Journal of Cleaner Production 255 (2020) 120209

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

The environmental impact of emissions from space launches: A comprehensive review

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ARTICLE INFO

Article history:
Received 5 May 2019
Received in revised form
2 January 2020
Accepted 20 January 2020
Available online 28 January 2020

Handling Editor: Lei Shi

Keywords:
Environmental impact
Space launch
Propellants

ABSTRACT

With the increasing accessibility of commercial space flight, the environmental impacts of space launches will become increasingly significant in the coming years. Here, for the first time, a review is presented of the environmental impacts of space launches, specifically of emissions from commonly used solid and liquid rocket propellants. While there are a number of environmental impacts resulting from the launch of space vehicles, the depletion of stratospheric ozone is the most studied and most immediately concerning. Solid rocket motors are the subject of most of the environmental studies on rocket launches, while the now more commonly used liquid rocket propellants are underrepresented in the literature. The limited studies of emissions from rocket engines using liquid propellent reveal that while they do result in stratospheric ozone loss, solid rocket motors are responsible for orders of magnitude greater loss. The comparison of commonly used propellants highlights the environmental trade-offs that must be made when selecting a launch system. This review highlights the need for further study of the cumulative impacts that frequent space launches have on all areas of the environment, including global climate, ecosystem toxicity, and human toxicity, and with consideration given to all commonly used propellants, to ensure that the impacts are well characterised and well understood before the number of launches greatly increases.

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https://doi.org/10.1016/j.jclepro.2020.120209
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1. Introduction and backgroundintroduction and background

With growing interest in human settlements in space (e.g., Arya et al., 2011; Borowski et al., 1995; Collins, 2008; Lowman, 1996) and the extraction of resources from extra-terrestrial bodies (e.g., Lewicki et al., 2013; Anand et al., 2012; Sanders and Larson, 2012; Sacksteder and Sanders, 2007), the frequency of space launches is set to increase significantly in the coming years. Determining the environmental impact of launches into orbit is therefore becoming increasingly important, as the compounding impact of a high number of annual launches is likely to be considerable.

The impact that rocket emissions have on the environment varies significantly based on the type of propellant used. Both solid and liquid propellants are commonly used (as summarised in Table 1), each producing different emission products. Solid rocket motors (SRMs), like those used for the lift off stage of the Space Shuttle launches, consist of solid aluminium fuel with an ammonium perchlorate (NH_4ClO_4) oxidiser, and some modern SRMs also contain the hydrocarbon, hydroxyl-terminated polybutadiene (HTPD) in addition. Benefits of SRMs include easy storability, reliability and design simplicity. However, once they are ignited, they cannot be turned off, nor throttled. As such, they are typically only used in the first stage of launches. The exhaust from these SRM fuels contains a number of compounds that are environmentally concerning, in particular hydrochloric acid (HCl) and alumina particles.

Liquid rocket engines (LRE) primarily use one of three common liquid fuel combinations: (i) oxidiser: liquid oxygen (LOx) + fuel: kerosene (RP-1), referred to hereafter as kerosene, (ii) oxidiser: LOx + fuel: liquid hydrogen (LOx/LH_2), and (iii) oxidiser: dinitrogen tetroxide (N_2O_4) + fuel: unsymmetrical dimethylhydrazine (UDMH) referred to hereafter as hypergolic propellant. In addition to UDMH and N_2O_4, some hypergolic propellants also contain hydrazine (N_2H_4).

LOx/LH_2 propellant is often used for the upper rocket stages, due to its high specific impulse, which means that exhaust from its combustion is usually emitted at high altitudes. LOx/LH_2 propellant

Table 1
A description of the four most commonly used space rocket propellants and their primary emission products. Emission product information from Bennett et al. (1992); Ross et al. (2004, 2009). A list of launch vehicles and launch systems that used each propellant type is given. The bracketed number beside each launch vehicle/system indicates what stage the propellant was used, where stage 0 is the booster stage used at launch (note not all rockets have boosters), stage 1 is also used at launch and beyond and the upper stages (2+) are used at very high altitudes. Launch vehicles in blue are from the United States of America, vehicles in red are from Japan, vehicles in green are from India, vehicles in orange are from Europe (European Space Agency), vehicles in blue are from China, and vehicles in grey are from Russia and previously the Soviet Union.

Propellants	Main emission products	Significant launch vehicles and launch systems associated with this propellant	Advantages	Disadvantages
Al/NH_4ClO_4± HTPB (solid)	HCl, H_2O, CO_2, NO_x, Al_2O_3, soot	Titan II (0), Titan IIIA/C/D/E (0), Titan IV-B (0), Delta II (0), Space shuttle (0), Ariane 5 ECA/ES (0), Atlas V (0), H-IIA/IIB (0), GSLV (1), PSLV (0, 1, 3)	• Easy to store • High propellant density • Relative design simplicity of engine • High thrust	• Relatively large environmental impact • Low specific impulse relative to LREs • No throttling or shut down
LOx/LH_2	H_2O, H_2, OH, NO_x	Space shuttle (1), Saturn I/V (2), Delta IV (1, 2), TitanIIIE (3), Atlas III/V (2), H-IIA/IIB (1, 2), Ariane 1/2/3/4 (3), Ariane 5 ECA (1, 2), Ariane 5 G+, GS, ES (1), GSLV (3)	• Low environmental impact due to water vapour exhaust • Highest specific impulse	• Requires cryogenic storage due to extremely low boiling point of LH_2 (-252.87 °C) • Low density • Difficult to handle due to temperature requirements and explosion risk
N_2O_4/UDMH ± N_2H_4(hypergolic)	H_2O, N_2, CO_2, NO_x, soot	Delta II (2) Titan II, Titan IIIA/B/C (1, 2, 3), Titan IIID/E (1, 2), Titan IV-A/B (1, 2), Long March 1-4 (1, 2), Proton (1, 2, 3), Ariane 1/2/3/4 (1, 2), Ariane 5 G+, GS, ES (2), GSLV (0, 2), PSLV (2)	• Can be stored for long periods • Relative design simplicity of engine	• High toxicity • Difficult to handle due to safety concerns
LOx/RP-1 (kerosene)	CO_2, H_2O, CO_x, OH, NO_x, soot	Delta II(1), Titan I (1), Atlas III (1), Delta I/II/III (0), Saturn I/V (1) Falcon-9 (1, 2), Atlas V (1), Soyuz (0, 1, 2), Electron (1, 2), Angara (0, 1, 2)	• High propellant density • Relatively easy to handle • More affordable than LH_2	• CO_2 and black soot emissions contribute to climatic warming

is not well suited for the first rocket stage compared to other liquid propellants due its low density, meaning a much larger tank would be required than for the same mass of kerosene or UDMH. The exhaust produced by engines burning LOx/LH_2 propellant is comprised primarily of water vapour, so the environmental concerns are few, although, as with all types of propellant, nitrous oxide (a common pollutant) is produced through the combustion of atmospheric nitrogen in the high temperature exhaust plume, however all propellants share this environmental concern.

An advantage of hypergolic fuels is that they do not require an ignition system. This feature allows for relatively simple engine designs that fire by simply opening and closing propellant valves. Such engines are favoured in high-reliability situations, and for this reason, hypergolic propellants are often used in orbital manoeuvring systems. Hypergolic fuels can also be stored for long periods without deterioration, so it is favoured for use in storable LREs. However, hypergolic propellants are sometimes referred to as the “Devil’s venom” due to the combination of highly corrosive nitric acid and highly toxic UDMH (e.g., Roy and Bandyopadhyay, 2018), that results in the use of these fuels producing a number of serious environmental impacts. Perhaps for this reason, UDMH appears to be in the process of being phased out as a rocket propellant. Russia is planning on retiring Proton rockets in favour of the Angara rockets (Ferster, 2015), which like Soyuz rockets are propelled by kerosene, with the exception of an optional third stage propelled by UDMH, the environmental impact of which should be less as it will not be used for the launch stage. The first commercial launch of the Angara launch vehicle is expected sometime in 2019. Similarly, a number of rockets in China’s Long March family (Long March 1, 2, 3 and 4) also use UDMH as a propellant, and while many rockets from these families are still active, the newer Chinese systems (i.e., Long March 5, 6 and 7) will use kerosene for lift off and LOx/LH_2 in the main engines (Jones, 2019).

Kerosene is a commonly used propellant for the first stage of a rocket launch, due to its high density and the ease of handling compared to LOx/LH_2 propellant. Being a hydrocarbon, environmental concerns regarding emissions from kerosene combustion from a rocket launch are relatively few compared to hypergolic and solid propellants. Albeit, the emission of CO_2 and soot particles from kerosene combustion is an important environmental consideration, particularly for global climate change.

Almost all vehicles launched to space use multiple rocket stages in order to minimise the non-payload mass that can be used to transport a given payload to burnout velocity (Curtis, 2005) and so that different stages can be customised to operate under different atmospheric pressures. Rockets typically have between 2 and 4 stages, a lift off stage (stage 0), an early launch stage (stage 1), and the upper stages (stage 3+) used at high altitudes. As stages 0 and 1 run out of fuel, they detach from the rocket and the next successive stage fires. This is repeated until the rocket reaches its desired final velocity. The number of stages used and the altitudes at which different stage boosters are used is variable and depends on the rocket.

Different propellants are usually used for all or some of the individual stages of a particular launch system (Table 1), however, the emissions from stages 0 and 1 typically have the highest environmental impacts, as the upper stage engines only burn at very high altitudes.

Newer propellants and engine types, such as hybrid rocket engines, are likely to be increasingly used in the future, however their environmental impacts have not yet been considered in any detail, and thus they are not considered in this study. However, it will be important to study the impacts of these new propellant types on the environment if they are to be commonly used.

As noted in Table 1, emissions from SRMs and most liquid rocket engines (LREs) also contain free radicals (e.g., NO, OH, Cl), along with HCl and/or H_2O (both of which are sources of radicals), inert N_2 and CO_2, and the under-oxidised compounds H_2 and CO. Some propellant types also produce alumina (Al_2O_3) and soot particles in the exhaust, with the proportions of each depending on the type of propellant used (Ross et al., 2004). Emissions can be direct, i.e., from propellant combustion or indirect, i.e., emissions formed from the mixing of air into the exhaust plume. Hybrid rockets are a relatively new addition to the space industry and as such are not the primary subject of environmental studies of rocket launches, however, they run on a combination of a solid propellant (HTPB, a hydrocarbon) and a liquid propellant (RP-1, UDMH or LH_2), and thus emissions will be a combination of those mentioned in Table 1.

Rocket launches produce both local environmental changes resulting from the interaction of the rocket exhaust contrail with the atmosphere as well as the formation and wind transport of a ground cloud, and global effects resulting from the far ranging distribution of exhaust emissions in the mid to upper atmosphere (Fig. 1). While a number of studies have carried out investigations of these changes and the mechanisms by which they come about, there are still many unknowns. Early considerations of the environmental impact of space launches began with the U.S. space shuttle program in the 1970s (e.g., Cicerone et al., 1973; Pergament et al., 1977). In 1978, NASA released the Final Environmental Impact Statement (EIS) for the space shuttle program, in accordance with the U.S. National Environmental Policy Act (1970), for which a number of environmental studies were carried out (Malkin, 1978). The space shuttle program was the subject of many subsequent environmental studies, and, thus, the majority of the information in the literature on the environmental impacts of space launches comes from studies of the space shuttle program, and therefore is focussed on SRM launches. However, other propellants are underrepresented in environmental studies of launches, as demonstrated by the environmental studies included in this review (Table 2). Stratospheric ozone depletion has been the environmental focus of the majority of these studies (Table 2). This highlights the need for further studies across all propellant types, particularly LREs and across all environmental areas, in order to gain more of a complete understanding of the environmental impact of launching vehicles to space. Studies also typically focus on the environmental effect of singular launches or a small number (<5) of annual launches, it is important that the cumulative environmental impact of frequent launches is also considered.

2. Review methodology

An extensive literature search was carried out on SCOPUS, Web of Science, and Google Scholar websites for literature that reported environmental information relating to space vehicle launches or launch testing. NASA and ESA databases were searched for technical reports focusing on either environmental impacts as a whole, resulting from space launches or impacts to specific areas of the environment. A search of United Nations reports was conducted to ensure any reported environmental or development data regarding space launches was considered. As studies on this topic are relatively limited due to the low numbers of total studied launches, all literature encountered in the search that included quantitative data obtained through observational studies were included, provided the methodology was clearly stated. Technical reports were included, however, many recent NASA technical reports in particular, reference environmental data from earlier reports, so these reports were not included in the review unless they contained new data. In addition to observational studies, modelling studies were included if they provided a basis for comparison with observational studies, the modelling was carried out in conjunction with

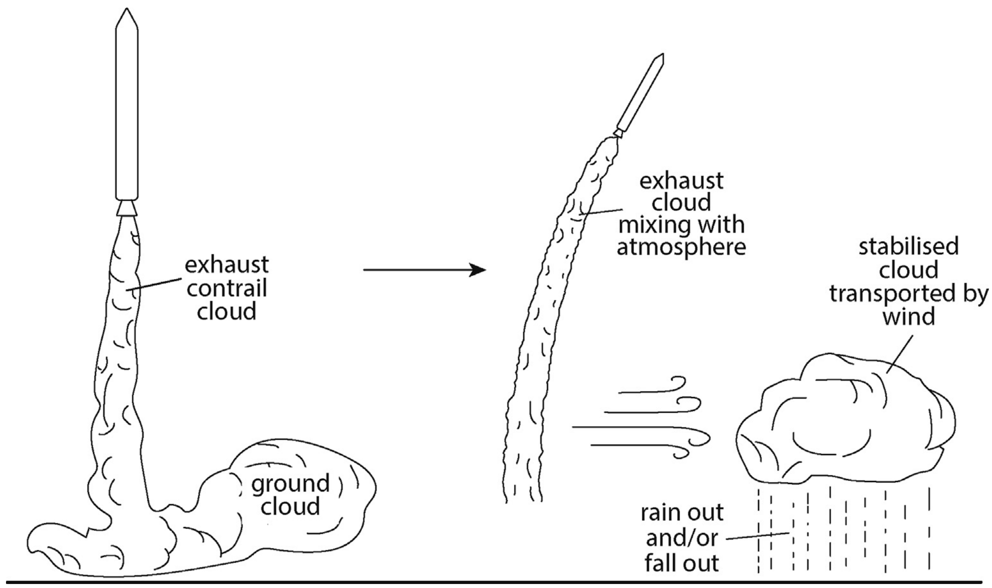

Fig. 1. Schematic illustration of the exhaust contrail and ground cloud immediately after launch (left) and some time after launch (right).

observational studies, or they represented the only data source where observational studies had not been conducted. Efforts were made to include new propellant types in this review, however, through the literature survey it was evident that environmental data was largely unavailable. As these propellant types are only used in a very small proportion of total launches, the focus was on studies regarding the most commonly used propellants. Considering the life cycle of launch emissions, this review focuses on studies that present mid-point data for the environmental considerations of stratospheric ozone depletion, mesospheric cloud formation, global climate change, ecosystem toxicity and human toxicity. In the environmental life-cycle of an activity, such as a rocket launch, mid-points are the points in the cause-effect chain between the environmental stressor at the beginning of the chain before the end of the chain is reached, as opposed to end point data which is typically focused on overall high-level impacts to human health, resource depletion and ecosystem quality. This approach to the review was used as virtually all studies on the environmental impacts of rocket launches use mid-point data.

3. Results and discussion

3.1. Ozone depletion

The ozone layer is a region of Earth's stratosphere that absorbs the majority of the Sun's ultraviolet (UV) radiation, preventing it from reaching the surface of the Earth. As implied by its name, this layer is comprised of a relatively high abundance of ozone (O_3) in comparison to the rest of the atmosphere, although other atmospheric gases still make up the majority of the ozone layer. Radical catalysts, including nitrogen oxides (NO_x), chlorine (Cl_x), bromine (Br_x), and hydroxyl (OH) radicals cause the greatest amount of ozone destruction. While these catalysts occur naturally, manmade compounds including chlorofluorocarbons, hydrofluorocarbons, chlorinated solvents and halons, now known as ozone depleting substances (ODSs), have resulted in increases in the stratospheric concentration of some of these catalysts, in particular chlorine and bromine. Rocket launch exhaust plumes, regardless of propellant type, all contain NO_x, OH, and H_2O, which lead to ozone loss (Table 1), while certain propellant types contain additional ozone depleting compounds. Stratospheric ozone loss can be both local, within the exhaust plume and also reduce the concentration of ozone globally within the stratospheric ozone layer.

Due to the ozone layer's crucial role in the absorption of UV radiation, which is harmful to human health, the depletion of the ozone layer has been an important global concern for several decades. Ozone depletion is one of the largest environmental concerns surrounding rocket launches from Earth, and with an increasing number of emerging national and private space organisations, the number of launches is expected to continue to increase significantly (e.g., Canis, 2016), particularly as the cost of space travel continues to decrease, which may result in ozone depletion from space launches becoming a serious problem, as noted by Ross et al. (2009).

Understanding the relationship rocket engine combustion emissions and exhaust have with ozone depletion is crucial as rocket emissions and engine exhaust are deposited directly into the middle to upper stratosphere, where the ozone layer is found (Ross et al., 2009). Different propellants impact the ozone layer in different ways, however, they all result in the emission of compounds that cause ozone loss. Studies of the relationship between rocket emissions, particularly from SRMs, and ozone depletion have been carried out for decades. The earliest of these studies was an investigation of the role of rocket emissions in ozone depletion carried out by Cicerone (1974), who focused on emissions from the space shuttle as a source of atmospheric chlorine. SRMs emit a considerable amount of HCl, which is converted in the exhaust plume to the ozone depleting radical catalyst Cl_x. Al_2O_3 particle emissions from SRM exhausts also contribute to ozone loss through chemical reactions that occur on the surface area of the particles (Ross and Vedda, 2018). Like all propellant types, SRMs exhausts also contain smaller amounts of the radical catalyst NO_x (Table 1).

3.1.1. Stratospheric ozone loss in SRM exhaust plumes

There are two primary methods for studying the impact of rocket exhaust emissions on the ozone layer: (i) exhaust plume and atmospheric modelling (e.g., Denison et al., 1994; Zittel, 1994), and (ii) real time in-situ measurements of exhaust plumes in the wake of rocket launches (e.g., Pergament et al., 1977; Pumphrey et al., 2010; Ross et al., 1997a,b, 2000). Early studies relied primarily on

Table 2
Summary of the environmental studies of rocket launches covered in this review.

Reference	Propellants	Focus	Publication type
Benbrook et al. (1997)	SRM	Stratospheric ozone	Conference paper
Bennett et al. (1992)	SRM, UDMH, LOx/LH_2, kerosene	Stratospheric ozone, global climate, acid rain, ecosystem toxicity	Journal article
Carlsen et al., 2007	UDMH	Ecosystem toxicity, human health	Journal article
Carlsen et al. (2008)	UDMH	Ecosystem toxicity, human health	Journal article
Carlsen et al. (2009)	UDMH	Human health	Journal article
Cicerone et al., 1973	SRM	Stratosphere, mesosphere, ecosystem toxicity	NASA Technical Report
Cicerone (1974)	SRM	Atmospheric emissions	NASA Technical Report
Danilin et al. (2001)	SRM	Stratospheric ozone	Journal article
Dreschel & Hinkle (1984)	SRM	Estuarine systems	NASA Technical Memorandum
Hall et al. (2014)	SRM	Wildlife, vegetation, water quality, soils, air quality	NASA Technical Report
Hawkins et al. (1984)	SRM	Estuarine fish	Journal article
Jackman et al. (1996)	SRM	Stratospheric ozone depletion	Journal article
Jackman et al. (1998)	SRM	Stratospheric ozone depletion	Journal article
Kelley et al. (2010)	SRM	Mesosphere changes	Journal article
Kenessov et al. (2008)	UDMH	Soil quality	Journal article
MacDiarmid et al. (2016)	Kerosene	Marine ecosystems	Report prepared for the Ministry of Environment, New Zealand
Malkin (1978)	SRM	Air quality, water quality, noise, natural resources	NASA Technical Report
Marion et al. (1989)	SRM	Soil quality	Journal article
Milligan & Hubbard (1983)	SRM	Estuarine fish	Conference paper
NASA report, 1983	SRM	Air quality, noise, fish, vegetation	Conference proceedings
NASA technical report, 2007	SRM	Air resources, water resources, land resources, geology and soil, biological resources, noise	NASA Technical Report
NASA technical report, 2011	SRM	Air resources, water resources, land resources, geology and soil, biological resources, noise	NASA Technical Report
NASA technical report, 2014	SRM	Air resources, water resources, land resources, geology and soil, biological resources, noise	NASA Technical Report
Nauryzbaev et al. (2005)	UDMH	Ecological toxicity	Journal article
Pellett et al. (1983)	SRM	Acid rain	Journal article
Pergament et al. (1977)	SRM	Stratospheric ozone depletion	Journal article
Prather et al. (1990)	SRM	Stratospheric ozone depletion	Journal article
Pumphrey et al. (2010)	SRM	Atmospheric water vapour	Journal article
Ritz et al. (1999)	UDMH	Human toxicity	Journal article
Ross et al. (1997a)	SRM	Stratospheric emissions	Journal article
Ross et al. (1997b)	SRM	Stratospheric ozone depletion	Journal article
Ross et al. (2000)	SRM	Stratospheric ozone depletion	Journal article
Ross et al. (2004)	UDMH	Stratospheric ozone depletion	Journal article
Ross et al. (2009)	SRM, UDMH, LOx/LH_2, kerosene	Stratospheric ozone depletion	Journal article
Ross & Sheaffer (2014)	SRM, UDMH, LOx/LH_2, kerosene	Global climate	Journal article
Schmalzer et al. (1985)	SRM	Terrestrial vegetation	NASA Technical Memorandum
Siskind et al. (2003)	SRM	Atmospheric water vapour	Journal article
Stevens et al. (2003)	SRM	Mesospheric cloud formation	Journal article
Stevens et al. (2003)	SRM	Mesospheric cloud formation	Journal article
UNDP (2004)	UDMH	Ecosystem toxicity, human health	UNDP Technical Report
Zittel (1994)	SRM	Stratospheric ozone depletion	Aerospace Corp Technical Report

modelling, however, once several real time measurements were made across rocket exhaust plumes over time, it was found that early models had underestimated ozone loss (e.g., Ross et al., 2000). The earliest in-situ measurements of rocket exhaust plumes were presented by Pergament et al. (1977), who observed a reduction in ozone levels of 40% during a single pass through a plume in the lower stratosphere in the wake of TitanIII launch. Subsequent plume measurements were typically made by instruments on NASA's WB-57F high-altitude research aircraft, which made multiple passes through exhaust plumes to measure plume chemistry and ozone depletion as the plume expanded. Such as the early measurements made multiple times in a single launch plume presented by Ross et al. (1997a), who measured Cl_2 and ozone concentrations across the 8 km wide exhaust plume of the Titan IV launch vehicle in the stratosphere following a twilight launch. High Cl_2 concentrations in the exhaust from the Titan IV's SRMs showed that a considerable amount of the HCl in the SRM exhaust was converted to Cl_2 in the plume. However, ozone concentrations in the plume were similar to ambient ozone levels, indicating that ozone depletion in the lower stratosphere does not result from night-time launches with SRMs, due to the lack of UV radiation (Ross et al., 1997a). These results are consistent with measurements of ozone in SRM plumes by UV absorption instruments on board the WB-57F, in the plumes of Titan IV and Delta II launch vehicles, the results of which demonstrated that launches at or after sunset did not result in ozone depletion. However, daytime launches resulted in considerable ozone loss in the lower stratosphere, demonstrating the significance of launch time on ozone loss

(Benbrook et al., 1997). Studies where measurements of ozone in the exhaust plumes of SRMs were made for >1 h, showed significant ozone loss after the launch of vehicles with SRMs, approaching 100% over an 8 km plume region between 30 and 60 min after launch Benbrook et al. (1997); Ross et al. (2000); Pergament et al. (1977); Pumphrey et al. (2010); Ross et al. (1997a,b, 2000). Beyond the first hour after launch, ozone levels begin to return to ambient concentrations, however, smaller pockets of significant ozone depletion still remained (Benbrook et al., 1997; Ross et al., 2000).

3.1.2. Global stratospheric ozone loss resulting from SRM launches

A number of modelling studies have focused on the global impact the rocket launches have on the ozone layer. A study published by Prather et al. (1990) modelled the global impact of chlorine from space shuttle launches on stratospheric ozone and found that, based on a scenario of nine space shuttle launches and six Titan IV launches per year, ozone loss would be 0.25%. This study did not consider local ozone loss in the wake of the rocket as they believed this occurrence would be prevented by factors including the time it would take to convert exhaust HCl to Cl_x and the shuttle trajectory. Aftergood (1991) argued against this in a comment on this study, citing in-situ measurements made of ozone loss by Pergament et al. (1977). While it is evident that HCl in SRM exhaust contributes to ozone loss, Jackman et al. (1996) noted that alumina particles may also promote reactions that could result in significant ozone loss, in addition to HCl. A later modelling study of the impact of both Al_2O_3 and HCl emitted from SRMs have on global stratospheric ozone determined that in 1997, annually averaged global ozone would decrease by 0.025% as a result of space launches, one third of which would result from Al_2O_3 emissions, while the remaining two thirds would result from HCl (Jackman et al., 1998). However, again local ozone loss in the wake of the rocket was not considered by this study. A further study that modelled the global ozone loss resulting from local exhaust plume ozone depletion plus HCl dispersion in the atmosphere from the launch of SRMs determined that the impact of ozone loss in the wakes of SRMs is an order of magnitude less than the effect of global atmospheric distribution of HCl emissions from launches Danilin et al. (2001). Global atmospheric circulation takes approximately three years to remove exhaust emissions from the stratosphere, resulting in a steady state where declining exhaust from older launches is replaced by fresh exhaust from recent launches (NASA technical report, 2014). However, this steady state will only continue to exist if there are no large increases in the number of space launches. At present, global atmospheric models of ozone depletion resulting from rocket launches primarily exist only for SRMs (NASA technical report, 2014).

3.1.3. Stratospheric ozone loss from LREs

Due to their use in the booster stage of the space shuttle program, SRMs have received much of the attention in studies of ozone depletion resulting from rocket launches, with much fewer studies focused on LREs. SRM emissions contain significantly more reactive chemicals and particles than the emissions from LREs, and therefore result in ozone loss an order of magnitude greater than the three types of LREs discussed (Ross et al., 2009). Because the ozone loss resulting from SRMs is so much greater than for LREs, it is unlikely the SRMs will be able to play a large role in the predicted increase in space launches in the future should international limits on the emission of ozone depleting substances be adapted to include rocket emissions, thus an increase in the number of vehicles powered by LREs is more likely (Ross et al., 2009). Given the prevalence of liquid fuelled launch systems, it is important to understand the impact that LREs have on the ozone layer. An observational study involving in-situ measurements of an exhaust plume in the wake of a Delta II launch, which was propelled by a combination of SRMs and LREs (kerosene), as well as modelling to estimate ozone loss, was carried out by Ross et al. (2000). Like previous studies, measured ozone loss in the plume was almost 100%, which exceeded the modelled estimate by a factor of ~two (Ross et al., 2000). However, the extent to which the kerosene combustion component of the exhaust contributed to this ozone loss is uncertain. Accumulation of black carbon emitted from LREs, largely from kerosene propelled rockets, in the stratosphere can cause both indirect changes in ozone levels, as it can result in stratospheric warming (as discussed in section 3.3) which can speed up ozone depletion reactions in tropical areas and reduce ozone loss in polar regions, and direct ozone loss due to reactions on the surface area of soot particles (Ross et al., 2000).

The Russian Proton rocket launch vehicle is the largest launcher that is powered by hypergolic propellant (UDMH/N_2O_4). The impact on the ozone layer from H_2O and NO_x emissions from hypergolic engine exhaust was modelled by Ross et al. (2004). The results of this modelling found that most ozone loss came from the NO_x component of the rocket emissions, and that the use of hypergolic propellant would like result in 66–90 times less ozone depletion than SRMs. However, these results need to be validated by in-situ plume measurements (Ross et al., 2004).

While studies show that local ozone levels return to ambient levels a few hours after launch, it is important to consider the global impact of space launches on the ozone layer resulting from the atmospheric distribution of radical catalysts from rocket launch emissions. Ross et al. (2009) note that a large increase in the number of rocket launches, even assuming they are propelled by LREs, could result in global ozone losses on the order of several percent. Trajectory models are typically used to study the transport of rocket exhaust plumes, an important factor for understanding how these plumes affect the ozone layer beyond local impacts. However, as discovered by Newman et al. (2001) after an unexpected encounter with the plume of a kerosene fuelled rocket in California, USA, that likely originated from a Soyuz rocket launched in Kazakhstan, models cannot reliably predict the transport and stratospheric impact of LREs. Models had failed to predict that a plume from a rocket launched in Eurasia could be encountered in California. While LOx/LH_2 rocket exhaust contains NO_x and H_2O, which do result in ozone loss, it is typically used for the upper stages of rockets, and this propellant is often burnt at higher altitudes than the ozone layer. In the environmental impact statement for their planned 2020 mission to Mars, NASA noted that considerable further research into the global impact of LREs on the ozone layer is required NASA technical report (2014). Global ozone loss from rocket launches will become a greater environmental concern as the number of rocket launches increases. This was highlighted in a modelling study which considered the cumulative impact of 1000 launches of hydrocarbon powered rocket engines per year and estimated that tropical stratospheric ozone would likely decline, while polar stratospheric ozone would likely increase, as a result of black carbon emissions (Ross et al., 2010).

3.2. Mesospheric cloud formation

Mesospheric clouds (also known as noctilucent or night-luminous clouds) are clouds that are typically observed at or near the poles during their respective summers. These clouds exist in the mesosphere, meaning they are the highest clouds in Earth's atmosphere. Their formation mechanisms are not completely understood, but it is thought that, unlike clouds in the lower parts of the atmosphere, mesospheric clouds may form from water vapour alone rather than nucleating around small particles (Russell et al., 2014). A number of studies have identified a link between the formation of mesospheric clouds and the exhaust from space launches (e.g., Kelley et al., 2010; Stevens et al., 2005, 2003; Siskind et al., 2003). Siskind et al. (2003) used the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) instrument on NASA's TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite to observe the mesosphere over a 10 month period. They found that liquid-propellant fuelled rocket launches, including all four of the space shuttle launches during this period, resulted in enhancements in the radiance of the mesosphere. While space shuttles used SRMs during lift off, liquid LOx/LH_2 propellant was used in the space shuttle main engines (SSMEs) which were used all the way into orbit, the exhaust of which is 97% water vapour. It is believed mesospheric clouds form after liquid propellant launches due to the enhanced water vapour in the very dry mesosphere (Siskind et al., 2003). The STS-85 mission of the space shuttle Discovery in August 1997 deployed the CRyogenic Infrared Spectrometers and Telescopes for the Atmosphere-Shuttle PAllet Satellite (CRISTA-SPAS), which observed the atmosphere for eight days, including measurements of OH as a proxy for water vapour. These measurements were used in conjunction with ground-based water vapour observations for a study conducted by Stevens et al. (2003), which investigated the formation of polar mesospheric clouds after the launch. Satellite observations showed that polar mesospheric clouds appeared in the Arctic a week after the launch, and the estimated water contents of the clouds were consistent with the water vapour injected into the mesosphere by the space shuttle's main engines (Stevens et al., 2003). It is believed that space shuttle plumes were transported to the poles by meridional winds, which would result in the plumes from mid-day launches being transported north, while later afternoon and evening launch plumes would be transported to the south (Stevens et al., 2003). A subsequent study used a ground-based microwave spectrometer to observe the transport of a space shuttle exhaust plume to Antarctica, with satellite observations following the related formation of mesospheric clouds (Stevens et al., 2005). This study estimated that a single shuttle launch was responsible for a 10–20% increase in the mass of polar mesospheric clouds during the 2002–2003 summer.

A similar study using radar, lidar and photography to observe mesospheric clouds above Alaska was carried out in 2007. That study noted the formation of an intense mesospheric cloud three days after a space shuttle launch from Cape Canaveral (Kelley et al., 2010). Additionally, the studies by Stevens et al. (2003, 2005) and (Kelley et al., 2010) all observed iron in the thermosphere (the atmospheric layer above the mesosphere) that likely resulted from ablation from the main engines of the space shuttle. The rapid timescales for plume transport to the poles observed in these studies highlights limitations in our understanding of mesospheric and thermospheric transport mechanisms.

As the number of vehicles launched into space continues to increase, it is important to consider the effect this will have on mesospheric cloud formation. Skylon is a proposed single-stage-to-orbit reusable space plane, which would be fuelled by hydrogen, and is intended to facilitate low cost, high turnaround rate space travel. A recent study by Larson et al. (2017) focuses on the atmospheric response resulting from estimated emissions from repeated Skylon rocket launches, simulating the number of space launches across a range of 10^4 through to 10^6 flights per year. Assuming a base case of 10^5 flights per year, it is estimated that water vapour would increase by 10% in the stratosphere and 100% in the mesosphere, resulting in an increase in high-latitude cloud. Limitations in the understanding of mesospheric cloud formation make prediction of its impact on the atmosphere and climate difficult.

3.3. Climate change

Understanding the impact rocket emissions might have on global climate, and, in particular, predicted future climate warming is complex and requires considerable further study. Black carbon is emitted from kerosene fuelled engines, while SRMs also emit alumina particles, and both of these have the potential to cause instantaneous radiative forcing. An accumulation of black carbon in the stratosphere can absorb some of the solar flux, resulting in cooling, but will also trap upwelling long-wave radiation from Earth that would otherwise be lost to space, which would result in warming (Ross and Sheaffer, 2014). Initially it was believed that alumina particles accumulating in the stratosphere would have a cooling effect by scattering solar flux back to Earth due to their white colouring. However, Ross and Sheaffer (2014) determined that, like black carbon, alumina particles absorb outgoing long-wave radiation from Earth, resulting in warming. While the total alumina emitted from SRMs is well quantified, uncertainty remains as to the amount of black carbon emitted from hydrocarbon-fuelled rocket engines, which makes the climate impact difficult to estimate.

At present, the number of rocket launches using kerosene as the propellant will likely have a negligible impact on global climate. However, there is a possibility that increasing future use of hydrocarbon fuelled rockets may have an impact. In addition to kerosene propelled engines, the relatively recent advent of hybrid rocket engines, gives rise to another potentially hydrocarbon-based propulsion system. Hybrid rocket engines run on both solid (HTPB) and liquid (kerosene, hydrazine or liquid hydrogen) fuel, thus presenting another potential source of black carbon from rocket exhaust. Hybrid rocket engines are relatively cost effective when compared to other rocket propulsion engines, which could lead to them becoming a popular option for commercial space launches (Davydenko et al., 2007). For example, hybrid rocket engines were used on SpaceShipTwo, Virgin Galactic's suborbital space craft that is intended to be used for space tourism. Based on measured alumina emissions from SRMs and estimated black carbon emissions from kerosene propelled rockets, a 2014 study determined that rocket launches at that time would have contributed a very minimal amount of positive (warming) radiative forcing (15 ± 8 mW m^{-2}), with black carbon contributing 70% of the radiative forcing and 28% contributed by alumina, with H_2O contributing the remaining 2% (Ross and Sheaffer, 2014). However, the assumed black carbon emission from hybrid rocket engines is much greater than for kerosene propelled engines (e.g., Ross and Sheaffer, 2014), so the impact that black carbon emissions from rocket exhausts have on global climate warrants further study.

A study comparing the impact on radiative forcing of CO_2 emissions from hydrocarbon propelled rocket launches compared to black carbon emissions found that black carbon emissions had a factor of 10^5 more impact on climate than CO_2 emissions (Ross and Sheaffer, 2014). A recent report by Ross and Vedda (2018) notes that while black carbon and alumina particles may cool the Earth's surface by absorbing solar flux from space or reflecting it back to space, respectively, this results in a warmer stratosphere, the implications of which are not entirely understood. Ramanathan and Carmichael (2008) note that black carbon emissions are the second highest contributor to global warming, following CO_2 emissions. A modelling study which examines the cumulative effect of emissions from 1000 launches per year of space vehicles powered by hydrocarbon engines, found that after a decade of continuous launches, the black carbon emissions would result in radiative forcing comparable to that estimated to result from current subsonic aviation (Ross et al., 2010).

A warmer stratosphere will likely contribute to ozone depletion, as higher temperatures speed up the chemical reactions that cause ozone loss (Ross and Vedda, 2018). Further research into the overall impact that black carbon and alumina particle emissions have on the global climate is imperative, particularly if hybrid hydrocarbon propelled rockets continue to gain popularity. Although black soot and alumina particles may have more an impact on global climate than CO_2, considering the amount of CO_2 emissions from hydrocarbon propelled rockets, it is important in understanding the impact of rocket launches on global warming. Although at present the total amount of CO_2 released by all space launches is dwarfed considerably by emissions from commercial air travel, there is potential for the CO_2 emissions from increasing numbers of space launches to have a significant impact on global climate. Further study is needed to identify and quantify potential impacts of space launches. Ross and Sheaffer (2014) estimated the radiative forcing resulting from CO_2 emissions from rocket launches (at a rate of one launch per year), and found that kerosene resulted in the highest instantaneous radiative forcing (6×10^{-6} mW m^{-2}), while LOx/LH_2 propellant has the least affect as it produces no CO_2. In addition to the impact of alumina particles from SRMs and black soot and CO_2 from kerosene fuelled LREs, stratospheric water vapour, which is produced in varying amounts by all rocket launches, also has the potential to cause changes to atmospheric temperatures. Reductions in stratospheric water vapour are associated with a decadal decrease in the rate of surface warming, indicating that stratospheric water vapour is an important factor in decadal climate change (Solomon et al., 2010). LOx/LH_2 produces the highest amount of instantaneous radiative forcing from water emissions (0.02 mW m^{-2}, at a rate of one launch per year), while the other propellant types all produce instantaneous radiative forcing of $\geq$0.05 mW m^{-2} at a rate of one launch per year (Ross and Sheaffer, 2014). When considering the amount of radiative forcing caused by CO_2, H_2O, black carbon and Al_2O_3 emissions from rocket launches, black carbon emission from launches with kerosene propellant produces the highest amount of instantaneous radiative forcing of 0.32 mW m^{-2} (at a rate of one launch per year), followed by alumina particle emissions from SRMs, which produce 0.18 mW m^{-2} of radiative forcing (Ross and Sheaffer, 2014). Mesospheric cloud formation from rocket launches, may also cause radiative forcing, although the amount is likely negligible (Ross and Sheaffer, 2014).

3.4. Ecosystem toxicity

3.4.1. Ecosystem toxicity resulting from SRM launches

Most of the known ecological impacts resulting from space launches come from studies on the space shuttle (Cicerone et al., 1973; Hall et al., 2014; Malkin, 1978; NASA report, 1983). Ecological studies focus on local impacts proximal to the launch site, after observations of ecological damage resulting from early space shuttle launches prompted further study to determine the impacts of repeated shuttle launches. Space shuttle launches produced a ground cloud, the major constituents of which are H_2O, CO_2, Al_2O_3 and HCl, which forms as a result of the SRMs, the SSMEs, and the deluge water used for energy suppression. The deluge water system used over 1.89×10^6 L of water for each launch, resulting in a considerable amount of water being entrained in the exhaust cloud (Milligan and Hubbard, 1983). Inside the ground cloud, turbulence from the rocket exhaust causes the water to atomise, and the water droplets then coagulate with alumina particles and scavenge HCl, resulting in the formation of acidic liquid droplets that can have extremely low pH (<0.5 pH) (Anderson, 1983). The near-field effects of this ground cloud can be severe due to the fall out of acidic droplets and alumina as it sweeps across the ground. As the cloud rises and is transported by the prevailing wind, it can also have effects further afield (Fig. 1; deposition at distance of up to 22 km from the launch site has been observed), including the rain out of acidic droplets as well as the deposition of alumina (Anderson, 1983). In 1975, the ground cloud generated by the launch of the Titan III SRMs crossed paths with a rain storm 20–30 min after launch, resulting in very acidic rain (pH < 1.5) as a result of rain water scavenging HCl from the ground cloud (Pellett et al., 1983). The fall-out and/or rain-out of acidic liquid after SRM launches has significant environmental implications. In order to evaluate the near-field environmental impacts of emissions from space shuttle SRMs, a study was carried out to quantify the deposition of HCl and particulates from launches. This study involved sampling across a 0.126 km^2 grid north of the launch pad (due to prevailing wind direction and launch trajectory), and found that HCl deposition was between 0 and 127 g m^{-2}, while particulate deposition (in the form of alumina, sand grains, paint chips and other debris) was in the range of 0–246 g m^{-2} (Dreschel and Hall, 1990). The deposition patterns were primarily determined by wind speed and direction, with up to 7.1×10^3 kg of particulates and 3.4×10^3 kg of HCl being deposited beyond the perimeter fence of the launch pad under particular weather conditions (Dreschel and Hall, 1990). The total deposition area after a space shuttle launch was approximately 0.23 km^2 (Dreschel and Hinkle, 1984).

Rocket launches have the potential to impact soil quality and local ecology, particularly through the emission of HCl from SRM exhaust. In a report examining the environmental effects of the first five space shuttle launches, it was noted that surface soil at the launch site showed significant increases in Al, Cd, Cr, and Mn, along with a significant decrease in iron levels (NASA report, 1983). A study carried out by Marion et al. (1989) simulated the effect that extreme HCl deposition from space shuttle launches would have on soil acid neutralisation and determined a rapid pH reduction would occur. The pH reduction was the greatest in poorly buffered soils, while older soils had a greater capacity to neutralise the pH after HCl deposition (Marion et al., 1989). NASA noted that the soils around their launch zone are alkaline and therefore have a high buffering capacity, so they do not expect the HCl content of exhaust plumes from launches to adversely affect these soils (NASA technical report, 2014).

The launch of space vehicles with SRMs can affect vegetation directly through physical damage from the turbulent cloud, the deposition of acidic droplets and alumina from the ground cloud onto plants, or through acidification of the soil system. Schmalzer et al. (1985) carried out a study on the effect that the first nine space shuttle launches had on near-field and far-field vegetation. They found that the launch that did the most damage to vegetation (STS-8) occurred in 95% humidity, a few hours after a thunderstorm had occurred in the area. The combination of the high humidity and wet condition of the vegetation is the likely reason for this launch causing more severe damage. Acute damage to vegetation was observed in the near-field area, with changes in plant species occurring across the entire zone, and the number of some plant species declining significantly (Schmalzer et al., 1985). Grasses and sedges were the plants most resilient to the effects of the ground cloud, while shrubs were the most affected, and the response of succulents and subshrubs was varied (Schmalzer et al., 1985). There was an overall decline in the vegetation ground-cover of the near-field area due to the loss of several species, in particular shrubs and small trees which could not withstand the frequent defoliation they would undergo after each launch (Schmalzer et al., 1985). Far-field effects were heavily dependent on the behaviour of the ground cloud, as differences in prevailing winds meant that most areas did not undergo frequent repeated exposure, but typically the far-field effects consisted of acid burns and deposition of alumina on leaves. The effects on far-field vegetation were minor enough that no plant deaths were observed. A study on the effect of HCl exposure from missile exhaust on marigolds found that high exposure (2071 ppm) resulted in complete plant death within 5 min of exposure, while at lower concentrations (95 ppm) there was no effect, and seeds from exposed plants were unaffected (Lind, 1971). Studies on the impact of HCl deposition on vegetation have focused more on short term exposure, and thus the long-term effect of repeated, chronic far-field exposure to HCl fall-out or rain-out from launch generated ground clouds requires further research. However, based on observations after past space shuttle launches, damaged vegetation usually regrows within the same growing season (NASA technical report, 2007).

Of the launch deposition area in these studies, water surfaces (i.e., lagoon, canals and an impoundment) comprise 38% of the deposition area, which means they are subject to a large portion of the >3000 kg of HCl that is deposited across this area after a space shuttle launch (Dreschel and Hinkle, 1984). The pH of the lagoon was measured before, during, and after the launch, and was observed to fall from a pH of 7 before the launch to a pH of 1 during the launch due large acid deposition (HCl) from the SRM exhaust (Dreschel and Hinkle, 1984). The pH level recovered to 7 approximately three days after launch, due to dilution with water from outside the lagoon and the buffering ions in solution in the brackish lagoon water (Dreschel and Hinkle, 1984). Unsurprisingly, changes in water chemistry had an impact on the fish living in the lagoon. After the first five space shuttle launches, a large fish kill was observed in the lagoon near the launch site. In order to investigate the fish kill, a study was carried out whereby three species of fish were placed in buckets near the launch site, in order to expose them to the SRM exhaust. Open buckets were used to provide full exposure, partially closed buckets provided intermediate exposure and a closed bucket was used as the control for the study. Three hours after the launch, the pH of the water in the full exposure buckets had decreased from 7 to 3, and Al and Fe levels had increased by 2–4 times (Hawkins et al., 1984). Some of the fish died from the exposure, and the results of the experiment showed that full exposure damaged the gills of most fish, while intermediate exposure also damaged the gills of some fish (Hawkins et al., 1984). The fish that died exhibited similar physiological symptoms to those that were exposed but lived. It is likely that gill damage caused by the sudden drop in the pH of the water resulted in fatal anoxia (Milligan and Hubbard, 1983; Hawkins et al., 1984). Field surveys conducted after each launch determined that fish kills were limited to the shallow waters nearest to the launch pad and stormwater ditches leading away from the launch pad (Hall et al., 2014). The fish kill locations were consistent with the near field deposition area of the launch. Beyond fish, there is a chance that burrowing animals may die if they live in the path of the ground cloud (NASA technical report, 2007).

3.4.2. Ecosystem toxicity resulting from LRE launches

The launch of the UDMH propelled Proton launch system from the Baikonur Cosmodrome in Kazakhstan results in the spill of a considerable amount of unburned UDMH from the fall of the expendable stages of the rocket and their impact with the ground. It is estimated that 30–40 kg of UDMH ultimately reaches the ground from these launches (Nauryzbaev et al., 2005). The separation of the first stage of the proton rocket occurs at an altitude of approximately 40 km, while the second stage separates at an altitude of over 100 km, resulting in a very large UDMH deposition area. A United Nations Development Programme (UNDP) report notes that UDMH fall areas are ecological disaster zones, while the areas impacted by the expended rocket stages are ecological crisis zones. The total area of these zones exceeds 7.7×10^5 km^2 (UNDP, 2004). Further study on the impact of UDMH on vegetation, waterways and wildlife is required to determine how UDMH effects each of these parts of the environment. A study modelling the environmental health impact of this unburned UDMH found that while a spill of intact UDMH would in itself result in environmental toxicity, the transformation products of UDMH may be even more toxic, demonstrating the necessity of further study on these compounds (Carlsen et al., 2008).

UDMH is believed to undergo rapid environmental degradation, however, the transformation products can persist in dry soils, like those found in Kazakhstan, lasting up to 34 years (UNDP, 2004). An examination of soils in Kazakhstan found many were contaminated with a toxic compound, 1-methyl-1H-1,2,4-triazole (MTA; a product of reactions with UDMH), at concentrations of up to 100 mg kg^{-1} (Kenessov et al., 2008). UDMH is water soluble, and the residence time in river waters has been determined as 0.75 of a year, while in lake water the residence time is 8.1 years (Carlsen et al., 2007). Most studies on the impact that UDMH rocket propellant and its products have on the environment and human health are relatively recent (within the last 20 years), despite the use of UDMH as a rocket propellant for many decades (the first UDMH propelled launch of a Proton rocket was in 1965). Due to the limited studies on UDMH, many of the environmental impacts of the fall of UDMH from rocket launches are not well understood, or perhaps even entirely unknown.

Rocket engines that use kerosene as propellant primarily emit CO, CO_2 and water vapour. While CO emissions could pose a threat to biological organisms, it is believed that most of the CO is quickly oxidised to CO_2 (due to high temperatures in the exhaust plume) which, if true, would mitigate the harm (NASA technical report, 2014). The impact of kerosene propelled space rocket exhaust on ecosystems has not been studied in detail, however, it likely has considerably less impact that UDMH or solid propellant. A report prepared by New Zealand's National Institute of Water and Atmospheric Research assessing the environmental impacts on marine environments from launching RocketLab's kerosene propelled Electron launch vehicles determined that kerosene poses a low risk of marine toxicity due to the surface evaporation of the likely small amounts of kerosene that may reach the ocean from a launch (MacDiarmid et al., 2016). It is unlikely that launches of space vehicles propelled by LOx/LH_2 emit any ecologically toxic material as the exhaust is water vapour. In addition, the more common use of LOx/LH_2 is in the upper stages of rockets, meaning that at low altitudes there is little exposure to the exhaust.

As noted in Table 1, all combustion engine emissions include NO which can form nitrogen oxides (NO_x), and N_2O emissions, which are major air pollutants and can result in numerous environmental and human health impacts (Price et al., 1997). NO_x can lead to the deterioration of water quality through increased nitrogen loading. Excess nitrogen in water bodies can lead to eutrophication, which can cause the death of fish and other biological organisms that live in the water body (EPA, 1998). Ecosystem eutrophication is problematic as certain species are adapted to nutrient poor conditions and can no longer compete in areas where nutrients have increased (Bouwman et al., 2002). In addition, NO_x also results in ecosystem acidification, changing soil pH and making forests vulnerable to stressors including pests and frosts (Bouwman et al., 2002). Studies have shown that the direct exposure of air pollution to plants can have a detrimental effect on vegetation, resulting in plant damage (Landolt and Keller, 1985) and stunted plant growth (Kammerbauer et al., 1986). However, NO_x exposure can also lead to increased growth of certain plant species, leading to changes in the relative competition between plant species and changes in the species makeup of areas exposed to high levels of NO_x through air pollution (Angold, 1997).

3.5. Human toxicity

3.5.1. Human toxicity resulting from SRM launches

Few human toxicity studies specifically related to the emissions of rocket launches exist, however impacts are likely to only be experienced proximal to the launch site. The most acute risk to human health associated with the launch of SRMs is exposure to HCl (NASA technical report, 2014). While HCl exposure is toxic to humans, most experiments carried out on HCl exposure are limited to short exposures at high concentrations, rather than longer periods of intermittent exposure at lower concentration. NASA's environmental impact assessments for SRM launches have determined that due to the remote location of the launch site and the launch trajectories being over the open ocean, it is unlikely that there is human exposure to most of the emission products (NASA technical report, 2007, 2011, 2014). This emphasises the importance that launch location, prevailing winds and launch trajectories have over the magnitude of impacts.

3.5.2. Human toxicity resulting from LRE launches

While long term indirect exposure of a population to UDMH and its products may come from soil or water, direct exposure primarily occurs through the atmospheric distribution of UDMH (Carlsen et al., 2007). As noted by Carlsen et al. (2007), UDMH is not bioaccumulating, so direct exposure may pose the biggest risk to human health.

There are many health effects that may result from exposure of biological organisms to UDMH and its transformation products, including high probabilities that it is carcinogenic, mutagenic and toxic to embryos (Carlsen et al., 2009). A study of 6107 aerospace workers, conducted to compare cancer mortality between workers exposed and unexposed to hydrazine fuels, found that exposed workers were 1.7–2.1 times more likely to die from lung cancer, with similar mortality rates, although less precise, for lymph, bladder and kidney cancers (Ritz et al., 1999).

Rocket engines that use kerosene as propellant primarily emit CO, CO_2 and water vapour. While CO emissions could pose a threat to human health, most of the CO is quickly oxidised to CO_2 which mitigates the harm (NASA technical report, 2014). As with ecosystem toxicity it is unlikely that launches of space vehicles propelled by LOx/LH_2 emit any substances that are toxic to human health.

4. Conclusion

In this study, a review of the environmental impact of space rocket launches is presented. Based on this review, it is clear that solid rocket motors have dominated studies of this kind, due primarily to their use in the U.S. space shuttle programme and associated legislative requirements. Despite predictions that space launches are likely to continue to increase as space travel becomes more accessible and affordable, there are few recent studies on the environmental impact of space launches, with most of the reviewed literature being published in the 1980s, 1990s and early 2000s. It is probable that the number of rockets propelled by kerosene and/or LOx/LH_2 will continue to increase by a larger amount than SRM and UDMH propelled launches. Possible future limits on the emission of ozone depleting substances from rocket launches will likely prevent a large increase in the number of SRM launches, due to the cumulative impact on stratospheric ozone, while the detrimental impact that the use of UDMH has had on human health means it is unlikely that it will continue to be used for a high number of launches in the future. This review highlights the relative lack of environmental studies on LRE launches, in particular for kerosene and LOx/LH_2, which is concerning given the likelihood that they will be the dominant propellant types used for launches, at least in the near future.

One key finding of this review is that it is clear that further studies are required, as our understanding must be improved to ensure the prevention and/or effective mitigation of any harmful environmental impacts resulting from both individual launch events and the possible cumulative effects of frequent launches. While economic and technical considerations are vital to the success of any space mission, it is important also that environmental considerations be included to avoid long term environmental damage, such as that observed in Kazakhstan due to the prolonged use of UDMH rocket propellant. The increasing frequency of space launches provides researchers and launch operators with the opportunity to characterise and quantify the environmental impact of these launches on a regular basis through the use of environmental monitoring systems, which would also allow cumulative impacts to be studied in more detail.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

The authors are grateful to two anonymous reviewers for their helpful and constructive feedback on this manuscript. Financial support for this research was provided by the Australian Government Research Training Program Scholarship.

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