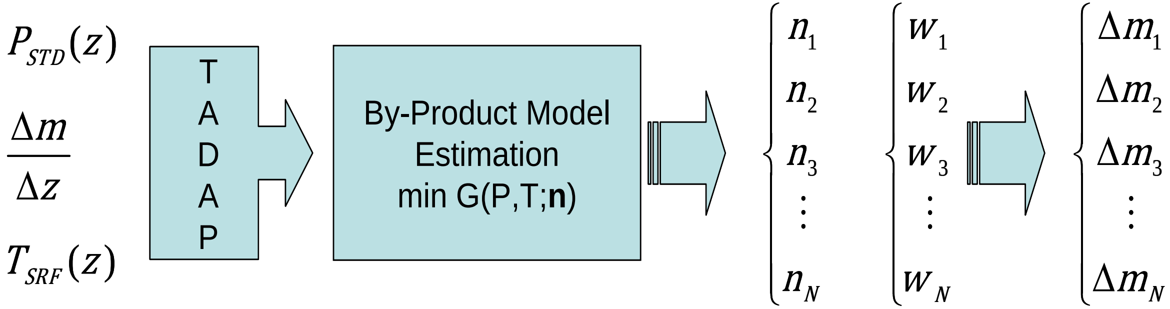


Easy-demisable demise profile

TASK 4: BY-PRODUCTS SIMULATIONS

- The evaluation of by-products of the ablation/partial ablation of the materials that could be released into the atmosphere depends on several criteria such as:
  - altitude/velocity (trajectory path)
  - relative velocity of the components
  - relative thermal properties of the individual components /compounds
  - relative aerothermal stresses at each particular trajectory point on the materials

The method is based on the determination of the chemical composition in a complex mixture for a closed system at given P, T conditions, minimizing the Gibbs free energy of all the possible chemical species.



$P_{STD}(z)$

$\frac{\Delta m}{\Delta z}$

$T_{SRF}(z)$

TADAP

By-Product Model Estimation
min G(P,T;**n**)

$\begin{cases} n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_N \end{cases}$ $\begin{cases} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_N \end{cases}$ $\begin{cases} \Delta m_1 \\ \Delta m_2 \\ \Delta m_3 \\ \vdots \\ \Delta m_N \end{cases}$

TASK 4: BY-PRODUCTS SIMULATIONS

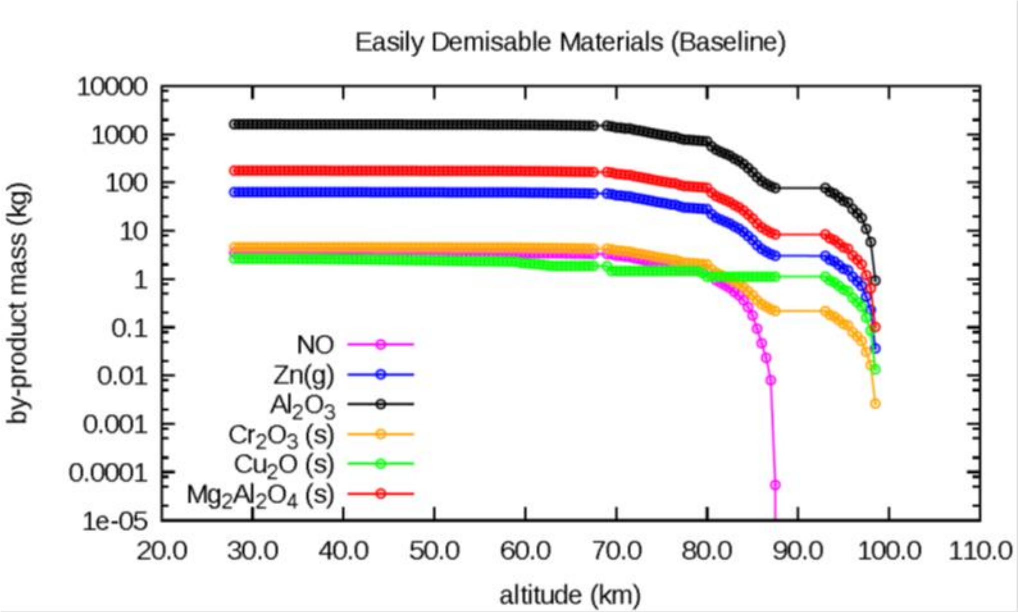
- The main classes of materials – Easy demisable, Hard demisable, PTFE, CFRP, as well as batteries and optical elements are studied and the importance of the different by-products are classified and quantified as inputs to the climate analysis.

- To evaluate the by-products, the thermodynamics of the material components have to be evaluated. For many complex materials, such as plastics (such as PTFE) and battery electrolytes, this presents within itself a challenge as no clear model exists, and has to be not only devised but also extended to high temperature conditions.

- An additional work was performed on soot and droplets formations and these are important also for aerosol estimations, this gives rise to the importance of these factors also.

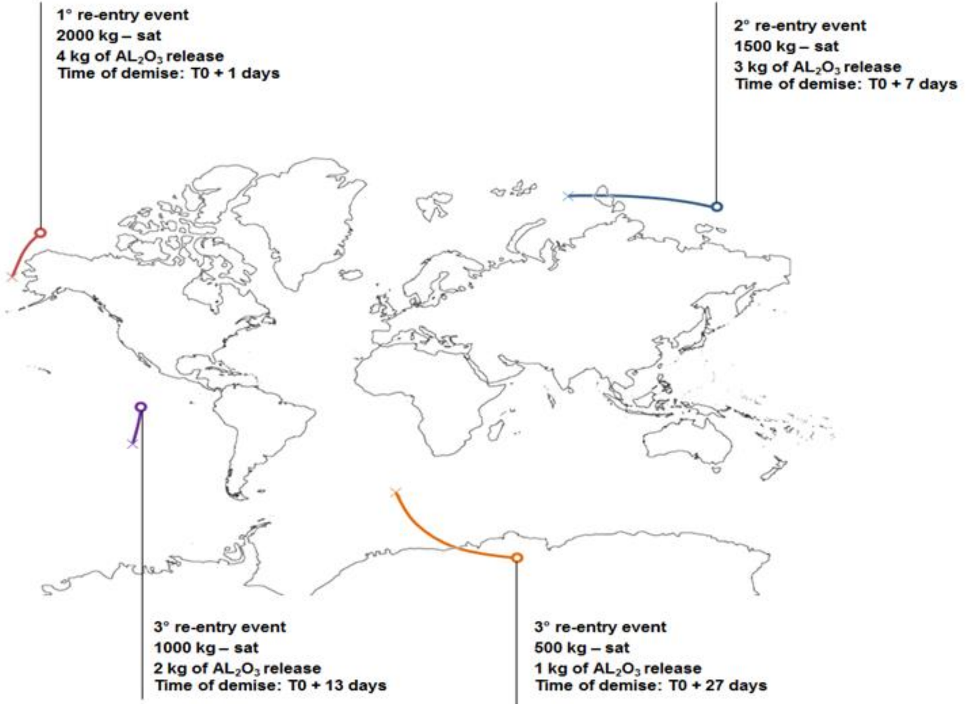
Al	Zn	Mg	Cu	Cr
88.7	6.1	2.9	2.0	0.3

AA7075 composition



TASK 4: GLOBAL SCENARIOS DEFINITION

- The goal of this activity was to collect and summarize the results of previous WPs generating the inputs for Task 5 and 6, i.e. taking into account the mass emitted by a different re-entry events. A Worst case scenario was developed taking into account potential mega-constellations and also taking conservative assumption whilst assessing the mass-loss data based on the by-product analysis.



1° re-entry event
2000 kg – sat
4 kg of AL_2O_3 release
Time of demise: T0 + 1 days

2° re-entry event
1500 kg – sat
3 kg of AL_2O_3 release
Time of demise: T0 + 7 days

3° re-entry event
1000 kg – sat
2 kg of AL_2O_3 release
Time of demise: T0 + 13 days

3° re-entry event
500 kg – sat
1 kg of AL_2O_3 release
Time of demise: T0 + 27 days

Example of global scenario
(relative to demise of one structural panel)

TASK 5: SHORT-TERM ATMOSPHERIC SIMULATIONS

- This task investigated the short-term atmospheric impacts of single spacecraft demise by using ECHAM/MESSy Atmospheric Chemistry (EMAC) model (ECHAM version 5.3.02, Roeckner et al., 2006; MESSy 2.54.0, Jöckel et al., 2005, Jöckel et al., 2010, Jöckel et al., 2016), coupling with the full-chemistry. Goal: investigate transport patterns and verify ozone depletion in view of long-term simulations

- Two single-event spacecraft demise scenarios (E1 and E2) were developed within this project were used, few sensitivity were made taking into account different re-entry locations and seasons.

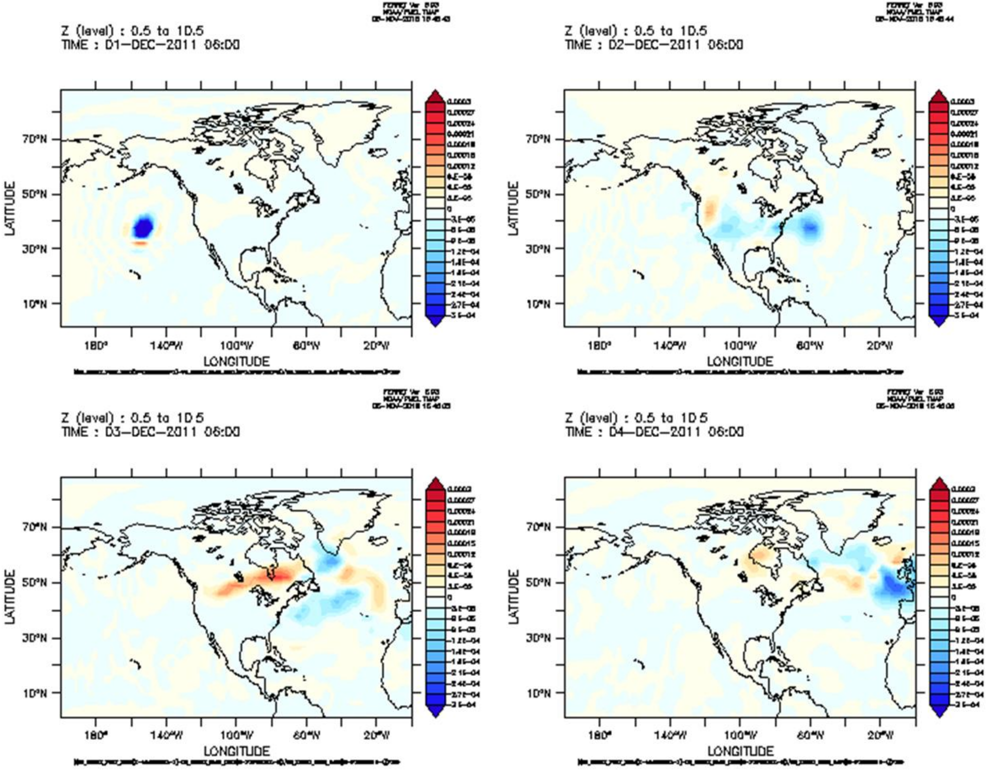
- Both events emit NO, CO2, Al2O3 and TiO2 particles in the upper atmosphere between 60 and 100 km. The Al2O3 and TiO2 particles potentially have importance on stratospheric ozone depletion. Thus, three heterogeneous reactions on Al2O3 and TiO2 particles, resulting in ozone depletion were newly implemented in EMAC.

TASK 5: SHORT-TERM ATMOSPHERIC SIMULATIONS

- Few different runs were made by changing season and re-entry locations, e.g. for winter 2011 with the E1 scenario, we observed that NOx and CO2 emissions are transported eastward followed by the prevailing wind (the strong west wind) at the re-entry site in the upper atmosphere. The perturbed NO concentration due to NO spacecraft demise emission changes ozone and methane concentrations. Figure shows the integrated concentration changes of ozone caused by this NO emission, as an example. The increased and decreased local ozone changes are observed due to the highly nonlinear ozone chemistry reactions. Similarly, methane concentration changes occur (not shown). The single spacecraft demise of E1 causes local ozone and methane changes from –0.6×10–2 to 0.1×10–1 % and from –0.1×10–4 to 0.3×10–5 %, respectively. These changes are modest, and the relative methane change is even less than that of ozone.

- The results showed that ozone certainly decreases due to the newly implemented heterogeneous reactions. The maximal local ozone reduction is less than that caused by the perturbed NO emission. The particles are relatively large and sediment quickly, which leads to deduced residence times for Al2O3 and TiO2 particles of approximately 24 and 15 days, respectively.

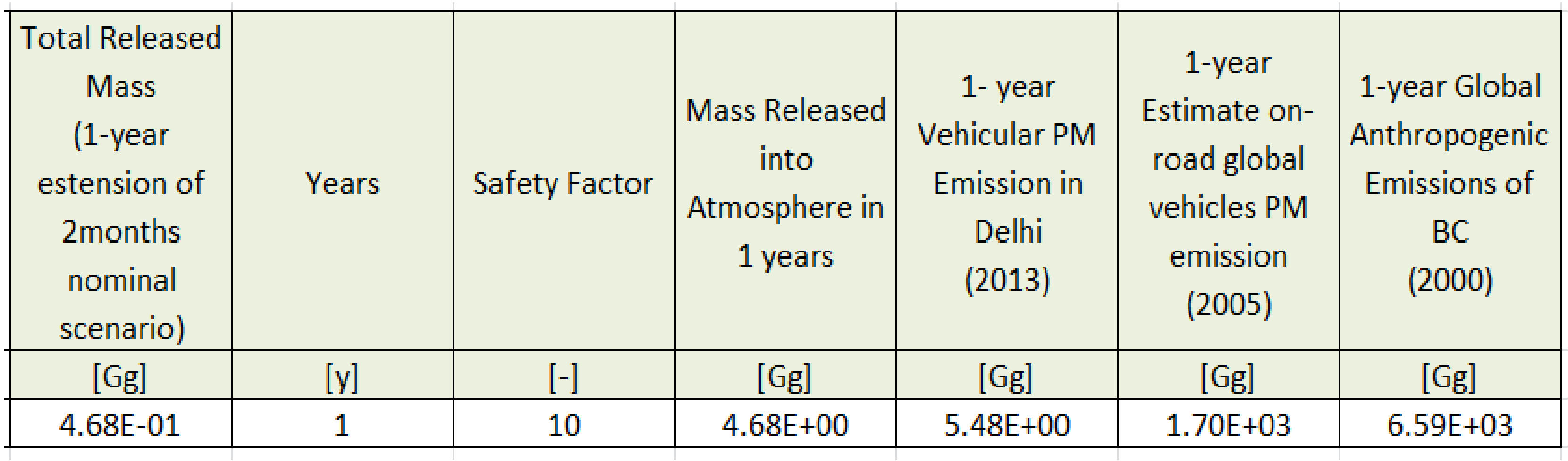
- Consequently, the transport pattern of NOx and CO2 emissions changes by season and geographic location of the spacecraft demise because of the different prevailing wind fields, which changes ozone and methane concentrations differently. The heterogeneous reactions on Al2O3 and TiO2 particles leading to ozone depletion should be taken into account in the investigation of climate impact of spacecraft demises. **This task concluded that the atmospheric short-term impact due to the single spacecraft demise is modest.**



Changes of ozone mass [%] caused by the single spacecraft demise scenario (E1) above 43 Pa (~ 55 km) for the first four days - Ref: Yamashita et al. (in prep)

TASK 5: TOXICITY ASSESSMENT

- A preliminary analysis was carried out by assuming that all the mass produced during demise totally contributes to particulate matter -PM concertation (likely unrealistic assumption, since no weather / environmental effects are considered).
- The overall produced mass in the 2-months nominal scenario has been extended 1 year and then compared with the following source of information, to have a feeling about the magnitude of risk posed by debris re-entry:



Total Released Mass (1-year estension of 2months nominal scenario)	Years	Safety Factor	Mass Released into Atmosphere in 1 years	1- year Vehicular PM Emission in Delhi (2013)	1-year Estimate on-road global vehicles PM emission (2005)	1-year Global Anthropogenic Emissions of BC (2000)
[Gg]	[y]	[-]	[Gg]	[Gg]	[Gg]	[Gg]
4.68E-01	1	10	4.68E+00	5.48E+00	1.70E+03	6.59E+03

TASK 6: LONG-TERM ATMOSPHERIC SIMULATIONS

/// 1st step Long-term simulation by EMAC

- Simulation period : Jan. 1, 2000-Dec. 31, 2006 (two year spin-up periods)
- Scenarios : Base (no demises) / Nominal / Worst
- Emitted substances : NO, H2O (idealized), Al2O3, TiO2

/// 2nd step Radiative impact calculations by RAD modeld

- Simulation period : Oct. 1, 2003-Dec. 31, 2004 (three months spin-up periods)

/// 3rd step Climate impact estimation for future spacecraft activities by AirClime

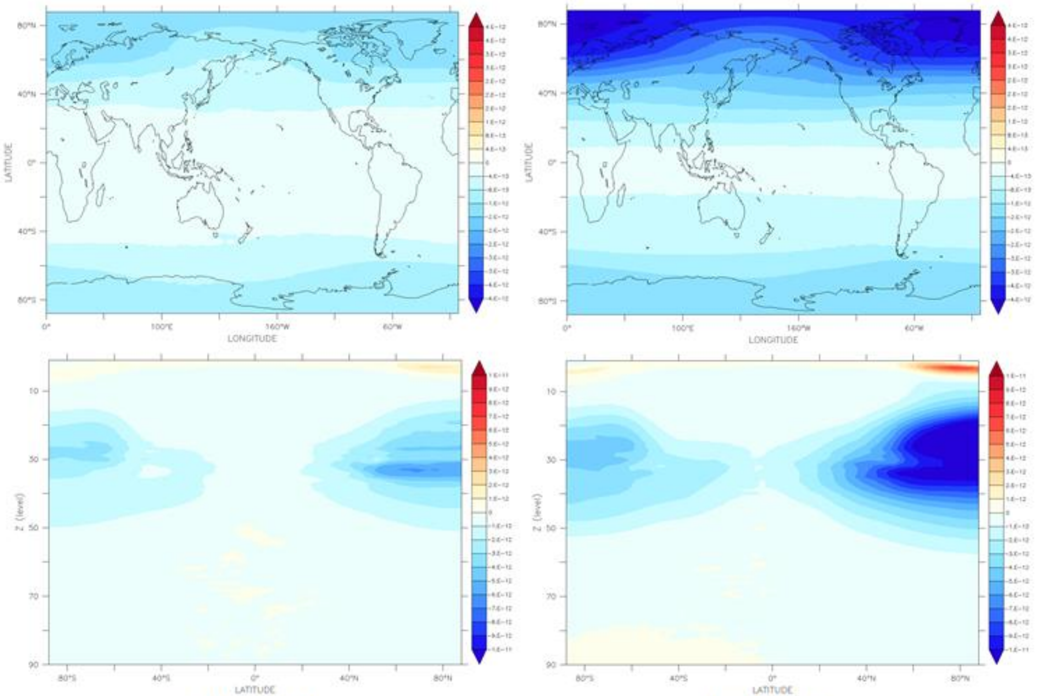
- Simulation period : 2017-2100 (repeated nominal/worst scenarios)
- Input data : RF (ozone, idealized H2O), methane lifetime changes, CO2

Items	**Unit**	**Nominal scenario**	**Worst scenario**
Number of events	events/year	73	314
Nitrogen oxide	kg/year	3378.0	7723.5
Carbon dioxide	kg/year	163526.1	345509.5
Alumina oxide	kg/year	284015.5	659365.4
Titanium oxide	kg/year	3113.5	6670.1
Water vapor	kg/year	62569.7	129678.6

[a]Roeckner et al., 2006; [b]Jöckel et al., 2005, 2010, 2016; [c]Jöckel et al., 2016;
[d]Dietmüller et al., 2016; [e]Grewe and Stenke, 2008, & Dahlmann et al., 2016.

TASK 6: LONG-TERM ATMOSPHERIC SIMULATIONS

Ozone changes of mixing ratio [mol/mol]. Top: geographical distribution; Bottom: vertical distribution. - Ref: Yamashita et al. (in prep)



(a) Nominal **(b) Worst**

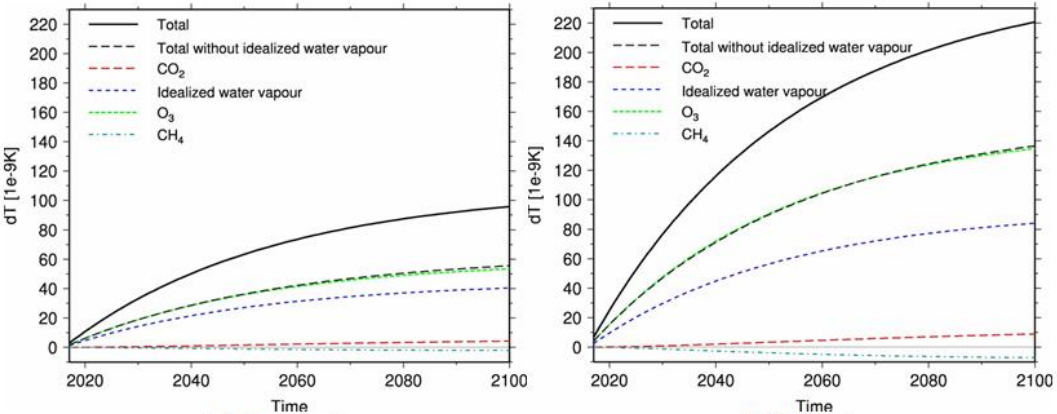
/// Global mean ozone column change (5 years):

- –0.77×10–5 % (nominal)
- –0.17×10–4 % (worst)

TASK 6: LONG-TERM ATMOSPHERIC SIMULATIONS

- The potential climate impact of spacecraft demises was estimated by using the AirClim model (Grewe and Stenke, 2008; Dahlmann et al., 2016). Time series of radiative forcing and corresponding temperature change due to ozone, the idealized water vapor, CO2 and CH4 were estimated. It was assumed that the effects of one year spacecraft demise scenario (i.e. the nominal and the worst scenario) were annually repeated for 2017-2100.

- The results show that the total temperature change in 2100 is 96×10–9 K for the nominal scenario and 220×10–9 K for the worst scenario (without the idealized water vapor, the changes are 55×10–9 K for the nominal scenario and 136×10–9 K for the worst scenario), and that ozone and the idealized water vapor dominate the temperature increase.



(a) Nominal

(b) Worst

Change in near-surface air temperature [K] caused by spacecraft demise for nominal (a) and worst (b) scenario. The spacecraft demise is assumed to be constant over time. - Ref: Yamashita et al. (in prep)

- The estimated annual mean total RFs of spacecraft demises for 2100 (including the idealized water vapor) are approximately 0.12×10–6 W/m2 for the nominal scenario and 0.27×10–6 W/m2 for the worst scenario

RF [10^{-9} W/m^2]	CO_2	Idealized H_2O	O_3	CH_4	Total
Nominal	7.9	54.8	60.3	–2.8	120.2
Worst	16.8	114.2	152.0	–9.5	273.5

STUDY RESULTS SUMMARY

- **Climate Impact**
- Global mean annual ozone column change:
  - –0.77×10–5 % (nominal); –0.17×10–4 % (worst)

- Climate impact in year 2100– RF and temperature impact
  - 0.12×10–6 W/m2 (nominal); 0.27×10–6 W/m2 (worst) – warming effect
  - is 96×10–9 K (nominal); 220×10–9 K (worst) – warming effect
- **The potential climate impact of the nominal scenario was substantially smaller (by factors of 500 (opposite sign), 6.5×10^5, and 1.5×10^6) than those of rocket launchers, aviation, and road sector (on the absolute value basis). For the worst scenario, the factors were ~200 (opposite sign), 2.9×10^5, and 6.5×10^5, respectively.**
- **Toxicity**
- The results presented before underline that the S/Cs and R/Bs re-entry, seem to pose a relevantly lower risk w.r.t. common human activities.
- **Eventually, the impact for human health posed by the potentially toxic substances is expected to be low/negligible since the product substance can be supposed to spread on a very high area, if a large number of re-entries is considered.**