The potential environmental impact of emissions from aviation and space launches

Wuhu Feng

National Centre for Atmospheric Science, University of Leeds

w.feng@ncas.ac.uk ***W.feng@leeds.ac.uk***

- Background (Whole atmosphere, Why we care aviation and space launches, Current understanding/knowledge gap, How we quantify these impacts and what we need to know)
- Impact of Iodine emission from Cubesat
- Impact of Chlorine emission due to rocket launches
- BC emission effect due to rocket launches
- Impact of NOx from rocket and aircraft
- Space debris/re-entry (Lithium and Aluminium as examples)
- Summary

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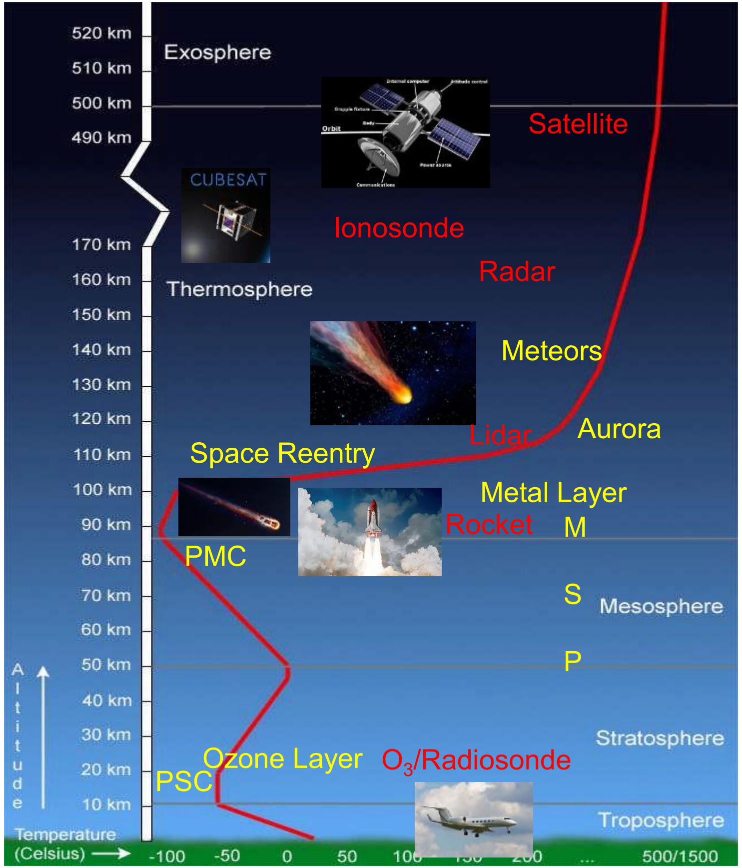
Acknowledgement: John Plane, Joanna Egan, Saskia Hawkins, Martyn Chipperfield, Daniel Marsh, Yuwen Li, Zhiqiang Cui, Weiyu Zhang, Alex Rap and Alex Archibald etc.

Understanding the whole atmosphere



Emissions

- A lot of interesting phenome occurring in the whole atmosphere
- High demands in space weather to understand/quantify the processes contribution to the atmospheric variability
- Geomagnetic activity causes the surface air temperature
- Weather forecast has significant improved by extension from stratosphere to mesosphere (for example ECMWF)
- Importance of stratosphere
- Limitation of measurements, Modelling studies are required
- Coupling processes and both model/measurements are required to understand the whole atmosphere
- Natural and anthropogenic emissions impact

Why we care aviation?

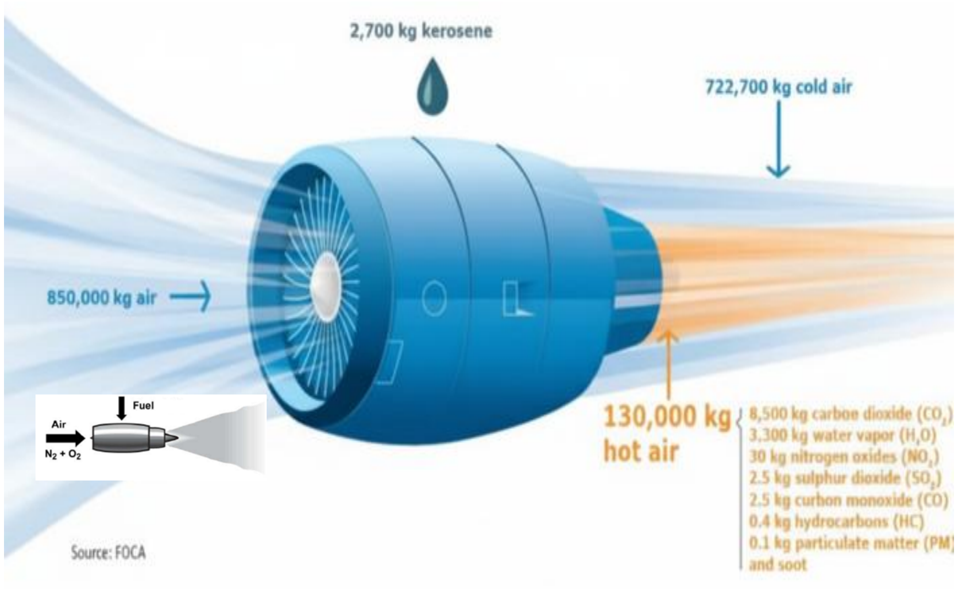
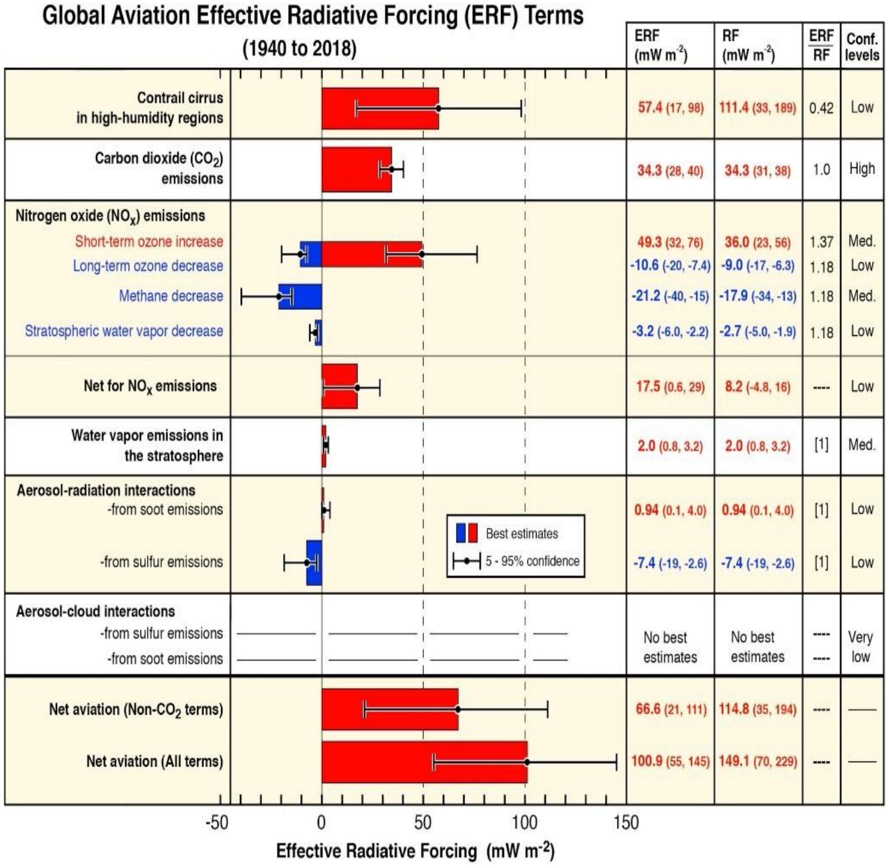


Figure 1 – Emissions from a Typical Two-engine Jet Aircraft During 1-hour Flight with 150 Passengers

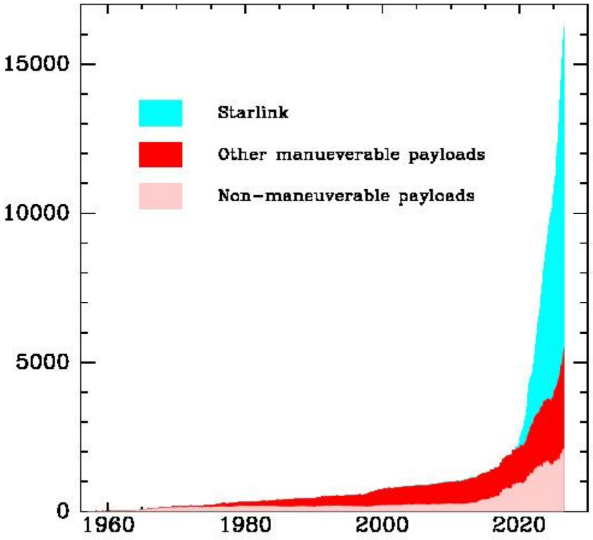


Lee et al. (2021)

Why we care space launches? Some Facts

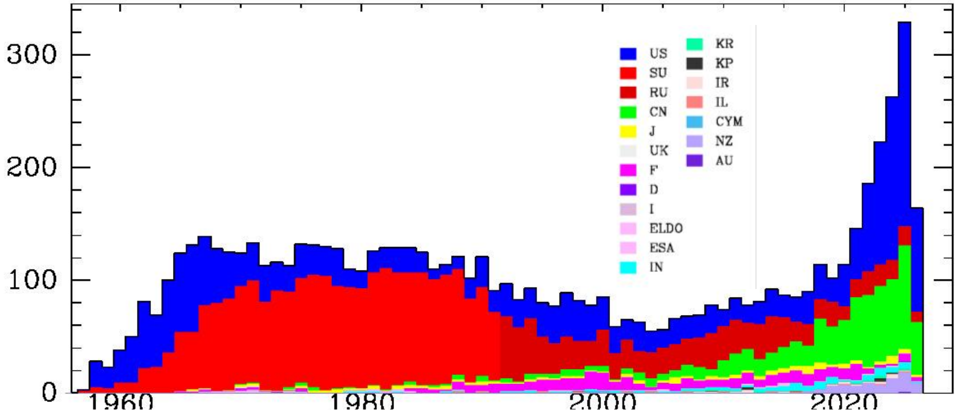
Space activities: ~80 countries

Active Satellites in Earth Orbit

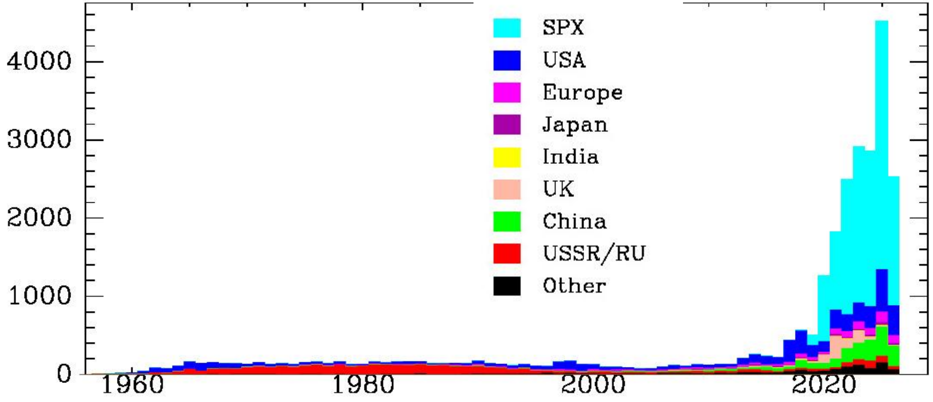


https://planet4589.org/space/stats/active.html

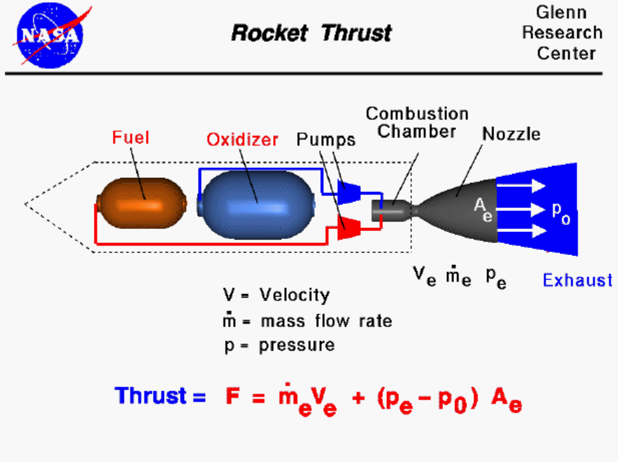
Orbital Launch Attempts – by Country



Payloads Launched Per Year



Space launches: Propellant/Emission



Fuel: Rocket type	Oxidiser	Emission products	Prevalence (Fraction of 2019 total propellant mass burned)
Kerosene (RP-1): *Falcon9(SpaceX), Atlas V*	Liquid Oxygen (LO_x)	CO_2, H_2O, NOx, **black carbon**	48%
Hydrogen: *(Ariane 6)*	LO_x	H_2O, H_2, NOx	6%
HTPB (Hydroxyl-terminated polybutadiene): *PSL, Vega, Titan IVB..*	Aluminium/Ammonium Perchlorate ($Al/NH_3ClO)_4$)	HCl, H_2O, CO_2, NOx, Al_2O_3, **black carbon**	16%
Hypergolic, N_2H_4/UDMH (Unsymmetrical dimethylhydrazine): *Chinese Long March, Russian Proton...*	Nitrogen Tetroxide (N_2O_4)	H_2O, N_2, CO_2, NOx, **black carbon**	30%

Updated from Brown et al. (2024), others are not included

Rocket Emission potential impact on atmosphere

Emission product	Propellant type	Impact *Brown et al. (2023)*
Carbon dioxide (CO_2)	*Solid, Kerosene, hypergolic*	Greenhouse gas; cools the stratosphere leading to increases in ozone
Water vapour (H_2O)	*Solid, Kerosene, hypergolic,* cryogenic	Greenhouse gas; breaks down in the upper stratosphere to produce ozone-depleting hydrogen oxides
Nitrogen oxides ($NOx = NO + NO_2$)	*Solid, Kerosene, hypergolic,* cryogenic	Ozone-depleting
Hydrogen chloride (HCl)	Solid	Converts readily to ClOx radicals, which are ozone-depleting
Black carbon (soot)	*Solid, Kerosene, hypergolic*	Heats the stratosphere, accelerating gas-phase ozone loss reactions and changing stratospheric dynamics; heterogeneous reactions occur on its surface as it accumulates sulfate coating
Alumina (Al_2O_3)	Solid	Heterogeneous reactions may occur on its surface, potentially enhancing ozone depletion
Hydrogen gas (H_2)	Cryogenic	Produces H_2O
Iodine (I_2), CubeSat	Solid	Heterogeneous reactions, 200 times more efficient than Clorine to destroy ozone (Solomon et al., 1994; Feng et al., 2023)

Why we concern CubeSats launches?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In-orbit demonstration of an iodine electric propulsion system

Dmytro Rafalskyi, Javier Martínez Martínez, Lui Habl, Elena Zorzoli Rossi, Plamen Proynov, Antoine Boré, Thomas Baret, Antoine Poyet, Trevor Lafleur, Stanislav Dudin & Ane Aanesland

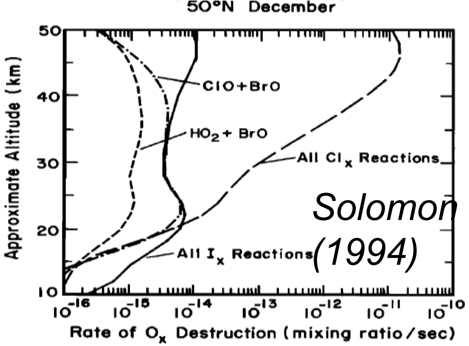
Nature 599, 411–415 (2021) | Cite this article

38k Accesses | 17 Citations | 395 Altmetric | Metrics

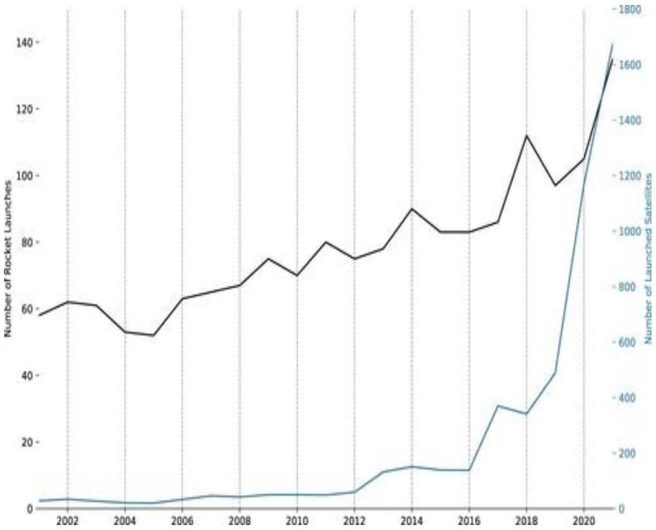

French and Chinese space startups make history together - The first iodine-propelled spacecraft succ

Only 15 days after the successful launch of the first ever iodine-propelled satellite, ThrustMe and Spacety announce that the first propulsive operations have been conducted.

After 10 intensive days in orbit, Spacety managed to complete the in-orbit commissioning of the satellite. It was time for the two parties, Spacety and ThrustMe, to test the I2T5 cold gas thruster for the first time.



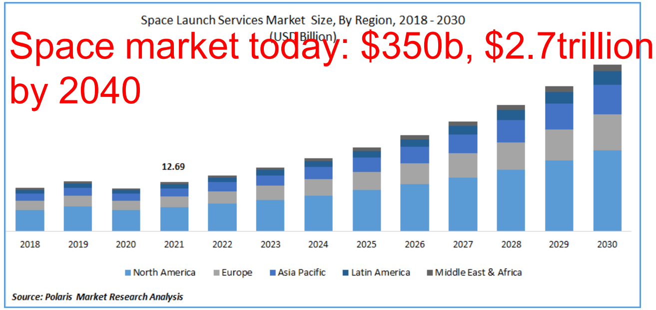
Solomon et al. (1994)



- First launched I_2-propelled CubeSat
- Small: <10kg, 10 cm cube (1U)
- Low cost, ~1-5yrs
- Not enough regulation for space launches to protect the atmosphere compared to the successful story by Montreal Protocol
- Space competitions

  UK Space Agency: 349 active satellites (non-ESA)

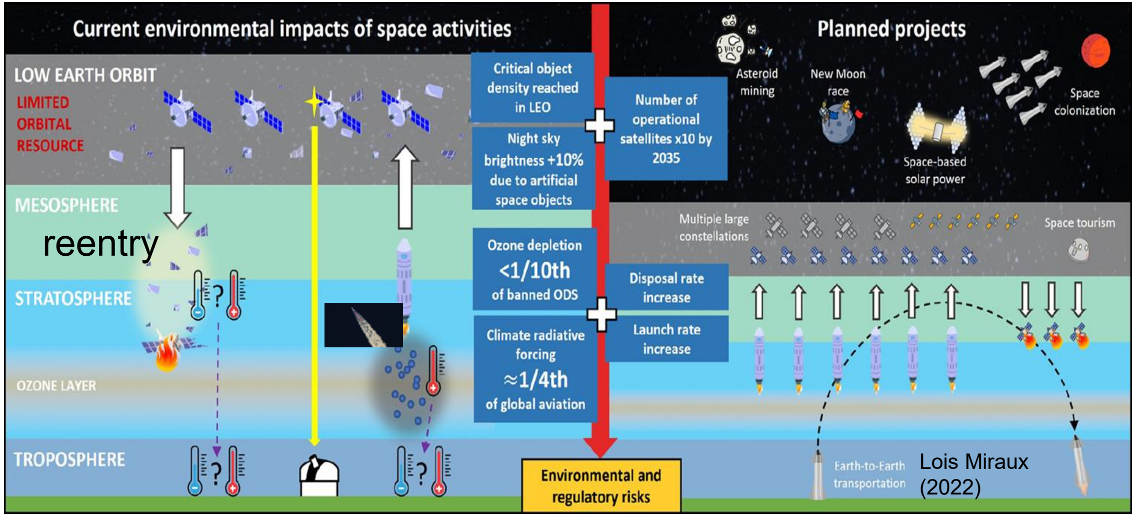
  Government civil space budget:$ 584million (2020)

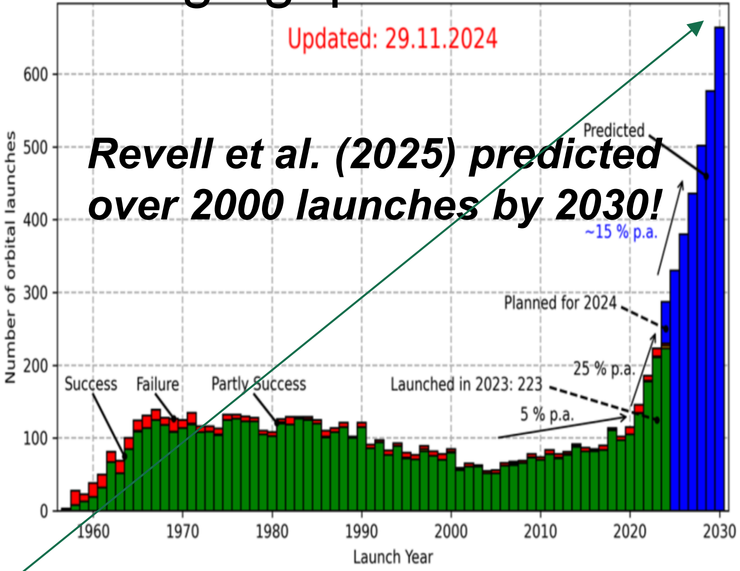


Space market today: $350b, $2.7trillion by 2040

What are the atmospheric impacts of space launches and their reentry?

Current Understanding and Knowledge gap





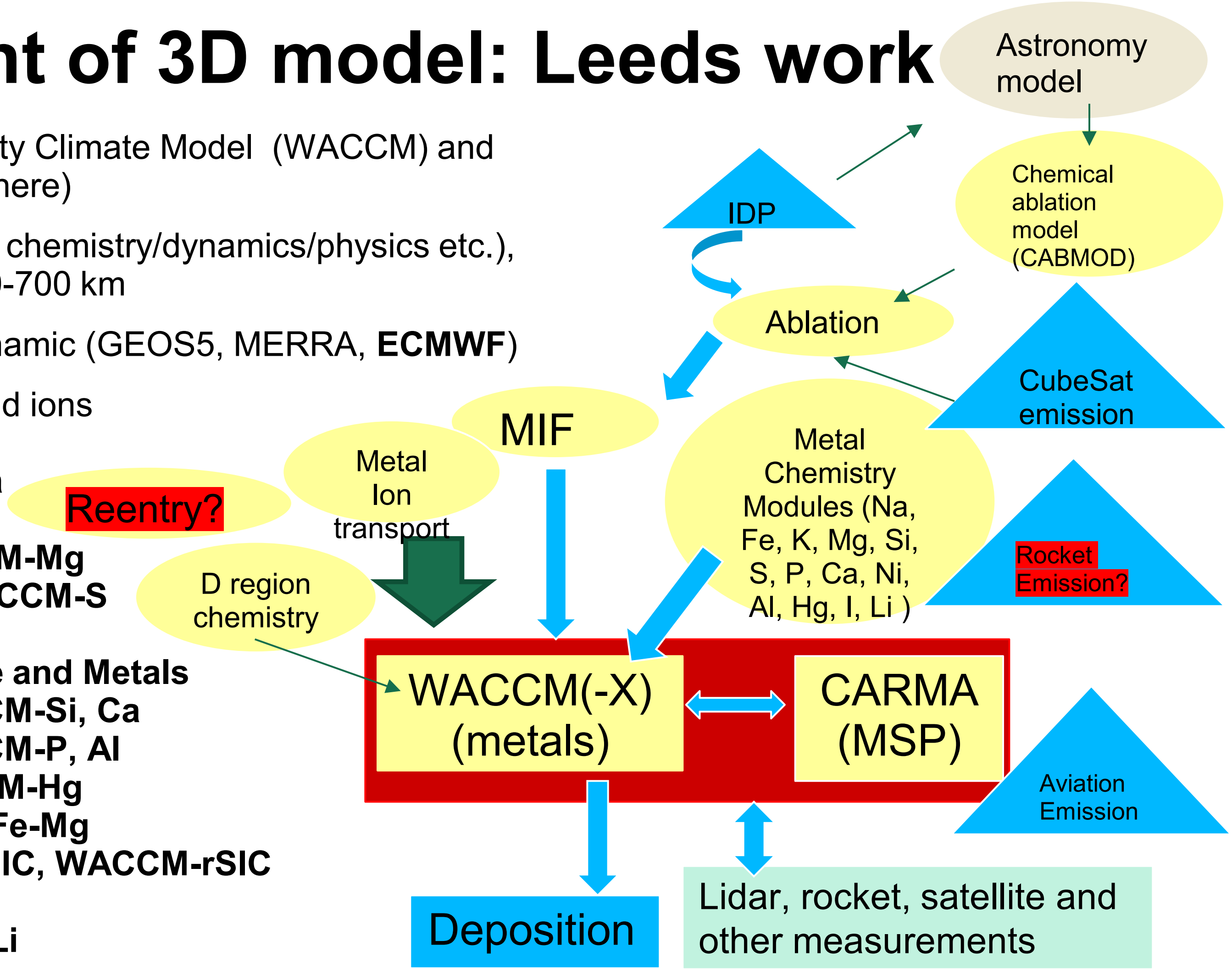
- First introduced in WMO 2022 ozone assessment report with ***limited modelling*** studies
- Less than 0.1% ozone change but the impact is ***expected to increase*** in the coming decades
- ***Poorly understood*** and in some cases, ***not yet studied***
- ***Uncertainties*** in these processes limit the confidence level
- ***Very little is known*** about of reentry particles or their possible impact on stratospheric ozone
- **New propellants could exert a substantial influence in the future.**

Urgent need to understand impacts of space launches on the atmosphere and thus climate

Self-Consistent of 3D model: Leeds work

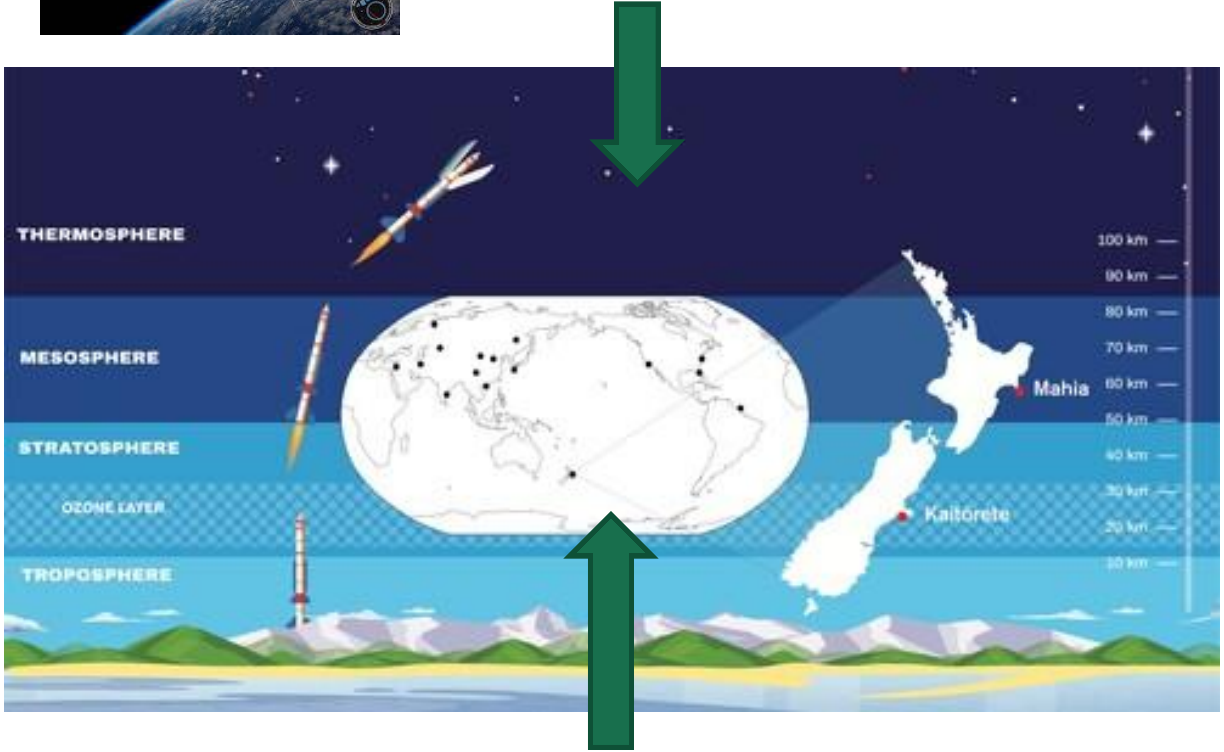
- Whole Atmosphere Community Climate Model (WACCM) and WACCM-X (extended ionosphere)
- WACCM: 0-140 km (detailed chemistry/dynamics/physics etc.), WACCM-X: surface up to 600-700 km
- Free running or specified dynamic (GEOS5, MERRA, **ECMWF**)
- Metal chemistry for neutral and ions

Feng et al. (2013): WACCM-Fe
Marsh et al. (2013): WACCM-Na
Plane et al. (2014): WACCM-K
Langowski et al. (2015): WACCM-Mg
Gomez Martin et al. (2017): WACCM-S
Daly et al. (2019): WACCM-Ni
Plane et al. (2015): Mesosphere and Metals
Plane et al. (2016, 2018): WACCM-Si, Ca
Plane et al. (2020, 2021): WACCM-P, Al
Saiz-Lopez et al. (2022): WACCM-Hg
Wu et al. (2021), WACCMX-Na-Fe-Mg
Kovacs et al. (2016), WACCM-SIC, WACCM-rSIC
Feng et al. (2023), WACCM-I
Gerding et al. (2025), WACCM-Li



What we need to consider emissions from CubeSat?

Iodine injection from small satellites (???): Our assumption for the Base Scenario is 8 ton/year I^+



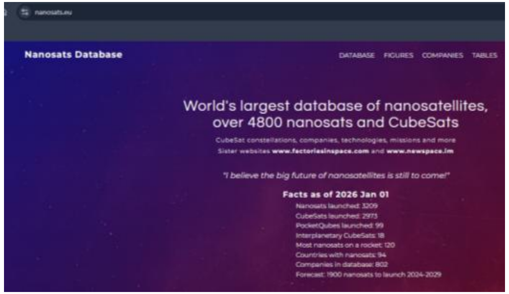
Surface Iodine Emissions (Cuevas et al., 2022)

- **Iodine Emissions (surface, top)**

1U nanosatellite contains 200g I_2
Rwanda Space Agency
Mega-constellation satellites.
Others plans: NASA, ESA, SpaceX, Virgin, Amazon and available info.

40000 cubesat with Iodine per year

- **Whole Atmosphere processes**



Iodine Chemistry in WACCM

Reaction	Liquid binary and ternary sulphate polar stratospheric cloud particles reactions
R1	N2O5 + H2O(l) → 2HNO3
R2	ClONO2 + H2O(l) → HOCl + HNO3
R3	BrONO2 + H2O(l) → HOBr + HNO3
R4	ClONO2 + HCl(l) → Cl2 + HNO3
R5	HOCl + HCl(l) → Cl2 + H2O
R6	HOBr + HCl(l) → BrCl + H2O
R7	HOCl + HBr(l) → BrCl + H2O
R8	HOBr + HBr(l) → Br2 + H2O
R9	HOCl + HI(l) → ICl + H2O
R10	HOBr + HI(l) → IBr + H2O
R11	IONO2 + H2O(l) → HOI + HNO3
R12	HOI + HCl(l) → ICl + H2O
R13	HOI + HBr(l) → IBr + H2O
R14	HOI + HI(l) → I2 + H2O
R15	IONO2 + H2O(l) → Ipart
R16	HOI + HCl(l) → Ipart

Nitric acid trihydrate reactions

R17	N2O5 + H2O(s) → 2HNO3
R18	ClONO2 + H2O(s) → HOCl + HNO3
R19	ClONO2 + HCl(s) → Cl2 + HNO3
R20	HOCl + HCl(s) → Cl2 + H2O
R21	HOBr + HCl(s) → BrCl + H2O
R22	HOCl + HBr(s) → BrCl + H2O
R23	HOBr + HBr(s) → Br2 + H2O
R24	HOCl + HI(s) → ICl + H2O
R25	HOBr + HI(s) → IBr + H2O
R26	BrONO2 + H2O(s) → HOBr + HNO3
R27	IONO2 + H2O(s) → HOI + HNO3
R28	HOI + HCl(s) → ICl + H2O
R29	HOI + HBr(s) → IBr + H2O
R30	HOI + HI(s) → I2 + H2O
R31	IONO2 + H2O(s) → Ipart
R32	HOI + HCl(s) → Ipart

Water ice polar stratospheric particles reactions

R33	N2O5 + H2O(s) → 2HNO3
R34	ClONO2 + H2O(s) → HOCl + HNO3
R35	BrONO2 + H2O(s) → HOBr + HNO3
R36	ClONO2 + HCl(s) → Cl2 + HNO3
R37	HOCl + HCl(s) → Cl2 + H2O
R38	HOBr + HCl(s) → BrCl + H2O
R39	HOCl + HBr(s) → BrCl + H2O
R40	HOBr + HBr(s) → Br2 + H2O
R41	HOCl + HI(s) → ICl + H2O
R42	HOBr + HI(s) → IBr + H2O
R43	IONO2 + H2O(s) → HOI + HNO3
R44	HOI + HCl(s) → ICl + H2O
R45	HOI + HBr(s) → IBr + H2O
R46	HOI + HI(s) → I2 + H2O
R47	IONO2 + H2O(s) → Ipart

Other reactions:

- $I + O_3 \rightarrow IO + O_2$
- $IO + O_3 \rightarrow OIO + O_2$
- IO, I, OIO, I_2, I_2O_2, I_2O_3, I_2O_4, HI, HOI etc also have other reactions for example IO+ClO, IO+BrO or Br, NO, NO_2, NO_3, OH etc which will destroy ozone…

This work considers extra reactions/species:

- $I^+ + O_3 \rightarrow IO^+ + O_2$
- $I + O_2^+ \rightarrow I^+ + O_2$
- $IO^+ + O \rightarrow I^+ + O_2$
- $IO^+ + e \rightarrow I + O$
- $CF_3I + hv \rightarrow CF_3 + I$
- $CF_3I + OH \rightarrow CF_3 + HOI$
- $HOI + H \rightarrow HI + OH$
- $HOI + H \rightarrow I + H_2O$
- $HOI + O \rightarrow OH + IO$
- $HI + O \rightarrow OH + I$

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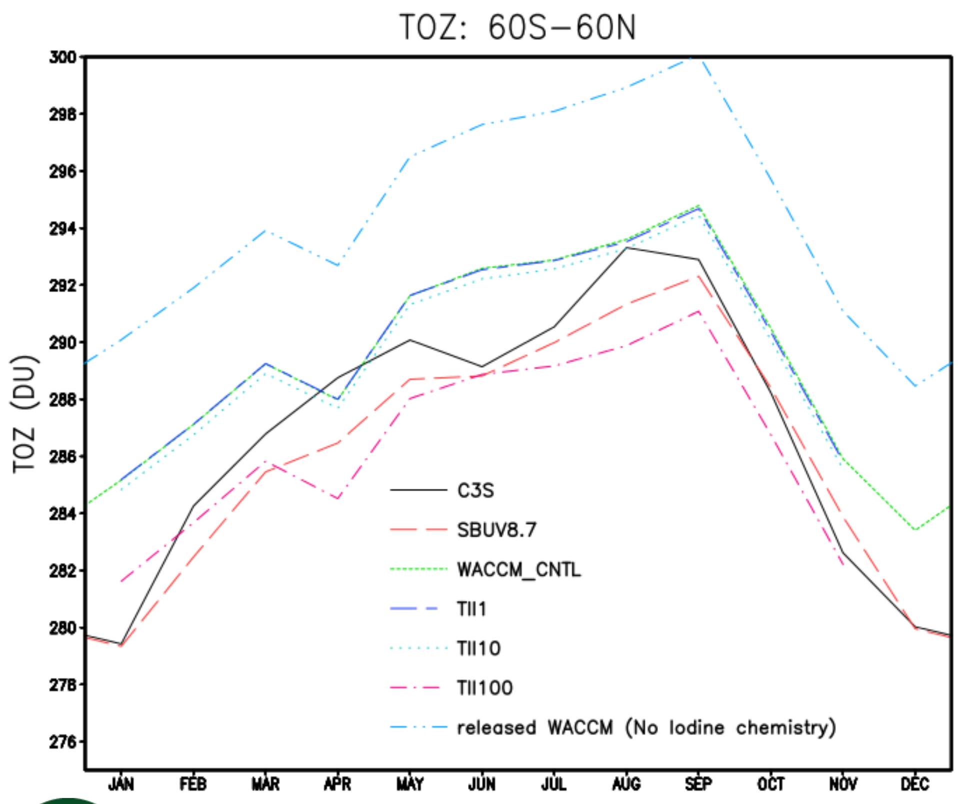
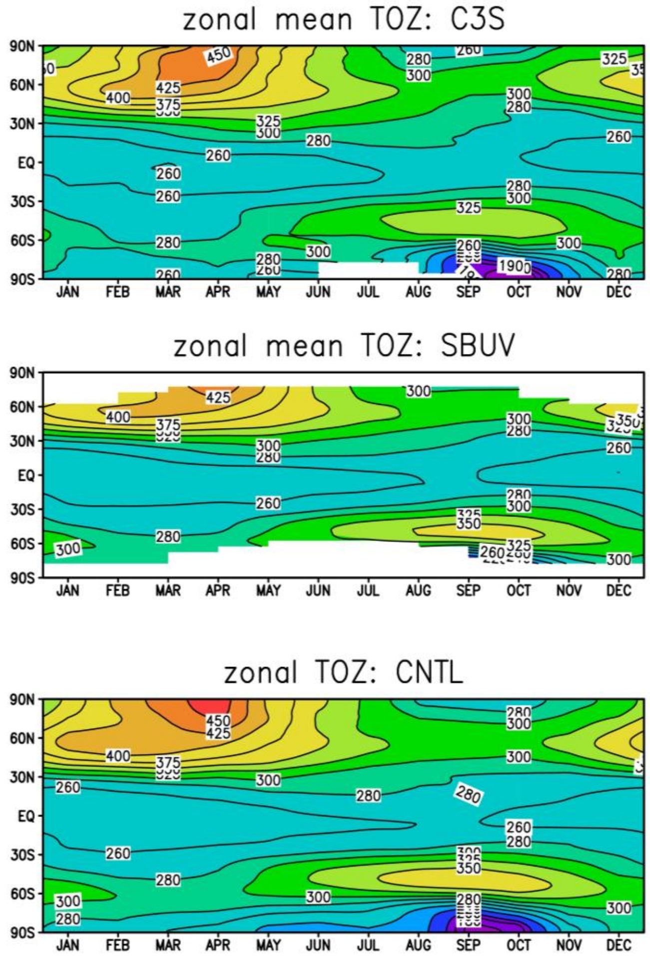
WACCM-I Model experiments

Experiments	Description	Thermosphere iodine injection (TII) rate from small satellites	Iodine surface emissions
CNTL (or TII0)	Control experiment	None	Surface emissions Cuevas et al. (2022)
TII1	As CNTL, but considering the base scenarios of thermosphere iodine injection (TII) from small satellites (see main texts)	Small satellite launch rate of 40,000 per year (8ton/year) 1.2e-4 cm^{-3} s^{-1} above 120 km	Same as CNTL
TII10	As TII1, but assuming 10 times of TII1 from small satellites	80ton/year 1.2e-3 cm-3 s-1 above 120 km	Same as CNTL
TII100	As TII1, but assuming 100 times of TII1 from small satellites	~800ton/year 1.2e-2 cm-3 s-1 above 120 km	Same as CNTL
TII1_S0	As TII1 but without any surface iodine emissions	1.2e-4 cm-3 s-1 above 120 km	None
TII10_S0	As TII10 but without any surface iodine emissions	1.2e-3 cm-3 s-1 above 120 km	None
TII100_S0	As TII100 but without any surface iodine emissions	1.2e-2 cm-3 s-1 above 120 km	None

- 15 years SD-WACCM simulation each (~9Tb)
- Perpetual runs year 2014, to avoid inter-annual variability.
- Constant TII (not location/season-dependent) for simplification.

WACCM performance





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Key results

Geophysical Research Letters

Research Letter | Open Access

Potential Stratospheric Ozone Depletion Due To Iodine Injection From Small Satellites

Wuhu Feng, John M. C. Plane, Martyn P. Chipperfield, Alfonso Saiz-Lopez, Jean-Paul Booth

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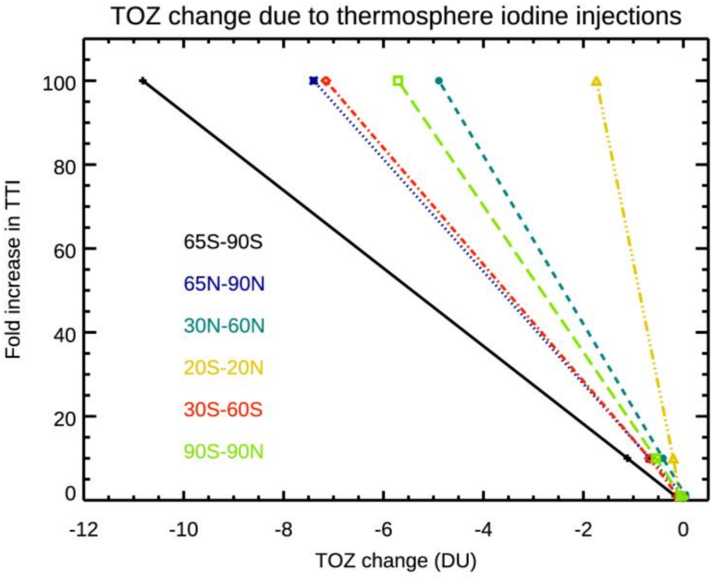

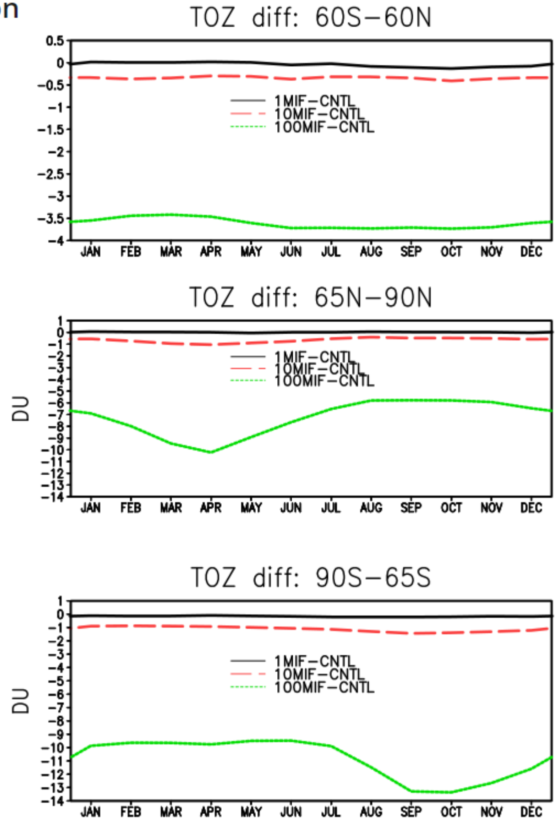

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RESEARCH HIGHLIGHT | 20 April 2023

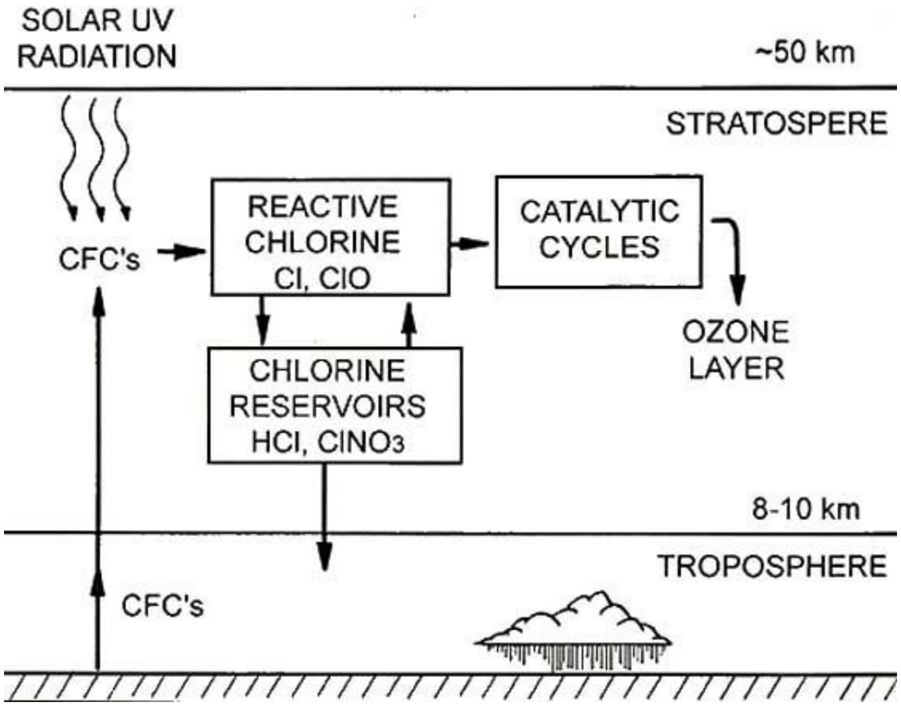
How CubeSats could harm the ozone layer

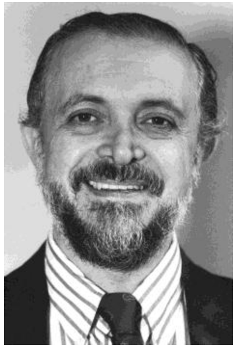
The proliferation of miniature satellites – and a possible switch to iodine exhaust – could have unintended consequences.

The analysis could help governments to ensure that the rapidly growing industry does not affect the ozone layer. *Nature* (2023)

This study assists regulatory authorities in assessing O_3 impact of I-propelled satellites in low Earth orbit.

CFC-Stratospheric Ozone Depletion Theory: 1970s





The Nobel Prize in Chemistry 1995 was awarded jointly to:
Paul J. Crutzen, Mario J. Molina and F. Sherwood Rowland "
for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone."

Discovered in the 1930s, CFCs seemed ideal compounds for a number of uses: e.g. refrigerants and aerosol propellants. They are non-toxic and inert (chemically unreactive). CFCs became more and more widely used through to the 1980s, and chlorine levels in the atmosphere increased accordingly.

$$CFCl_3 + \text{sunlight} \rightarrow 3Cl + \text{other products} \rightarrow HCl$$

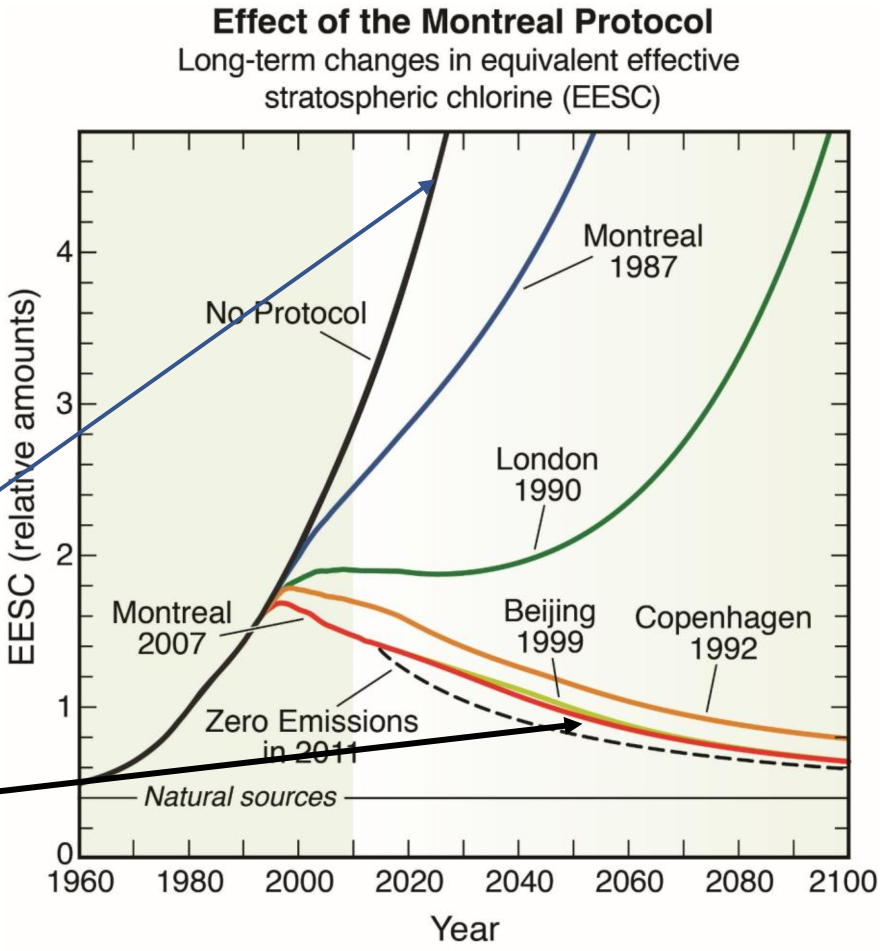
Predicted Cl and Br Loading of the Atmosphere

In 1987 Montreal Protocol placed first limits on use of CFCs. (Based on 'precautionary principle')

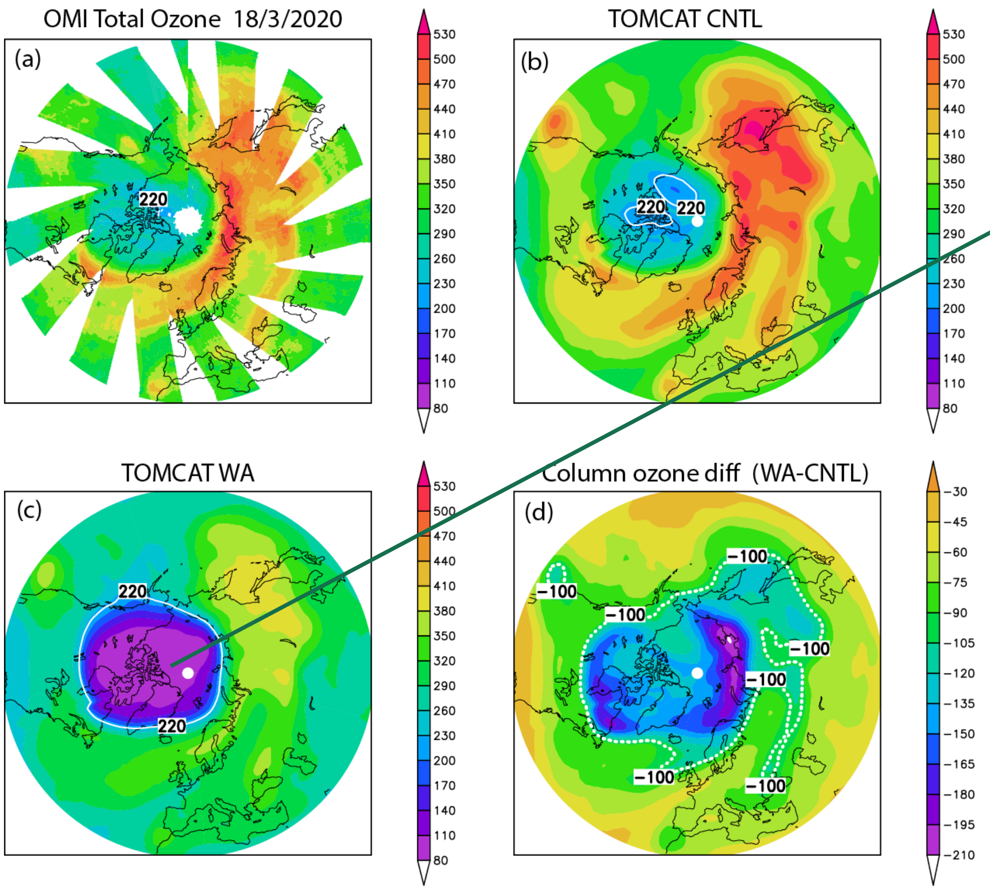
Later amendments strengthened control of Cl/Br source gases.

Without Protocol potential for global O_3 loss would have been catastrophic.

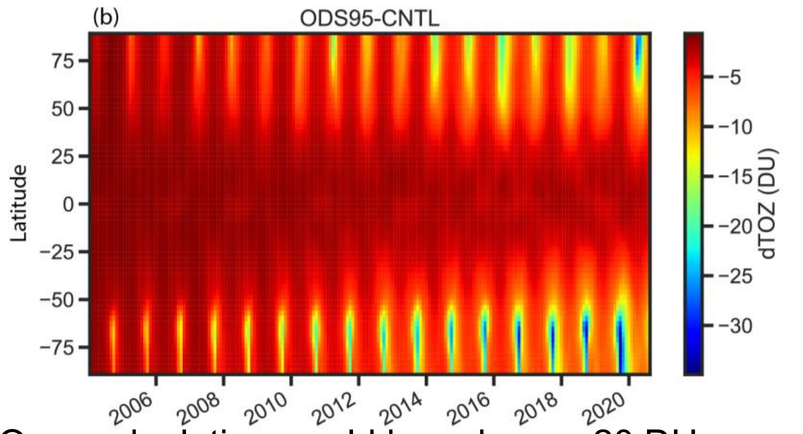
Now expect Cl loading to return to 1980 values (pre Antarctic O_3 hole) by 2050.



Success story of Montreal Protocol



With no Montreal Protocol at all ozone loss in cold Arctic winters like 2019/20 would already have become extreme, with a large Arctic Ozone Hole



Ozone depletion would have been ~20 DU worse if 2019/20 meteorology has occurred in late 1990s: Recovery of ozone layer from peak halogen

Feng et al. (GRL, 2021)

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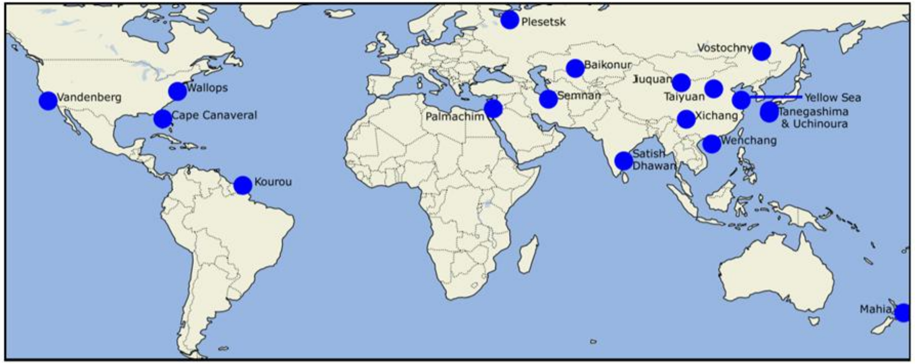
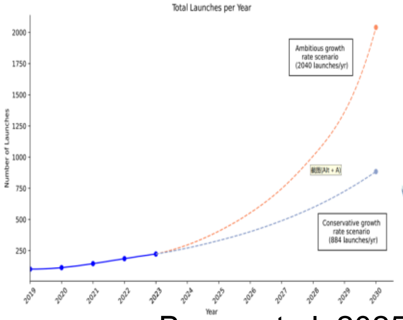
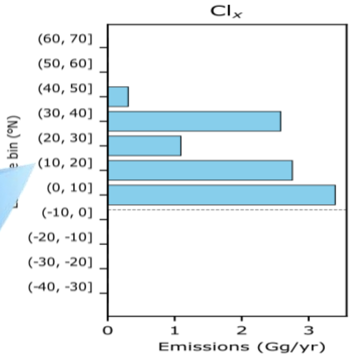
HCl produced when rockets burn chlorine-containing solid propellant







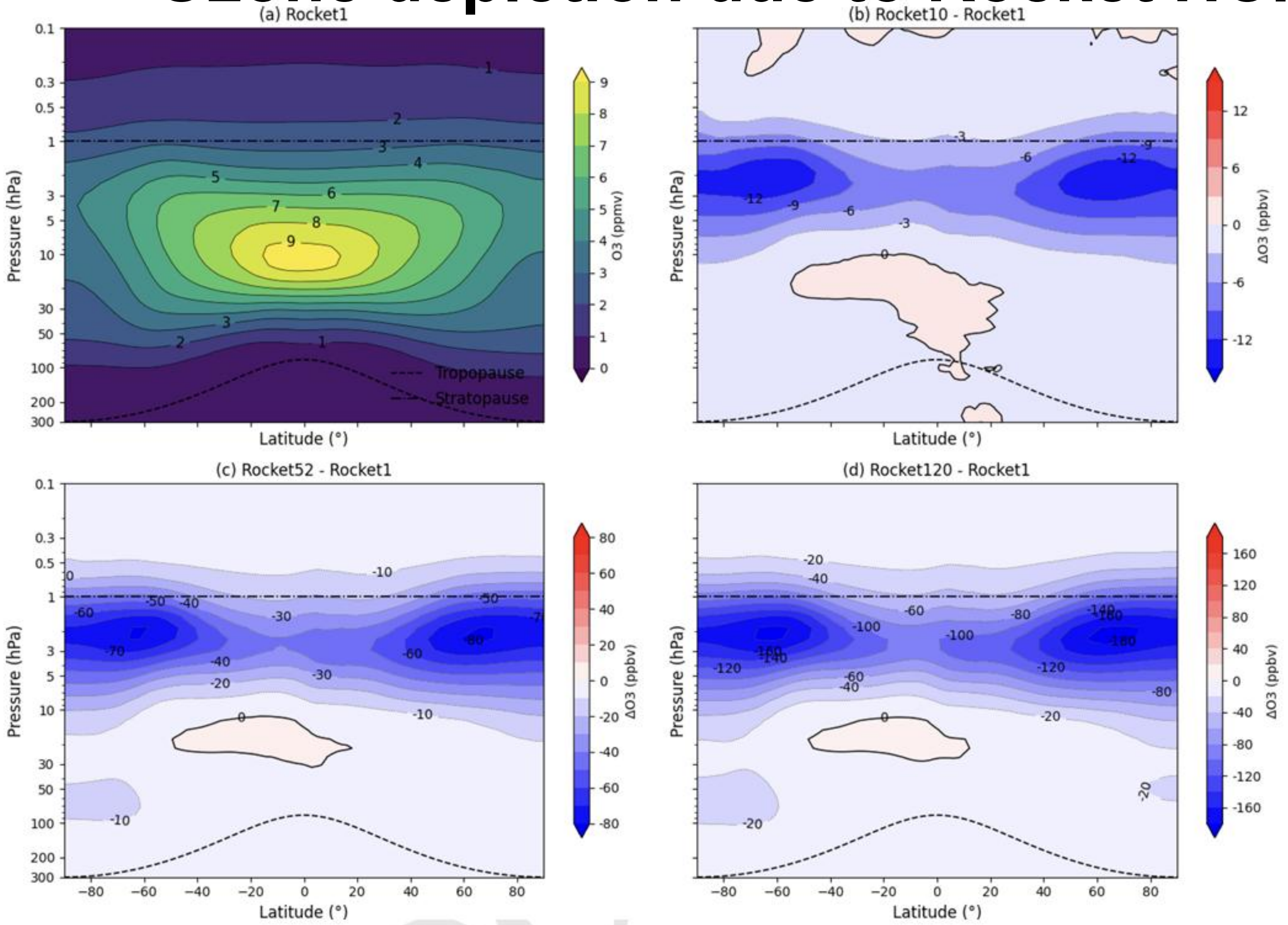
Brown et al. 2025

Simulation	Rocket launch scenario	Annual number of rocket launches	Mass of rocket emitted Cl_x	Description of growth
Rocket1	2019 data from Brown et al. (2024b)*	97	0.5 Gg	Actual 2019
Rocket10	10 × Rocket1	970	5 Gg	Modest
Rocket52	52 × Rocket1	5044	26 Gg	Large
Rocket120	120 × Rocket1	11 640	60 Gg	Extreme

* 2019 inventory of 65 vehicles from 11 launcher families and 97 launches.

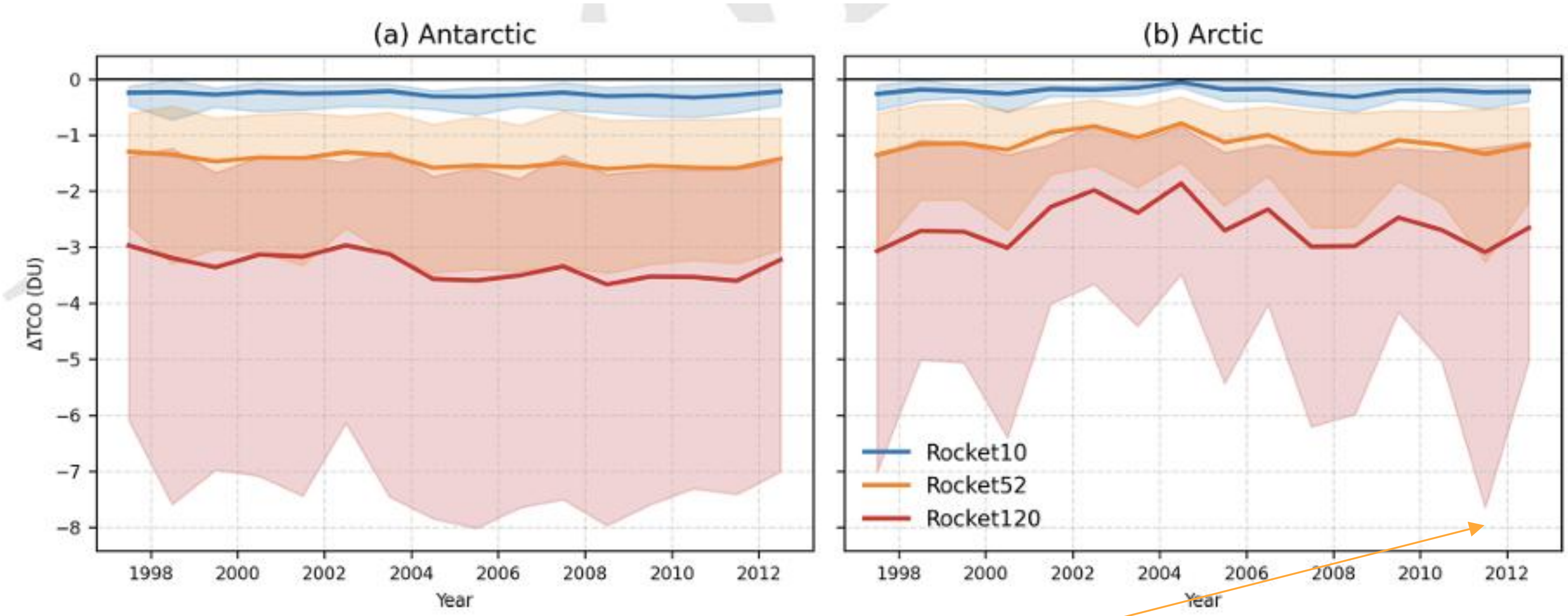
APCP (Ammonium Perchlorate Composite Propellant) is standard fuel for many large rocket boosters (Space shuttle and Space Launch system)

Ozone depletion due to Rocket HCl emissions



Rocket emissions cause widespread stratospheric O_3 depletion, strongest in the upper and high-latitude lower stratosphere, consistent with chlorine-driven chemistry.

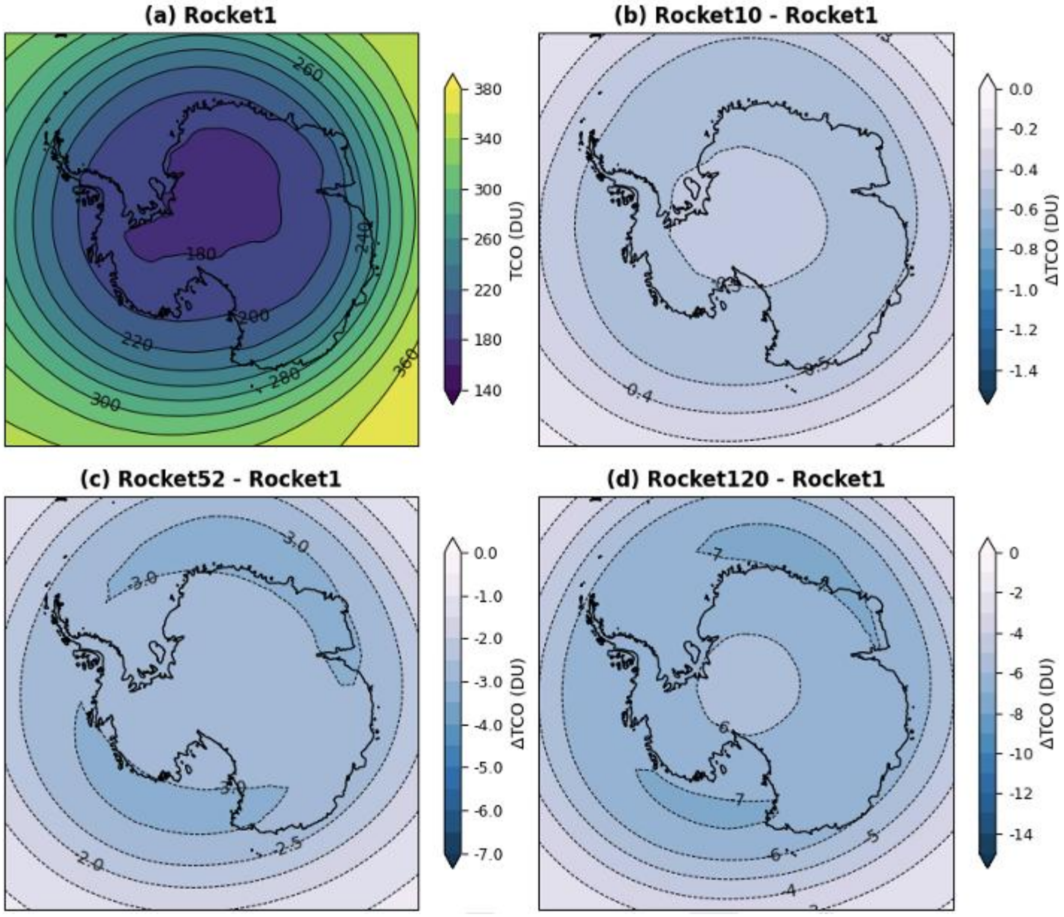
Interannual Variability of O_3 Depletion due to Rocket Chlorine Emissions



Shading on each line is the range of ozone depletion, indicating the minimum and maximum monthly values over each year.

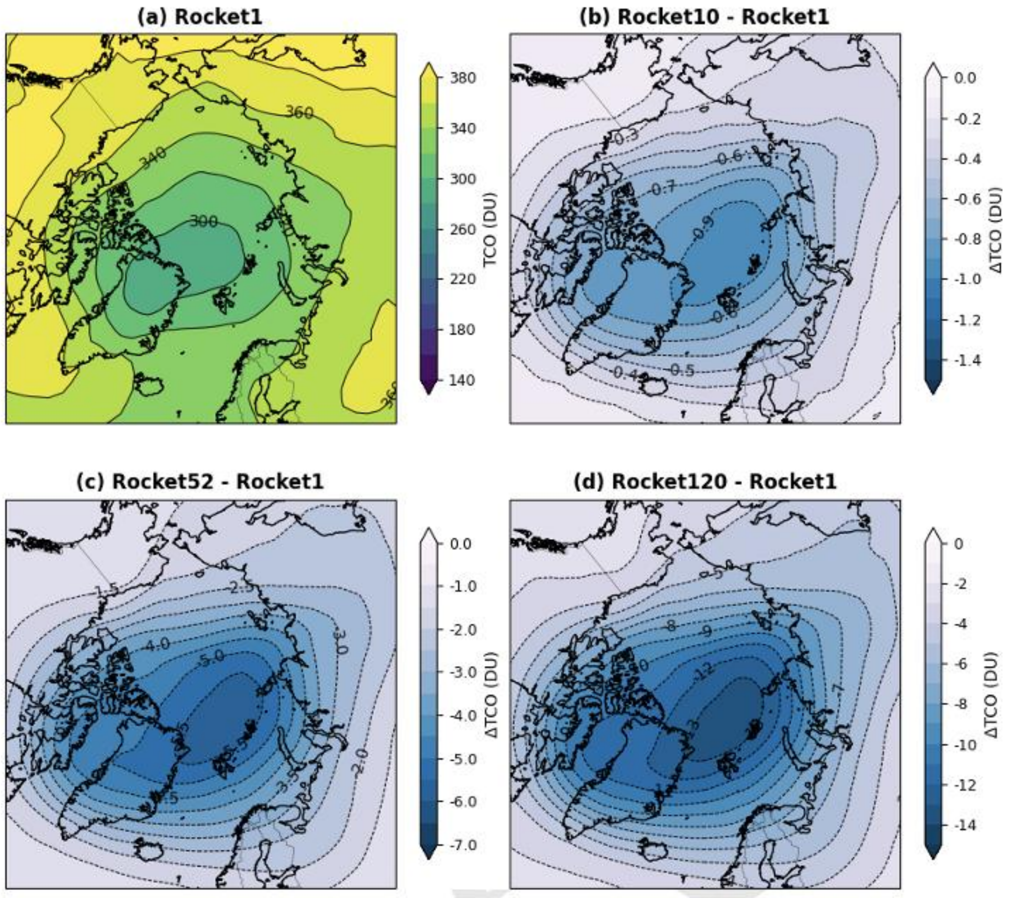
Arctic 2011/12 was one of the record cold year

Antarctic Total Column O_3 changes due to Rocket Chlorine Emissions



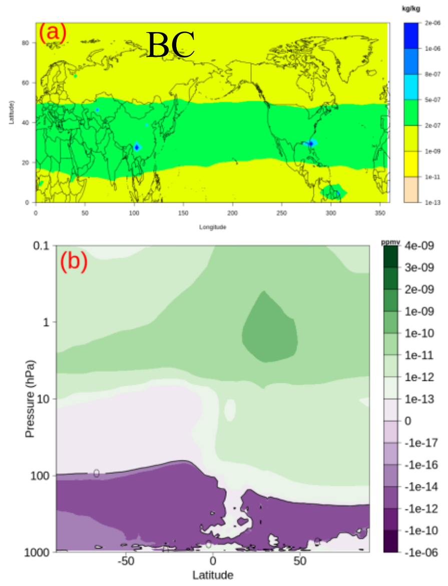
Rocket emission scenarios lead to Antarctic spring ozone depletion that increases with emission intensity, reaching up to ~7 DU. The impact is modest but can partially offset ozone recovery.

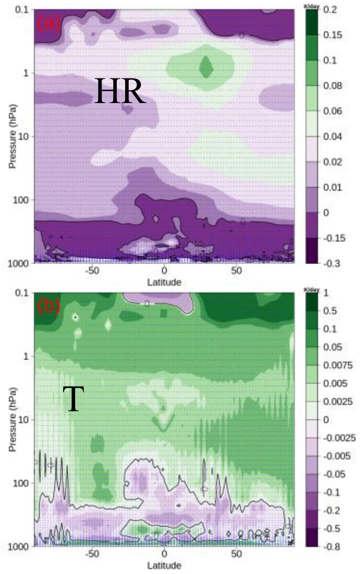
Arctic Total O_3 Depletion due to Rocket Chlorine Emissions

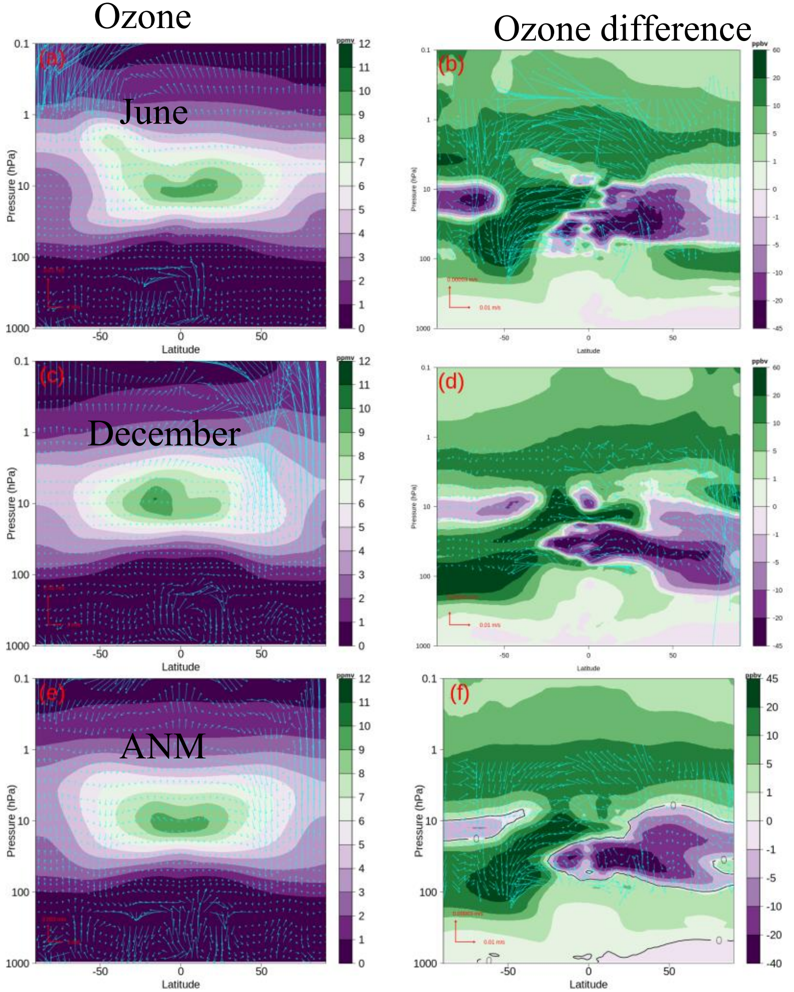


The Arctic response is highly sensitive to meteorological conditions, and under extreme situations, the impact can be significantly amplified

BC Alters Circulation and Drives Ozone Redistribution





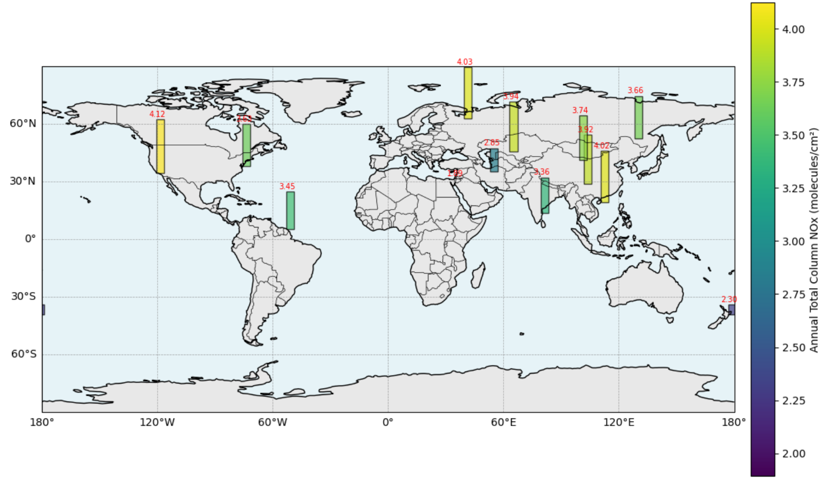


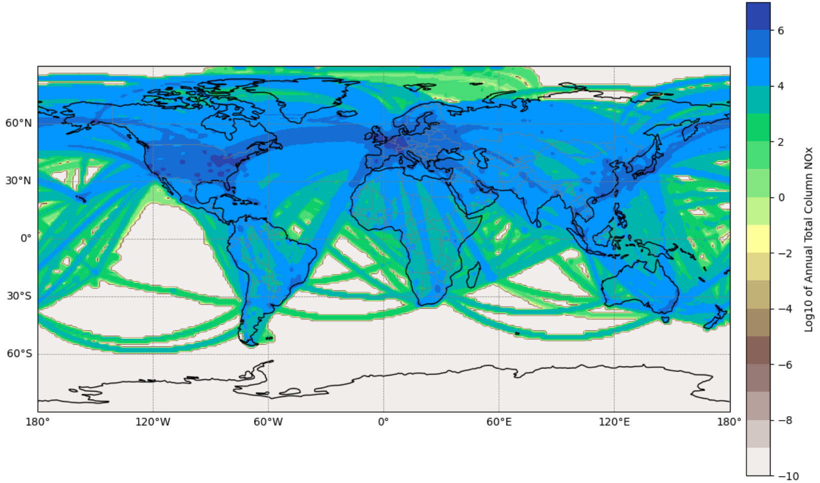
Above: Annually averaged (a) horizontal distribution of total column BC, and (b) zonal mean BC difference between the BC100 and CTL simulations.
Middle: Annually averaged changes of zonal mean difference in (a) merged short- and long-wave heating rate and temperature between the BC100 and CTL simulations.

Right: Averaged zonal mean ozone and its changes due to rocket BC emissions: (a) Zonal mean ozone in June from the control simulations, (b) Change in zonal mean ozone in June between the BC100 and CTL simulations, (c) Zonal mean ozone in December from the control simulations, (d) Change in zonal mean ozone in December between the BC100 and CTL simulations, (e) Annually averaged zonal mean ozone from the control simulations, (f) Annually averaged change in zonal mean ozone between the BC100 and CTL simulations. Arrows indicate residual meridional and vertical velocities. The red arrow in each panel shows the scale of v* and w* in m/s.

NOx emissions from Rocket and Aircraft

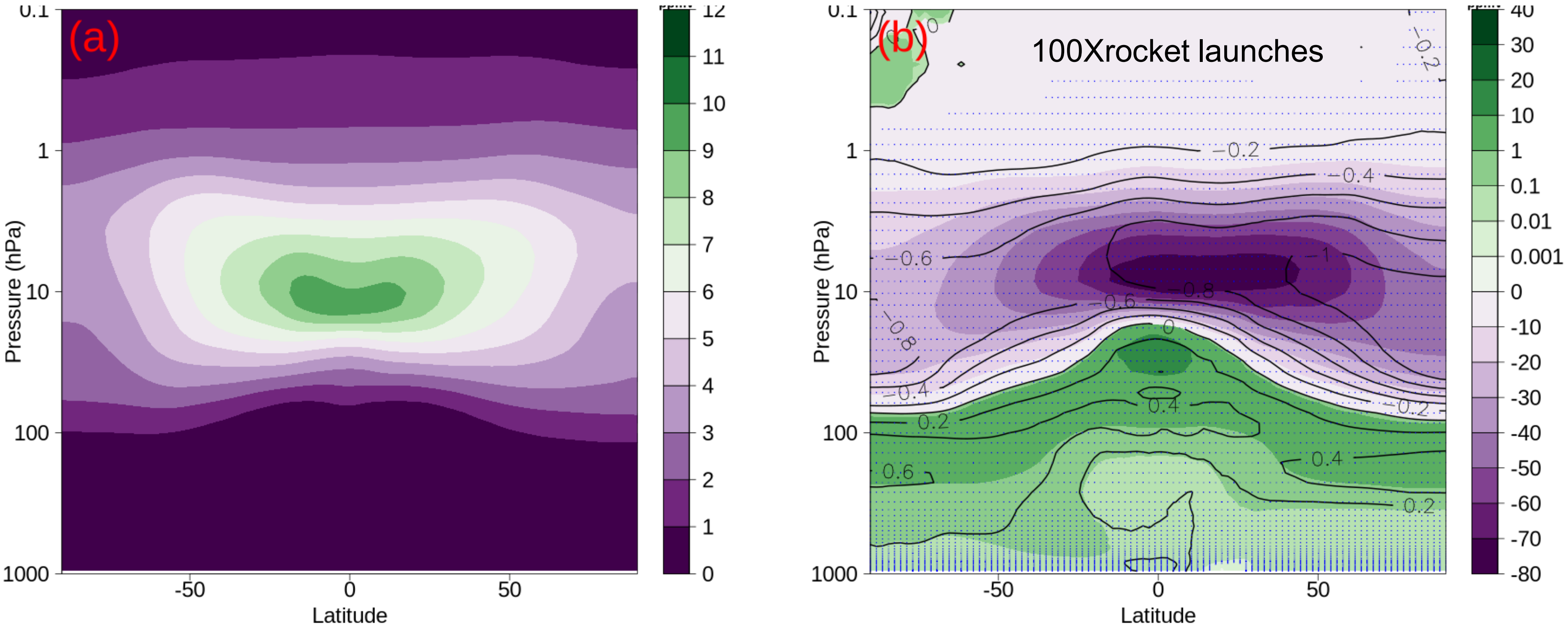
Global aviation emits ~2.5-3 Tegrams per year (10^{12} grams/year)





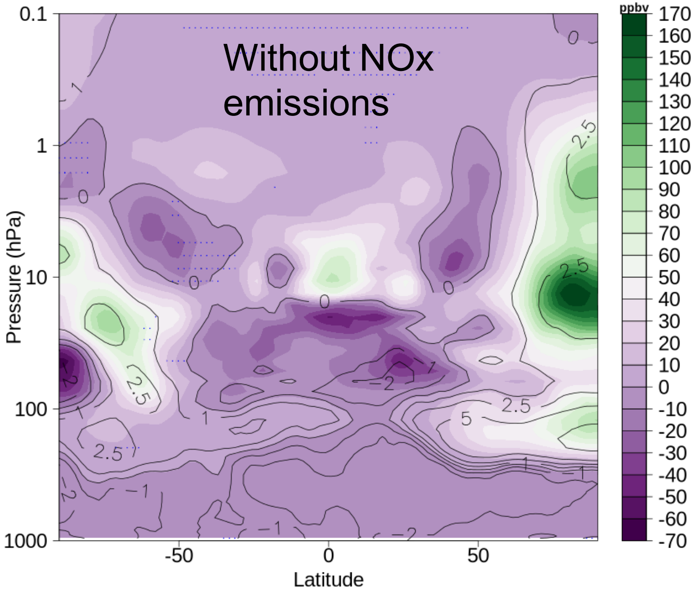
Global rocket emits ~2.1 gigagrams per year (10^8 grams/year):
Rocket launches: ~0.22 gigagrams per year
Reentry: ~1.8 gigagrams per year

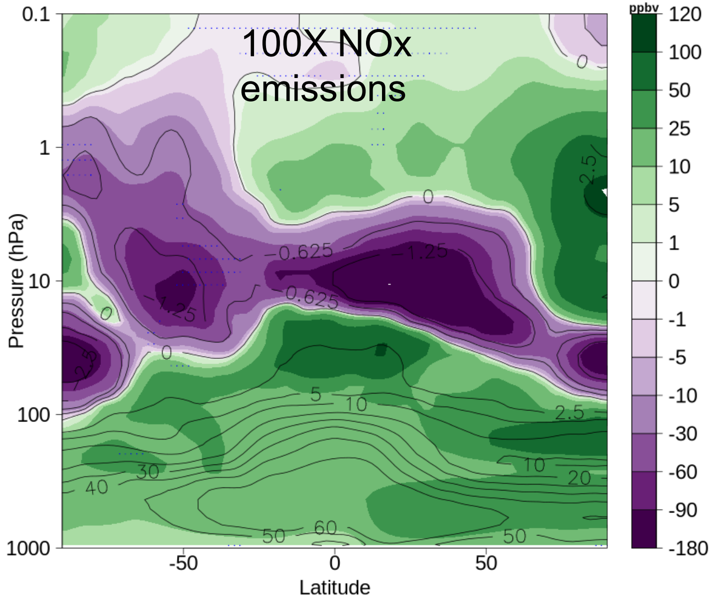
Ozone reduction due to NOx emissions from rocket launches



DfT: Research on upper atmospheric pollution due to rocket launches

Ozone changes due to NOx emissions from aircraft



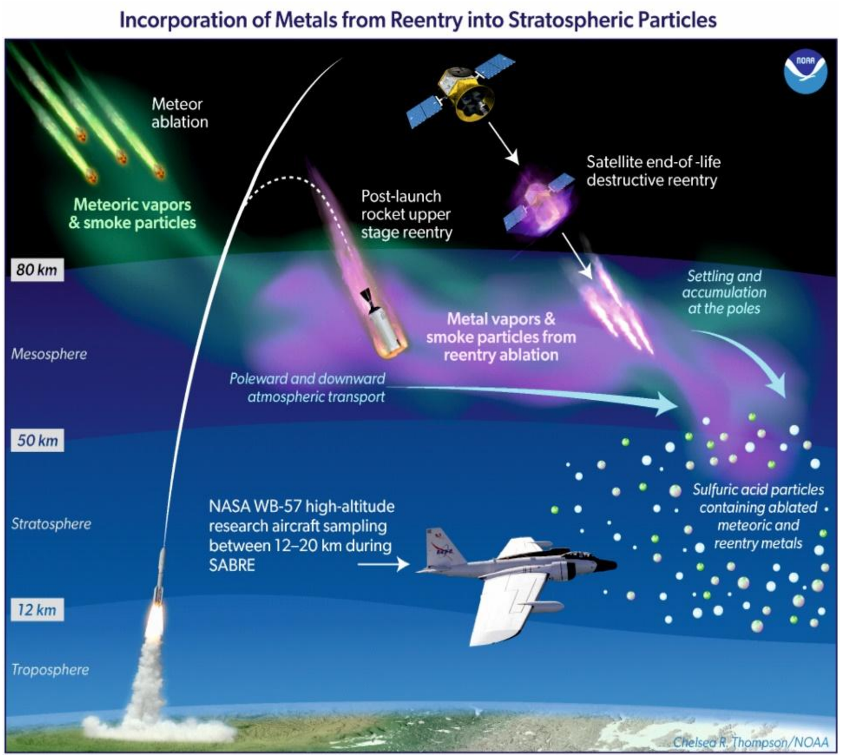


Ozone levels increase at high latitudes throughout the stratosphere in the absence of NOx emissions from aircraft.

A 100-fold increase in NOx emissions leads to ozone reduction, primarily in the lower and mid-stratosphere.

NERC funding: REVEAL-NOx: Reducing aviation Emissions' uncertain climate impacts: NOx

Spacecraft metals reentry in stratospheric aerosol particles

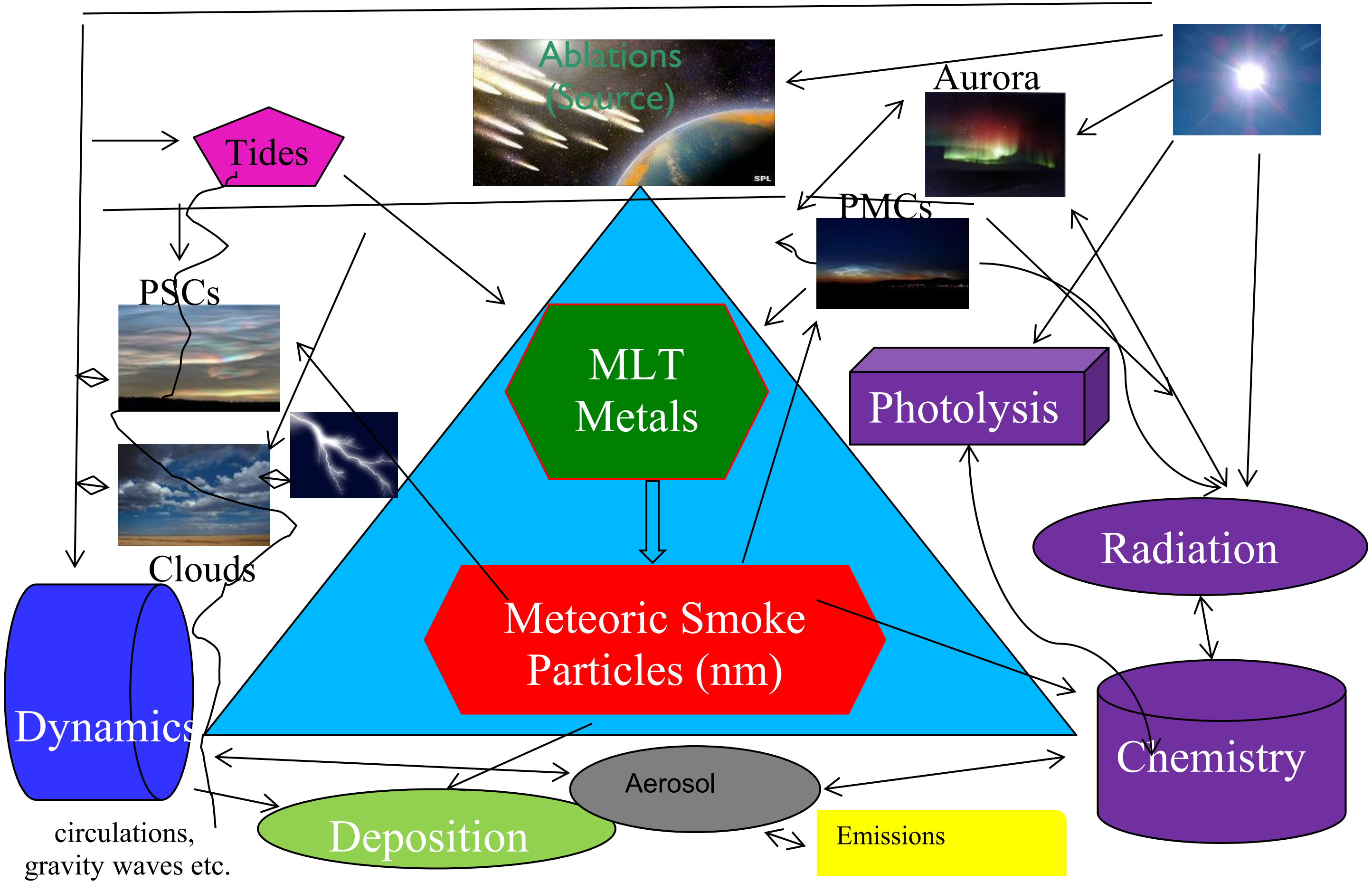


Credit: Chelsea Thompson/NOAA

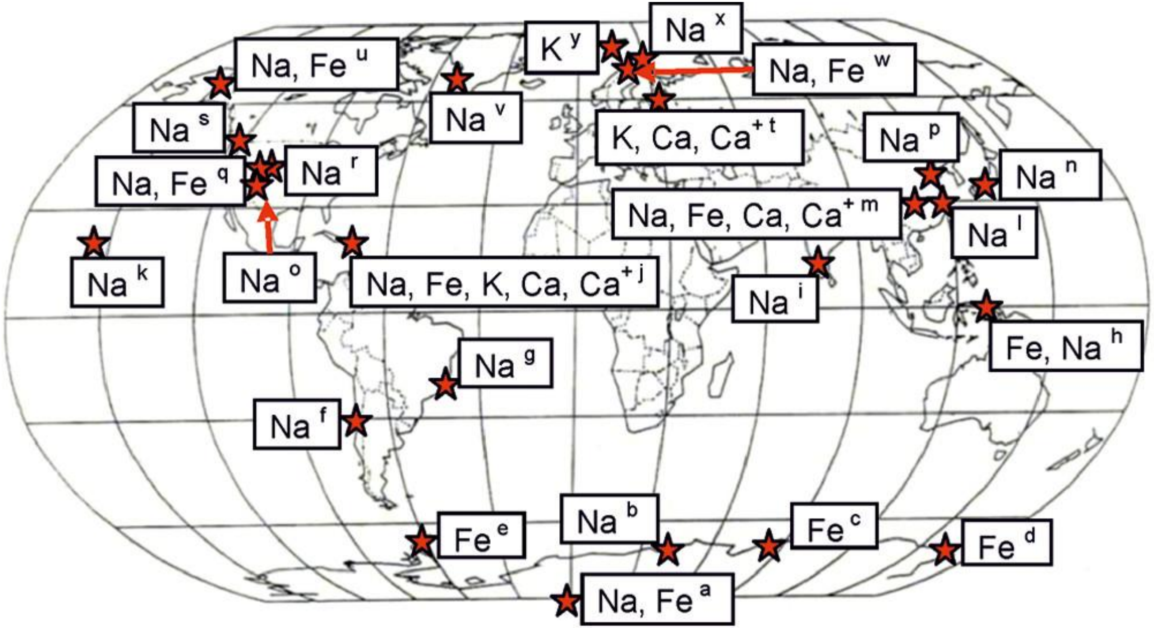
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

- When spent rocket bodies and defunct satellites re-enter the atmosphere, they produce metal vapours that condense into aerosol particles that descend into the stratosphere
- The mass of lithium, aluminum, copper, and lead from the reentry of spacecraft was found to exceed the cosmic dust influx of those metals.
- About 10% of stratospheric sulfuric acid particles between 120 and 500 nm in diameter contain aluminum and other elements from spacecraft reentry, the influence of this level of aerosol perturbation on the properties of stratospheric particles is unknown
- WACCM-Fe (Feng et al., 2013), WACCM-Na (Marsh et al., 2013), WACCM-Al (Plane et al.,2021) have been sent to Massachusetts Institute of Technology (MIT) to investigate Space debris in 2022
- Two pioneering studies funded by ESA, DfT

Complex Processes controlling metal layers



Global measurements for Metals since 2004



a, South Pole; b, Syowa: c, Davis; d, McMurdo; e, Rothera; f, Cerra Pachon; g, São José dos Campos; h, Kototabangl; i, Gadanki; j, Arecibo; k, Maui; l, Hefei, China; m, Wuhan; n, Uji; o, Albuquerque; p, Beijing; q, Boulder; r, Ft. Collins; s, Vancouver; t, Kühlungsborn; u, Poker Flat; v, Sondrestrom; w, Andøya; x, Tromsø; y, Spitsbergen

Plane, Feng and Dawkins (2015)

Earth's atmosphere:

- Lidar: First observed Na layer at Lowell Observatory (35 ° N, 111° W) by Slipher (1929), Intensive observations Chinese Meridian Project (Fe, Na, K Ca, Ni, Ca^+ and possible AlO?)
- Rocket: Metal Ions
- Satellite(GOME, OSIRIS/ODIN, SCIAMACHY: Na, Mg, Mg^+, K

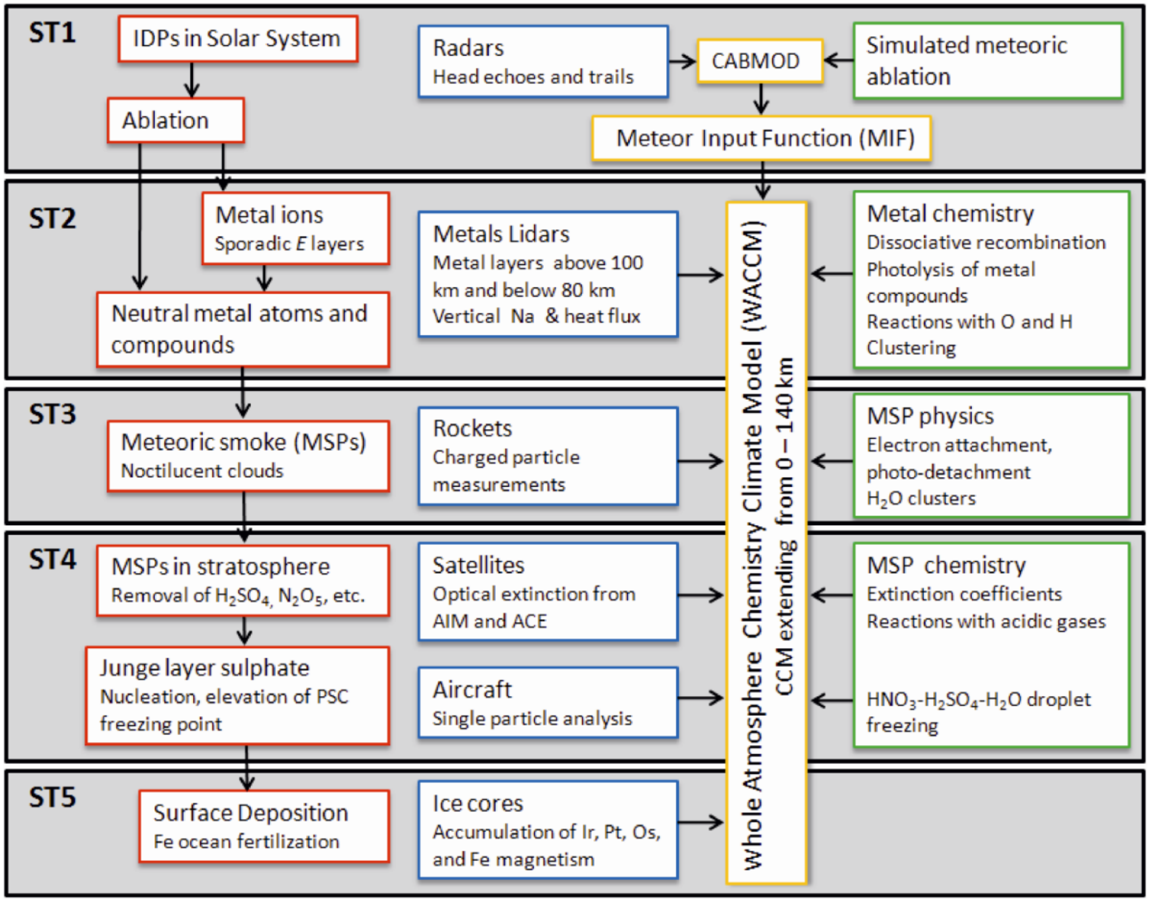
Martian atmosphere

(NASA's Mars Atmosphere and Volatile EvolutioN)：First time that metals have been directly observed in the atmosphere of another solar system planet (cf. exoplanets!)

- Spacecraft IUVS (Imaging Ultraviolet Spectrograph：
- Neutral Gas Ion Mass Spectrometer (NGIMS)：

We have developed CESM and LMD-Mars models with new capability for meteoric particles and evaluated the model results by making comparison with measurements

Cosmic Dust in the Terrestrial Atmosphere (CODIAT) Project



PI: John Plane

Advanced ERC grant (2.5M Euro)

Question to address: *How much cosmic dust enters the Earth's atmosphere?*

Outcome: > 80 papers

28+-16 tonnes/day

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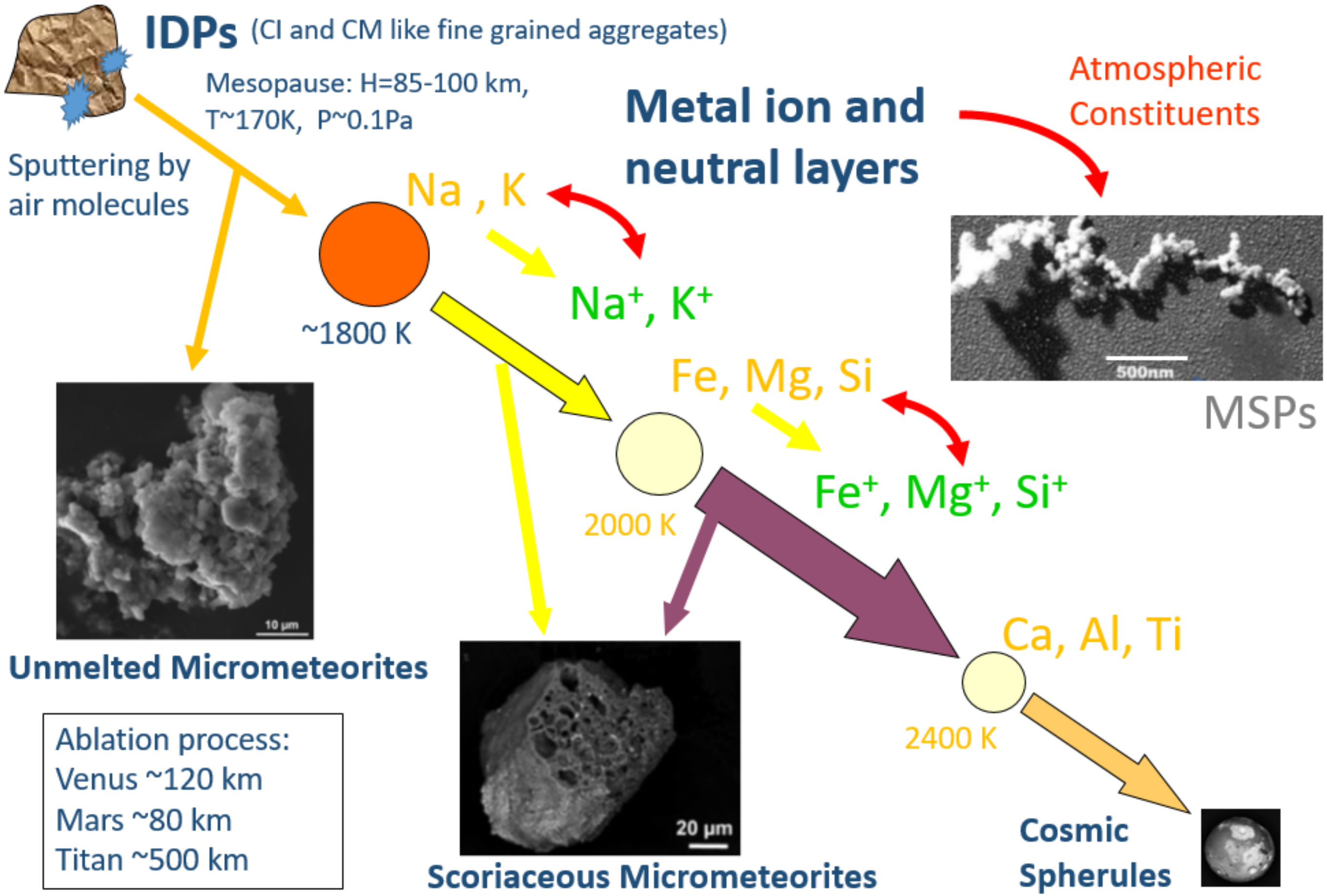
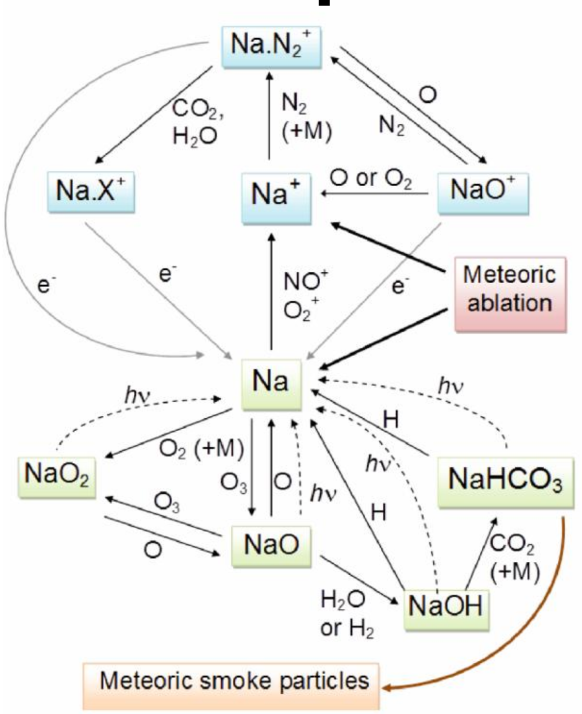
NATURAL ENVIRONMENT RESEARCH COUNCIL

Meteoric ablation



- Meteoroid particles enters the Earth's atmosphere at high velocity (11-72 km/s)
- **Sputtering:** Mass loss by hypethermal collision with air molecules.
- **Unmelted MMs:** All those particles that do not reach the melting temperature (T < 1800 K).
- **Ablation:** Mass loss by metal evaporation (T > 1800 K).
- **Cosmic Spherules:** All those particles that are completely melted.

Complex Metal Chemistry: Example



Plane, Feng, Dawkins (*Chem Rev.*, 2015)

- Meteoric ablation injects metal neutral atoms and ions (source terms)
- Then undergo the neutral and ion-molecule chemistry: oxidised by **reactions involving O3, O2, O, H2O, H, CO2 et al.**; Charge transfer with **NO+, O2+** and undergo dissociative recombination with **electron** to yield neutral metals.
- EPP affects NOx and HOx thus O3 chemistry, thus potential affect metal layer, but how?
- Most of rate constants can be made from lab, some are **T-dependent**
- PMC can also deplete metals: Note PMC Also known as noctilucent ("night-shining") clouds, since naked-eye observations occur after sunset or before sunrise,
  - Only exist at very high altitude (80-85 km) in summer with very cold T< 150 K).
  - Mostly seen at high latitudes (> 50º). Large horizontal extent (hundreds of km), small vertical thickness (1-3 km) → optical depth is ~10-4 or less. Composed of water ice crystals (size ~ 20-60 nm). First ground-based observations reported in 1880s. First satellite obs in 1969 showed greater latitudinal extent, presence in both hemisphere

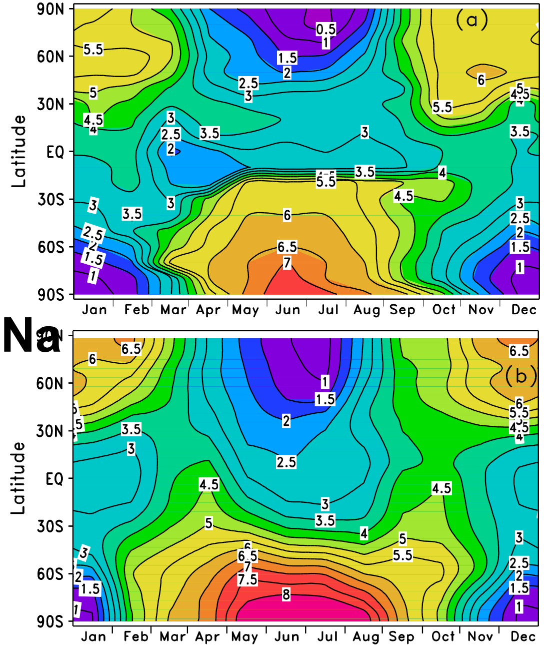
WACCM model performance: Global picture (Na, K, Mg, Mg^+)

Plane (2010)

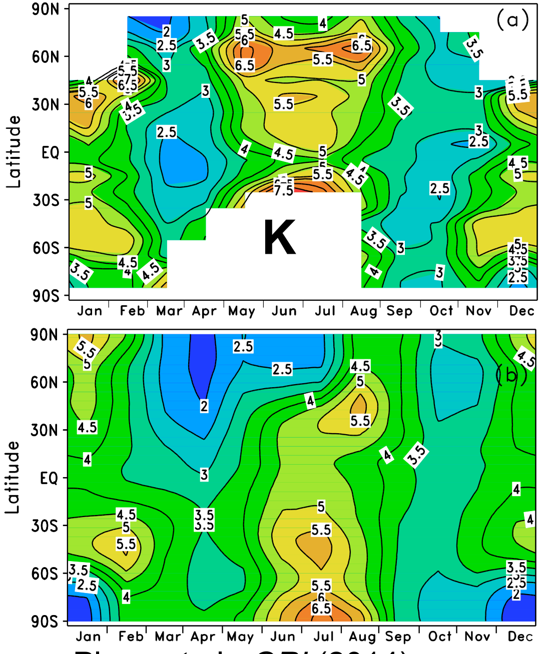
OSIRIS ODIN

Dawkins et al., *GRL*(2014)

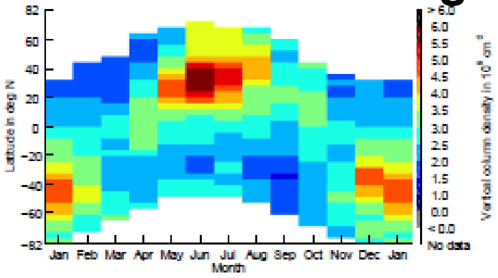
SCIMACHY Mg^+



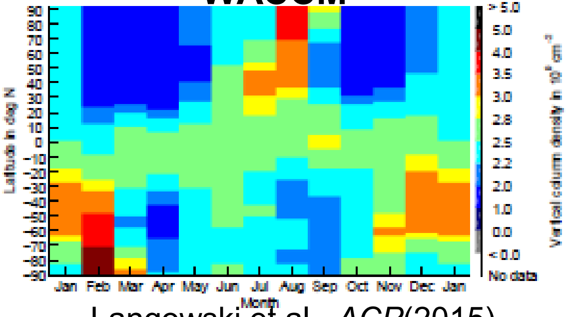
Marsh et al. *JGR* (2013)



Plane et al., *GRL*(2014)



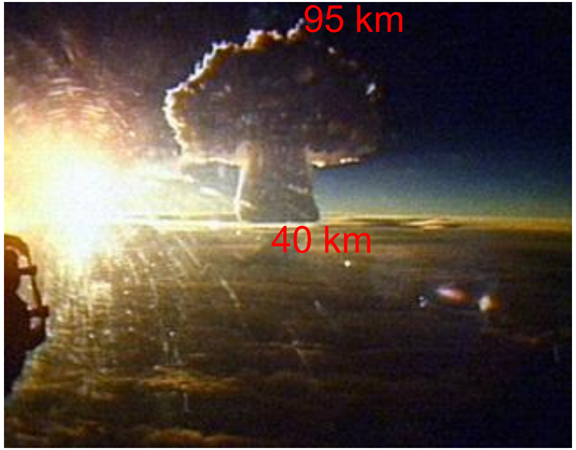
WACCM



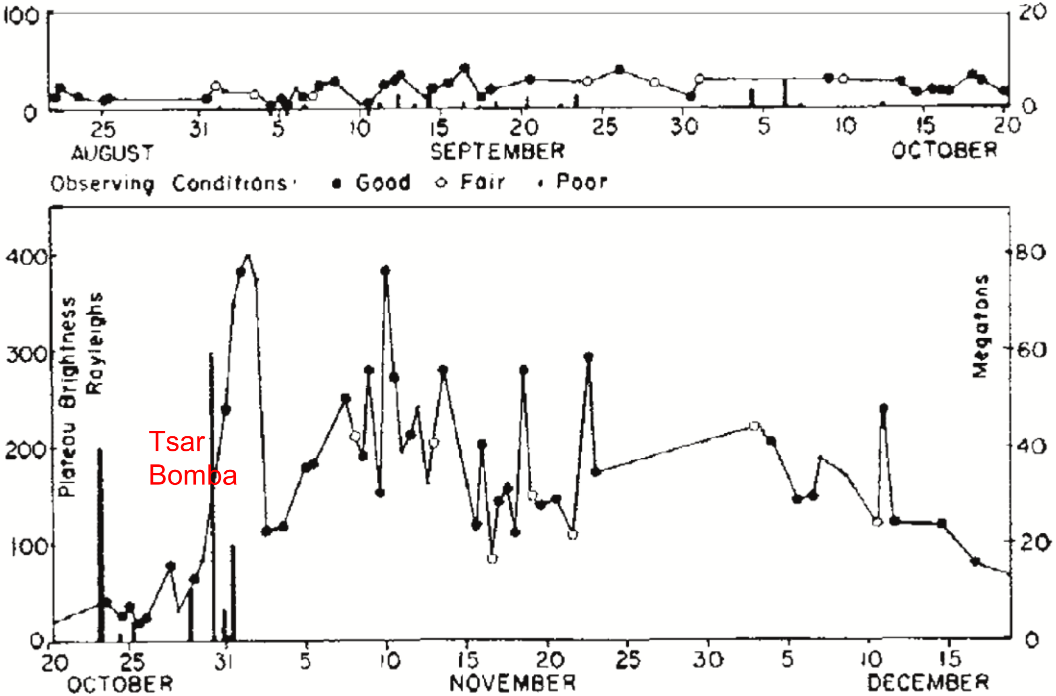
Langowski et al., *ACP*(2015)

- ➢ WACCM-metals simulates well the abundances of metals' neutral and ions (Note Mg MIF needs to be scaled in WACCM4 to match the measurements in our first simulation)
- ➢ Different seasonal behaviours seen in Na and K

Tsar Bomba: the most powerful nuclear weapon ever tested



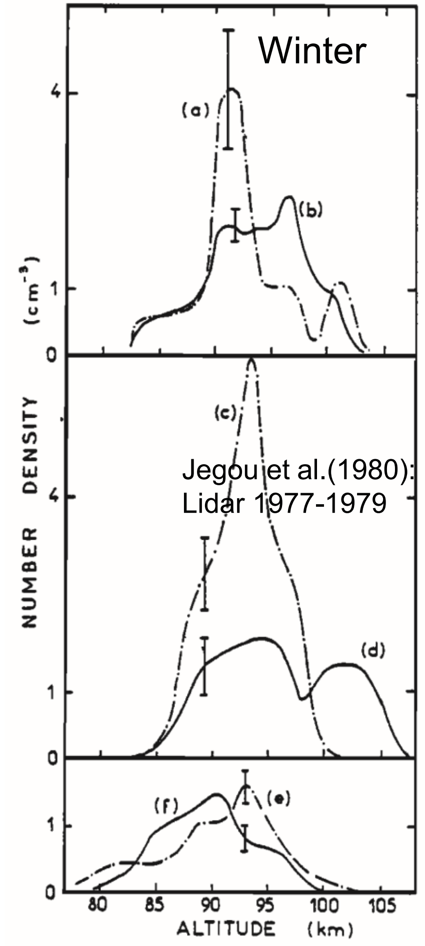
The mushroom cloud was about 67 km high, well inside the mesosphere when it peaked.

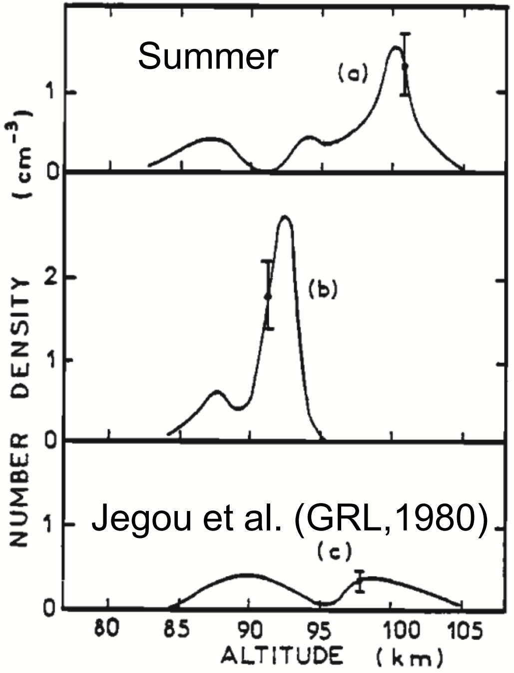


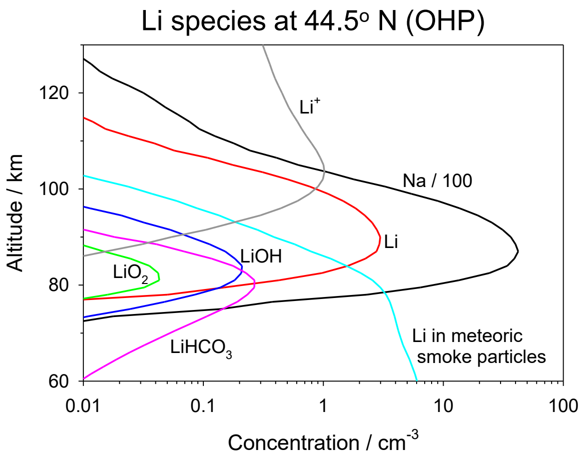
The Li column abundance increased after the major Soviet nuclear bomb tests in October 1961

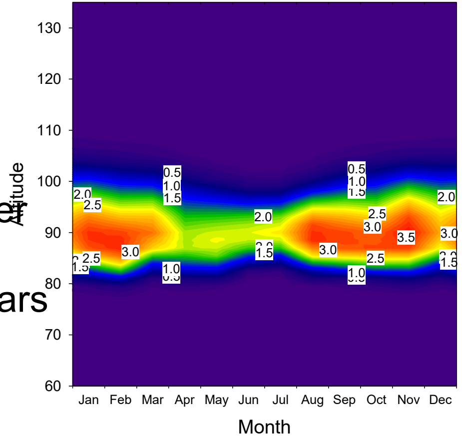
(Sullivan&Hunten, Nature, 1962)

Did the Tsar Bomba explosion Li enhancement?









The Nuclear Test Ban Treaty was signed in October 1963, and this ended testing in the atmosphere. The lidar measurements were made at least 14 years after testing ceased.

Li increase in October could be mostly natural!

Geophysical Research Letters
Research Letter | Open Access

New Li Lidar Observations and Model Simulations: A Window to Anthropogenic Signatures

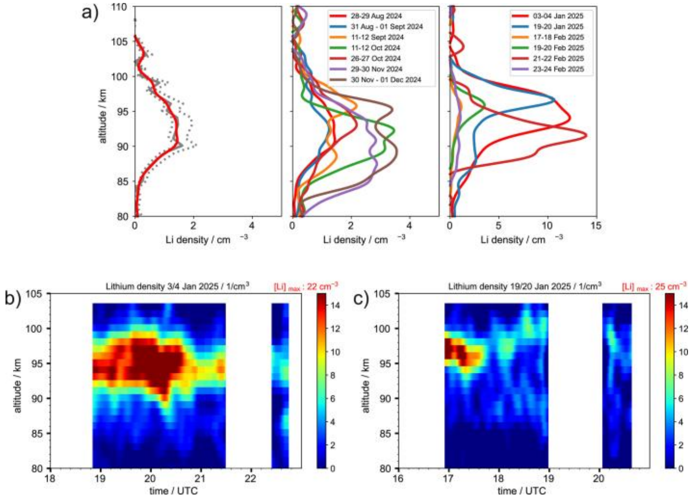
M. Gerding, R. Wing, W. Feng, J. M. C. Plane, G. Baumgarten

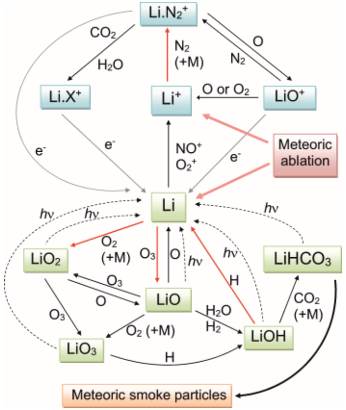
First published: 12 November 2025 | https://doi.org/10.1029/2025GL118710

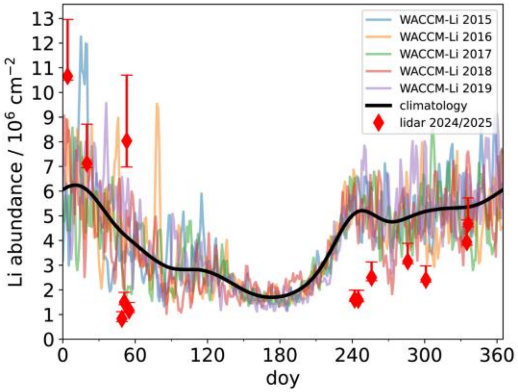
SECTIONS PDF TOOLS SHARE

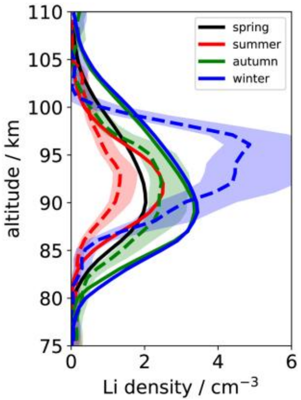
Abstract

We present Li lidar observations in the mesopause region above Kühlungsborn, Germany (54°N, 12°E). The lithium layer is mainly formed by meteoric ablation. But lithium has a much higher relative abundance in space debris compared with meteoroids, making it a good indicator of anthropogenic influence in the upper mesosphere. Our measurements reveal a strong seasonal increase in Li abundance between August and December 2024, growing from $\sim 1.6 \times 10^6$ to $4.7 \times 10^6\ \mathrm{cm}^{-2}$. These values are in reasonable agreement with the first simulations based on the Whole Atmosphere Community Climate Model (WACCM6) with a newly developed Li chemistry network; however, WACCM-Li does not explain high Li abundances of up to $10.7 \times 10^6\ \mathrm{cm}^{-2}$ observed in January/February 2025. This may be due to anthropogenic effects or an unidentified natural mechanism. This study highlights the potential of lithium observations for monitoring the consequences of re-entering space debris on the composition of the atmosphere.





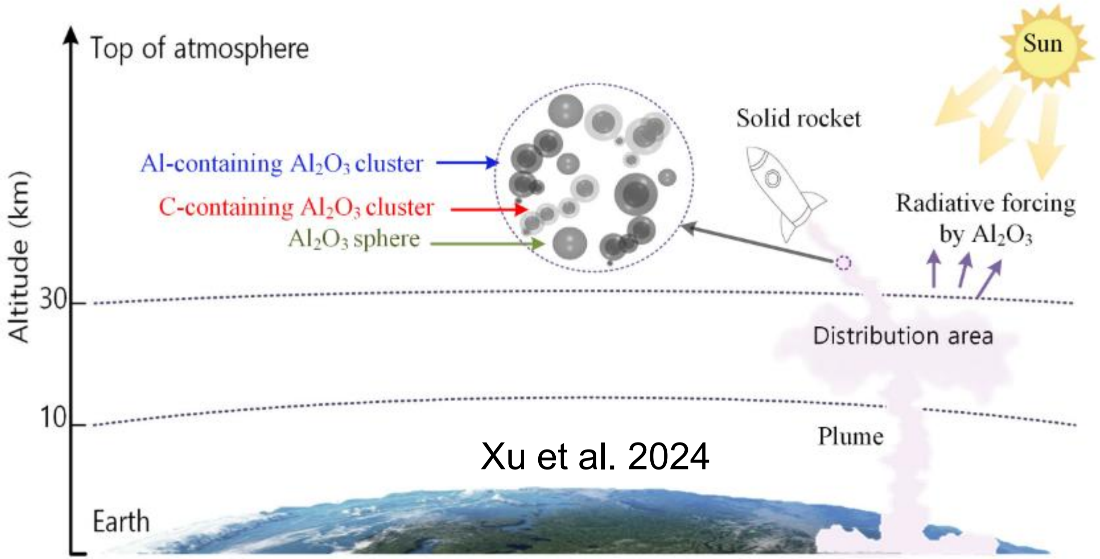




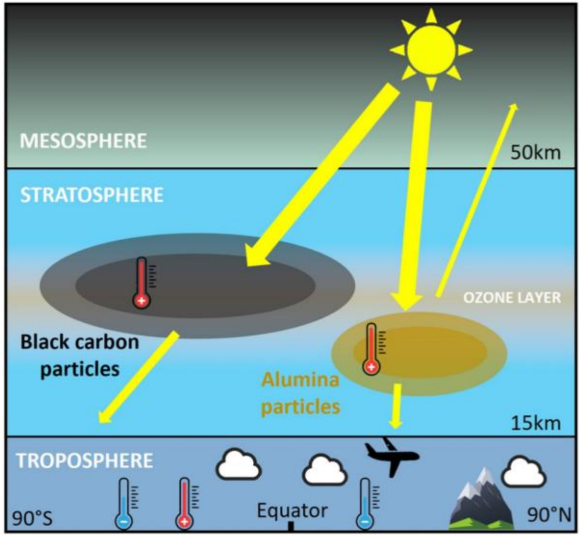
Many of the first Starlink satellites have already reached the end of their useful life. In January 2025 alone, 120 of them had lost enough altitude to fall into the atmosphere and burn up.

https://phys.org/news/2025-10-satellites-space-trash-threaten-ozone.html

Alumina



Xu et al. 2024



Miraux 2022

Al_2O_3 provide a surface for heterogeneous reactions.

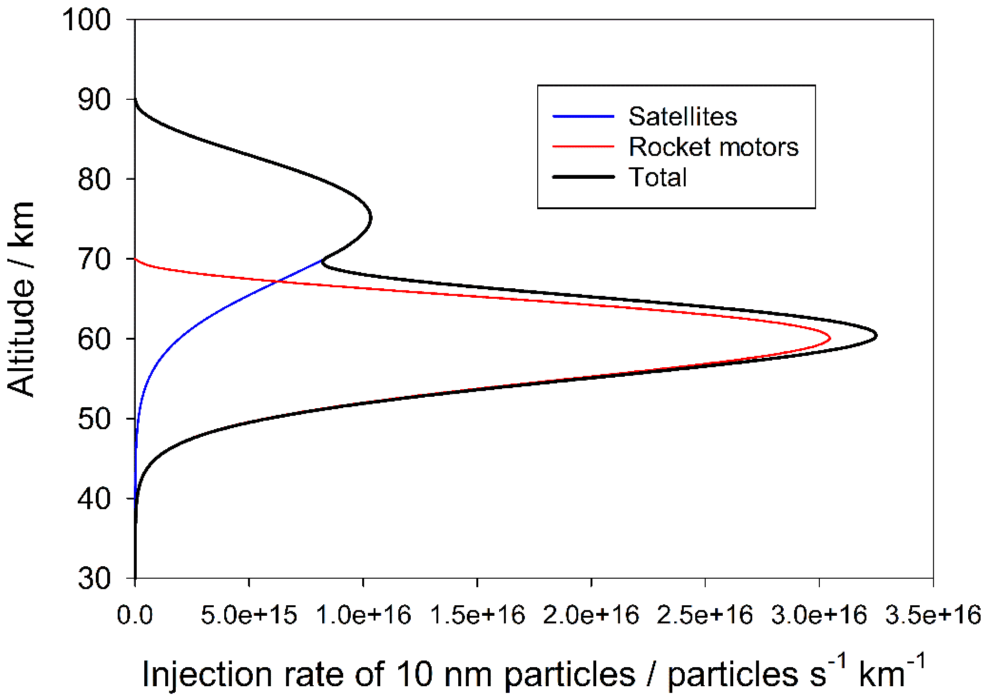
$ClONO_2(g) + HCl(s) \rightarrow Cl_2(g) + HNO_3(s)$

$HOCl + HCl \rightarrow H_2O + Cl_2$

leading to the formation of Cl_2, which subsequently contributes to the destruction of stratospheric ozone.

Molina et al. (*Geophys. Res. Lett., 1997)*

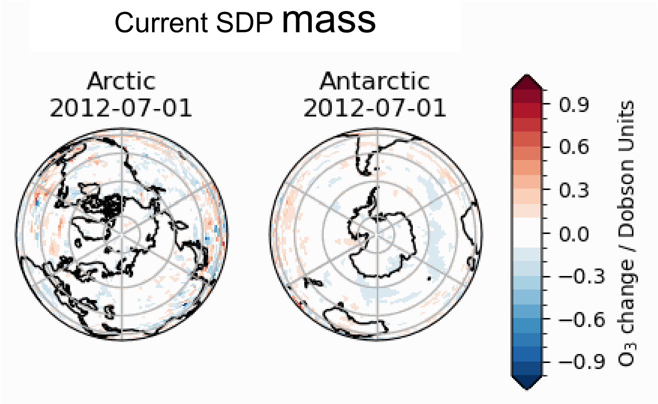
Aluminium from re-entering space debris: Space Debris Particles (SDPs)



Injection of 0.52 t d^{-1} satellites and 1.9 t d^{-1} sub-orbital rockets at 40 – 90 km between 40° – 80° N, 40° – 80° S

Bekki et al.(2021), Murphy et al. (PNAS, 2023); Plane et al. (2021), Schultz & Glassmeier (2021)

Cl chemistry on Space Debris particle surfaces causes O3 destruction



New Industry Initiative on Spacecraft Reentry&Atmospheric Impact

https://www.astroscale.com/en/news/astroscale-leads-new-industry-initiative-on-spacecraft-reentry-and-atmospheric-impact

A primary challenge in assessing the effects of re-entry emissions on the upper atmosphere is the scarcity of high-quality data required for robust modelling and evidence-based analysis

Aim to expand access to actual spacecraft data, reduce uncertainty in atmospheric modeling, and support evidence-based decision-making for the future of low Earth orbit

The Innovation

CellPress

Volume 6, Issue 8, 4 August 2025, 101012

Review

Dynamics, chemistry, and modeling studies in the aviation and aerospace transition zone

Zheng Sheng [1 6], Yang He [1 2 6], Sicheng Wang [1], Shujie Chang [3 4], Hongze Leng [1], Ju Wang [1], Jie Zhang [1], Ying Wang [1], Huanwei Zhang [1], Haoyang Sui [1], Yuyang Song [1], Gangyao Wu [1], Sheng Guo [1], Jing Chai [5], Wuhu Feng [4], Junqiang Song [1]

the atmospheric effects of spacecraft reentry remain an underexplored area of research.

making it difficult to directly measure or model. Furthermore, current simulations rely on simplified spacecraft assumptions due to limited availability of actual manufacturing data. Without access to real-world industry data, the results of advanced academic modeling may have limits on relevance and applicability.

Summary

- Studies of impacts of space launches/reentry on atmosphere are required.
- Thermosphere iodine of nanoSatellite I_2 propulsion system could destroy ozone depletion if there is no control in the Cubesat with solid I2 Propellant.
- The potential impact of chlorine needs to be considered when deciding on fuel usages for future rocket launches
- Lithium is a key component of space debris, which is made up of old satellites and rocket parts. Because of this, lithium is a good indicator of whether human activities are affecting the upper atmosphere
- Space launches, debris/reentry have been explored but many unknown/assumptions

Key Research Outcomes, challenges and Opportunities

Geophysical Research Letters

Research Letter | Open Access

Potential Stratospheric Ozone Depletion Due To Iodine Injection From Small Satellites

Wuhu Feng, John M. C. Plane, Martyn P. Chipperfield, Alfonso Saiz-Lopez, Jean-Paul Booth

First published: 10 April 2023 | https://doi.org/10.1029/2022GL102300 | VIEW METRICS

Could have unintended consequence to destroy ozone (*Nature, 2023*)

Articles / Volume 26, issue 5 / ACP, 26, 3621–3635, 2026

https://doi.org/10.5194/acp-26-3621-2026

Article | Assets

Research article |

The impact of rocket-emitted chlorine on stratospheric ozone

Yuwen Li, Wuhu Feng, John M. C. Plane, Tijian Wang, and Martyn P. Chipperfield

- Small but offset some of the gains of the Montreal Protocol

Geophysical Research Letters

Research Letter | Open Access

New Li Lidar Observations and Model Simulations: A Window to Anthropogenic Signatures

M. Gerding, R. Wing, W. Feng, J. M. C. Plane, G. Baumgarten

- Li enhancement during reentry
- Model failed: missed ablation source

Big challenges:

- Types of Propellants
- fuels (gas and particles),
- Emissions Uncertainties,
- Location/timing of rocket launches,
- Rocket Trajectory,
- Combustion chemistry,
- rocket/satellite reentry/ablations,
- Complex coupling systems across different scales….

Opportunities

Expand National Capability

Using: *TOMCAT/SLIMCAT/GLOMAP, UKCA/UKESM, CESM on national ARCHER2&Leeds AIRE*

Leeds@NCAS development: Ablation and chemistry/aerosol/models

International Collaborations: *ESA/UK Space Agency…..*

Continue Active research: Department for Transport, ESA IDEAS, NERC-DTP (2024-27), YES-DTN (2025-28), EU SLICE (2026-29)….