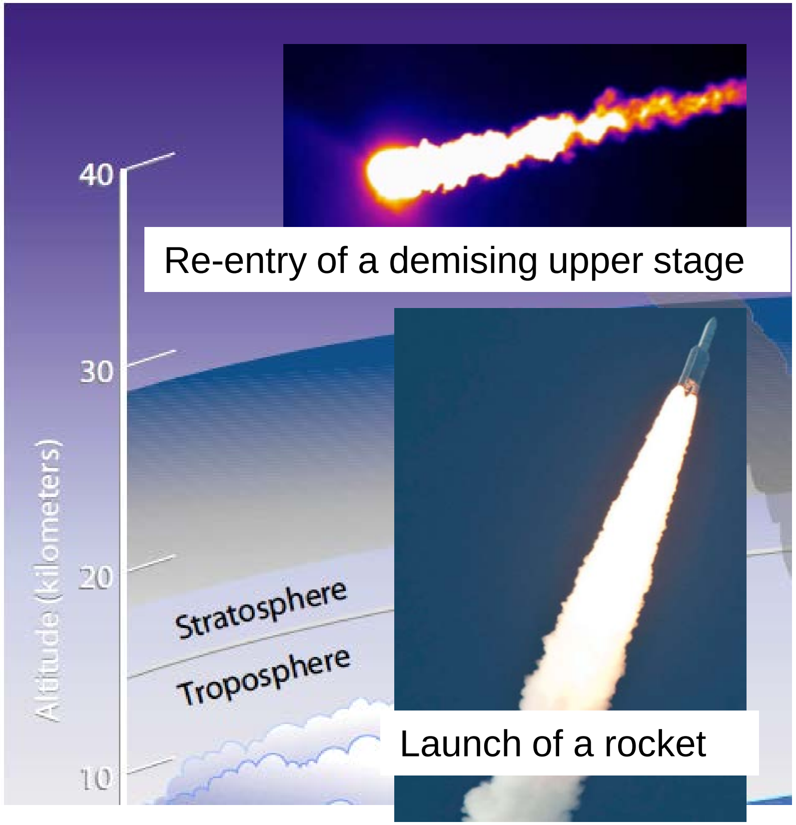
Impacts of space vehicles' launch & re-entry on the ozone layer and climate

BEKKI, Slimane (CNRS/ Imperial College)
CARIOLLE, Daniel (CERFACS)
MURRAY, Neil (ESA)
TOUMI, Ralf (Imperial College)
BECK, James (Belstead)
LIPS, Tobias (HTG)
AUSTIN, Julian (ESA)

Context: ESA Clean Space initiative

One of the main aims: **quantify environmental impacts of space activities,** a prerequisite before developing mitigation strategies



Re-entry of a demising upper stage

Launch of a rocket

- Launches & re-entries lead to large emissions of gases and particles (chlorine, alumina particles, H_2O, NOx for AR5 or Vega) into the atmosphere. They are **the only in-situ sources of anthropogenic material** above 20 km, region of the ozone layer.

- **What are the environmental impacts (e.g. ozone, climate, pollution) of launch & re-entry emissions?**

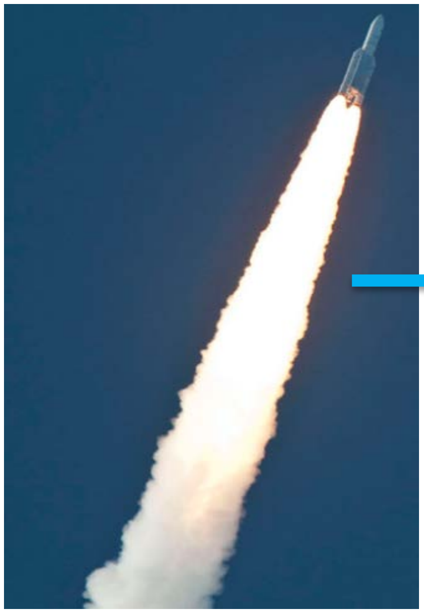
Standard approaches, notably Life Cycle Analysis, can to be used to assess environmental impacts from 'surface' emissions, **but not from launch and re-entry emissions whose ozone-destroying and climate-forcing potentials are not known.**

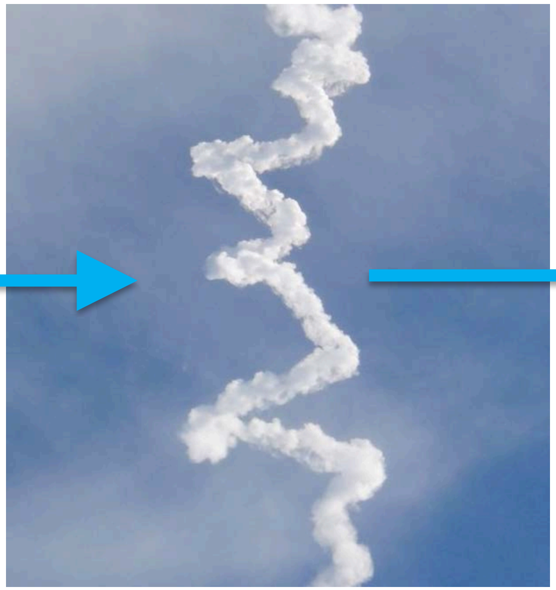
Rocket launch: Life cycle of exhaust plume

1) Hot jet
supersonic, microsec
1 cm to 100 m

2) Cold plume
Turbulence/wind, mn to hrs
100 m to 10 km

3) Globally dispersed
Large-scale winds, days to yrs
100 km to 1000s km





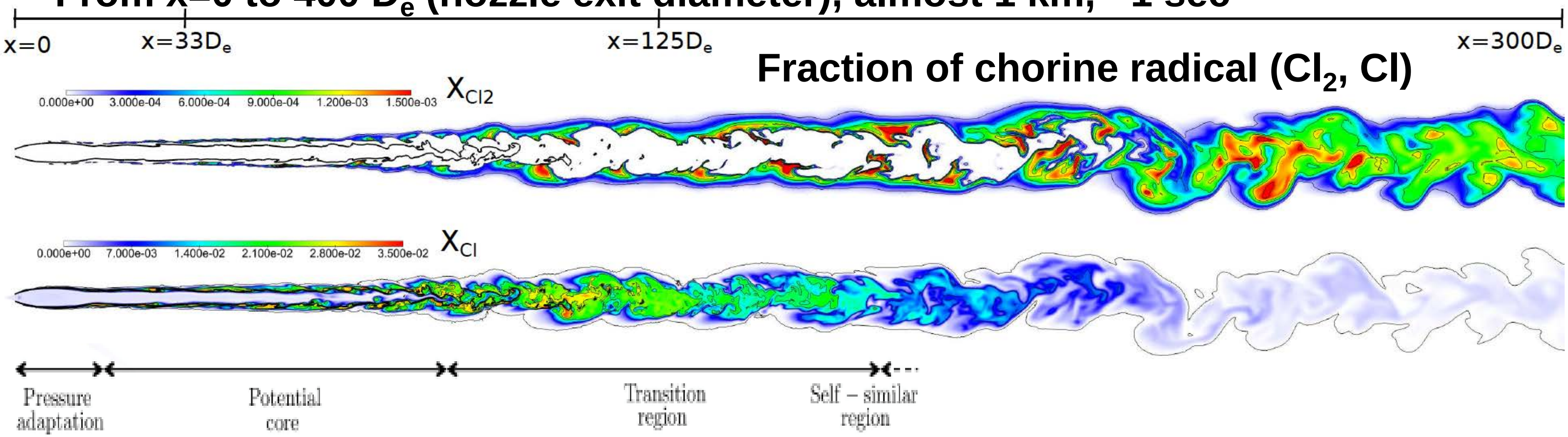
Each phase has its own spatio-temporal scales & dynamical/chemical processes

To simulate the evolution and impacts of an exhaust plume, radically different models need to be coupled → multiscale modelling system

1) Reactive hot jet from an Ariane-V booster: Model simulations

° Large Eddy Simulation, CERFACS model (AVBP code, solve 3-D reactive compressible Navier-Stokes equations on unstructured grids)

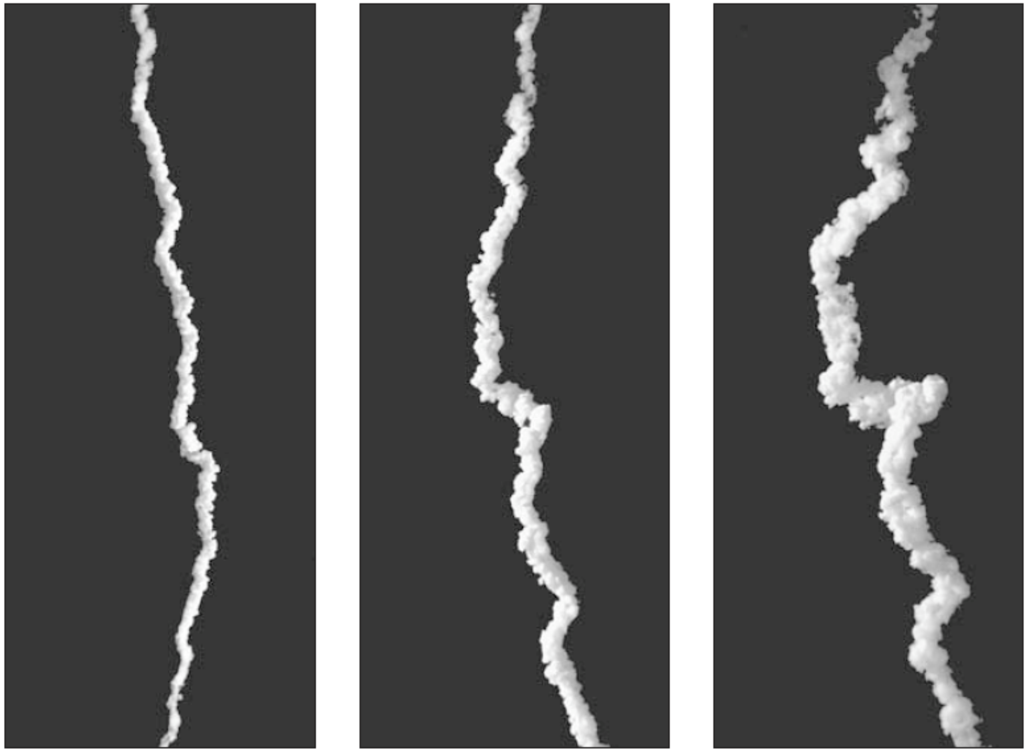
Fraction of chorine radicals (Cl_2, Cl) in the jet at 20 km.
From x=0 to 400 D_e (nozzle exit diameter), almost 1 km, ~1 sec



- **Within the hot jet, conversion of ~30% of the main chlorine species (HCl) into ozone-destroying radicals (Cl and Cl_2) at 20 km.**
- **Fraction of ozone-destroying chlrine radicals increases with altitude.**

Figure from A.Poubeau PhD thesis,
Supervisor: D. Cariolle

2) Deformation/dispersion of a cold plume: Observations

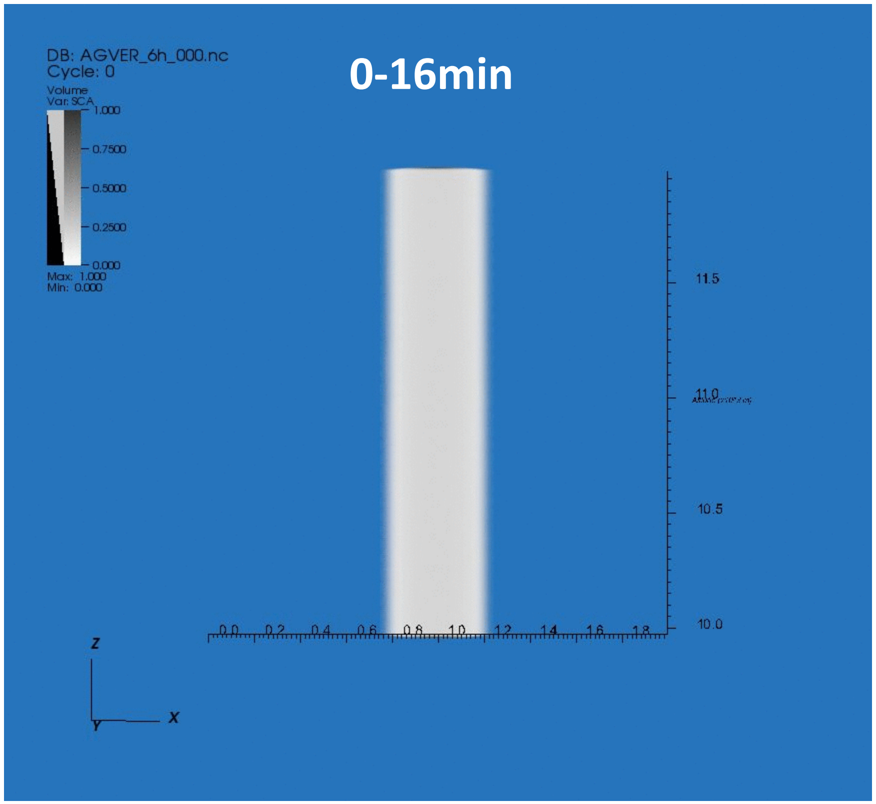


Ariane 5 (10 dec 1999)

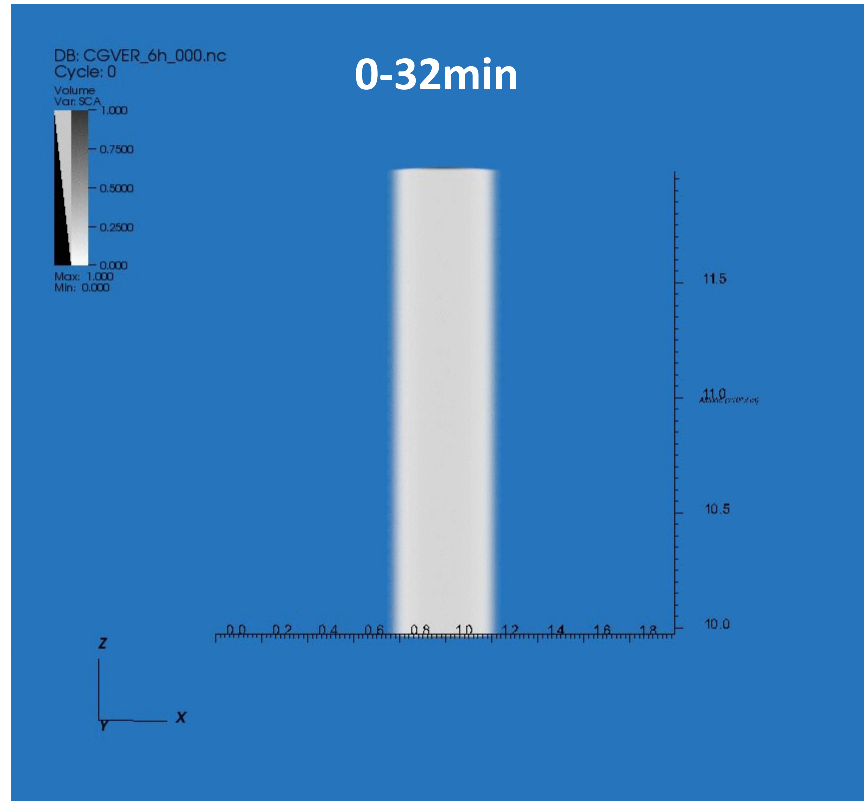
Deformation and dispersion of the plume under the effect of atmospheric turbulence and wind shear

2) Deformation/dispersion of cold plume: Simulations from 3-D mesoscale model

Strong turbulence



Weak turbulence

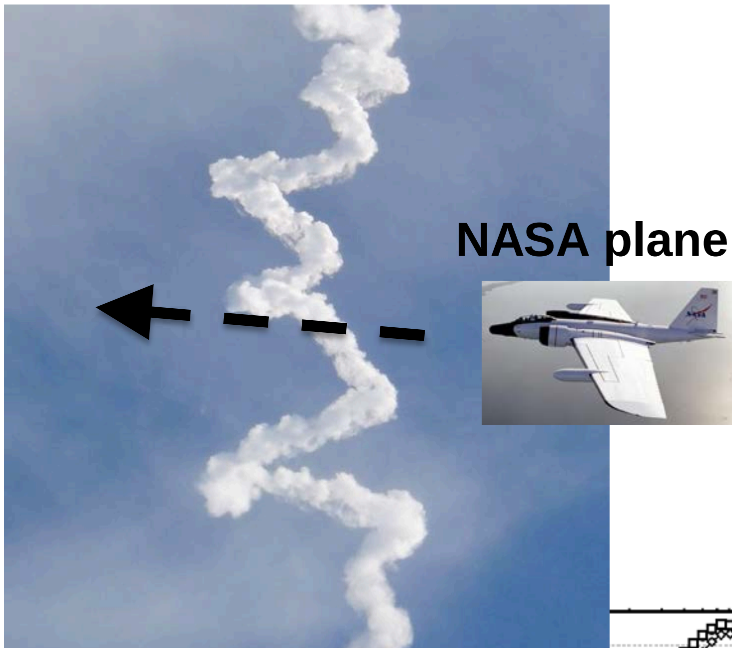


- Parallelogram domain of 8 km x 8 km (horizontal) x 4 km (vertical)
- Model resolution: 20 m in each direction (400 x 400 x 200 = 32 millions of grid cells)
- Model input: two levels of turbulence forcing (weak/strong)

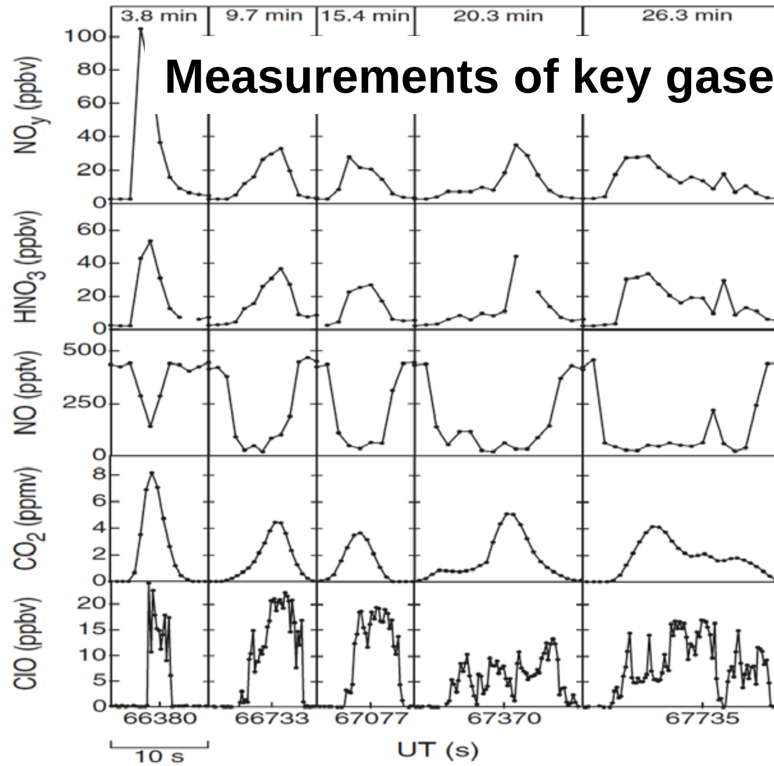
CERFACS MesoNH calculations

2) Chemical composition of SRM plumes: In-situ observations

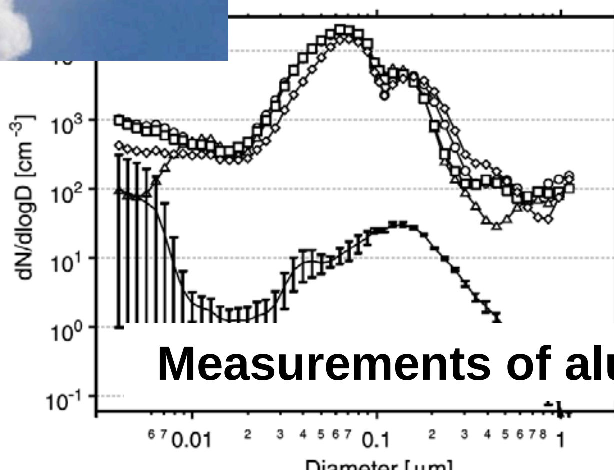
NASA instrumented plane flew across multiple rocket plumes & made chemical measurements in 80s-90s.



NASA plane



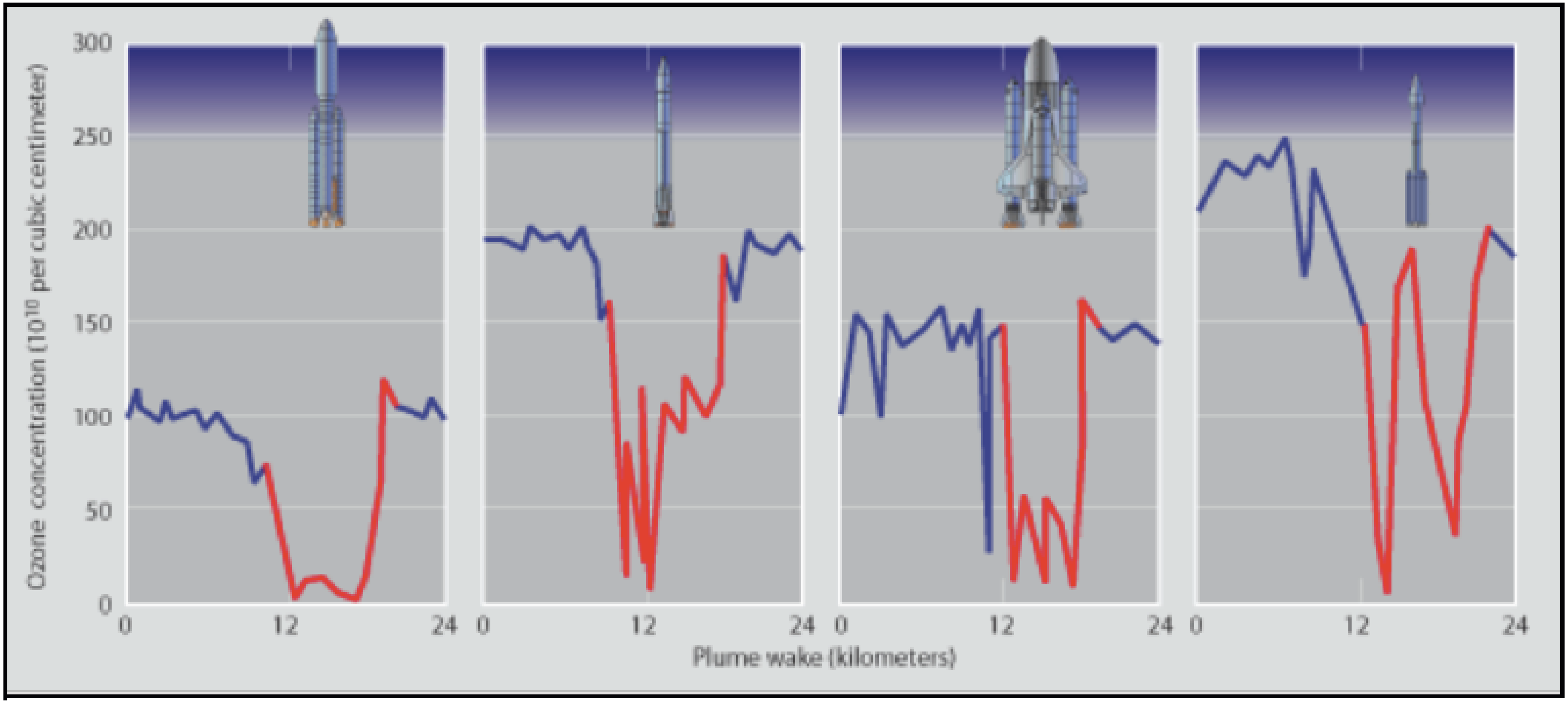
Measurements of key gases



Measurements of alumina particles

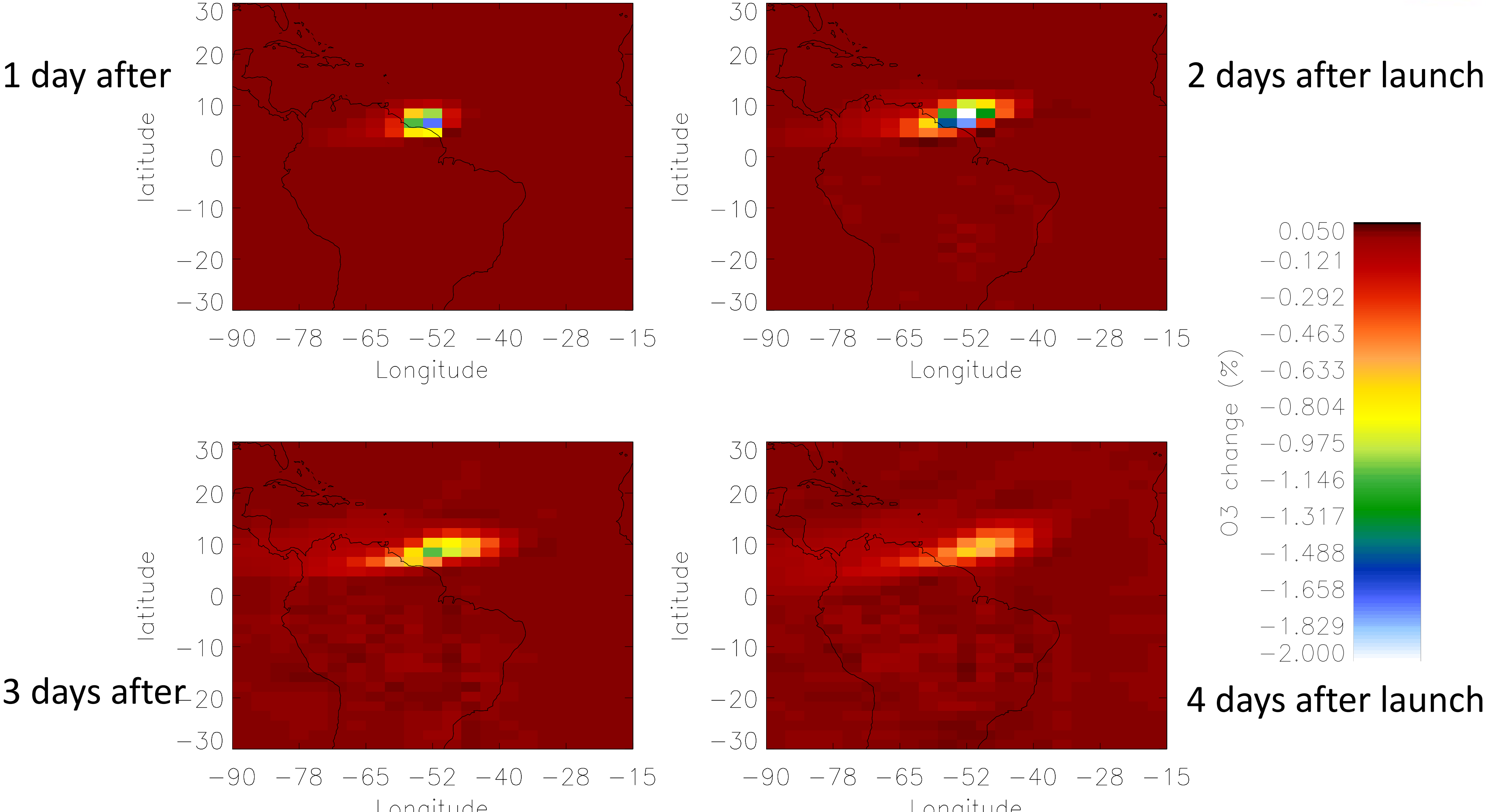
2) Ozone evolution within SRM plumes: In-situ observations

Ozone concentrations across plumes of American launchers (Titan IV, Atlas II, Space Shuttle and Delta II) probed about ½-1 hr after launch at ~18 km



Quasi-complete ozone destruction within SRM plumes-> caused by exhaust chlorine

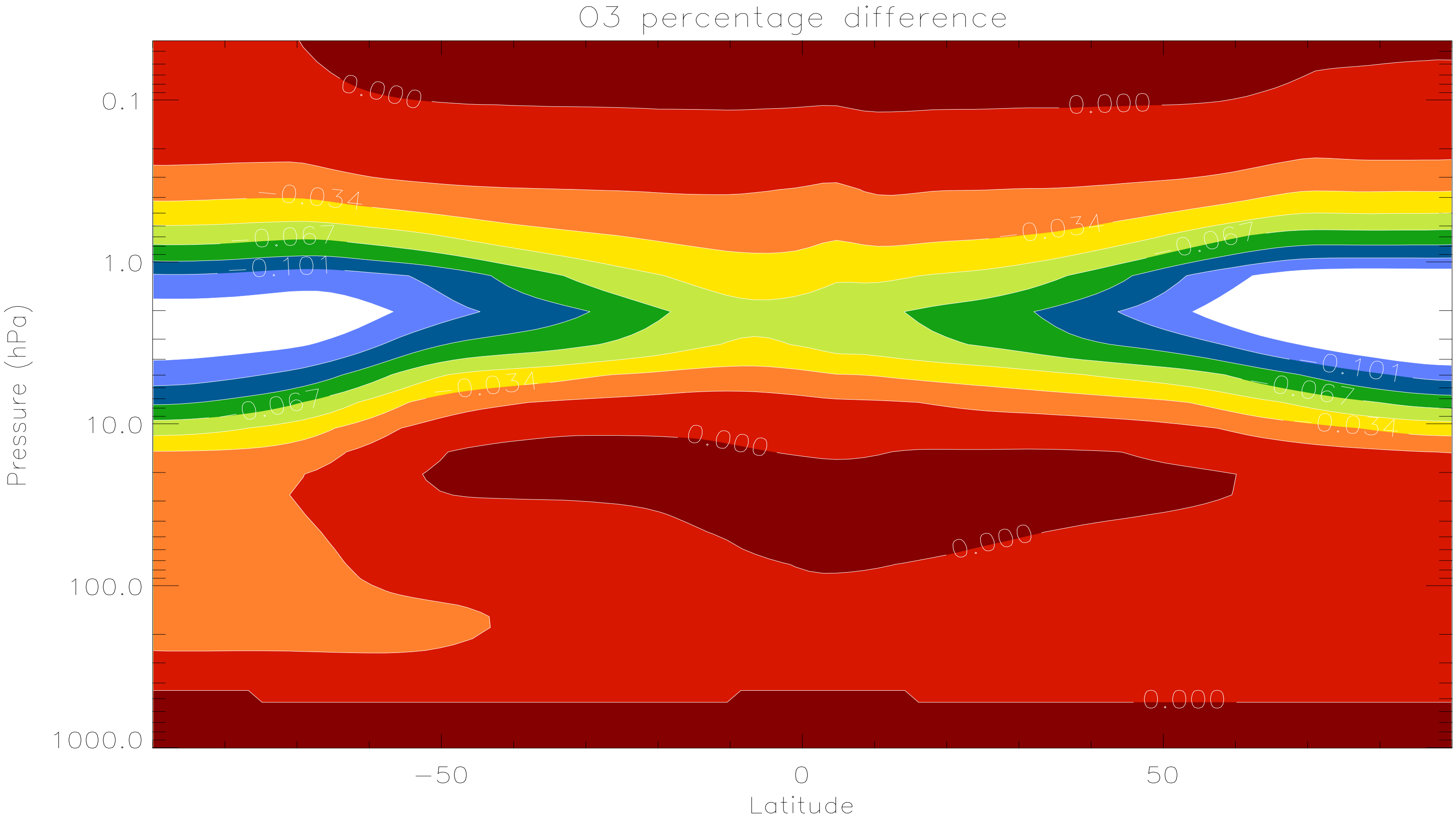
3) Ozone depletion after a single AR5 launch: Global 3-D model simulations



O_3 change (in %) due to a single Ariane 5 launch at 3 mb.

Transient regional O_3 loss ~ 1-2% (barely detectable in satellite data)

3) Global O_3 depletion, 10 years of AR5 launch Model simulations (6 launches/year)



- **Long-term O_3 depletion (cumulative effect) peaks around 40 km (~0.1%), almost entirely due to exhaust chlorine**
- **BUT no heterogeneous chemistry on alumina particles**

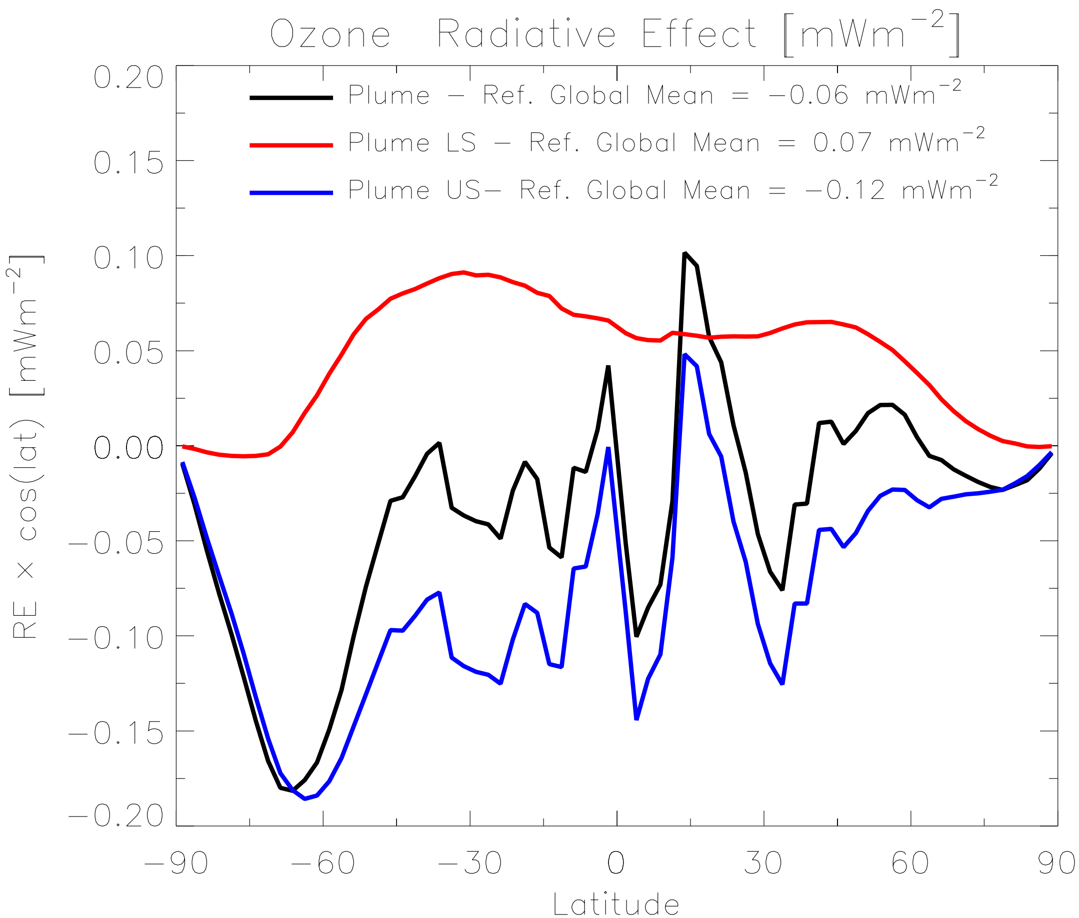
3) Global O_3 depletion, 10 years of AR5 launch Model simulations (6 launches/year)

AR5 simulation	Global mean ozone loss (%)	ODP (relative impact on O_3 of a kg of burned fuel with respect to impact of a kg of CFC-11)
Chlorine only (semi-empirical)		0.13[17]
Chlorine only (3-D model)	0.005-0.011	
Chlorine only (2-D model)	0.0076	0.12
Al_2O_3 only (2-D model) - Athena II (3 particle modes)	0.0014	0.02
Al_2O_3 only (2-D model) – small particles (Athena II small mode)	0.08	1.2

- **Agreement between 2-D model, 3-D model and semi-empirical estimate for the impact of exhaust chlorine on ozone.**

- **Depending on their size, exhaust alumina particles could play a negligible role compared to exhaust chlorine or be vastly dominant.**

3) Climate forcing from global O_3 depletion: Radiative transfer model calculations



Black line: Total radiative forcing (RF) generated by O_3 changes

Red line: RF generated by O_3 changes above 20 mb (Plume LS)

Blue line: RF generated by O3 changes below 20 mb (Plume US).

- **Global O_3 depletion (caused by AR5 rocket exhaust chlorine) generates a negative radiative forcing (RF) of -0.06 mW/m^2**
- **RF of O_3 depletion >> RF from exhaust CO_2**

Launch: rocket propellant

Solid Rocket Motor (SRM)

The focus here

Composite propellant:
ammonium perchlorate (oxidizer) +
aluminum powder (fuel) + binder

Ariane 5

Delta II Heavy

Space Shuttle

<u>Exhaust material impacting O_3</u>

Chlorine, **alumina particles**

NOx (nitrogen oxides), H_2O

Liquid Rocket Motor (LRM)

- H_2/O_2 (Vulcain 2 on Ariane 5)
- Kerosene/O_2 (Soyuz, Falcon 9, 1st stage Delta II)
- UDMH/N_2O_4 (Proton, 2nd stage Delta II)

Soyuz

Vulcain 2 (Ariane 5)

Falcon 9

<u>Exhaust material impacting O_3</u>

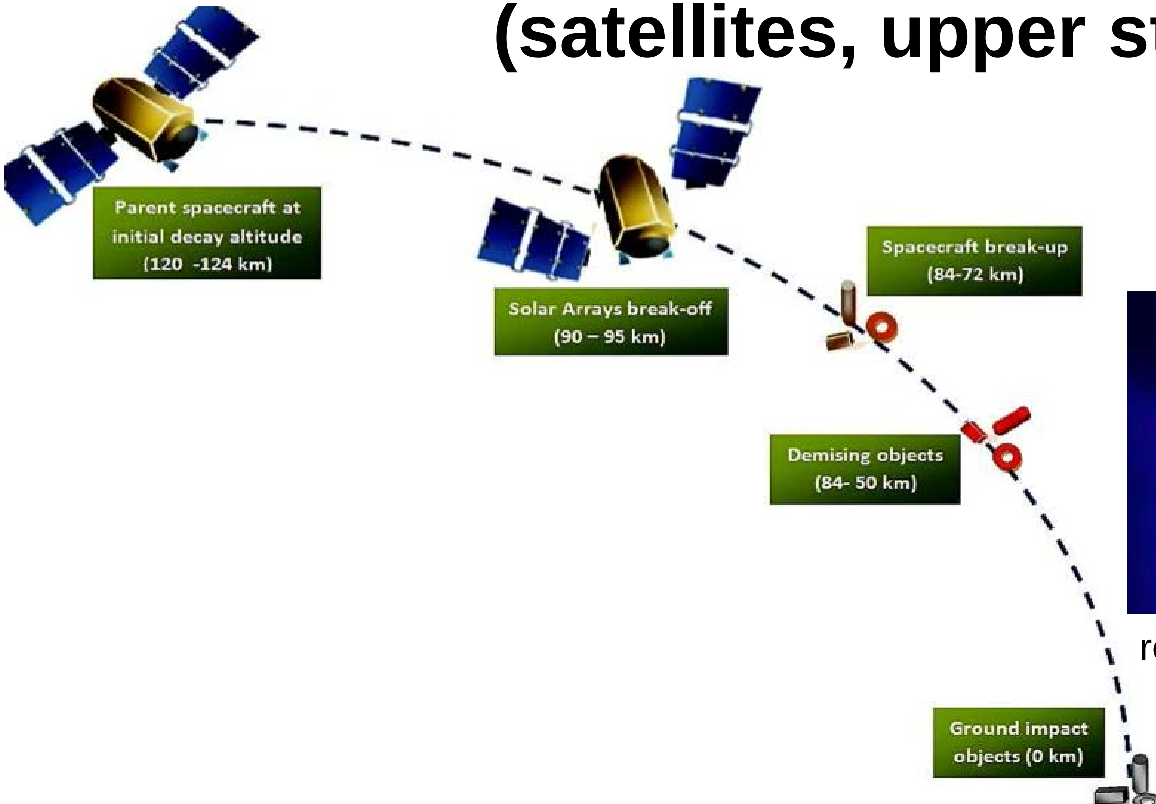
Organics, soot particles,

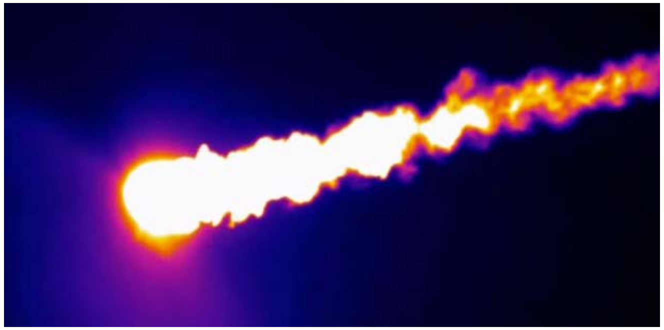
NOx, H_2O,

A part from H_2/O_2, no such thing as a 'clean' propellant

Figure: courtesy of A/ Poubeau

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



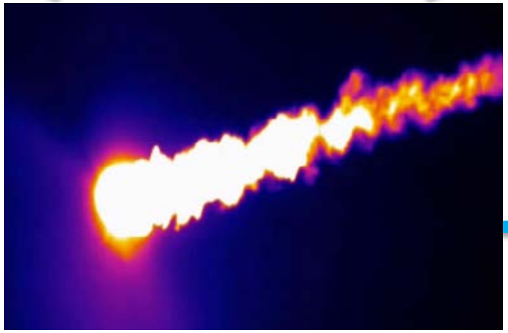

re-entry of a demising Falcon 9 first stage

Typically, ~10-40% of debris mass can survive and reach the ground
→ mass loss & re-entry casualty risk (extensively studied & assessed)

Remaining 90-60% ends up in the atmosphere as gases and particles, some are ozone-destroying, climate forcers, or toxic to ecosystems
→ environmental impacts, notably ozone layer & climate

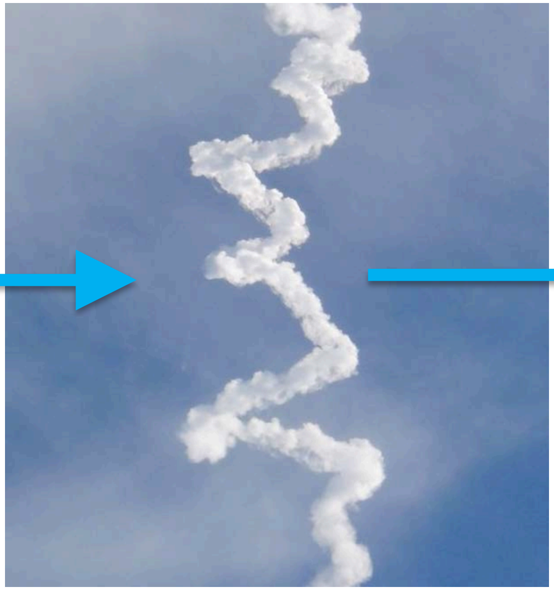
Space vehicle's re-entry: Life cycle of plume

1) Hot jet behind demising object
supersonic, microsec
1 cm to 100 m



Destructive re-entry (aerothermodynamics)
-> gas and particle emissions

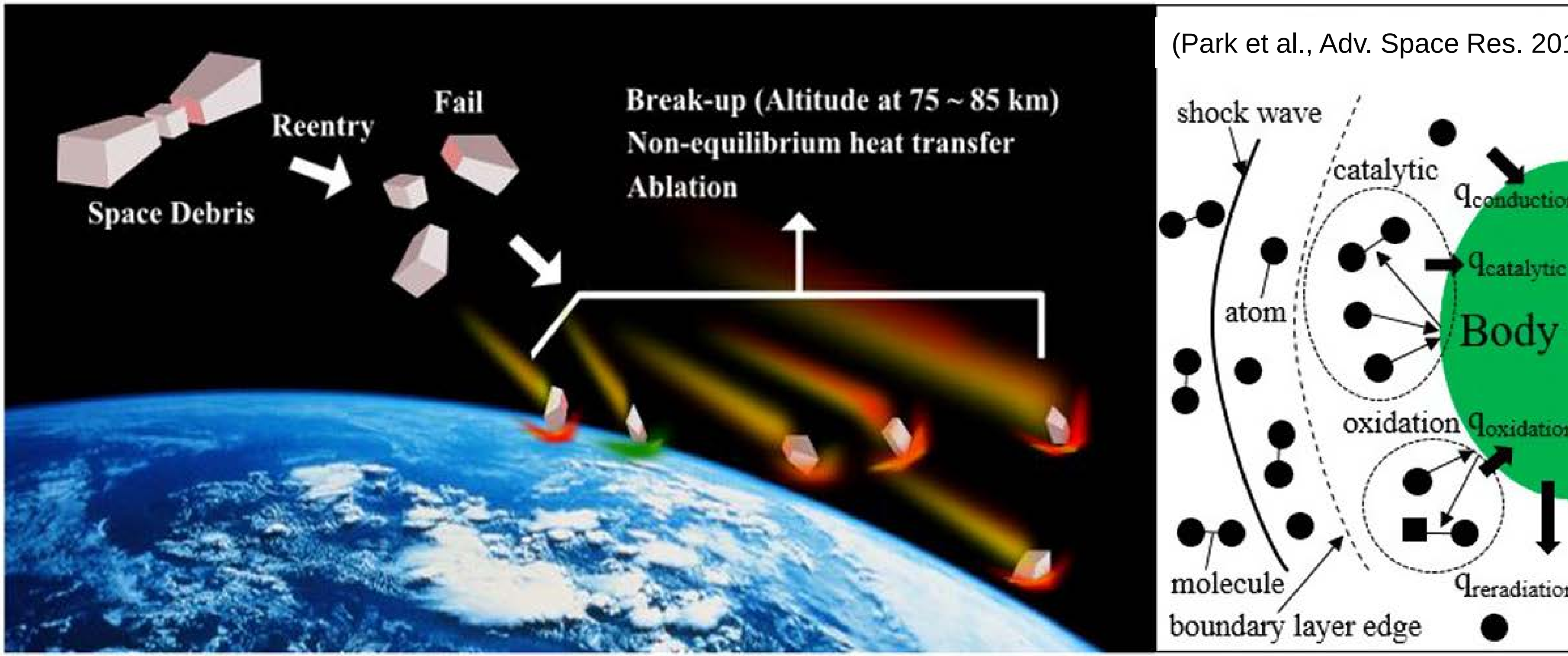
2) Cold plume
Turbulence/wind, mn to hrs
100 m to 10 km



3) Globally dispersed
Large-scale winds, days to yrs
100 km to 1000s km

To simulate evolution & impacts of a re-entry emission plume, radically different models need to be coupled → multiscale modelling system

Complex physical/chemical processes on & around demising space vehicles

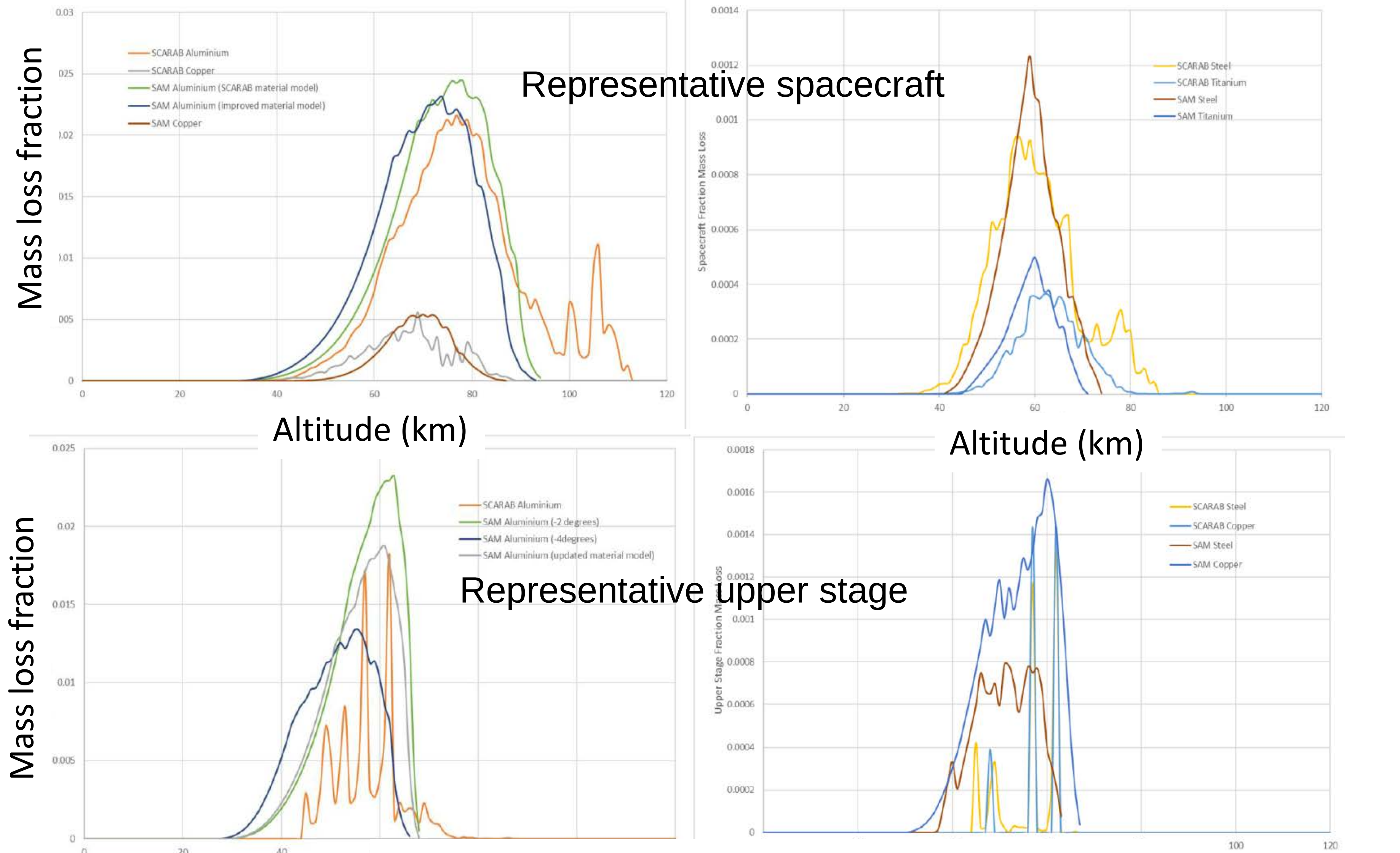


(right) Re-entry destructive processes with (left) illustration of some of them at/near the surface

Surface ablation mechanisms: Melting (e.g. metals, glass, ceramics); Vaporization (liquid layers from melted materials); Sublimation; Oxidation (e.g; carbon); Spallation (resulting into ejection of particulates),…
High-T chemistry within shock wave and wake (including phase transitions)
→ **Re-entry gaseous/particulate emissions**

Re-entry emissions of metals: model calculations

Destructive re-entry codes (SCARAB, SAM) + several intermediate modelling steps to convert mass loss maps into gaseous and particulate emissions



Also, emissions of ozone-destroying radical NOx

Space vehicle's re-entry: Life cycle of plume

2) Cold plume

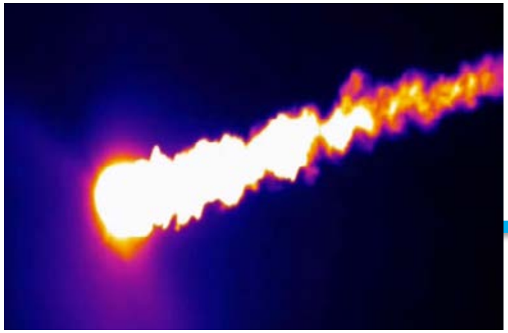
Turbulence/wind, mn to hrs

100 m to 10 km

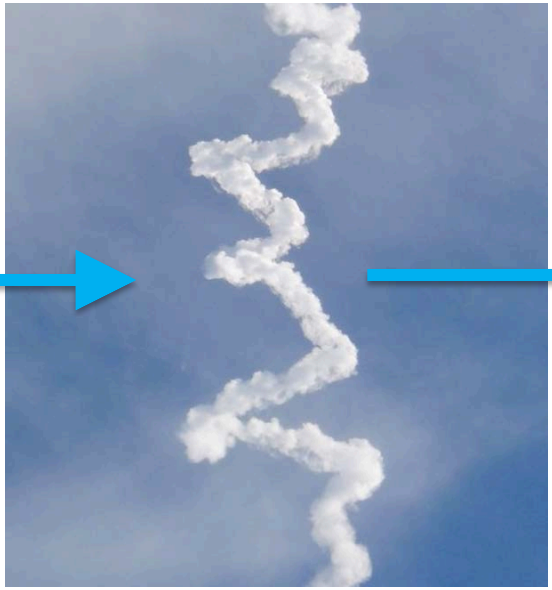
3) Globally dispersed

Large-scale winds, days to yrs

100 km to 1000s km



-> gas and particle emissions



THANK YOU