The future chemistry and climate impacts of large, fully-reusable methane-fueled rockets

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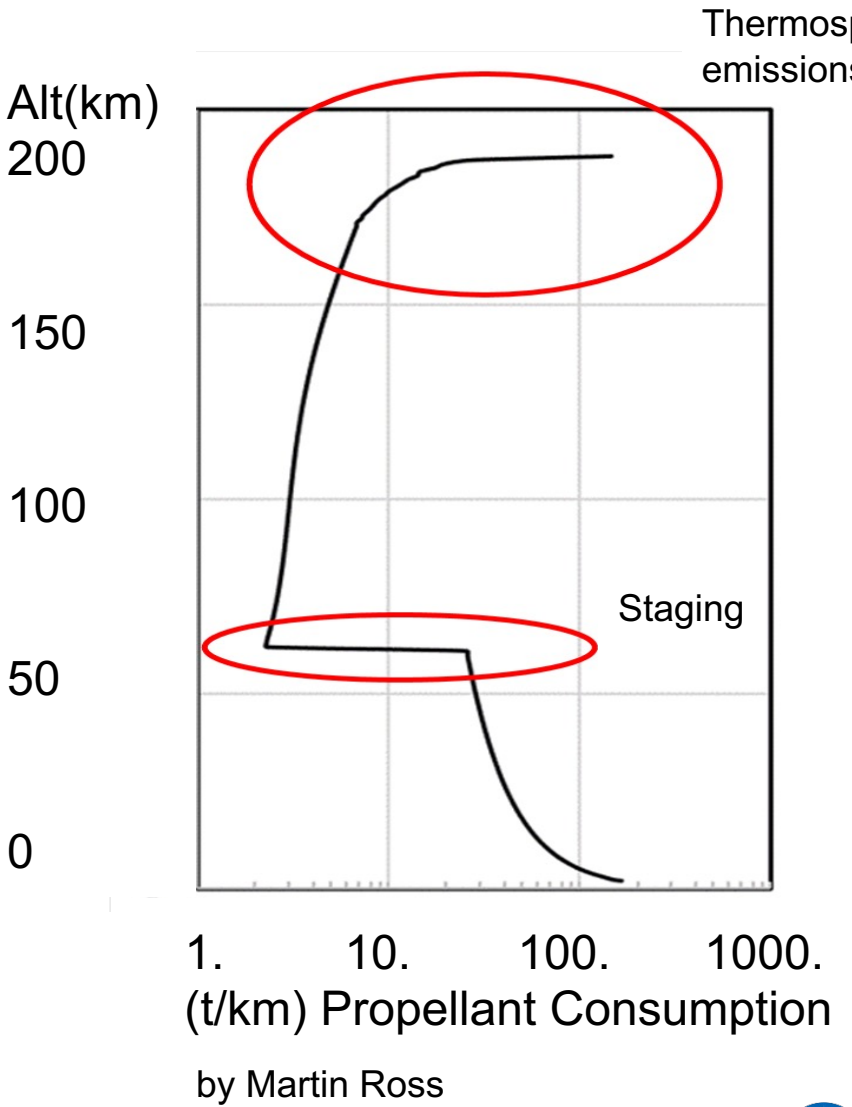
Special thanks to Martin Ross
(Aerospace Corp)

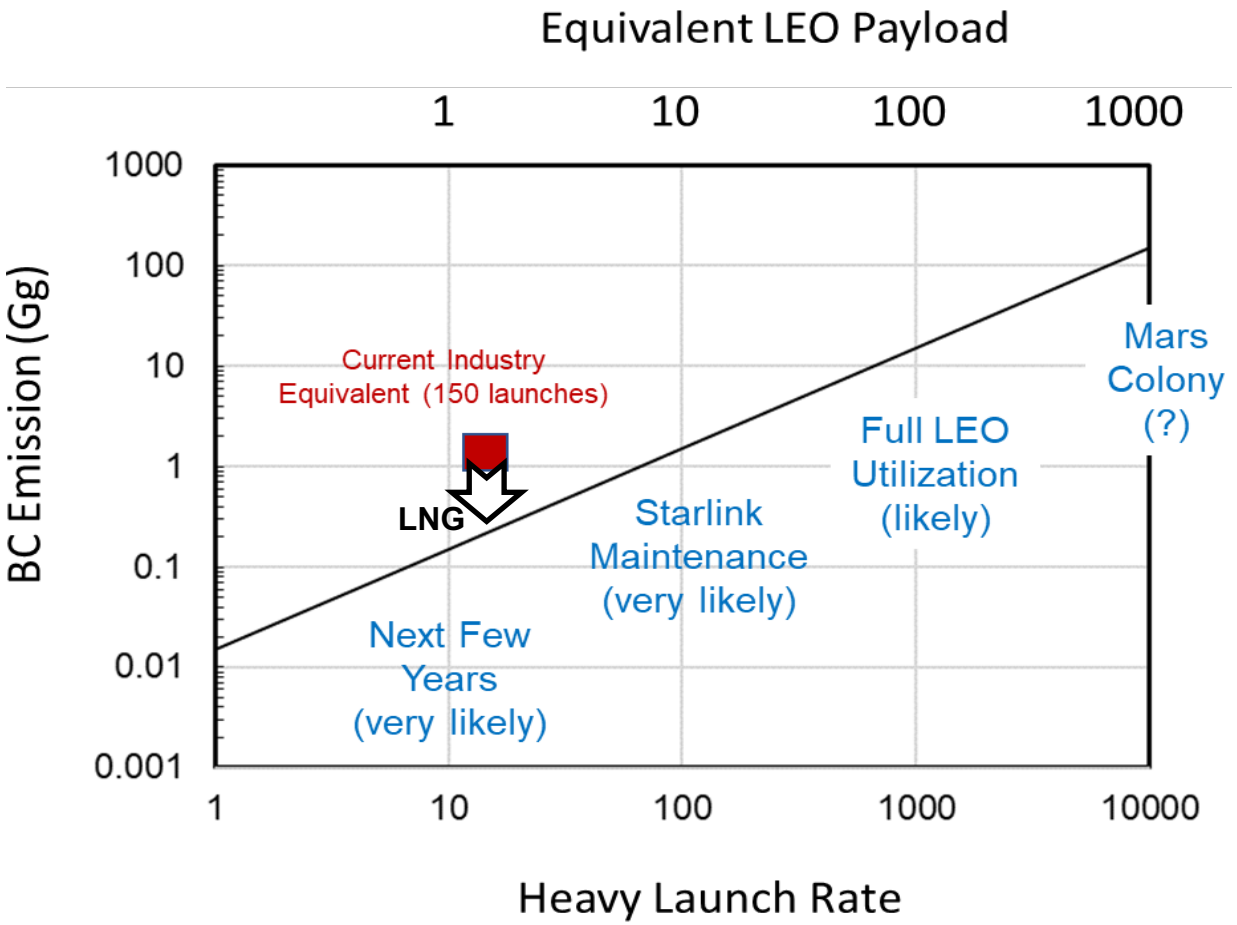
Rocket launch emissions

- Propellants
  - Present: solid, kerosene, hydrogen, hydrazine.
  - Current-Future: liquefied natural gas (LNG; mostly CH_4).
- Burning: one or two stages, increasingly include re-entry.
- Emission: BC, CO, NO_x, H_2O, CO_2
- 188 km circular orbit (100 t payload).
- 22% of propellant consumed > 80 km.
- Total BC emission into middle atmosphere is not a strong function of afterburning details.

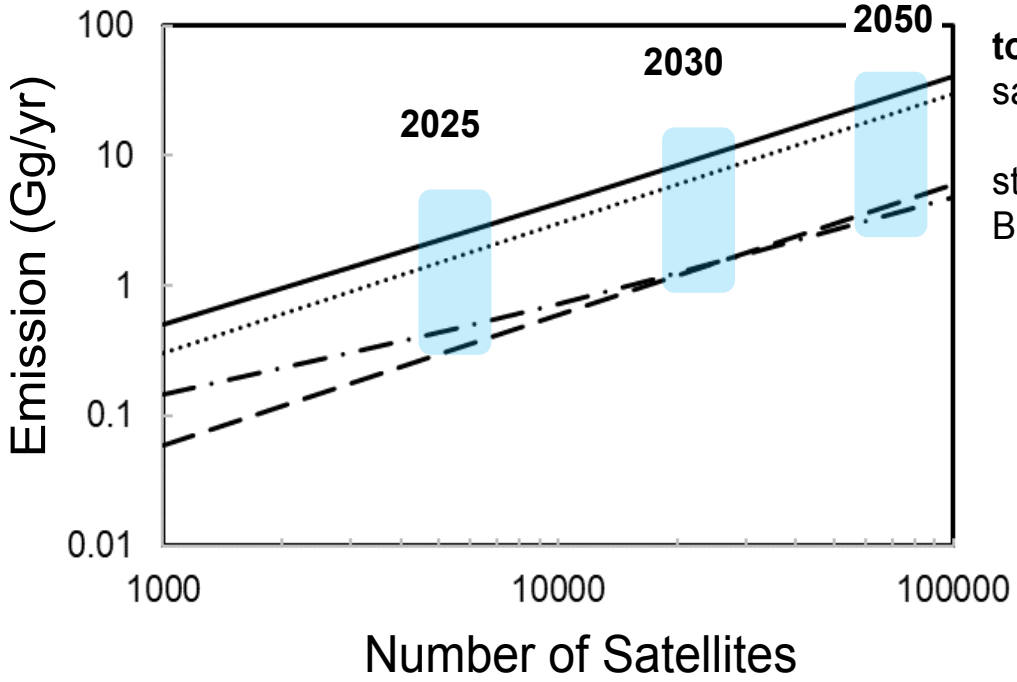


by Martin Ross

BC emissions from rocket launches



Launch Emission Scenarios: Large LEO Constellation



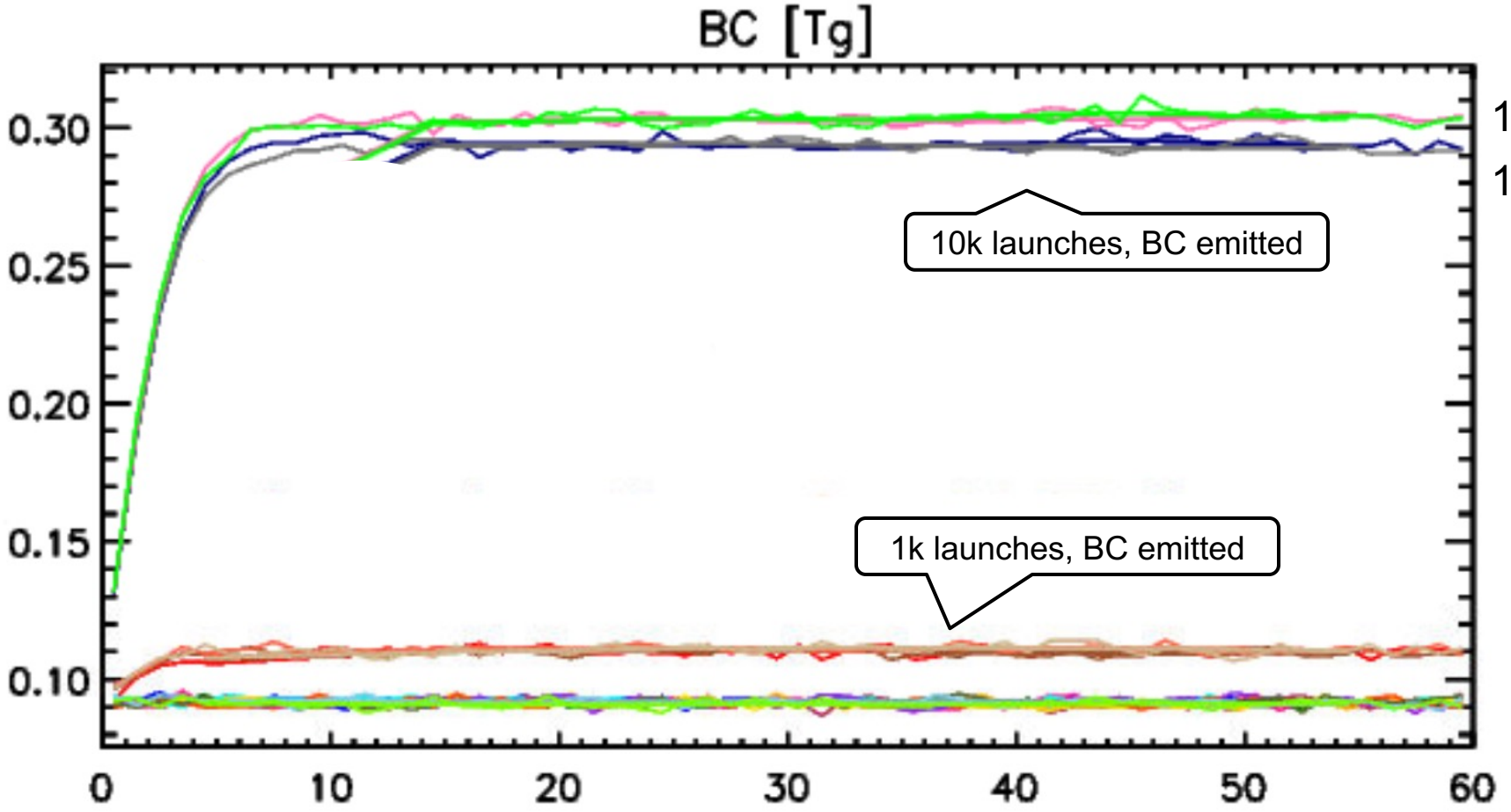
(1) 2025 is assured since the satellites have already been built
(2) 2030 is very likely since the satellites have US regulatory approval
(3) 2050 includes planned non-US constellations

Experimental setup

- GISS ModelE Earth system model (E2.1), using fully interactive gas and aerosol microphysical modules.
- Year 2050, following SSP2-4.5.
- 2045-2055 climatological mean ocean.
- GHGs and emissions from 2050.
- Model top at 0.1 hPa (~65 km).

- Simulations (20 plus control):
  - 10 years of spin up, 50 years for analysis
  - 2 locations (Cape Canaveral, FL, USA; Māhia, New Zealand)
  - 2 launch scenarios (1k and 10k launches per year)
  - 5 emission scenarios (BC, CO, NO_x, water, all at once)

Global Mean BC Load time series over 60-year long simulation:



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Emissions (year 2050, SSP2-4.5) [Tg a^{-1}]

	Anthropogenic	Biomass burning	Aircraft	1k launches	10k launches
BC	4.8	1.5	0.016	0.0084	0.084
CO	445	285	1.0	0.020	0.20
NO_x	30	5.5	2.0	0.013	0.14
Water	0.0	0.0	0.0	1.7	18

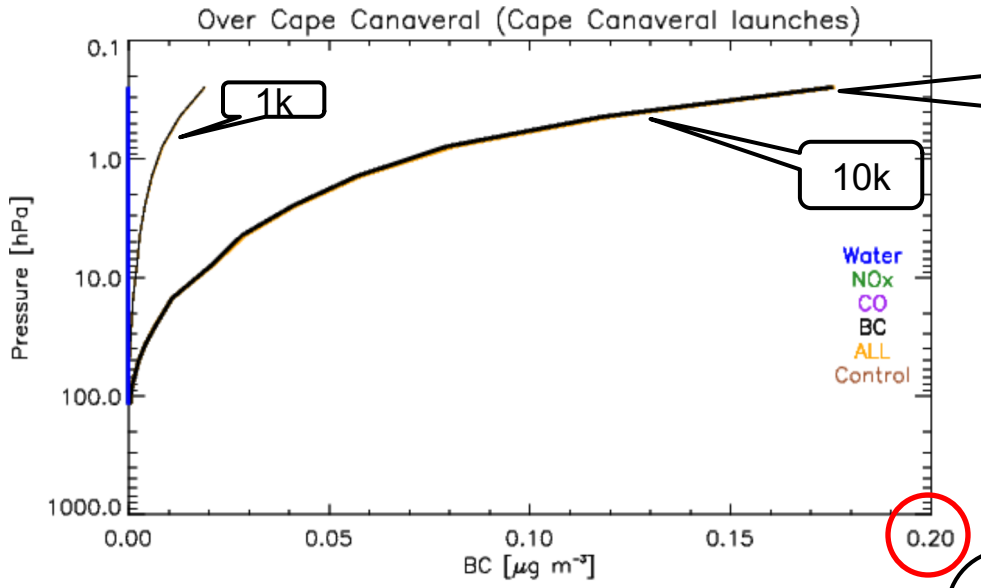
- BC emissions from aircraft and rockets comparable in magnitude.
- CO from CH_4 oxidation (control): 1031.
- NO_x from lightning (control): 8.3; from soil (fixed): 2.7.
- Water from CH_4 oxidation (control): 663.
- Water from Hunga Tonga-Hunga Ha'apai eruption: 100-150 (in 6 hours!).

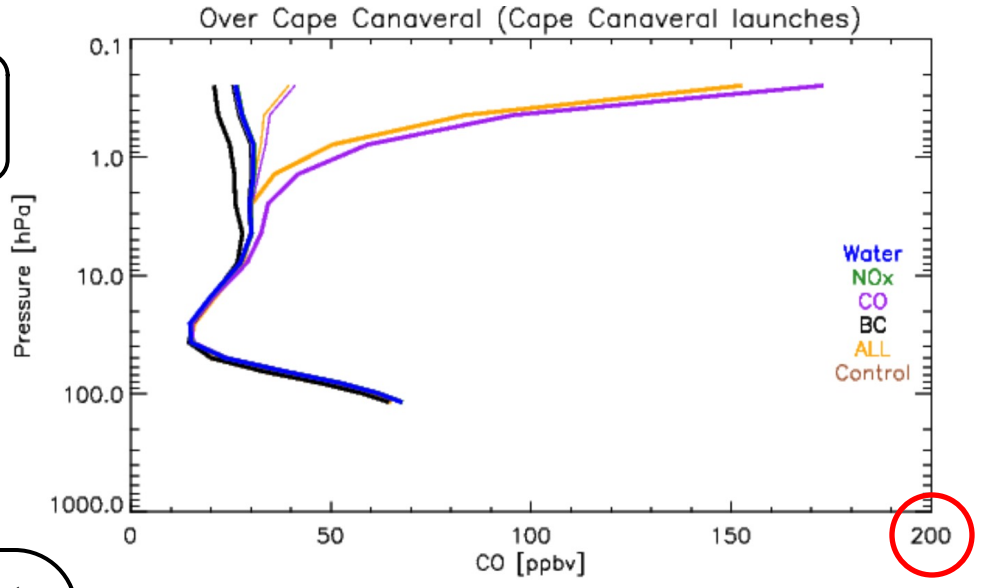
BC

CO

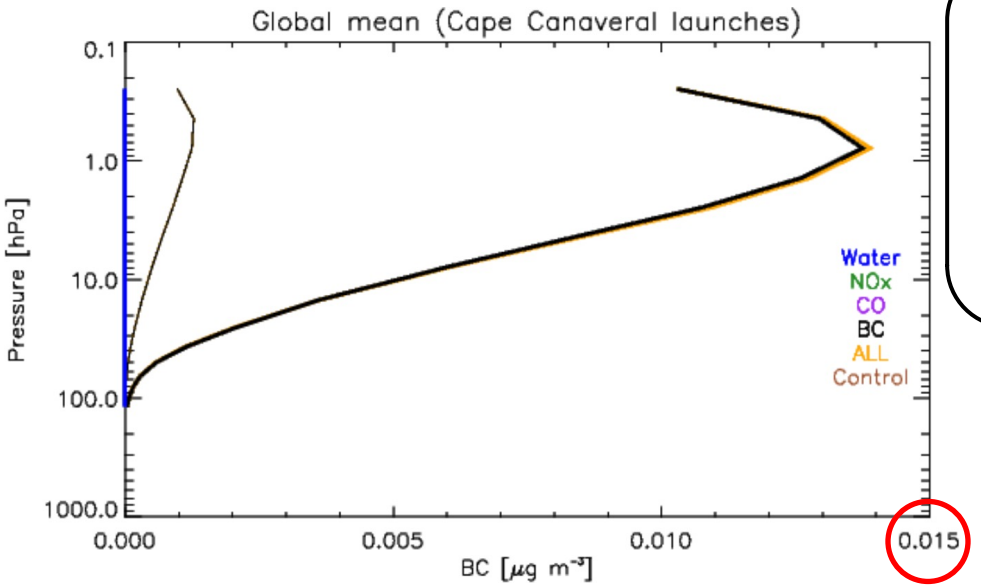
Over launch site

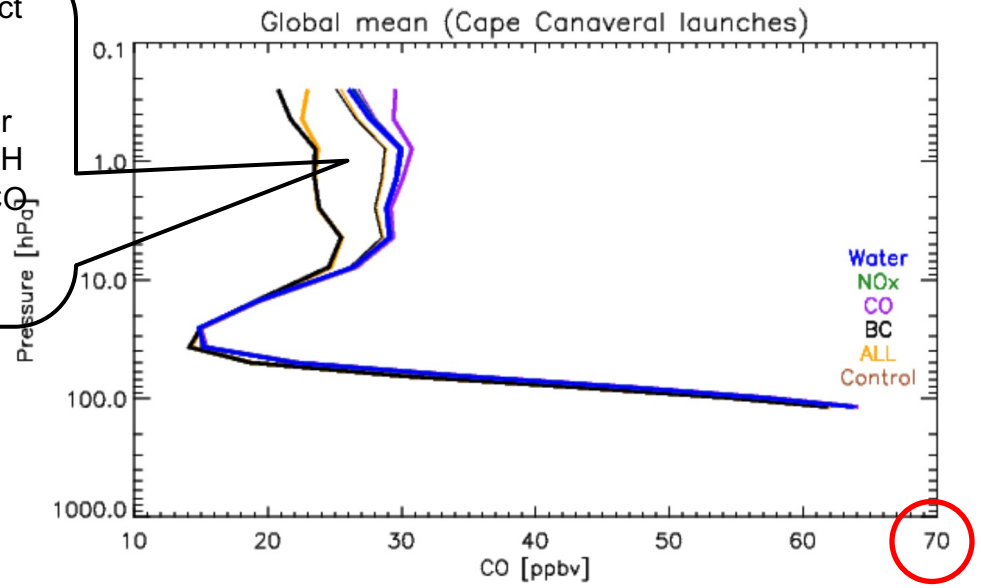
Global mean





BC and **ALL** on top of each other





BC emission impact on CO

BC changes water which increases OH which consumes CO faster.

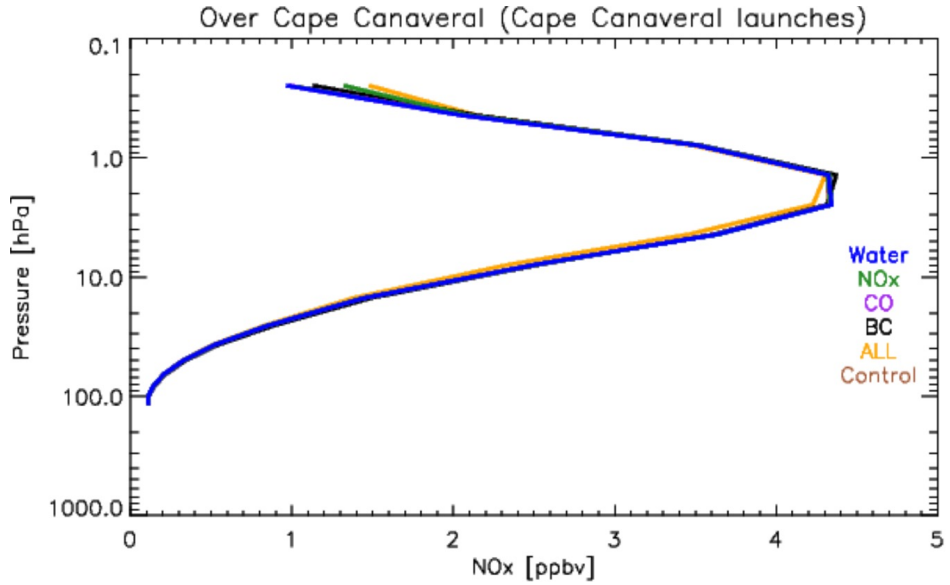
Thin/thick lines: 1k/10k launches

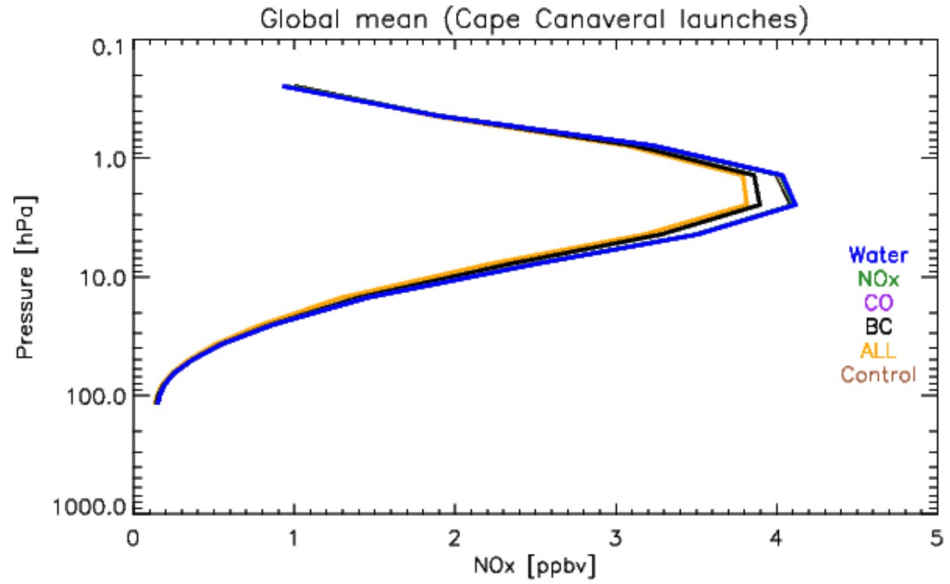
NO_x

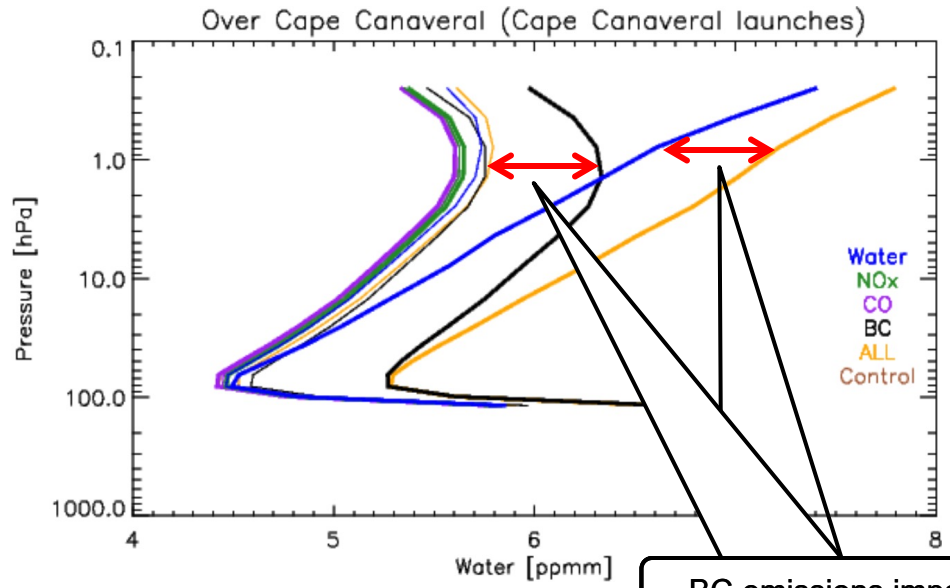
Water

Over launch site

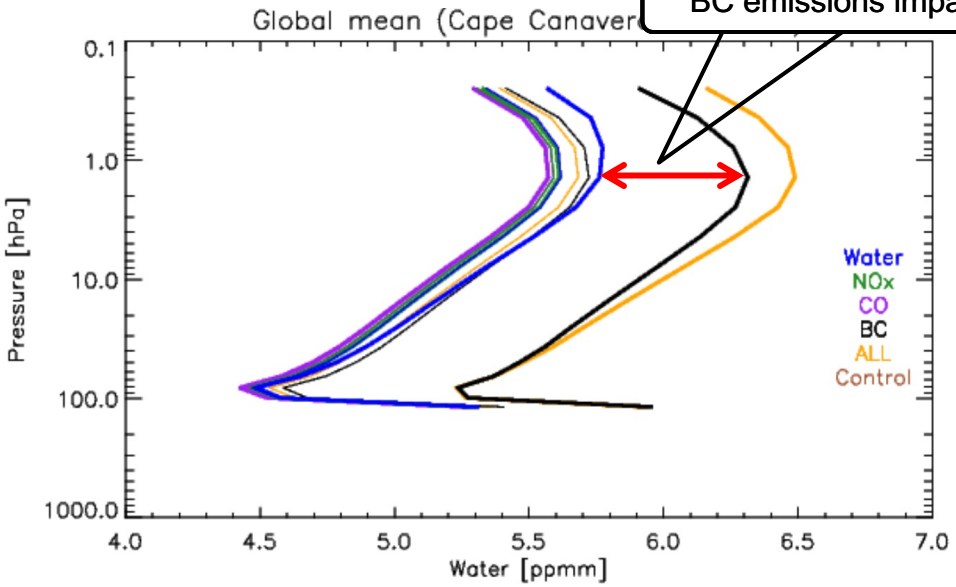
Global mean







BC emissions impact water



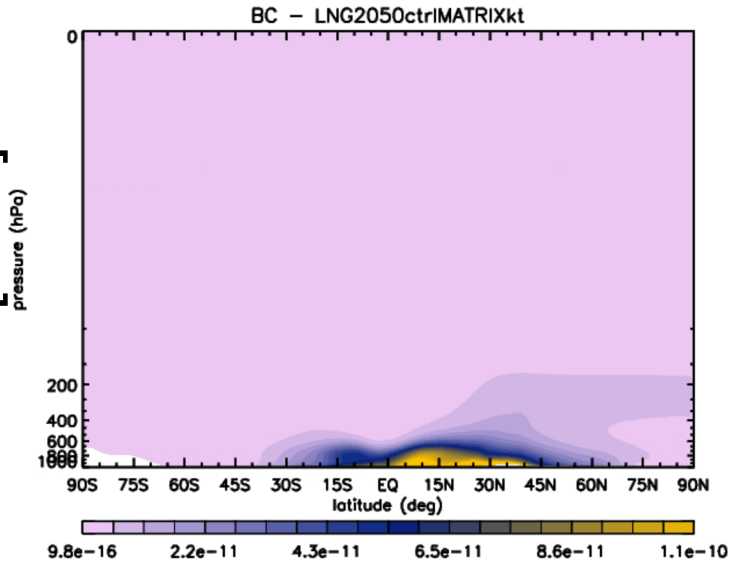
Control

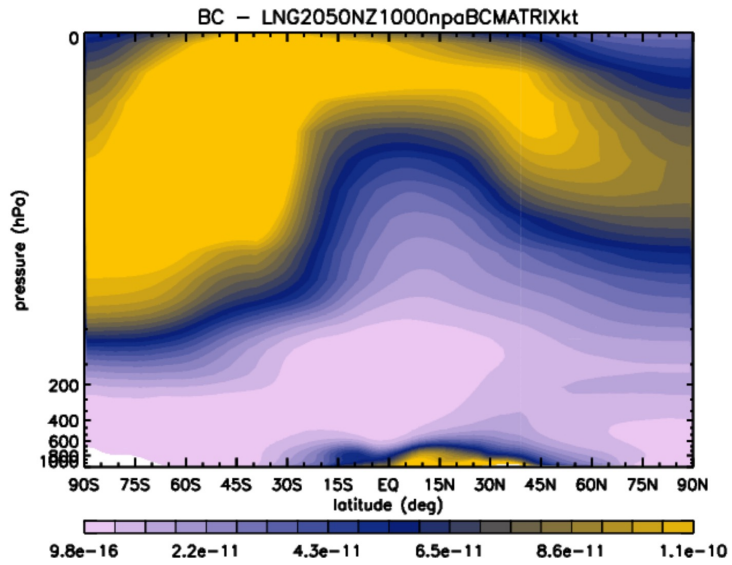
Māhia(NZ)

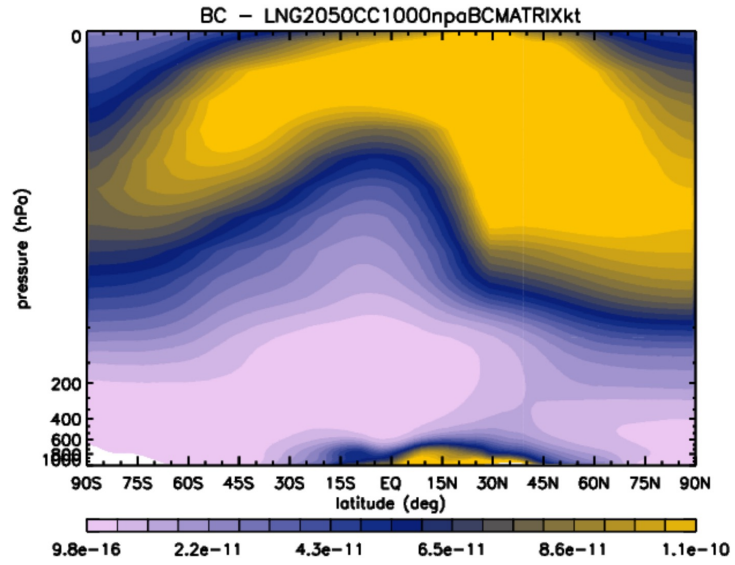
Cape Canaveral

BC [mmr]

1k launches

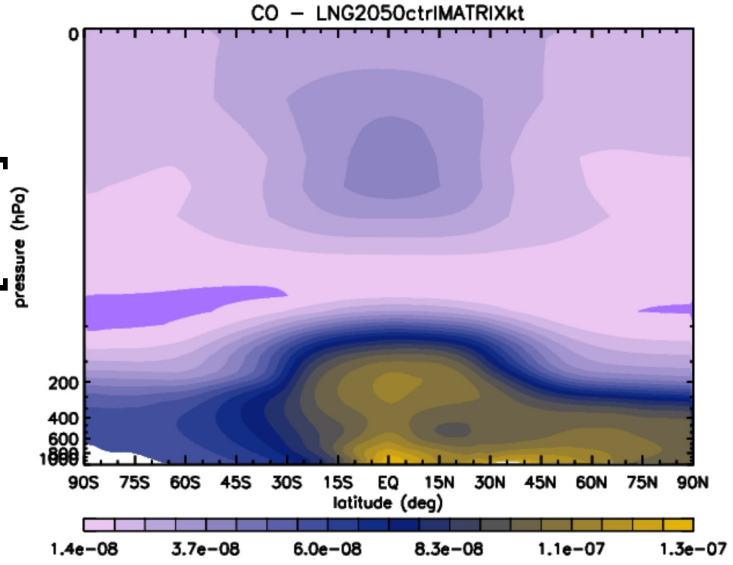


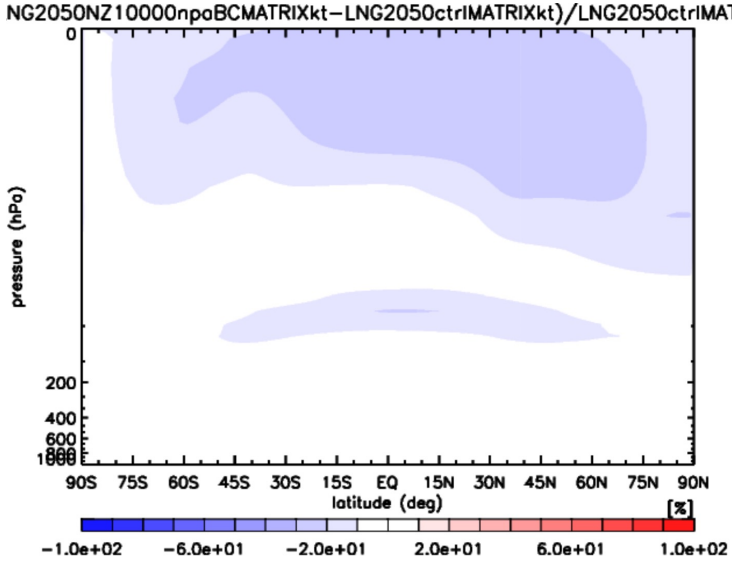


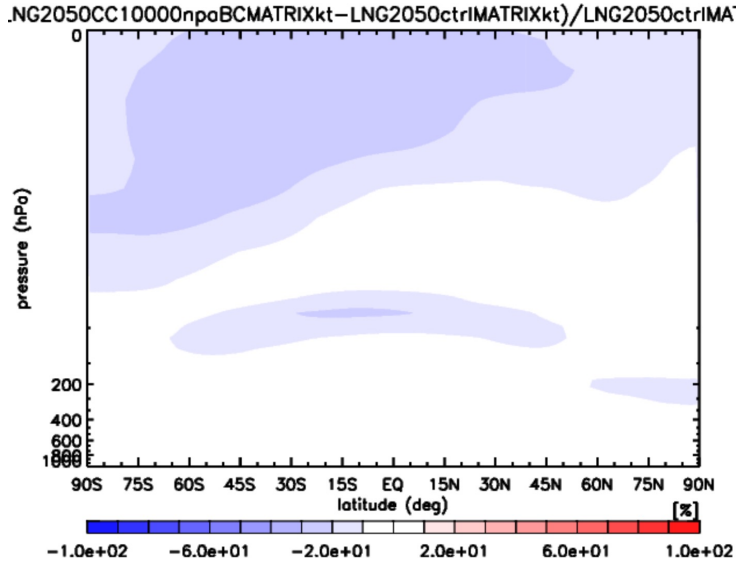


CO [vmr]

10k launches







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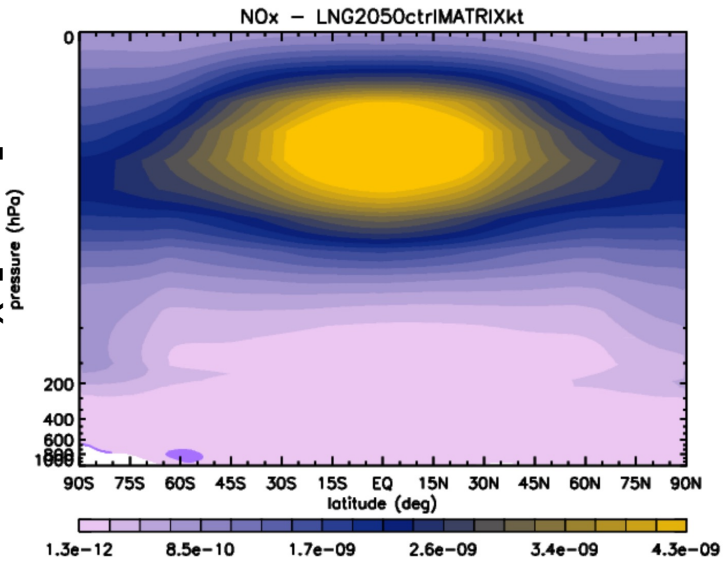
Control

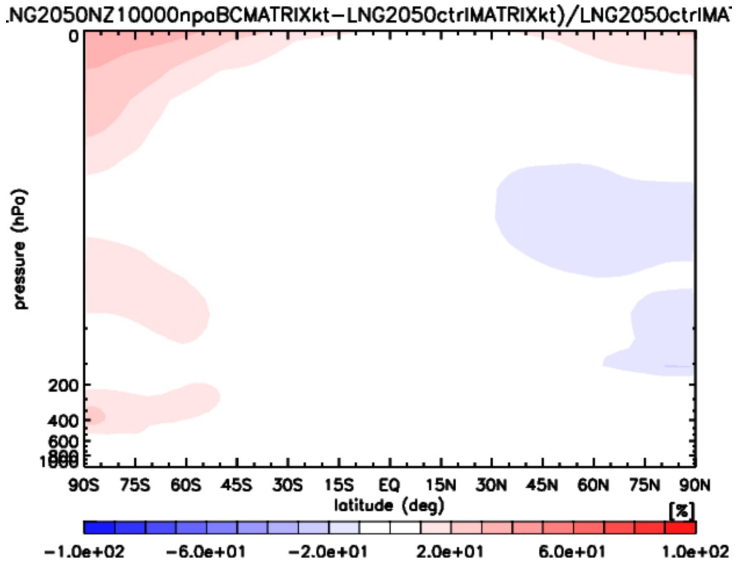
Māhia (NZ)

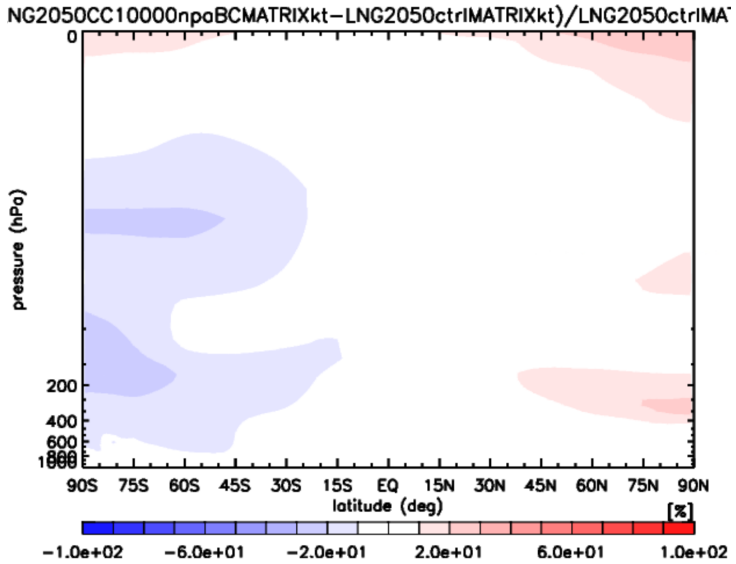
Cape Canaveral

NO_x [vmr]

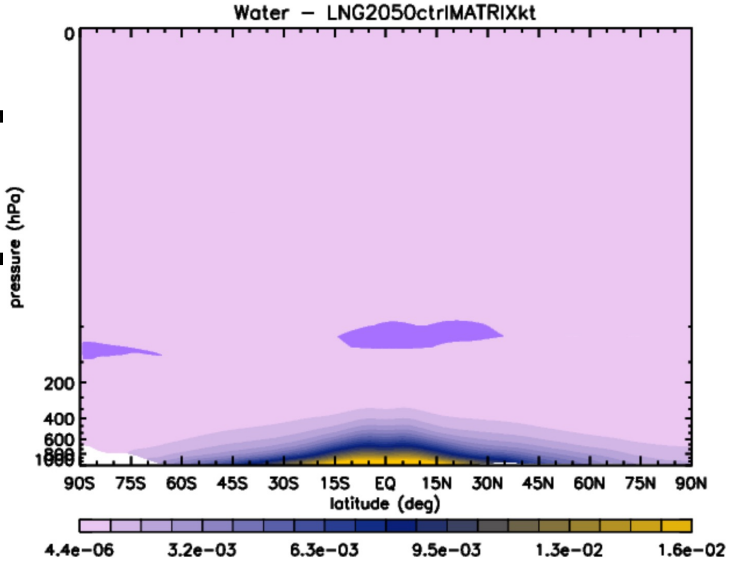


10k launches

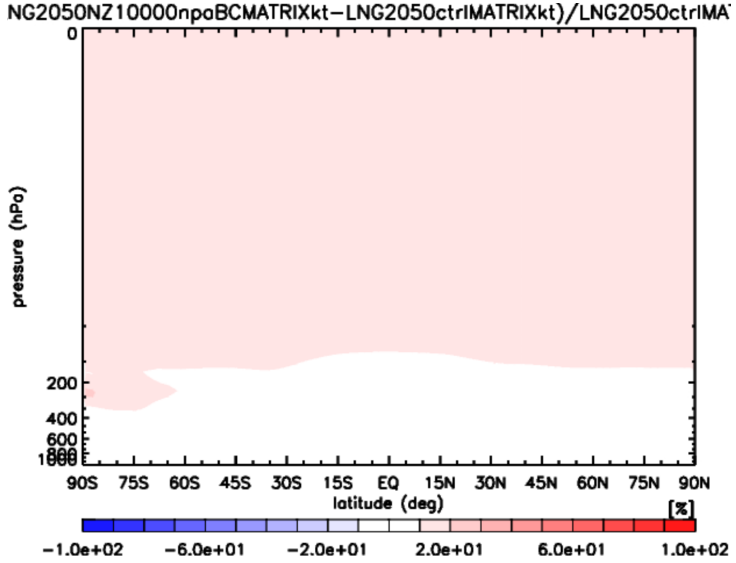


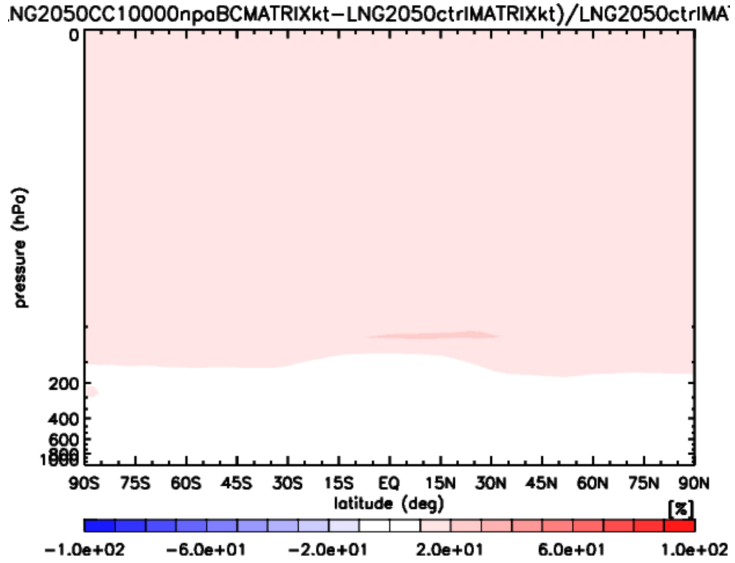


Water [mmr]



10k launches





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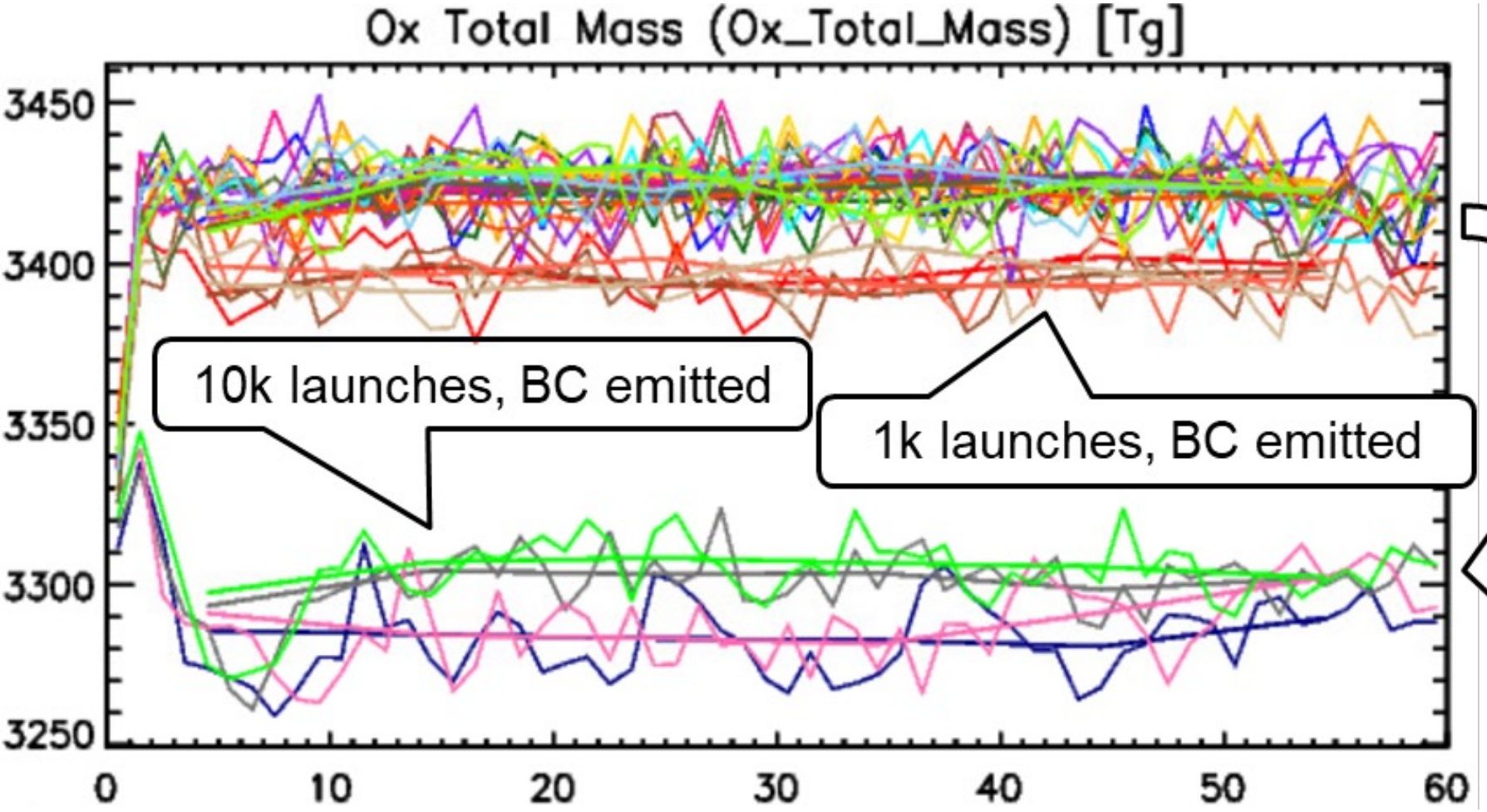
Ozone impacts caused by BC and water

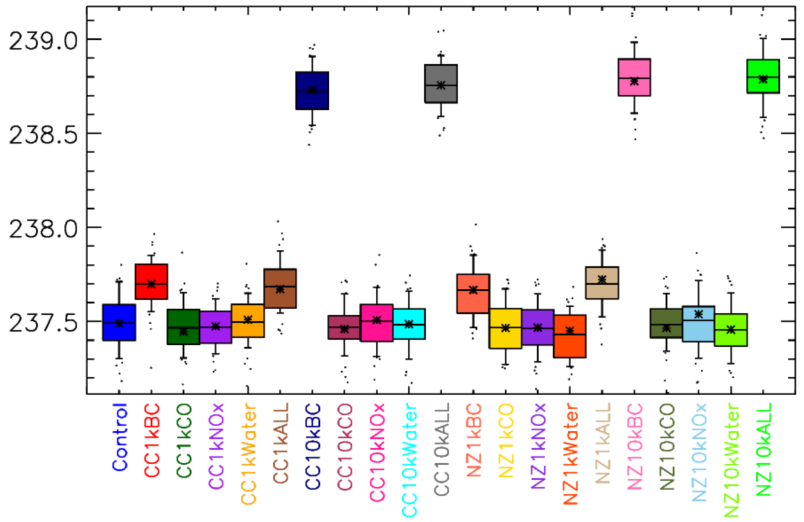


- BC heating weakens tropopause cold trap, allowing water to “leak” into the stratosphere.
- The change of chemistry induced by enhanced water amounts destroys O_3.
- Water injection alone not enough to have a large effect.

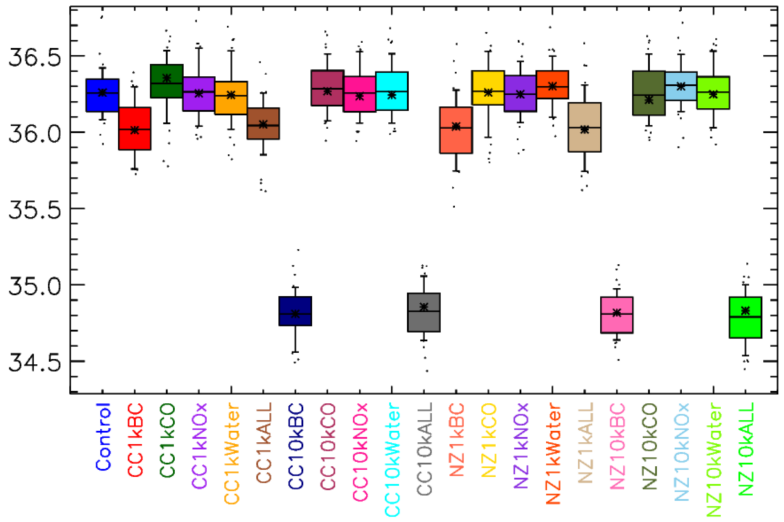
Ozone response is subject of further analysis!

Climate impacts

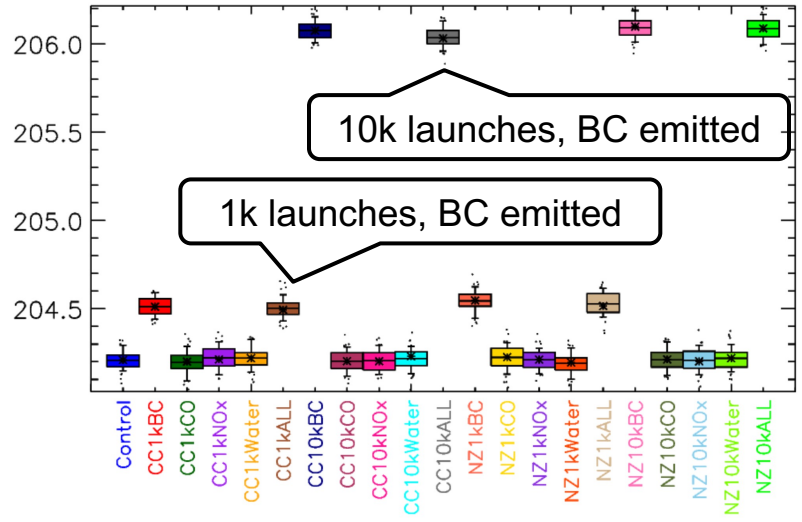
Net solar radiation fluxes (TOA) [W m^{-2}]



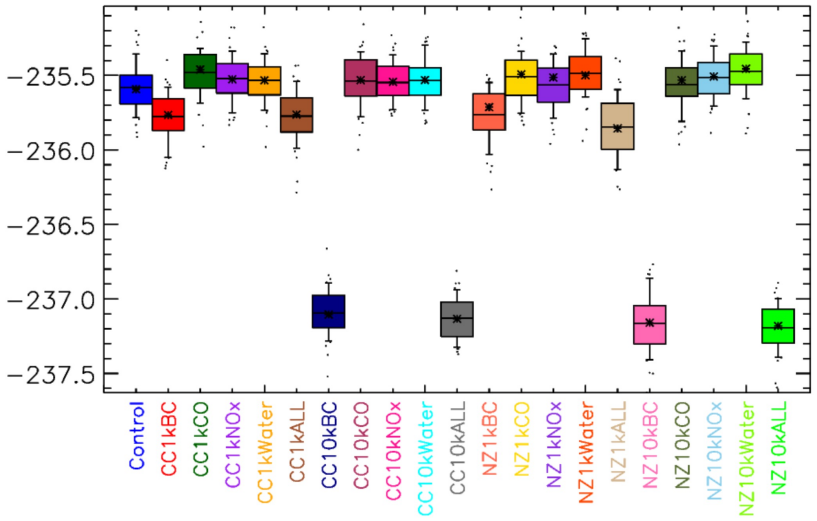
High clouds fraction [%]



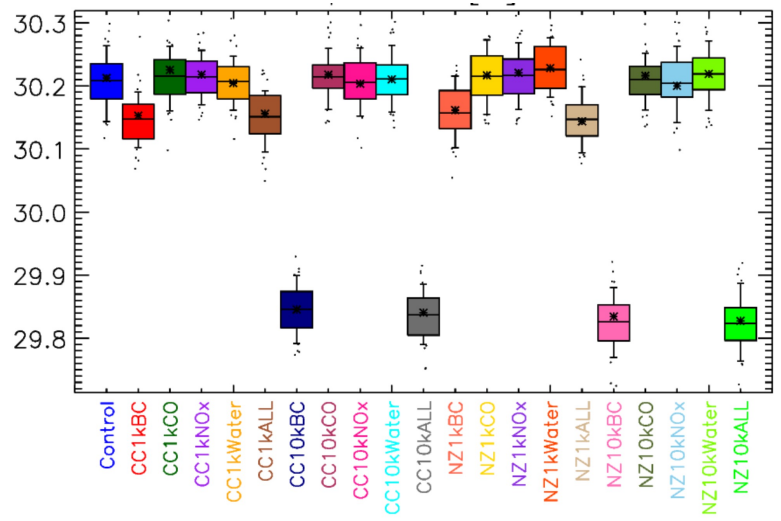
Tropopause temperature [K]



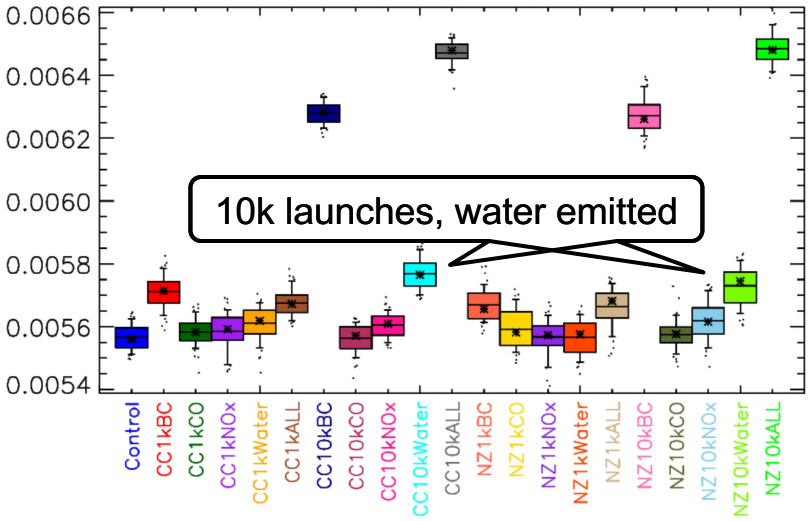
Net thermal radiation fluxes (TOA) [W m^{-2}]



Planetary albedo [%]



Specific humidity at 1 mb [g kg^{-1}]



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Conclusion and steps forward

Conclusions:

- Global atmospheric and coupled models can be successfully used to estimate environmental impacts of rocket launches.
- Initial results suggest that the biggest impacts will be related to Black Carbon (even for LNG fuels) Launch impacts on stratospheric temperatures, ozone, and high cirrus clouds are clear at 1000/yr, and very large @ 10k/yr see *Tsigaridis et al (2023, doi: 10.2514/6.2024-2168)*

Observational and modeling needs:

- Plume chemistry is not resolved in global models, needs parameterization (in situ obs and high-resolution modeling)
- In-situ observations for aerosol composition, mixing state, particle size distribution
- Transient scenarios based on actual plans

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