Atmospheric impacts of space industry require oversight

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As the rapid growth of space activity continues, gases, and particulates from rocket exhaust and debris re-entering from orbit are being injected into all layers of the atmosphere[1,2,3], with potentially substantial detrimental effects on the environment (Figure 1). While air-quality legislation and the Montreal Protocol[4] provide some formal protection for the troposphere and stratosphere, there is no equivalent for the outer layers of the Earth's atmosphere where the negative impacts from these emissions are likely severe[5]. Important knowledge gaps also remain regarding the atmospheric impacts of rockets [6], and how anthropogenic debris is altering atmospheric chemistry, especially considering this ozone-modulating debris re-entry could soon equal natural meteoroid debris[3]. Despite these challenges, space activity contributes a growing array of societal benefits, including, somewhat paradoxically, the satellites critical to observing and understanding Earth's climate. The growing scale and pace of these space activities may lead to new unforeseen impacts on the environment and climate. Focused research is required now to build the policy and legal frameworks necessary to support a successful and more environmentally sustainable space industry.

The global space industry is estimated to be annually worth $350 billion and expected to reach more than $1 trillion by 2040[7]. The industry has a heavy reliance on rockets; and the launch rate is likely to quadruple within the next four years[1] as agencies and companies including SpaceX, Blue Origin, and Virgin Galactic look to serve exploration, tourism, and satellite markets. These activities are now actively influencing all layers of the global atmosphere; and while these impacts are likely to increase with time, the consequences for global climate and weather are largely unknown. The rapid development cycles of new space technology illustrates the need to act now to ensure space activities become more environmentally sustainable. It also suggests that industry is well-placed to quickly adapt and reinforce these efforts.

The exponential increase in rocket launches that we are already witnessing[1], along with the re-entry of a growing amount orbital debris[3], can have a range of negative impacts on the chemistry of the atmosphere. Rocket combustion releases black carbon, aluminium, carbon dioxide, and reactive gases like chlorine and nitrogen oxides into the global atmosphere[2], influencing the radiative balance throughout. This includes the injection of ozone-destroying compounds directly in to the ozone layer[2], where even small amounts can have an outsized impact and future levels associated with increased launches could exceed acceptable environmental limits[8]. Furthermore, black carbon emissions associated with the expected increase in rocket launches could cause north polar surface temperatures to increase by 1°C [5] and contribute to further sea ice loss.

Another side effect of the success of the space industry are the now 9300 metric tonnes of human-made objects orbiting Earth[9], of which only <5% are likely functioning[10]. Destruction in the atmosphere following orbital decay is the only effective mechanism for eliminating this debris[10], a process that results in a proliferation of fine metal particles and contaminants as these objects burn up. The resulting re-entry shock wave also creates nitrogen oxides, with peak emissions occurring in the mesosphere, that are directly transported into the stratosphere at the poles where they modify ozone levels[11,12].

Reduction in satellite costs have furthermore led to the development of large satellite constellations that, once complete, will result in a constant flow of de-orbiting debris as craft die and are replaced. This debris could double the annual injection of aerosol particle mass into the mesosphere [3] and increase the amount of aluminium particles[3,13] that can reach the stratosphere where they encourage ozone loss[14]. Constellations consisting of 110,000 satellites have been proposed[3] and the resulting atmospheric aluminium input could be considered an uncontrolled geo-engineering experiment[13].

Rocket emissions could exacerbate debris accumulation

Collectively, current space activities have the potential to damage the ozone layer[1,2,3,13,14,15], enhance climate change[5] and accidentally create geo-engineering experiments[13] (Figure 1). But space activities could also negatively interact with each other in unexpected ways. Rocket greenhouse gas emissions are only a few percent of annual global tropospheric emissions[1,2], but carbon dioxide injected into the thermosphere acts as a primary radiative cooling agent, which in turn could lead to atmospheric contraction and a reduction in the drag on orbiting objects[16]. Future rocket emissions could therefore drive a cooling trend in the lower thermosphere reducing the de-orbiting of debris, slowing clearance and increasing accumulation. There is now a need for focused research on the combined impacts of rockets and deorbiting debris on all atmospheric layers.

The way towards environmentally sustainable exploration

The success of the space industry has provided unprecedented advances in our ability to observe the Earth's environment and this should be embraced and fully exploited. But space policy is needed to guide industry towards considering the wider implications of expanding activities, and to minimise their impact whilst maximising data collection that could soon be required for more detailed evidence-based policy oversight. Clearly any such data must be shared, or made publicly available, as data siloed within individual companies are unlikely to be useful to meet these aims. It is imperative that policy-makers, researchers and industry work together to ensure environmentally sustainable exploitation. But we must act now to avoid a situation similar to that of plastic pollution in the oceans, where the issue was identified 50 years too late, resulting in rushed policy response and the discovery of entrenched impacts to human life and the environment. A similar situation in space could negatively limit the long-term viability of the industry and remedial approaches may not even be feasible.

A review and analysis is needed to identify the magnitude of space industry emissions into the global atmosphere and to identify the opportunities for scientific advancement in the understanding of the global atmosphere that can be enabled by industry. The first assessment of the space industry emissions (1957-present) into the global atmosphere from rocket launches and debris can be calculated through exploiting existing historical data and engine burn profiles. Some of this work has begun (e.g. [2,17]) but progress is hindered by a lack of data on relevant launch vehicles and satellite content. Industry will need to begin collecting standard measurements during launches (eg emissions from launch vehicles) to support and enable these efforts with, in particular, a focus on the novel fuel types being tested; and such measurements may highlight easy opportunities to reduce particularly harmful emissions. These data combined with existing modeling frameworks (eg Whole Atmosphere Community Climate Model eXtension as used by Cnossen[18]) will allow the current extent of anthropogenic influence to be identified.

Novel ways of using satellites to quantify the inputs of historical and contemporary space activities (Figure 2) may be possible to immediately begin characterising the magnitude of space industry emissions into the global atmosphere. The injection of all anthropogenic substances across all layers and their potential impacts, particularly those that alter chemistry, need to be quantified. Identifying which layers, processes and substances to consider important should be an area where research is focussed.

What little is known of the impacts of space activities is drawn from a small number of studies and models that are largely based on inference due to the lack of information forthcoming from industry. Much of the publically available emissions data and modelling focus on pre-1980s launch designs, and so overlook novel propellants and launch methods. Funding bodies should focus research activities on expanding and updating this small base of studies.

Industry needs to include environmental life cycle assessments within all space activities[eg19], extend environmental impact assessment to potentially transboundary harms to the atmosphere, and take precautionary measures during planning and launches (eg managing emissions through prudent choice of propellants[20]).

Simple first steps would be to address space industry specific regulatory gaps that likely exist within the Montreal Protocol[4] due to gaps in understanding of the combined chemical, radiative, and dynamical impacts of rocket emissions on the stratosphere[6]. Environmental regulation standards for spaceports need to be extended, beyond air quality, noise and localised biodiversity impacts, to consider the environmental impact of the launch vehicle and launched objects, during their entire flight and lifetime. Propellant choices are a key area where regulation could guide industry. A review to identify practical implications for space law policy would enable the development of global agreements or the formation of an international working group to regulate space activities. Legal perspectives that will need addressing include international agreement on the need to protect the atmospheric environment (which could arise from the work of the UN International Law

Commission on the protection of the atmosphere), irrespective of, and across, the boundaries between national airspace and the atmospheric layers above, and reviewing the lack of any clear obligation of industry to prevent or minimise harm to the atmosphere.

The collective influences on the global atmosphere from space activities remain unquantified, making it impossible to currently understand and evaluate their environmental impact. There is now an urgent need to direct research and policy decisions towards quantifying and minimising the space industry’s impact on the global atmosphere.

The authors declare no competing interests.

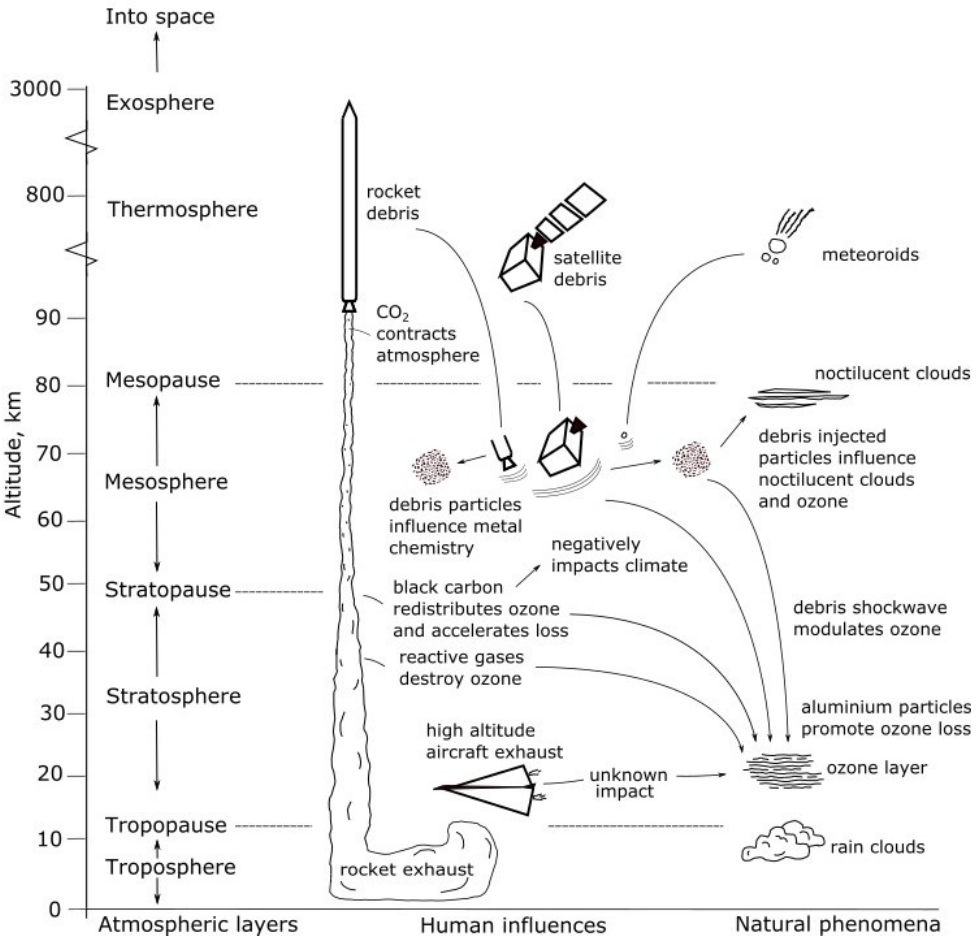
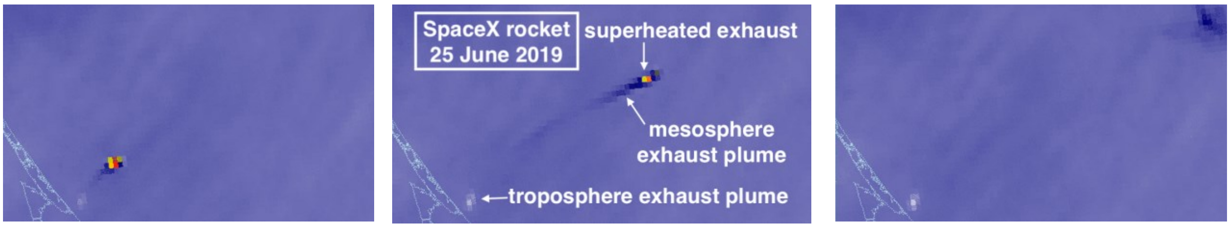


Figure 1: The atmospheric layers from the ground up to the boundary with space, showing natural phenomena, human inputs and resultant impacts. These human inputs impact the troposphere (by enhancing climate change), the stratosphere (through ozone loss from multiple causes), the mesosphere (by influencing metal chemistry and accumulation and increasing noctilucent clouds), and the thermosphere (by likely causing contraction which will impact orbiting satellites).



<1 minute after launch

2 minutes

3 minutes

Figure 2: A SpaceX rocket launches from Cape Canaveral in the United States of America on 25 June 2019 at 06:30 UTC. The launch was seen by the Geostationary Operational Environmental Satellite (GOES 16) allowing the exhaust plume within the troposphere and mesosphere to be clearly identified. Combining satellite observed visible and thermal signatures of rocket launches with rocket engine burn profiles and trajectories can be used to characterise historic rocket emissions into the layers of the global atmosphere. Original image credit: Scott Bachmeier, University of Wisconsin-Madison Space Science and Engineering Centre.

Data availability

No datasets were generated or analysed during the current study.

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