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Potential Atmospheric Impact Generated by Space Launches Worldwide—Update for Emission Estimates from 1985 to 2013

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1. Executive Summary

This report evaluates the exhaust products generated from launch vehicles worldwide. The report addresses the potential for environmental impact from emissions due to space launches both from the United States Air Force (USAF) and from worldwide sources. The impacts considered are ozone destruction and global climate change. This report contains updated information on atmospheric deposition of carbon dioxide, soot, water vapor, nitrogen oxides, sulfates, inorganic chlorine, and alumina particulates due to launch vehicles. Several areas of concern for future National Environmental Policy Act (NEPA) analysis are addressed. This update contains new information concerning deposition of substances of atmospheric concern for the launch years 1985 to 2013 and insight into deposition of future programs.

Solid rocket motors containing the propellants aluminum and ammonium perchlorate (NH_4ClO_4) are of particular interest because of the impact the inorganic chlorine compounds from the exhaust of these vehicles can have on stratospheric ozone. The inorganic chlorine generated in the exhaust has the potential for both transient and long-term damage to stratospheric ozone. Aluminum oxide (alumina) particles are generated in this exhaust and can also have an impact on ozone concentrations in the stratosphere. Nitrogen oxides in certain launch vehicle exhaust (mostly those that contain nitrogen in the propellant) can impact ozone concentrations in the stratosphere as well.

The exhaust from every launch vehicle contains many components that have the potential to affect atmospheric concentrations of greenhouse gases. These greenhouse gases absorb and emit radiation within the thermal infrared range. The loss or gain of greenhouse gases has the net effect of changing the total global radiative balance. Exhaust components such as soot, alumina, and upper atmospheric clouds have the potential to scatter incoming light in addition to absorbing longwave radiation light, and thus they also have the potential to affect the total global radiative balance. Launch vehicles are different from many other anthropogenic sources of these exhaust components, such as automobile emissions and power generation, in that launch vehicles deposit exhaust components directly into all levels of the Earth's atmosphere rather than just the lower troposphere.

To date, the largest environmental concern generated by launch vehicles comes from solid rocket motors. Solid rocket motor exhaust makes a relatively small contribution to global ozone losses, which are dominated by chlorofluorocarbons (CFCs) and halons. These substances are the subject of international controls and are currently decreasing in concentration in the atmosphere. However, due to their long atmospheric lifetimes, CFCs will still be the dominant source of stratospheric chlorine well into the next century barring a dramatic increase in current launch rates.[1] Solid rocket motors also contain ammonium perchlorate that can contaminate ground water if released accidentally.

Historically, the Space Shuttle has had the largest emissions impact among launch vehicles into the atmosphere. The current era is tracking the post retirement of the shuttle program. The contribution of launches to stratospheric chlorine had previously been predicted to be greatly influenced by the retirement of the Space Shuttle, the launch schedule, and selection of a Space Shuttle replacement vehicle. The 2012 and 2013 emission totals provide a first glimpse at the emission environment in the post-shuttle era. Currently, the replacement vehicle for the Space Shuttle is a combination of a variety of launch vehicles, all using similar propellants: the Falcon 9 vehicles, the Antares vehicle, and the European Union (EU) Soyuz have replaced the Space Shuttle for resupplying the International Space Station. Several other launch vehicles that utilize different propellants are planned to compete for future NASA contracts. Before the end of the shuttle program, foreign launches, particularly from Europe, Japan, and India, were becoming a greater influence on the stratospheric chlorine levels from launches. Now with the retirement of the Space Shuttle, they potentially could become the major source of stratospheric chlorine and alumina from launches. Foreign launches are already the major source of stratospheric NO_x launch emissions.

Prior to 2006, the United States Air Force (USAF) launches had historically contributed 20–25% of the stratospheric chlorine from launches worldwide. This percentage has greatly decreased since 2006 with the retirement of the Delta II, Titan IV, and Atlas IIAS. The current fleet of USAF launch vehicles releases much less inorganic chlorine into the stratosphere than the Titan IV and Atlas IIAS. The current fleet uses smaller thrust solid rocket motors for added thrust-to-orbit needs. This type of motor increases the amount of ozone destroyed by alumina particles because they generate more small long-lived particulates than large thrust motors. However, many of the motors are used primarily during launch assist and thus burn the vast majority of their propellant in the troposphere.

1.1 Introduction

This report is an update of the 2007–2012 reports addressing the environmental impact of emissions from space launches.[2–5] The report, "Potential Impact of Space Launches Worldwide to Global Climate Change," focused on ozone destruction from inorganic chlorine sources. The environmental effect of chlorine from anthropogenic sources was of great interest beginning in the mid-1970s as scientific evidence showed that prolonged stratospheric ozone depletion resulted from the presence of stratospheric chlorine.[6] The "Montreal Protocol on Substances that Deplete the Ozone Layer" was ratified in 1989 and places controls on the production and consumption of halogen source gases known to cause ozone depletion. There have been three subsequent amendments to the protocol to further restrict production (London 1990, Copenhagen 1992, and Beijing 1999). As a result of these restrictions, the chlorine concentration from halogen sources is now decreasing in the atmosphere.[7,81] Solid rocket motors containing the propellants aluminum and ammonium perchlorate (NH_4ClO_4) are of particular interest due to the impact the inorganic chlorine and alumina compounds from the exhaust of these rockets can have on stratospheric ozone. The solid rocket motor exhaust has the potential for both transient and long-term damage to stratospheric ozone.[8–16]

The reports[2–5] also addressed the contribution of space launches to long-term climate change due to anthropogenic changes to the atmosphere. The basic principle that certain gases (referred to as greenhouse gases) can absorb and radiate heat has been understood for almost 150 years.[17] It was soon thereafter speculated that changes in the concentration of these greenhouse gases could potentially lead to a change in global temperature.[18–23] The advent of the computer age led to an improved ability to model global climate and make predictions of long-term global temperature trends.[24–26] In 1979, the National Academy of Science first convened to examine the evidence for the effect of greenhouse gases on long-term global temperature trends. The academy concluded that a doubling of carbon dioxide concentration in the atmosphere would lead to 1.5 to 4°C change in global temperatures.[27] Better computer models and an increased accuracy of long-term temperature data have led to more accurate predictions since 1979. The conclusion that greenhouse gases from anthropogenic sources are building up in the Earth's atmosphere and that this will lead to significant future global temperature increases relative to historical trends has been reaffirmed by the National Academy of Science,[28–30] the Environmental Protection Agency,[19] and the Intergovernmental Panel on Climate Change.[31–36,77,79]

This report will attempt to summarize and characterize the potential impact of emissions from space launches on the environment since 1985. The report will compare global worldwide launches to the USAF launches. This updated report has three primary objectives:

- Determine an estimate of the amount of emissions from launches for the years 1985 to 2013 based on vehicles used and launch rates.
- Estimate near-term future emissions.
- Estimate the potential extent of the environmental impact from these emissions from 1985 to 2013.

The current report differs from previous studies in that it:

- Determined US emissions based on launch site.
- Changed the emissions formulas of NO_x and NO_{xstrat} to better match previous modeling of emissions by altitude.
- Changed the emissions formula of Cl_x and alumina to better match previous modeling of emissions by altitude.
- Included a brief section summarizing new Aerospace Corporation estimates of radiative forcing impacts due to launch vehicles.
- Modified previous estimation methods based on recent reports from The Aerospace Corporation. The significant difference from the previous report is an increase in water vapor's radiative forcing estimate and the addition of a better estimate of alumina radiative forcing. The original report estimated impact based on comparison to silica, but new reports suggest this comparison was not accurate.
- Compared previously reported estimates to literature estimates determined by new methods.
- Called for more direct atmospheric modeling of launch vehicle components to more accurately determine impacts.
- Previous reports only looked at emissions above the troposphere for most emission components. This report lists in the appendix emissions in four generic atmospheric ranges: troposphere 0–15 km, stratosphere 15–50 km, mesosphere 50–80 km, and thermosphere above 80 km.
- Added a summary of propellants used by the existing worldwide fleet in Table A2 of the appendix of the report.

1.2 Contents of the Report

Section 1 is the introduction.

Section 2 is a summary of the emissions data for launch activities from the years 1985–2013. Emissions data from ballistic missile tests were not included in the 1994 report but have been included in the updates.[15,2,3] The current summary also includes the emission data for several new launch vehicle programs and suborbital programs. The section also includes emissions data for inorganic chlorine and alumina from upper stages with solid rocket motors. The emissions data now estimates soot emissions in the upper atmosphere for launch vehicles. The actual emissions data is compared to previous predictions. Future emission data is predicted by using current launching trends and the introduction of new vehicles to replace the Space Shuttle launches (Falcon 9, Soyuz, Antares, and possibly Space Launch Systems (SLS)).

Section 3 is a summary of the environmental impact of emissions. The role of inorganic chlorine, alumina, and oxides of nitrogen (NO_x) emissions in the catalytic destruction of ozone is discussed. Then the change in the Earth's radiative balance caused by changes in greenhouse gas concentrations due to launch vehicle emissions is discussed. The impact of USAF launches is presented separate from the impact due to total worldwide launches.

Section 4 is the conclusion.

2. Amount of Emission Deposition by Launch Vehicle

An estimation of the composition of the exhaust plume for a launch vehicle can be determined by converting the available propellant on the launch vehicle to their combusted exhaust products. Many launch vehicles use a combination of fuels and oxidizers that change depending on the stage of the launch vehicle. Table 7 in the appendix lists the current vehicles in the worldwide fleet as of 2013 and their propellant types used by stage. The individual propellants must be converted to relevant exhaust products in order to evaluate them.

2.1 Inorganic Chlorine and Alumina

An estimation of the composition of the exhaust plume can be determined by converting the weight of solid propellant to alumina (Al_2O_3) and hydrochloric acid (HCl) since these two substances dominate the immediate exhaust plume. The results from this estimate are similar to results from flight simulation codes that estimate the rate of propellant consumption as a function of altitude for U.S. launch vehicles and predict the immediate composition of the exhaust plume.[37] The previous report had emission data for Delta II, Atlas IIAS, Titan IV, and the Space Shuttle from flight simulation codes. The total solid propellant mass (TSPM) is converted to mass alumina (MA) in the immediate exhaust plume by the following expression:

$$\mathrm{MA} = \mathrm{TSPM} * \%\mathrm{Al}_{\text{(in solid propellant)}} * \frac{(26.98\,\mathrm{g} * 2 + 16.00\,\mathrm{g} * 3)}{(26.98\,\mathrm{g} * 2)} \tag{1}$$

The total solid propellant mass (TSPM) is converted to mass HCl (MHCl) in the immediate exhaust plume by the following expression:

$$\mathrm{MHCl} = \mathrm{TSPM} * \%\mathrm{NH_4ClO}_{4\,\text{(in solid propellant)}} * \frac{(35.45\,\mathrm{g} + 1.008\,\mathrm{g}))}{(35.45\,\mathrm{g} + 16.00\,\mathrm{g} * 4 + 14.01\,\mathrm{g} + 1.008\,\mathrm{g} * 4)} \tag{2}$$

The percentage of aluminum and ammonium perchlorate in the solid rocket fuel varies from rocket to rocket. The ammonium perchlorate is generally between 65 and 75% of the propellant mass, and aluminum is generally 15–18%. The remaining propellant mass is a binder. The binder is usually a synthetic polymer based on a form of polybutadiene or polyurethane. Many papers refer to Cl_x emissions in terms of mass of chlorine instead of HCl; however, the difference in mass of Cl and HCl make negligible difference (3%) for comparison purposes.

Not all the inorganic chlorine generated is deposited in the stratosphere. Most launch vehicles use solid rocket motors in the initial boost stage only. Thus, most of the launch vehicles will burn large portions of their solid fuel in the troposphere. For launch vehicles, the deposit of inorganic chlorine in the troposphere has only a small effect on stratospheric ozone. In the troposphere, the inorganic chlorine is rapidly reacted away to form water-soluble products and particles that are washed out of the atmosphere by rain in a time that is shorter than the transport time from the troposphere to the stratosphere. The height of the troposphere-stratosphere boundary varies in latitude, temperature, and atmospheric conditions. The previous report[37] assumed the boundary to be a constant value of 15 km. In order to determine an estimate of the total amount of inorganic chlorine deposited in the troposphere and stratosphere, typical trajectories of the launch vehicle in question must be known. As determined previously, the trajectory and propellant burn rate of each vehicle depend on the payload and mission. It was found previously that the total deposition in the stratosphere versus troposphere will only change by a few percent at most with each launch.[37] Typical launch profiles where available were used to determine the amount of inorganic chlorine deposited.[38] For those launch vehicles where the data was unknown, launch profiles of similar launch vehicles were used. The total inorganic chlorine and alumina deposited above 15 km from launch vehicles is given in Table 1.

Table 1. Total Inorganic Chlorine and Alumina (Tons per launch) Generated Above 15 km from Launch Vehicles

Vehicle	Inorganic Chlorine (Tons/launch)	Alumina (Tons/launch)
Titan IVB SRMU	56.9	87.8
Titan IVA SRMU	36.9	69.0
Titan 34D	27.0	40.0
Delta II 79X5H	10.4	16.1
Delta II 79X5	7.1	11.1
Delta II 73X5	0.4	0.7
Delta II 74X5	0.4	0.7
Delta II 89XX	10.0	15.5
Delta II 69X5	6.0	10.0
Delta II 39XX	5.7	8.8
Delta II 49X0	6.1	10.4
Delta II 59X0	6.1	9.4
Delta IVM	0.0	0.0
Delta IVM +(4,2)	0.7	1.0
Delta IVM +(5,2)	0.7	1.0
Delta IV H	0.0	0.0
Atlas IIAS	3.3	5.4
Atlas V X5Z	14.7	23.9
Atlas V X4Z	11.7	19.1
Atlas V X3Z	8.8	14.3
Atlas V X2Z	5.9	9.6
Atlas V X1Z	2.9	4.8
Atlas V X0Z	0.0	0.0
Scout G-1	2.5	3.6
Pegasus	3.2	4.4
Pegasus XL	3.9	5.3
Taurus G	7.5	11.2
Taurus XL	8.2	12.3
Space Shuttle	92.2	129
Space Launch System	130	182
ARES 1 (Liberty)	57.9	81.1
Athena 1	5.8	8.7
Athena 2	16.3	23.7
Minotaur I	3	4.5

Vehicle	Inorganic Chlorine (Tons/launch)	Alumina (Tons/launch)
Minuteman III	2.8	4.3
Minotaur IV	10.8	16.7
Minotaur V	11.0	16.9
Minotaur VI	18.6	31.2
Peacekeeper	10.4	15.4
Ariane 4LP	0	0
Ariane 44P	0	0
Ariane 42P	0	0
Ariane 5	55	84.9
Ariane 6	75.8	127.2
VEGA	19.3	26.6
N2	0	0
H1	6.3	9.3
H2 2020	11.3	15.5
H2 2022	16.9	23.4
H2 2024	22.5	31.3
H2 2040	25.9	36.0
H2 B 3040	25.9	36.0
M-V	13.7	19
M-3SII	4.3	6.0
Epsilon	8.6	11.0
START 1	4.3	5.9
ASLV	3.0	6.2
PSLV	20.1	27.6
GSLV	14.6	20.0
GSLV Mk3	18.2	25.0
Spaceloft	0.006	0.008
Spaceloft XL	0.033	0.045
KSLV1	0.976	1.339
Super Strypi	3.3	5.6
Antares	2.7	4.6

Note: New vehicles added to study since the last report are shown in blue.

2.2 Carbon Dioxide

The amount of carbon dioxide emission produced depends heavily on a combination of the fuel and oxidizer used for the launch vehicle. Many launch vehicles use a combination of fuels and oxidizers that changes depending on the stage of the launch vehicle. The individual propellants must be converted to relevant exhaust products in order to evaluate their emissions. Hydrocarbon fuels like kerosene or RP-1 are composed of long chains of hydrocarbons that oxidize to produce carbon dioxide and water vapor. They can be simulated as being composed of a series of (CH_2) groups. The total kerosene mass is converted to mass of CO_2 (MCO2) in the immediate exhaust plume by the following expression:

$$\mathrm{MCO2} = (\mathrm{Mass\ \ kerosene}) * \frac{(12.01\,\mathrm{g} + 16.00\,\mathrm{g} * 2)}{(12.01\,\mathrm{g} + 1.008\mathrm{g} * 2)} \tag{3}$$

The same conversion can be used to simulate the burning of RP-1 rocket fuel.

Aerozine 50 is a UDMH (unsymmetrical dimethyl hydrazine, $C_2H_8N_2$) rocket fuel mixed with hydrazine (N_2H_4). The total UDMH mass in Aerozine 50 is converted to mass of CO_2 (MCO2) in the immediate exhaust plume by the following expression:

$$\mathrm{MCO2} = 0.50 * (\text{Mass Aerozine50}) * \frac{(2 * 12.01\,\mathrm{g} + 16.00\,\mathrm{g} * 4)}{(60.104\,\mathrm{g})} \tag{4}$$

Launch vehicles sometimes burn straight UDMH, mono methyl hydrazine (MMH, $CH_3N_2H_3$) or a mixture of hydrazine and UDMH called UH25. The total UDMH mass converted to mass of CO_2 (MCO2) in the immediate exhaust plume is evaluated using the following expression:

$$\mathrm{MCO2} = (\text{Mass UDMH}) * \frac{(12.01\,\mathrm{g} * 2 + 16.00\,\mathrm{g} * 4)}{(60.104\,\mathrm{g})} \tag{5}$$

Another launch vehicle propellant is monomethyl hydrazine ($CH_3N_2H_3$). The total MMH mass can be converted to mass of CO_2 (MCO2) in the immediate exhaust plume by the following expression;

$$\mathrm{MCO2} = (\text{Mass MMH}) * \frac{(12.01\,\mathrm{g} + 16.00\,\mathrm{g} * 2)}{(46.078\,\mathrm{g})} \tag{6}$$

The total UH25 mass converted to mass of CO_2 (MCO2) in the immediate exhaust plume by the following expression:

$$\mathrm{MCO2} = 0.75 * (\text{Mass UH25}) * \frac{(12.01\,\mathrm{g} * 2 + 16.00\,\mathrm{g} * 4)}{(60.104\,\mathrm{g})} \tag{7}$$

Many launch vehicles use solid rocket motors for additional thrust. Ammonium perchlorate does not release any carbon dioxide upon burning. However, about 12–16% of the propellant mass is composed of binding material (generally a hydrocarbon binder) that will burn to form carbon dioxide. The amount of carbon dioxide produced is thus determined by the amount of the propellant mass that is not composed of ammonium perchlorate or aluminum.

$$\mathrm{MCO2} = (1 - \%\ NH_4ClO_4 - \%\ Al) * \frac{(12.01\,\mathrm{g} + 16.00\mathrm{g} * 2)}{(14.026\mathrm{g})} \tag{8}$$

The carbon dioxide has a long lifetime in the atmosphere, with estimates of a carbon dioxide release decaying to 0.368 (l/e) of its original value in 100 to 300 years,[77] and thus the layer in which it gets deposited is not as significant. The exact removal process is complicated, and as much as 20% of the carbon dioxide released can last in the atmosphere for thousands of years after release.[77]

2.3 Black Carbon Soot

Not all the carbon in the fuel will ultimately be fully oxidized into carbon dioxide. Thus, the amounts determined in Subsection 2.2 are an overestimate. The exact mass of black carbon soot formed is dependent on engine design and flight profile. In the lower atmosphere, the soot in plume exhaust is generally modeled to be oxidized due to afterburning. This process decreases in significance as the density of the atmosphere and temperature of the afterburning plume changes with increased altitude. Previous modeling of the soot plume of kerosene engines used a value of 20–40 g of soot formed per kg propellant in the stratosphere.[39] This fits observations of Alexeenko et al. for Atlas II launches with a low mass fraction at 15 km (0.001) and a higher mass fraction at a higher altitude of 40 km (0.02). [40] The higher numbers generally reflect older Atlas engines that ran with fuel-rich gas generators. Previous reports of the Atlas E have mass fractions of 0.025.[41] A comparable mass fraction was measured in the exhaust of a model of the Saturn F-1 engine in studies conducted at Rocketdyne.[42,43] Modern kerosene engines designed in Russia are thought to generate less soot than these older kerosene engines. Observations of the mass fraction of soot (0.0017 at 21 km) are less than expected based on observations from reference 39 and fit this assumption.[44–46] The Atlas II was modeled with values of 0.001 to 0.0017 to verify experimental data obtained during an Atlas II flight in May 2000 at altitudes 11–51 km.[46] The higher soot numbers,[39,40] in general, do not fit the current information available and used in this report. In the lower stratosphere, the soot formation is likely an order of magnitude lower than the Ross et al. values.[39] In the upper atmosphere (>100 km), the mass fraction of soot likely scales to around 1% of the plume. A conservative estimate of 0.5% soot mass fraction for the lower stratosphere will be used here, and 1% will be used for the soot formation of kerosene engines above the stratosphere. This possibly overestimates the soot formed in the lowest parts of the stratosphere and may underestimate soot formation in the upper atmosphere. Part of the reasoning for using a slightly higher estimate in the upper stratosphere is that several newer launch vehicles are likely to produce more soot than Russian engines. The relatively new Falcon 9 vehicle runs fuel rich currently and thus may generate soot emissions similar to the older launch vehicles. The Falcon 9 engine design has gone through several iterations and does not represent a large percentage of the worldwide launch fleet. The soot production (sooting) from the Chinese-fueled engines is also much less certain than the Russian fleet.

All hydrocarbon combustion engines have the potential to produce soot. The engines that utilize propellants kerosene and liquid oxygen are the best characterized engines for soot formation in the plume. There is no available information on soot formation from engines that use hydrazine derivatives. These hydrazine engines are/were often operated under more fuel-rich conditions than a kerosene/LOX engine.[38] Thus, they were operated under conditions more likely to produce soot. However, these engines use a fuel with much less carbon density. UDMH engines are 40% carbon by mass, and MMH is 26% carbon by mass. Since there are no experimental measurements to benchmark the soot formation from these motors, it is assumed here that they will be similar to kerosene engines scaled by the reduced mass fraction of carbon loading in the fuel.

Solid rocket motors also contain hydrocarbon fuel and thus can potentially produce soot in the plume as well. High-altitude plume measurements (114 km) have assumed a 2% soot mass fraction for solid rocket motors.[47] The plume observations are less sensitive to black carbon soot due to the alumina particulates in the plume. The soot mass fraction is lower at lower altitude. Plastinin et al.[48] modeled the Atlas II with solid rocket motor boosters with about 1% soot loading at 15 km and 40 km. Some of the soot was modeled to be oxidized in the lower stratosphere. A conservative estimate of 2% soot mass loading of soot formation in the upper stratosphere and above from solid rocket motors is used here. Once again it is assumed in the lower atmosphere that afterburning reduces the amount of soot formation, and the lower 1% number needs to be used. This potentially overestimates soot formation (sooting) in the lower stratosphere.

The lifetime of soot in the upper atmosphere is currently modeled with a decay constant of 4 years.[80]

2.4 Water Vapor

The amount of water vapor emission produced also depends heavily on a combination of the fuel and oxidizer used for the launch vehicle. Hydrocarbon fuels like kerosene or RP-1 are composed of long chains of hydrocarbons that oxidize to produce carbon dioxide and water vapor. They can be simulated as being composed of a series of (CH_2) groups. The total kerosene (RP-1) mass is converted to mass of water vapor (MH2O) in the immediate exhaust plume by the following expression:

$$\mathrm{MH2O} = (\mathrm{Mass\ kerosene}) * \frac{(1.008\,\mathrm{g} * 2 + 16.00\,\mathrm{g})}{(12.01\mathrm{g} + 1.008\mathrm{g} * 2)} \qquad (9)$$

The total hydrazine mass in Aerozine 50 (A50) is converted to MH2O in the immediate exhaust plume by the following expression:

$$\mathrm{MH2O} = (\mathrm{Mass\ Aerozine}) * (0.5 * \frac{(1.008\,\mathrm{g} * 8 + 4 * 16.00\,\mathrm{g})}{(60.104\,\mathrm{g})} + 0.5 * \frac{(1.008\,\mathrm{g} * 4 + 2 * 16.00\,\mathrm{g})}{(32.052\,\mathrm{g})} \qquad (10)$$

The total UDMH mass is converted to MH2O in the immediate exhaust plume by the following expression:

$$\mathrm{MH2O} = (\mathrm{Mass\ UDMH}) * \frac{(1.008\,\mathrm{g} * 8 + 4 * 16.00\,\mathrm{g})}{(60.104\,\mathrm{g})} \qquad (11)$$

The total MMH mass is converted to MH2O in the immediate exhaust plume by the following expression:

$$\mathrm{MH2O} = (\mathrm{Mass\ MMH}) * \frac{(1.008\mathrm{g} * 6 + 3 * 16.00\,\mathrm{g})}{(46.078\,\mathrm{g})} \qquad (12)$$

The total UH25 mass is converted to MH2O in the immediate exhaust plume by the following expression:

$$\mathrm{MH2O} = (\mathrm{Mass\ UH25}) * (0.75 * \frac{(1.008\,\mathrm{g} * 8 + 4 * 16.00\,\mathrm{g})}{(60.104\mathrm{g})} + 0.25 * \frac{(1.008\,\mathrm{g} * 4 + 2 * 16.00\mathrm{g})}{(32.052\,\mathrm{g})} \qquad (13)$$

The amount of water vapor produced by a solid rocket motor is determined by the amount of the propellant mass that is composed of ammonium perchlorate and binder.

$$MH2O = (1 - \%NH_4ClO_4 - \%Al) * \frac{(1.008g * 2 + 16.00\,g)}{(14.0126g)} + \%NH_4ClO_4 * \frac{(1.008g * 4 + 16.00\,g * 2)}{(117.492\,g)}) \tag{14}$$

The location of the generation of the water vapor exhaust is important. Water vapor released in the troposphere has a short lifetime and simply participates in the natural hydrological cycle. Stratospheric water vapor has a much longer lifetime and thus the amount deposited in the stratosphere and above must be tracked.

The estimate predicts about 222 tons of water vapor from a Proton launcher, which approximately matches the amount predicted from Ross et al. (218 tons).[49] The shuttle main engine produced about 700 tons of water vapor during launch.[50,51] This determination is from using the on-board oxygen. The fate of unspent released hydrogen in the atmosphere is to be oxidized to water vapor slowly—about 2 years lifetime for hydrogen in the atmosphere.[52] For rocket motors that release significant hydrogen into the atmosphere, the current water vapor determinations probably overpredict initial water vapor produced.

2.5 Sulfates

Sulfur is an impurity in kerosene fuel. There is 0.03 g of sulfur per kg of RP-1 fuel.[53] Sulfur will oxidize during the burning of the fuel to form sulfate H_2SO_4. This expelled sulfate will form aerosols in the stratosphere.

2.6 NO_x

Afterburning is the major factor in NO_x production from exhaust plumes. In general, all propellants produce NO_x *via* afterburning in the troposphere where atmospheric nitrogen densities are high. In the stratosphere, only vehicles that use nitrogen-based propellants produce significant NO_x concentrations. The unspent nitrogen tetroxide propellant does not contribute significantly to the NO_x exhaust concentrations. The NO_x produced was determined by scaling the NO_x emissions to the total launch vehicle emissions by using the NO_x mass flow per total mass flow determinations of Zittel for different types of rocket motors.[54] Zittel also previously determined the changes in NO_x production with changes in altitude for different fuel/oxidizer combinations.[54] Previous reports overestimated NO_x generated in the upper atmosphere, and the new determination more closely resembles prediction of Zittel for the predicted fall-off in afterburning with altitude.

Popp et al.[55] have measured the NO_2 emission at 18 km from an Athena II solid rocket plume. They measured the mass (g) of NO_2 released per mass (kg) of fuel to be 2.7±6. The current calculation used for this work is based on the Athena II a value of 2.8 g NO_2 per kg of fuel, which is in good agreement with experiment. In the same study, Popp et al.[55] also measured a CO_2 exhaust of 382 g per kg while 345 g per kg were predicted from the above equations. This shows there is reasonable agreement between experimental measurements and predicted exhaust values for solid rocket motors.

2.7 Exhaust Totals for Launch Vehicles

Table 2 lists the total carbon dioxide and sulfate generated for each launch vehicle; the amount of NO_x, alumina, soot, and water vapor generated in the stratosphere and upper atmosphere for each vehicle; and the amount of NO_x generated in the troposphere. The table is not all inclusive. There are vastly more vehicles designed and proposed than can be listed. To accomplish the task, the table reflected vehicles that either have previously flown or have been proposed to launch in the near future. There are several proposed launch vehicles for which not enough information is available to estimate their likely emissions: Chengzhang 11, China; H-III, Japan; ULV, India; Unha X, North Korea; Safir-3, Iran.

Table 2. Mass (in tons) of Greenhouse Gases and Particulates Generated in the Exhaust Plumes of Launch Vehicles. The carbon dioxide is the total amount for the launch. The water vapor is determined for the stratosphere and above since water vapor released into the troposphere has a short lifetime. Nitrogen dioxide is separated between short-lived tropospheric NO_x, which contributes to the formation of tropospheric ozone and stratospheric and above releases that contribute to the formation of stratospheric aerosols. Also shown is stratospheric release of sulfate.

Vehicle	Total CO_2	Stratospheric Soot	Stratospheric Water Vapor	Tropospheric NO_x	Stratospheric NO_x	Stratospheric Sulfate
Brazil						
VLS	7.2	0.22	5.25	0.06	0.01	0.0000
VLM	4.9	0.07	2.14	0.08	0.00	0.0000
China						
Kaitouzhe-1	11.9	0.19	3.55	0.23	0.00	0.0000
Long March 2C	101.1	0.42	49.03	0.65	1.05	0.0000
Long March 2D	101.2	0.43	49.08	0.65	1.05	0.0000
Long March 2C/SD	101.2	0.43	49.08	0.65	1.05	0.0000
Long March 2E	198.7	1.05	105.50	1.13	2.21	0.0000
Long March 2F	198.7	1.05	105.50	1.13	2.21	0.0000
Long March 3	83.3	0.35	53.32	0.54	0.87	0.0000
Long March 3 A	93.6	0.41	74.05	0.58	1.00	0.0000
Long March 3 B	138.1	0.59	95.49	0.87	1.45	0.0000
Long March 3 C	173.4	0.68	109.19	1.16	1.75	0.0000
Long March 4 A	107.9	0.60	61.81	0.53	1.12	0.0000
Long March 4 B	107.9	0.60	61.81	0.53	1.20	0.0000
Long March 4 C	107.9	0.60	61.81	0.53	1.20	0.0000
Long March-5 340	359.3	1.89	94.04	0.62	0.00	0.0031
Long March-5 540	218.8	1.48	271.08	0.74	0.00	0.0020
Russian						
Angara A1.2	127.2	0.55	42.30	0.20	0.00	0.0011
Angara A3	381.9	1.66	126.90	0.60	0.01	0.0033
Angara A5	614.8	2.56	211.52	1.01	0.02	0.0053
Cyclone 2	68.2	0.33	32.06	0.46	0.69	0.0000
Cyclone 3	69.5	0.34	33.09	0.46	0.72	0.0000
Cyclone 4	72.2	0.37	35.45	0.46	0.79	0.0000
DNEPR-1	74.7	0.36	36.64	0.48	0.79	0.0000
Kosmos 3M	41.1	0.18	19.54	0.27	0.42	0.0000
Molniya 2BL	248.7	1.27	66.09	0.42	0.00	0.0013

Vehicle	Total CO_2	Stratospheric Soot	Stratospheric Water Vapor	Tropospheric NO_x	Stratospheric NO_x	Stratospheric Sulfate
Molniya ML	248.7	1.27	66.09	0.42	0.00	0.0013
Molniya M	248.7	1.27	66.09	0.42	0.00	0.0013
Proton K	260.7	1.29	133.42	1.57	3.03	0.0000
Proton K/DM	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM1	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/D-1	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/D-2	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM-2	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM-2M	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM-3	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM-3M	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM-4	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/DM-5	273.3	1.45	138.81	1.57	3.03	0.0000
Proton K/Br.M	261.8	1.31	134.37	1.57	3.06	0.0000
Proton M/Br.M	261.8	1.31	134.37	1.57	3.06	0.0000
Rockot/ Br.K	40.2	0.24	22.87	0.20	0.51	0.0000
Rockot/Br. KM	40.2	0.24	22.87	0.20	0.51	0.0000
Shtil-1	13.8	0.09	8.15	0.06	0.18	0.0000
Shtil-2	13.8	0.09	8.15	0.06	0.18	0.0000
Soyuz 2-1A	240.3	1.27	62.64	0.42	0.00	0.0012
Soyuz FG/Fregat	245.4	1.29	65.84	0.42	0.07	0.0012
Soyuz FG	242.9	1.27	63.70	0.42	0.00	0.0012
Soyuz U	243.0	1.27	63.73	0.42	0.00	0.0012
Soyuz U2	243.0	1.27	63.73	0.42	0.00	0.0012
Soyuz U/Ikar	243.3	1.27	64.01	0.42	0.01	0.0012
Soyuz U/fregat	245.5	1.29	65.87	0.42	0.07	0.0012
Start	15.6	0.23	6.63	0.25	0.01	0.0000
Strela	37.9	0.19	19.19	0.23	0.41	0.0000
Volna	13.8	0.09	8.15	0.06	0.18	0.0000
Vostok	179.3	1.24	45.09	0.40	0.15	0.0006
Zenit-2	341.7	2.32	100.28	0.48	0.00	0.0027
Zenit-3SL	356.5	2.49	107.05	0.48	0.00	0.0027
Israel						
Shavit-1	9.6	0.12	3.90	0.16	0.00	0.0000
South Korea					0.00	
KSLV	111.6	0.78	33.76	0.25	0.00	0.0011
Iran						
Safir	7.5	0.05	4.39	0.65	0.89	0.0
Europe						
Ariane 1	105.7	0.80	84.94	0.42	1.42	0.0000
Ariane 2	105.7	0.80	84.94	0.42	1.42	0.0000
Ariane 3	113.4	0.80	84.94	0.59	1.42	0.0000
Ariane 44L	168.9	1.08	114.71	0.85	2.05	0.0000
Ariane 44LP	145.6	0.80	99.90	0.84	1.73	0.0000
Ariane 40	105.7	0.80	84.94	0.42	1.42	0.0000
Ariane 42L	137.3	0.94	99.90	0.64	1.73	0.0000
Ariane 42 P	113.4	0.80	84.94	0.69	1.42	0.0000
Ariane 44 P	121.2	0.80	84.94	0.89	1.42	0.0000
Ariane 5	170.5	3.16	299.14	2.56	1.99	0.0000
Ariane 6	148.0	5.80	141.1	1.26	0.90	0.0000

Vehicle	Total CO_2	Stratospheric Soot	Stratospheric Water Vapor	Tropospheric NO_x	Stratospheric NO_x	Stratospheric Sulfate
Soyuz ESA	245.5	1.29	65.87	0.42	0.07	0.0000
VEGA	34.2	1.14	28.42	0.41	0.04	0.0000
JAPAN						
N 2	96.2	0.59	28.88	0.43	0.07	0.0008
H I	93.5	0.55	38.56	0.43	0.00	0.0000
H IIA 202	51.2	0.51	154.59	0.91	0.03	0.0000
H IIA 2022	61.5	0.62	154.59	3.63	0.03	0.0000
H IIA 2024	71.8	0.72	163.26	1.18	0.04	0.0000
H IIA 204	102.4	1.02	174.33	1.75	0.05	0.0000
H IIB 304	102.4	1.02	244.51	1.81	0.05	0.0000
Mu-3s-2	17.4	0.28	5.46	0.33	0.01	0.0000
M-V	44.4	0.77	21.71	0.64	0.02	0.0000
Epsilon	30.8	0.45	14.60	0.45	0.02	0.0000
North Korea						
Naro-1	113.0	0.03	36.13	10.42	36.13	0.0
Unha-3	26.0	0.11	10.89	10.78	10.89	0.0000
INDIA						
ASLV	11.3	0.02	0.68	0.28	0.00	0.0000
PSLV	97.4	1.90	53.68	1.18	0.44	0.0000
GSLV	127.8	1.27	85.90	0.99	0.31	0.0000
GSLV MK3	144.9	1.20	93.5	0.94	0.97	0.0000
U.S.A.						
Athena I	19.3	0.24	6.18	0.41	0.01	0.0000
Athena II	33.4	0.99	23.70	0.41	0.03	0.0000
Atlas I	130.0	1.07	66.87	0.10	0.00	0.0013
Atlas II	146.1	1.22	75.16	0.11	0.00	0.0014
Atlas IIA	146.1	1.22	75.16	0.11	0.00	0.0014
Atlas IIAS	156.4	1.63	82.08	0.30	0.01	0.0014
Atlas E	106.2	0.87	37.38	0.08	0.00	0.0010
Atlas G	130.0	1.07	66.87	0.10	0.00	0.0013
Atlas H	106.2	0.87	37.38	0.08	0.00	0.0010
Atlas IIIA	151.3	0.87	63.16	0.26	0.00	0.0015
Atlas IIIB	151.3	0.87	68.56	0.26	0.00	0.0015
Atlas V X5Z	297.2	2.49	125.65	1.66	0.03	0.0023
Atlas V X4Z	284.4	2.35	120.69	1.39	0.03	0.0023
Atlas V X3Z	271.6	2.20	115.74	1.11	0.02	0.0023
Atlas V X2Z	258.7	2.06	110.79	0.84	0.01	0.0023
Atlas V X1Z	245.9	1.92	105.84	0.57	0.01	0.0023
Atlas V X0Z	233.1	1.77	100.88	0.29	0.00	0.0023
Delta 4925	117.6	0.93	38.55	0.75	0.06	0.0009
Delta 5920	123.3	0.93	39.22	0.77	0.06	0.0009
Delta 3914	121.1	0.93	38.56	0.73	0.06	0.0009
Delta 3920	120.9	0.93	38.56	0.73	0.06	0.0009
Delta 6925	117.6	0.93	38.55	0.75	0.06	0.0009
Delta 792X	128.7	0.88	40.96	0.88	0.06	0.0009
Delta 792XH	144.1	1.10	46.26	1.20	0.08	0.0009
Delta 742X	109.4	0.60	29.94	0.59	0.03	0.0009
Delta 732X	105.3	0.60	29.94	0.47	0.03	0.0119
Delta 8930	144.6	0.79	41.72	1.31	0.05	0.0009
Delta 4M	33.2	0.00	208.76	0.24	0.00	0.0

Vehicle	Total CO_2	Stratospheric Soot	Stratospheric Water Vapor	Tropospheric NO_x	Stratospheric NO_x	Stratospheric Sulfate
Delta 4M (4,2)	18.1	0.70	215.06	0.81	0.01	0.0000
Delta 4M (5,2)	18.1	0.70	215.06	0.81	0.01	0.0000
Delta 4M (5,4)	36.1	1.41	221.37	1.37	0.01	0.0000
Delta 4H	0.0	0.00	632.25	0.54	0.00	0.0000
Falcon I	21.5	0.11	5.73	0.04	0.00	0.0002
Falcon V	0.0	0.00	0.00		0.00	
Falcon 9	326.6	1.94	94.72	0.71	0.00	0.0028
Falcon 9 v1.1	441.3	2.81	129.54	0.93	0.01	0.0037
Falcon H	1112.8	7.79	301.77	2.78	0.02	0.0052
K-1	293.0	3.00	88.46	0.41	0.03	0.0000
Minotaur	9.9	0.27	6.30	0.14	0.01	0.0000
Minotaur IV	27.0	0.61	15.05	0.40	0.02	0.0
Minotaur V	27.4	0.64	15.51	0.40	0.02	0.0000
Minotaur VI	40.1	1.44	32.4	0.40	0.15	0.0000
Pegasus XL	6.7	0.18	5.48	0.05	0.01	0.0000
Pegasus XL/HAPS	6.7	0.18	5.48	0.05	0.01	0.0000
Pegasus Std	5.5	0.15	4.52	0.04	0.01	0.0000
Pegasus Std/HAPS	5.5	0.15	4.52	0.04	0.01	0.0000
Scout 3G	5.0	0.15	3.61	0.01	0.00	0.0
Space Shuttle	442.9	4.27	975.70	6.87	0.22	0.0000
Taurus 1X10	19.6	0.72	20.89	0.09	0.03	0.0000
Taurus 2X10	19.6	0.72	20.89	0.09	0.03	0.0000
Taurus 3X10	19.6	0.72	20.89	0.09	0.03	0.0000
Titan IVA NUS	159.5	2.38	86.29	3.18	0.60	0.0016
Titan IVA 401	159.5	2.38	117.71	3.18	0.60	0.0016
Titan IVA 402	163.3	2.63	91.12	3.18	0.63	0.0016
Titan IVB NUS	156.3	2.67	92.17	3.53	0.58	0.0016
Titan IVB 401	156.3	2.67	123.60	3.53	0.58	0.0016
Titan IVB 402	160.2	2.92	97.01	3.53	0.51	0.0016
Titan II	36.0	0.23	16.60	0.27	0.34	0.0012
Titan 34D	133.1	1.58	57.98	3.23	0.49	0.0014
Titan 34B	133.1	1.58	57.98	3.23	0.49	0.0014
Titan III	133.1	1.58	57.98	3.23	0.49	0.0014
ARES I(Liberty)	280.0	3.0	284.0	1.9	0.145	0
Spaceloft	0.0	0.0	0.0	0.0	0.001	0
Black Brant XII	0.8	0.1	0.1	0.0	0.0	0
Spaceloft XL	0.3	0.0	0.1	0.0	0.001	0
Blue origin PM-2	17.4	0.3	16.0	0.1	0.001	0.0001
Super Strypi	8.9	0.2	4.1	0.06	0.03	0
Spaceship two	~26.5	0.396	~11	0	~0.1	~0
Antares	236.8	1.8	76.5	0.29	0.01	0.0015
Space Launch Systems	538	6	1346	8.3	0.3	0
South Africa						
Cheetah-1	52.5	0.6	12.3	0.2	0.001	0.0004

Note: New vehicles added to study since the last report are shown in blue.

2.8 Exhaust Totals

Table 3 lists the emissions for the USAF for the years 1985 to 2013. The emissions are also identified by launch site location. The USAF launches primarily from either Cape Canaveral or Vandenberg AFB. Several other minor launch sites, such as Wallops Island and Kodiak Island, from time to time

Table 3. Emissions (in tons) from all USA and USAF Launches for the Years 1985 to 2013. The carbon dioxide (CO_2) is the total amount generated for the year. The water vapor (H_2O) total is determined for the stratosphere and above since water vapor released into the troposphere has a relatively short lifetime. Nitrogen dioxide emissions are separated between short lived tropospheric NO_2 (NO_xtrop), which contributes to the formation of tropospheric ozone formation and stratospheric (NO_xstrat) and above releases that contribute to the formation of stratospheric aerosols. The amount of stratospheric inorganic chlorine (Cl_x) and alumina (Al_2O_3) emissions are shown. Also shown is stratospheric release of sulfate (SO_x) and soot. The emissions are separated by launch site: Vandenberg AFB, Cape Canaveral and other.

Year	USA Vandenberg	USA Cape Canaveral	USA Total	USAF Vandenberg	USAF Cape Canaveral	USAF Other	USAF Total
				CO_2			
1985	478.6	4376.5	4855.1	281.2	885.9	0.0	1167.1
1986	345.4	1257.9	1603.3	310.8	120.9	0.0	431.7
1987	478.6	505.1	983.7	434.8	254.0	0.0	688.8
1988	381.4	1139.9	1521.3	192.8	697.0	0.0	889.7
1989	159.3	3479.7	3639.0	232.1	1906.6	0.0	2138.7
1990	212.3	4814.2	5032.0	128.5	2371.9	0.0	2500.4
1991	531.3	3565.9	4102.7	455.0	1143.2	0.0	1598.2
1992	195.5	5767.9	5963.4	281.8	1214.9	0.0	1496.7
1993	301.6	4715.2	5022.3	418.3	900.6	0.0	1319.0
1994	273.4	4836.8	5122.4	125.0	781.8	13.5	920.3
1995	425.8	5468.4	5894.2	405.2	646.3	0.0	1051.5
1996	603.3	5465.5	6074.3	587.0	712.6	0.0	1299.5
1997	840.8	6026.5	6887.5	278.6	740.9	0.0	1019.5
1998	737.5	5317.5	6068.5	118.5	449.0	0.0	567.5
1999	745.8	3753.7	4506.2	364.9	605.4	0.0	970.3
2000	453.0	4215.8	4674.2	394.2	730.3	30.1	1154.6
2001	570.2	4029.9	4619.3	376.0	734.0	19.3	1129.3
2002	311.4	3320.1	3631.5	89.2	160.2	0.0	249.4
2003	413.6	2366.6	2780.2	205.9	1092.3	0.0	1298.1
2004	276.9	1831.3	2108.3	49.5	859.0	0.0	908.4
2005	444.6	1356.3	1800.9	376.8	128.7	9.9	515.4
2006	224.6	2521.6	2767.7	219.7	386.0	0.0	605.7
2007	274.0	3055.1	3350.6	255.3	869.1	0.0	1124.4
2008	569.9	2303.3	2929.8	414.4	0.0	6.7	421.1
2009	720.7	2894.2	3646.4	615.6	656.7	9.9	1282.2
2010	369.5	2102.8	3179.5	407.5	1194.1	27.0	1628.6
2011	526.5	2566.8	3130.3	425.2	497.1	36.9	959.2
2012	249.0	1976.	2233.5	249.	1071.	6.7	1429.
2013	913.0	2341.	3766.7	249.9	1071.1	37.	1358
				Soot			
1985	4.9	41.6	46.5	3.7	8.5	0.0	12.3
1986	3.3	11.5	14.8	4.1	0.9	0.0	5.1
1987	4.9	4.5	9.4	5.7	2.5	0.0	8.2
1988	3.5	11.1	14.6	2.5	6.8	0.0	9.3
1989	1.2	33.8	35.0	2.5	19.0	0.0	21.5
1990	1.7	46.6	48.5	1.9	23.6	0.0	25.5
1991	6.5	32.3	39.0	7.1	10.3	0.0	17.4
1992	2.6	51.3	53.9	4.4	9.5	0.0	13.9
1993	3.5	42.4	57.9	5.7	6.1	0.0	11.8

Year	USA Vandenberg	USA Cape Canaveral	USA Total	USAF Vandenberg	USAF Cape Canaveral	USAF Other	USAF Total
1994	2.8	48.5	51.7	2.3	11.4	0.4	14.1
1995	4.7	53.7	58.4	5.6	9.5	0.0	15.1
1996	7.2	50.4	57.8	8.2	7.9	0.0	16.1
1997	6.1	60.6	67.2	4.4	10.2	0.0	14.6
1998	6.6	50.1	57.0	2.6	6.7	0.0	9.3
1999	9.8	34.7	44.7	5.0	8.4	0.0	13.4
2000	5.8	38.7	44.6	6.1	7.9	0.5	14.5
2001	6.8	39.3	46.3	5.4	9.2	0.2	14.9
2002	2.7	31.5	34.2	1.3	2.9	0.0	4.3
2003	3.1	21.3	24.3	2.4	11.1	0.0	13.5
2004	2.5	16.7	19.2	0.7	8.8	0.0	9.5
2005	6.7	10.9	17.5	6.9	0.9	0.3	8.1
2006	3.0	21.6	24.7	2.3	2.6	0.0	4.9
2007	2.2	25.4	27.7	2.0	6.7	0.0	8.7
2008	3.7	21.1	25.4	3.4	0.0	0.2	3.6
2009	5.5	26.2	32.1	4.4	6.1	0.3	10.8
2010	3.0	20.0	28.1	3.8	9.3	0.6	13.7
2011	4.7	24.0	29.6	4.1	4.4	0.9	9.4
2012	2.5	16.	18.7	2.5	9.6	0.2	12.3
2013	8.4	21.1	30.4	2.1	9.7	0.9	12.6
			H_2O				
1985	190.7	8981.9	9172.7	185.6	1951.4	0.0	2137.0
1986	132.7	2095.4	2228.1	212.8	38.6	0.0	251.3
1987	190.7	202.0	392.7	239.6	96.5	0.0	336.1
1988	149.3	2048.0	2197.3	95.8	1072.2	0.0	1168.0
1989	55.8	5383.8	5439.6	125.1	2377.9	0.0	2502.9
1990	74.8	6698.9	6778.2	106.7	3396.3	0.0	3503.0
1991	247.3	6198.6	6450.5	342.2	2033.3	0.0	2375.5
1992	102.9	8668.5	8771.4	218.1	1221.4	0.0	1439.6
1993	140.3	7487.3	7632.1	287.6	286.7	0.0	574.3
1994	116.8	7763.2	7890.0	114.2	511.8	11.0	637.0
1995	212.2	8079.7	8291.9	280.5	435.2	0.0	715.7
1996	307.8	7854.9	8167.3	396.1	358.3	0.0	754.4
1997	279.5	9094.0	9389.9	217.3	384.0	0.0	601.3
1998	278.6	7849.6	8139.2	100.4	225.3	0.0	325.7
1999	373.4	4738.4	5117.3	191.0	307.4	0.0	498.4
2000	212.4	5780.7	5997.6	229.2	338.2	7.9	575.3
2001	270.9	6492.1	6769.1	220.3	348.3	6.2	574.8
2002	313.6	5439.4	5753.0	65.0	92.2	0.0	157.1
2003	573.7	1839.0	2412.7	121.9	430.1	0.0	551.9
2004	102.8	1430.6	1533.4	39.8	379.2	0.0	419.0
2005	295.2	1337.4	1632.6	221.3	41.0	6.3	268.6
2006	697.9	3362.3	4065.9	490.0	122.9	0.0	612.8
2007	725.9	4212.8	4312.2	84.2	991.1	0.0	1075.3
2008	195.7	4100.8	4318.9	172.0	0.0	5.5	177.5
2009	263.6	4587.9	4863.5	233.9	1315.0	6.3	1555.2
2010	145.9	4307.0	4672.4	173.4	1468.4	15.0	1656.9
2011	844.9	3857.9	4724.2	1013.3	421.8	21.3	1456.5
2012	315.5	1802	2123.6	315.5	1506	5.5	1827

Year	USA Vandenberg	USA Cape Canaveral	USA Total	USAF Vandenberg	USAF Cape Canaveral	USAF Other	USAF Total
2013	1013	2042	2454.7	744.9	873.3	21.4	1640
NO_x							
1985	6.6	62.1	68.7	4.6	13.7	0.0	18.4
1986	3.4	15.3	18.7	4.9	0.7	0.0	5.6
1987	6.6	4.8	11.4	8.6	4.0	0.0	12.6
1988	3.7	17.7	21.4	4.2	10.8	0.0	15.0
1989	1.0	48.6	49.6	2.0	27.1	0.0	29.1
1990	0.2	65.8	66.0	1.3	31.6	0.0	32.9
1991	6.5	45.7	52.2	7.7	15.5	0.0	23.2
1992	3.5	68.1	71.5	4.3	12.1	0.0	16.5
1993	3.5	55.0	58.5	4.3	6.1	0.0	10.5
1994	0.6	64.2	64.8	1.0	13.6	0.1	14.7
1995	4.7	61.3	66.0	4.1	9.9	0.0	13.9
1996	8.3	62.4	70.8	8.3	9.0	0.0	17.3
1997	6.1	74.6	80.8	4.2	12.0	0.0	16.2
1998	5.0	62.5	67.6	1.2	7.9	0.0	9.1
1999	7.2	42.2	49.4	5.3	8.2	0.0	13.6
2000	5.2	44.0	49.2	5.8	5.9	0.2	11.9
2001	5.3	52.7	58.4	4.5	9.1	0.4	14.1
2002	2.8	39.6	42.4	1.2	3.5	0.0	4.7
2003	1.9	21.6	23.5	0.8	12.3	0.0	13.2
2004	1.8	10.7	12.5	0.5	6.8	0.0	7.3
2005	7.9	10.3	18.2	7.9	0.9	0.1	8.9
2006	3.1	27.5	30.6	2.5	2.6	0.0	5.2
2007	2.5	28.2	30.1	1.7	3.2	0.0	4.9
2008	2.2	30.4	32.8	2.1	0.0	0.1	2.1
2009	3.1	29.4	32.6	3.1	4.2	0.1	7.4
2010	1.3	5.7	27.5	1.9	4.5	0.4	6.8
2011	2.9	27.2	30.7	3.3	1.7	0.5	5.5
2012	0.8	7.3	8.5	1.0	5.5	0.1	6.7
2013	2.9	8.6	11.3	1.0	5.0	0.5	6.5
NO_x Strat							
1985	1.0	2.0	3.0	0.6	0.4	0.00	1.1
1986	0.5	0.6	1.0	0.7	0.1	0.00	0.7
1987	1.0	0.6	1.6	1.1	0.6	0.00	1.7
1988	0.8	1.0	1.8	0.5	0.8	0.00	1.3
1989	0.4	3.1	3.5	0.2	2.3	0.00	2.5
1990	0.0	4.7	4.7	0.1	2.2	0.00	2.3
1991	1.2	1.6	2.9	1.3	0.6	0.00	1.9
1992	0.9	2.9	3.9	0.7	0.6	0.00	1.3
1993	0.9	2.0	3.0	0.7	0.4	0.00	1.2
1994	0.4	4.2	4.6	0.1	2.5	0.01	2.6
1995	0.7	3.5	4.2	0.7	1.8	0.00	2.5
1996	1.4	3.3	4.6	1.4	1.4	0.00	2.8
1997	0.7	4.4	5.2	0.7	1.9	0.00	2.6
1998	0.7	3.1	3.9	0.1	1.2	0.00	1.3
1999	1.4	2.4	3.9	0.7	1.2	0.00	1.9
2000	1.0	2.0	3.0	0.7	0.7	0.01	1.5
2001	0.6	2.8	3.4	0.6	1.3	0.01	1.9

Year	USA Vandenberg	USA Cape Canaveral	USA Total	USAF Vandenberg	USAF Cape Canaveral	USAF Other	USAF Total
2002	0.5	1.7	2.2	0.1	0.6	0.00	0.6
2003	0.7	1.8	2.6	0.1	1.5	0.00	1.6
2004	0.2	0.9	1.0	0.0	0.8	0.00	0.8
2005	1.2	0.4	1.6	1.2	0.1	0.01	1.3
2006	0.1	1.0	1.1	0.1	0.2	0.00	0.3
2007	0.1	1.0	1.2	0.1	0.1	0.00	0.2
2008	0.1	1.0	1.2	0.1	0.0	0.01	0.1
2009	0.2	1.0	1.2	0.2	0.1	0.01	0.3
2010	0.1	0.7	0.8	0.1	0.0	0.02	0.1
2011	0.1	0.8	1.0	0.1	0.0	0.02	0.1
2012	0.01	0.08	0.1	0.01	0.1	0.01	0.08
2013	0.02	0.09	0.2	0.02	0.1	0.02	0.11
				Cl_x			
1985	53.7	829.6	883.3	88.1	184.4	0.0	272.4
1986	26.9	195.8	222.7	101.3	5.7	0.0	107.0
1987	53.7	38.3	92.0	110.9	32.6	0.0	143.5
1988	26.9	216.9	243.8	43.7	124.8	0.0	168.4
1989	6.1	600.1	606.2	46.5	305.2	0.0	351.7
1990	0.0	796.9	799.5	50.8	388.2	0.0	439.0
1991	92.1	588.0	682.7	124.6	198.7	0.0	323.3
1992	46.1	841.3	887.3	84.9	135.3	0.0	220.2
1993	46.1	701.8	750.5	82.9	50.3	0.0	133.2
1994	10.2	857.4	873.4	53.2	154.8	6.3	214.3
1995	62.8	812.2	875.0	80.5	114.3	0.0	194.8
1996	119.1	798.5	920.2	140.1	95.4	0.0	235.5
1997	53.2	994.5	1057.2	85.3	159.5	0.0	244.8
1998	60.2	803.7	870.2	42.5	115.4	0.0	157.9
1999	117.8	511.9	632.9	88.9	119.1	0.0	207.9
2000	76.2	557.9	636.7	105.2	75.7	4.6	185.5
2001	75.7	691.0	770.5	79.3	126.2	3.8	209.4
2002	16.7	522.2	538.9	30.0	54.1	0.0	84.1
2003	10.3	262.7	273.0	22.4	151.4	0.0	173.8
2004	22.0	110.0	132.0	18.8	82.9	0.0	101.7
2005	119.6	116.0	235.6	126.5	7.2	3.9	137.5
2006	22.7	330.9	353.6	21.8	21.6	0.0	43.3
2007	21.4	322.5	343.9	13.5	16.7	0.0	30.2
2008	4.5	392.6	403.4	21.5	0.0	3.2	24.7
2009	22.9	328.0	354.8	25.7	18.1	3.9	47.7
2010	9.1	290.6	317.0	23.2	14.1	8.6	45.9
2011	27.1	323.8	363.4	22.2	5.5	12.5	40.2
2012	2.3	32.2	37.6	2.3	29.8	3.1	35.3
2013	3.1	34.4	56.2	5.9	29.8	12.5	48.2
				Al_2O_3			
1985	79.4	1161.3	1240.7	132.7	258.1	0.0	390.7
1986	39.7	275.8	315.4	151.5	8.8	0.0	160.3
1987	79.4	57.4	136.7	182.4	48.5	0.0	230.9
1988	39.7	306.6	346.3	75.4	177.6	0.0	253.0
1989	9.5	859.0	868.4	76.8	455.3	0.0	532.1
1990	0.0	1147.8	1152.2	80.2	585.0	0.0	665.2

Year	USA Vandenberg	USA Cape Canaveral	USA Total	USAF Vandenberg	USAF Cape Canaveral	USAF Other	USAF Total
1991	134.6	829.1	968.0	214.8	280.3	0.0	495.1
1992	67.3	1192.8	1260.1	141.5	195.6	0.0	337.2
1993	67.3	991.5	1063.2	135.8	77.7	0.0	213.5
1994	17.2	1216.5	1243.3	80.4	280.4	10.6	371.3
1995	93.9	1152.1	1246.0	129.2	208.1	0.0	337.3
1996	178.0	1132.9	1315.2	231.4	167.9	0.0	399.3
1997	83.0	1424.8	1523.7	140.8	256.5	0.0	397.4
1998	96.1	1145.7	1252.4	74.2	178.1	0.0	252.3
1999	184.6	739.0	928.8	142.5	184.3	0.0	326.8
2000	119.4	796.8	920.5	171.6	118.1	7.5	297.2
2001	118.8	988.3	1112.9	126.3	195.4	5.8	327.5
2002	25.8	740.8	766.6	54.5	83.5	0.0	138.0
2003	17.4	393.5	410.9	36.9	233.6	0.0	270.5
2004	35.0	173.1	208.1	30.7	129.2	0.0	159.8
2005	184.9	166.6	351.5	202.0	11.1	6.0	219.1
2006	35.5	473.2	508.7	38.5	33.3	0.0	71.8
2007	33.4	458.6	492.0	24.5	26.4	0.0	50.9
2008	7.2	553.6	571.4	40.0	0.0	5.3	45.3
2009	36.4	467.9	510.3	42.9	28.5	6.0	77.4
2010	15.2	409.7	453.9	42.8	22.6	14.5	79.9
2011	44.2	462.5	527.2	37.6	8.7	20.5	66.7
2012	3.6	51.8	60.7	3.6	48.2	5.3	57.0
2013	5.3	55.4	90.8	11.2	48.2	20.5	79.9
SO_x							
1985	0.005	0.004	0.009	0.001	0.000	0	0.001
1986	0.003	0.003	0.007	0.001	0.001	0	0.002
1987	0.005	0.004	0.009	0.003	0.002	0	0.005
1988	0.005	0.002	0.007	0.001	0.002	0	0.004
1989	0.002	0.011	0.013	0.001	0.009	0	0.010
1990	0.002	0.018	0.021	0.000	0.009	0	0.009
1991	0.005	0.007	0.012	0.003	0.002	0	0.005
1992	0.003	0.018	0.021	0.002	0.005	0	0.007
1993	0.004	0.013	0.017	0.003	0.006	0	0.009
1994	0.003	0.016	0.019	0.000	0.007	0	0.007
1995	0.004	0.022	0.026	0.003	0.006	0	0.009
1996	0.005	0.020	0.025	0.004	0.006	0	0.010
1997	0.007	0.022	0.029	0.002	0.005	0	0.007
1998	0.006	0.030	0.036	0.000	0.004	0	0.004
1999	0.007	0.028	0.035	0.002	0.006	0	0.008
2000	0.027	0.018	0.044	0.002	0.006	0	0.009
2001	0.016	0.023	0.039	0.003	0.006	0	0.009
2002	0.003	0.011	0.014	0.002	0.002	0	0.004
2003	0.016	0.016	0.032	0.006	0.009	0	0.010
2004	0.002	0.027	0.028	0.000	0.007	0	0.007
2005	0.015	0.008	0.023	0.003	0.001	0	0.004
2006	0.001	0.009	0.010	0.001	0.003	0	0.004
2007	0.002	0.015	0.016	0.002	0.008	0	0.010
2008	0.016	0.004	0.020	0.003	0.000	0	0.003
2009	0.028	0.013	0.041	0.005	0.005	0	0.010

Year	USA Vandenberg	USA Cape Canaveral	USA Total	USAF Vandenberg	USAF Cape Canaveral	USAF Other	USAF Total
2010	0.003	0.007	0.014	0.003	0.005	0	0.008
2011	0.015	0.010	0.025	0.003	0.005	0	0.008
2012	0.002	0.015	0.017	0.002	0.009	0	0.011
2013	0.006	0.017	0.014	0.002	0.009	0	0.011

launch small vehicles such as the Pegasus, Minotaur, and Antares. Also shown is the total emission for the USA including non-USAF missions from commercial and NASA launches by launch location. In general the amount of USAF emissions for each compound has decreased during the past decade compared to the previous decade. NO_{strat} production has decreased in the 2000s to 1.3 tons/yr from 2.6 tons/yr in the 1990s. H_2O_{strat} production has decreased in the 2000s to 660 tons/yr from 1102 tons/yr in the 1990s, although it is recently increasing due to use of Delta IV. HCl_{strat} production has decreased in the past decade to 100 tons/year from 233 tons in the 1990s. The average since 2006 was 39 tons/yr. $Alumina_{strat}$ production has decreased in the 2000s to 153 tons/yr from 363tons/yr in the 1990s. The average since 2006 was 66 tons/yr. Carbon dioxide production has decreased in the past decade to 966 tons per year from 1242 tons/yr in the 1990s. Soot production has decreased in the 2000s to 10 tons per year from 14 tons/yr in the 1990s. Part of this is due to a slightly reduced launch rate. There were ~15.6/yr launches during the 1990s compared to ~11.7 launches/yr during the 2000s. Some of the reduction in pollution products is due to changes in launch vehicle usage since the 1990s. In the 1990s, the USAF used several vehicles that used large solid rocket motors, such as the Space Shuttle and Titan IV. The USAF Evolved Expendable Launch Vehicle **(**EELV) program eliminated these types of vehicles. Also, the Titan IV was the only USAF vehicle to use nitrogen based-propellants on a large scale.

Figure 1 shows the total amount of carbon dioxide generated by launch vehicles worldwide for the years 1985 to 2013. The amount of carbon dioxide generated by launch vehicles, in general, trends

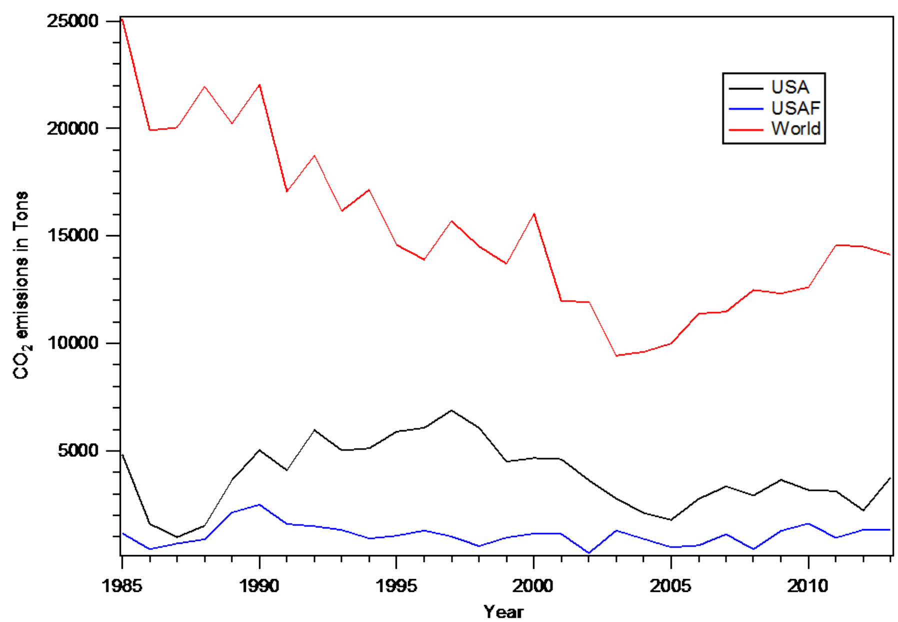

Figure 1. Total carbon dioxide emissions worldwide from launch vehicles.

with the total amount of launches worldwide. As seen in Figure 1, the USA contribution has clearly decreased from the peak launch years in the 1990s.

Figure 2 shows the total amount of chlorine generated in the stratosphere by launch vehicles worldwide for the years 1985 to 2013. In general, the total amount has remained relatively constant since

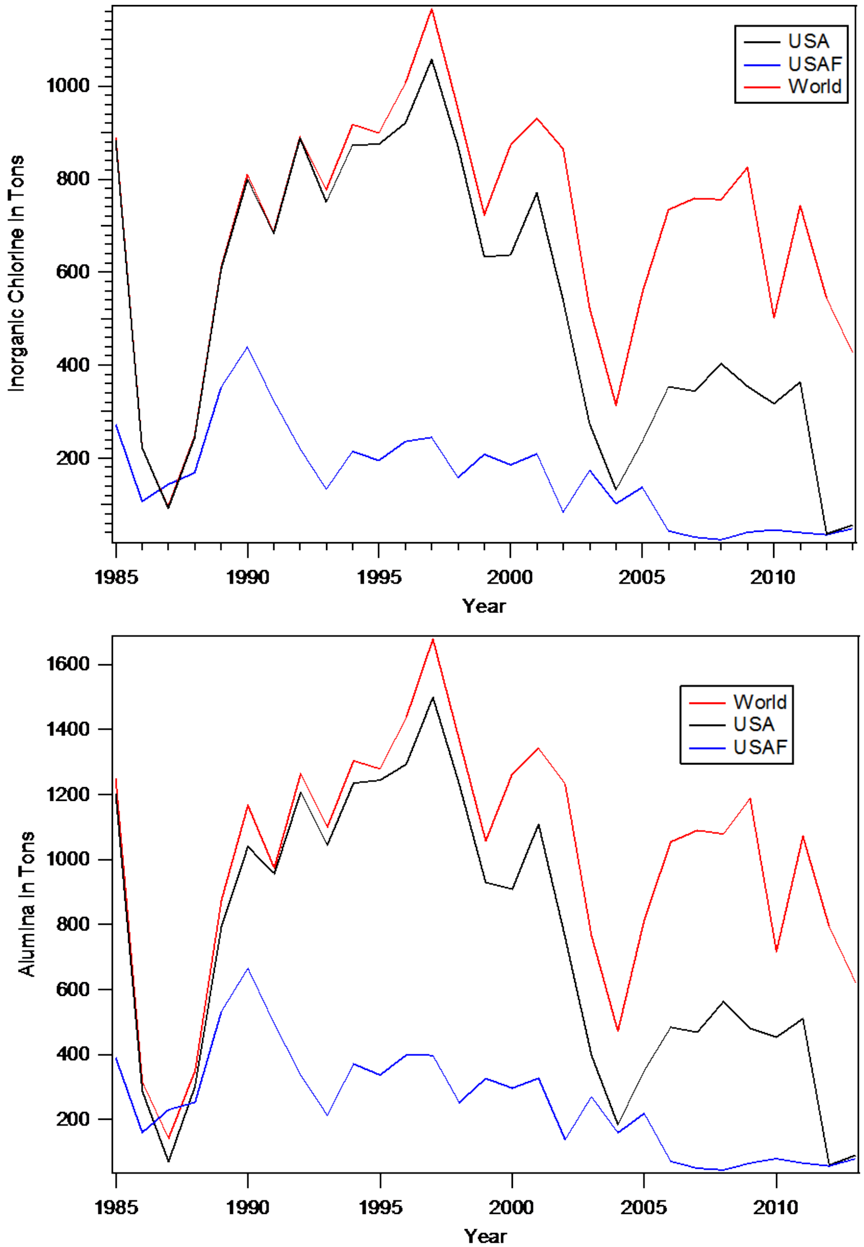

Figure 2. Total stratospheric inorganic chlorine and alumina emissions worldwide from launch vehicles. The total worldwide amount is shown in red. The amount generated by US launch vehicles is shown in black. The amount generated by USAF launches is shown in blue. The USAF includes both military space launches and ballistic missile tests.

the mid 1990s, with a small dip due to Space Shuttle program problems. While the shuttle launches have decreased in the 2000s compared to the 1990s, several countries (European Space Agency and India) have developed heavy lift vehicles that use solid rocket motors. Thus, while during the 1990s, the US contributed almost all the inorganic chlorine exhaust, since then it only contributes roughly half of the worldwide total. The retirement of the Space Shuttle program greatly reduced the amounts of these two exhaust components produced by the US, but this may not remain low if the Space Launch System becomes an actuality. As seen in Figure 2, the USAF contribution has clearly decreased from the peak launch years in the 1990s. This is mainly due to the end of USAF missions on the Space Shuttle in the early 1990s and the end of the Titan IV program. The totals for alumina mirror inorganic chlorine. The change in this trend for the future is uncertain. The Europeans have discussed plans for the Ariane 6 being an all solid rocket motor launch vehicle and have started launching the all-solid VEGA launch vehicle. The US has plans for a heavy lift vehicle for space exploration that will include large solid motors (SLS). The Chinese are also planning a solid launch vehicle to enhance launch on demand capabilities (Changzheng 11). Thus, the current decrease in emissions post-Space Shuttle, particularly for the US, may only be a temporary decrease as solid rocket motors seem to have earned a niche in the industry, and new vehicles are being developed with solid motors.

Figure 3 shows the total amount of water vapor generated in the stratosphere by worldwide launches for the years 1985 to 2013. The US launches are the major contributor to water vapor released into the

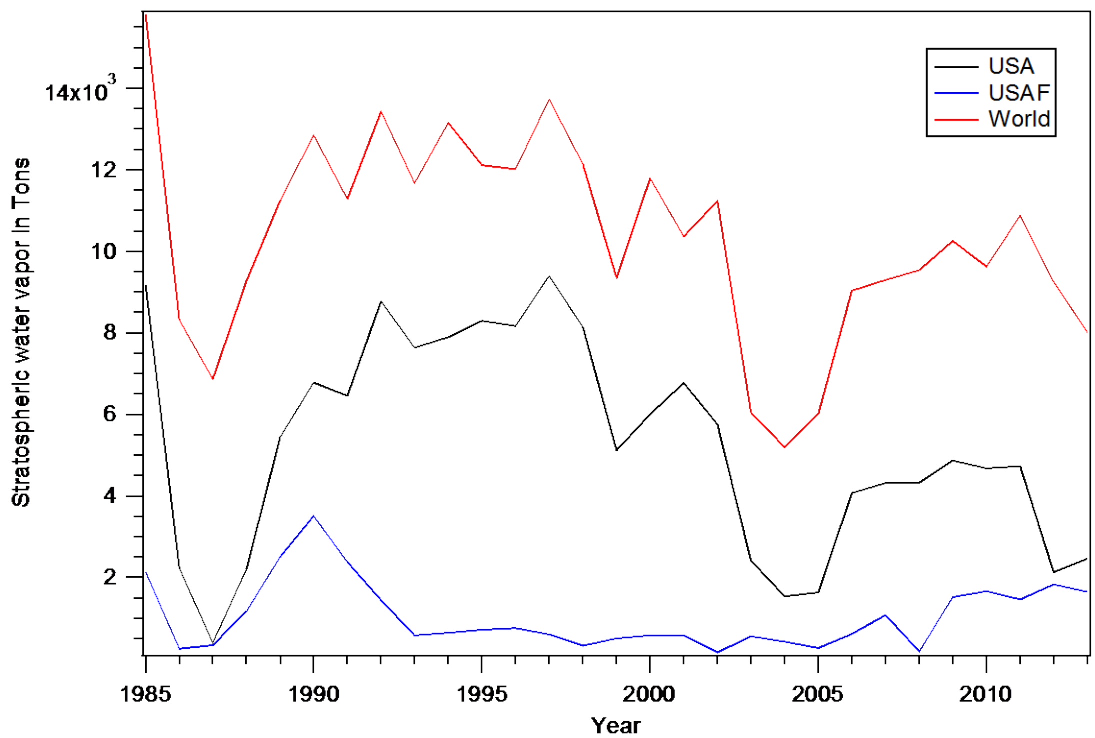

Figure 3. Total stratospheric water vapor emissions worldwide from launch vehicles. The total worldwide amount is shown in red. The amount generated by US launch vehicles is shown in black. The amount generated by USAF launches is shown in blue. The USAF includes both military space launches and ballistic missile tests.

stratosphere (averaging 40% of released water vapor from the past decade 2004 to 2013). The major generator of water vapor emissions was the Space Shuttle. After the end of the Space Shuttle program in 2011, the US launches continued to be the major contributor to water vapor released into the stratosphere (averaging 23% of released water vapor from 2012 to 2013). The Space Shuttle used liquid hydrogen and oxygen as its main fuel and oxidizer and thus produced water vapor as the only product of its main engines. The water vapor released was fairly consistent from 1990 to 2002. The European Ariane 5 also uses liquid hydrogen and liquid oxygen as its main engines propellant. The European contribution has steadily increased as the usage of Ariane 5 has increased (ESA produced only 3.6% of stratospheric water vapor released in 1985 compared to 16.8% in the past decade). The Russians do not launch H_2/O_2 rocket motors; however, in 1985, they were a major contributor to water vapor release due to the large number of missions launched. Their water vapor output has decreased as their launch schedule has decreased since then. The USAF contribution had remained fairly constant from 1993 to 2006 at 508 tons/yr. It has increased in recent years due to use of the Delta IV heavy (1259 tons/yr average since the introduction of Delta IV).

Figure 4 shows the total amount of soot generated in the upper atmosphere from launch vehicles. In general, soot formation tracks total vehicle launches since most launch vehicles contain some type of hydrocarbon fuel. The worldwide fleet has averaged 91 tons/yr for the past decade. The USA contributes ~28% of the total soot in the upper atmosphere.

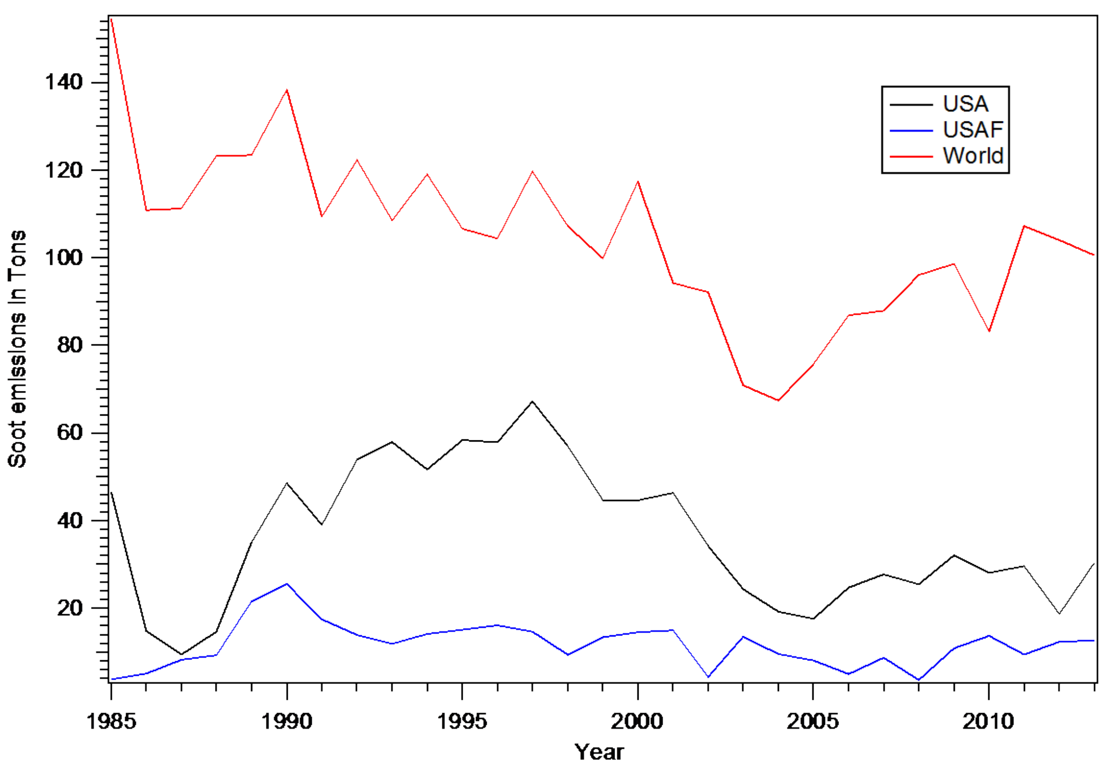

Figure 4. Total soot emissions worldwide from launch vehicles. The total amount worldwide is shown in red. The amount generated by US launch vehicles is shown in black. The amount generated by USAF launches is shown in blue. The USAF includes both military space launches and ballistic missile tests.

Figure 5 shows the total amount of NO_x generated in the upper atmosphere from launch vehicles. The stratospheric NO_x generated by launch vehicles has averaged 58±13 tons/yr for the last 28 years. The general trend of total launches that was observed for CO_2 emissions was not shown because many launch vehicles do not generate significant NO_x in the stratosphere. Russian and Chinese launch vehicles are seen to be the major contributor (averaging 72% of all emissions over the past 28 years) to stratospheric NO_2 since they launch nearly all their rockets with UDMH and nitrogen tetroxide as propellants. These propellants generate NO_x in the stratosphere. Solid rocket motors also can produce stratospheric NO_x. The increased use of solid rocket motors that burn ammonium perchlorate is the most likely explanation for the lack of an observed decrease in NO_x over the time period. Indeed solid rocket motors generated only 2 tons/yr in the 1985 to 1990 time period but have averaged 7.5 tons/yr since 1995 to 2005. The USAF averaged about 2.3% of the total emissions since 1985. The major source of stratospheric NO_x emission (80% of USAF emissions) from 1985 to 2005 was the Titan rocket program that used Aerozine 50 as a fuel. The end of the Titan program has significantly reduced stratospheric NO_x emission by the USAF launch vehicles since EELV does not use large hydrazine/nitrogen tetroxide motors in boost phase. The worldwide fleet might also change in the near future by using even more kerosene motors and solid rocket motors, which should significantly decrease stratospheric NO_x.

In general, sulfate emissions have tracked launch schedules and make up only a minor component of the exhaust plume. Sulfate emissions peaked at 0.091 tons/yr in 1985 and dropped to about 0.050

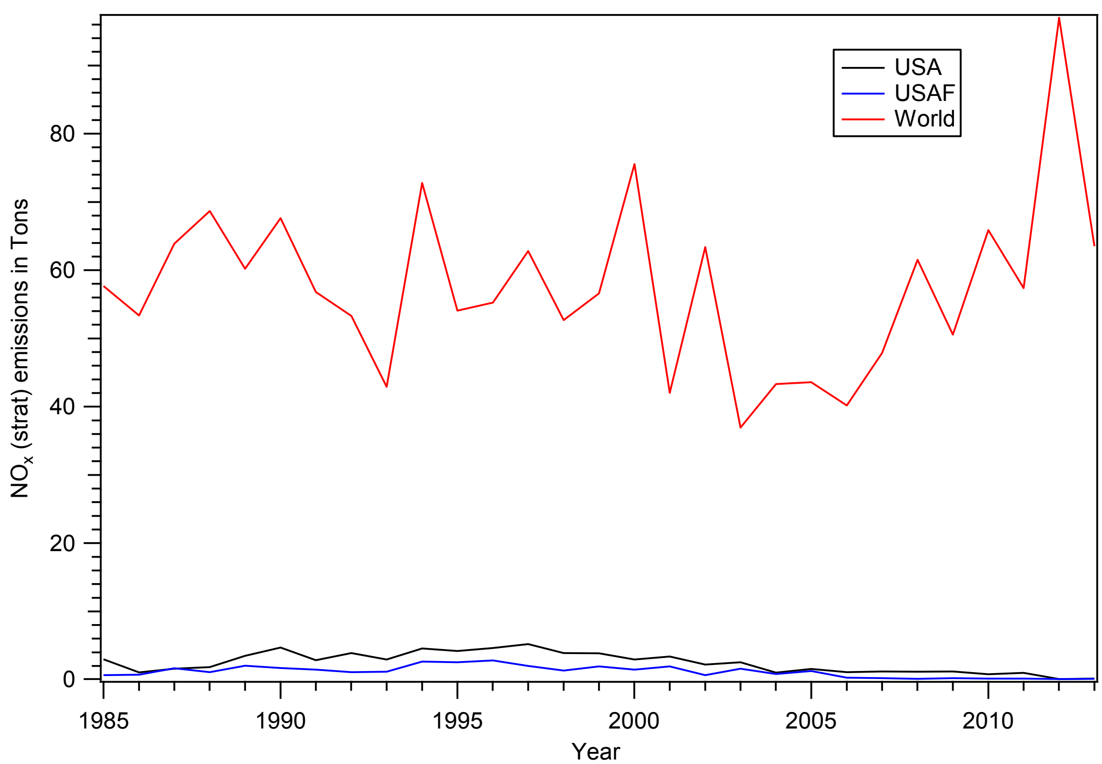

Figure 5. Total NO_x (stratosphere) emissions worldwide from launch vehicles. The total amount worldwide is shown in red. The amount generated by US launch vehicles is shown in black. The amount generated by USAF launches is shown in blue. The USAF includes both military space launches and ballistic missile tests.

tons/yr over the period of 2000 to 2009. The worldwide fleet averaged about 0.045 tons/yr for the past decade. Atlas V and the Falcon 9 launch vehicles produce sulfate from small impurities in the RP-1 fuel. The USAF generates about 22% of the worldwide sulfate emissions over the last decade.

2.9 Projecting Future Emissions from Launch Vehicles

Figure 6 shows the number of launches worldwide and the worldwide number broken down by component of the launches for various launch programs. In general, the total number of launches world

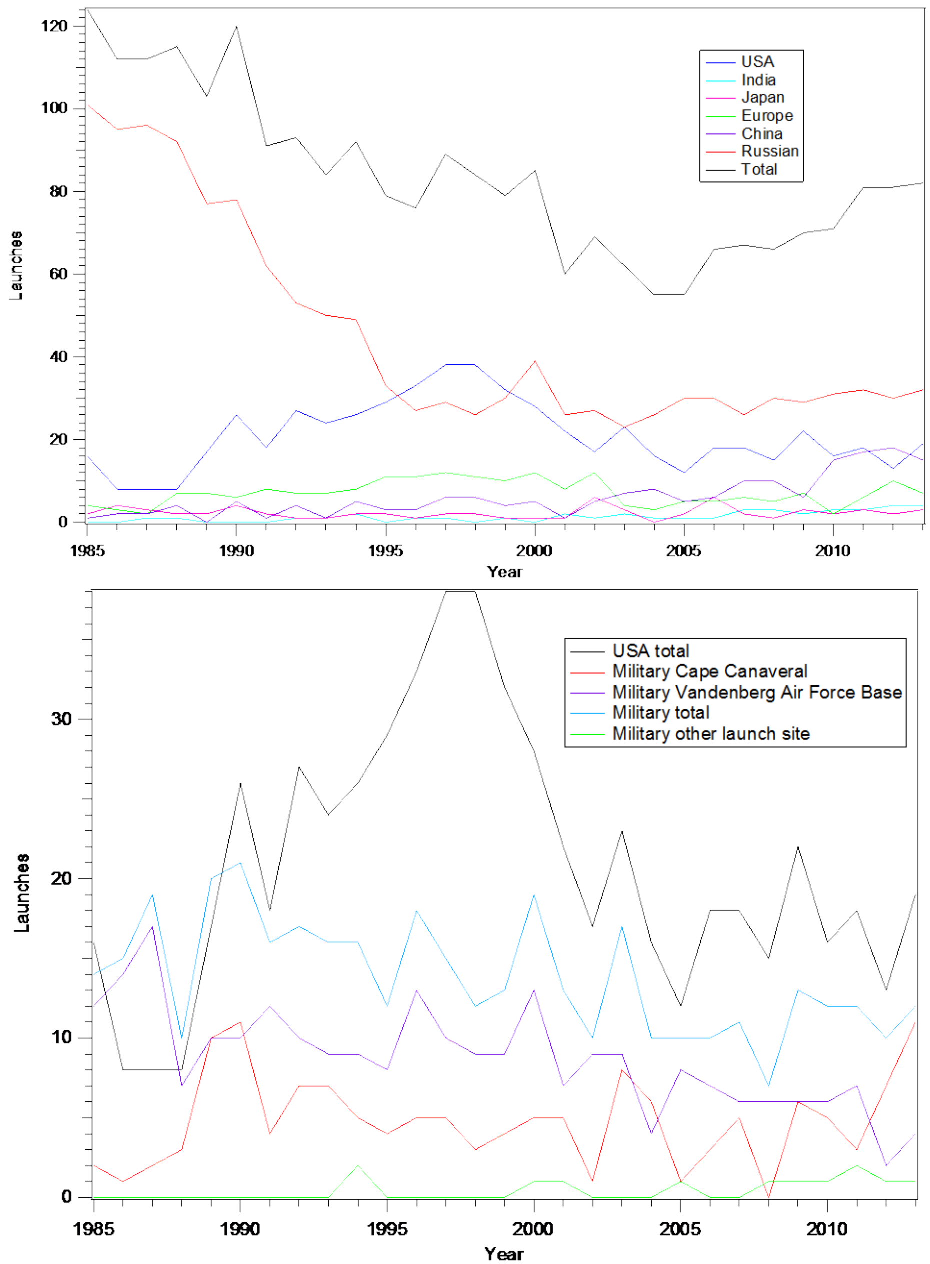

Figure 6. Launches per year for different space programs. The USAF includes both military space launches and ballistic missile tests.

wide had been trending downward for 20 years until 2000. However, from 2000 to 2013, the launch rate has remained fairly stable with a slight increasing trend due to increased launch rates in Chinese launches. It would appear that about 72±12 launches per year are currently needed to maintain the worldwide space infrastructure. Previous reports projected future emissions using launch rate averages for the 2002 to 2005 time period.[2] These numbers were adjusted by switching Titan IV and Atlas IIAS payload types to the new heavy lift launch vehicles Delta IV, Delta IV H, and Atlas V. Table 4 has the projected emissions compared to the actual emissions for the time period 2006 to 2013. In general, inorganic chlorine, alumina, and NO_x were all predicted accurately. The carbon dioxide and water vapor are only slightly off projection. This is due to the Atlas V being used slightly more than predicted. The Delta IV H produces primarily water vapor while the Atlas V produces carbon dioxide and water vapor.

Another interesting trend in Figure 6 is the increased usage of non-traditional launch sites over the past decade. This is a trend that potentially could continue as more states build small launch sites for small payload launch vehicles.

The USAF emissions predictions were slightly in error. This is due to an incorrect assumption of Delta IV and Atlas V usage rates for payloads, which also accounts for the larger disparity for projected yearly average carbon dioxide emissions. Also, the USAF was launching approximately five Minuteman III ballistic missiles and one Peacekeeper missile per year. These test rates have been reduced, and the Peacekeeper is no longer in active service. This resulted in a further decrease in inorganic chlorine and alumina than predicted. Peacekeepers will, in the future, be used in Minotaur IV and V launches. The Ares I motor was tested in 2009. Ares has projected lift capabilities similar to Delta IV and Atlas V to low Earth orbit. The USAF or NASA could potentially start to launch on the Ares (Liberty) vehicles between 2010 and 2015. Although this appears to be doubtful because talk of Space Launch Systems (SLS) currently seems favored. Currently, NASA is planning to replace shuttle activity with launch activity from one or more of the following vehicles: Soyuz, Atlas V, Falcon 9 and Antares. Near-term Soyuz launches are scheduled for maintaining space station operation. Missions with the Falcon fleet of vehicles are scheduled for NASA, and the USAF could potentially also use these vehicles. However, the current conservative projection is for the USAF to continue its current EELV usage. The USAF will soon likely have certified Falcon 9 for EELV usage. The conclusion of all this is that while the total world launches seems consistent at 72±12 launches per year, the actual vehicle make-up in the future is uncertain.

Table 4. Projected Emissions in Tons from Space Launches for the Years 2006 to 2011 and the Actual Emissions for 2006 to 2013

Exhaust component	Worldwide Projected yearly average	Worldwide Actual Yearly Average	Projected yearly average USAF	Actual yearly average USAF
Total CO_2	12081	12940	569	1088
Stratospheric Water Vapor	9139	9494	878	1250
Tropospheric NO_2	70	80	2	6
Stratospheric NO_2	60	60	0.16	0.2
Stratospheric Alumina	1014	951	68	66
Stratospheric Chlorine	689	660	46	39

Worldwide launches were easier to project in previous reports. The Russian space program has launched 28±4 vehicles per year consistently for several years. The Russians also have a solid investment in certain types of rocket designs that change only slightly in propellant composition with time. They have expressed plans to switch to a more kerosene-based launch fleet, thereby, making a major change in current projections. The Japanese launch rate has also been fairly consistent, averaging two launches per year. The Japanese have plans for the H-III vehicle that is similar in propellants to previous vehicles. India continues to have growing space programs. However, the pace of growth is not dramatic at present. The launch rate of India is growing much more slowly than China at a rate of one more launch per 11 years. This is slightly up from previous reports. The Indian rocket program currently uses *hybrid rockets* that rely on both liquid and solid rocket motors. Note that hybrid rockets are not the same as hybrid rocket motors that use a solid propellant fuel with a liquid oxidizer. India is planning a kerosene propellant-based vehicle, the ULV, for future use. The Chinese launches have grown at a steady rate of one more launch every two years from the time period of 1985 to 2013. This is slightly up from previous reports. This is mostly due to a large increase in launches in years 2008 to 2010. The Chinese launch rate was comparable to US launch rates from 2011 to 2013. It is unclear whether the Chinese launch rate will continue to increase and approach Russian launch rates or whether they will stabilize at similar yearly launch rates that compare to the US. The fuel and oxidizer used by the Chinese series of launch vehicles are similar to those used by the current hypergolic Russian launch vehicles. The Chinese are planning vehicles that use kerosene and solid rocket motors so this once again suggests there is currently more flux in the future of the composition in the worldwide launch fleet. Other countries, such as North Korea, South Korea, Iran, Argentina, and Brazil ,are currently designing launch vehicles, although successful launch schedules have not been achieved.

Table 5 has the projected mass in tons of greenhouse gases and particulates in the exhaust of launch vehicles worldwide. The projections have been slightly adjusted from the 2005 report for the actual

Table 5. Projected Mass (in tons) of Greenhouse Gases and Particulates in the Exhaust of Launch Vehicles Worldwide for the Future. The projections have been slightly adjusted from the 2005 report for the actual launch rates of Delta IV, Atlas V, as well as soot formation estimates. The projections have also included new average use rates for the Chinese, European, and Indian launch vehicles. The USAF projections are seven year averages for active programs. For Delta IV and Atlas V, launch rates for Titan IV (counting as either Delta IV or Atlas V launches) were included for years prior to 2006 for the 2005 prediction.

Exhaust component	World wide predicted yearly average 2005	World wide predicted yearly average 2008	World wide predicted yearly average 2011	World wide 2008	World wide 2009	World wide 2010	World wide 2011	World wide 2012	World wide 2013	Projected yearly average USAF (2006-2013)
Total CO_2	11448	11918	12081	12490	12329	12624	14586	14505	14128	1088
Stratospheric Water Vapor	10909	9007	9139	9537	10254	9623	10877	9246	8011	1250
Tropospheric NO_2	66	68	70	82	82	76	85	99	66	6
Stratospheric NO_2	52	62	60	62	51	66	57	97	64	0.2
Stratospheric Alumina	1009	1007	1014	1079	1188	717	1072	792	621	66
Stratospheric Chlorine	686	689	689	756	825	502	743	543	426	39
Soot			97	96	99	83	107	104	101	10
SO_x			0.05	0.05	0.07	0.03	0.05	0.04	0.04	<0.1

usage rates for Delta IV and Atlas V observed for the 2005 to 2008 and the 2008 to 2011 time periods. The projections have also included new average use rates for the Chinese, European, and Indian launch vehicles. The USAF projections are eight-year averages for active programs. For Delta IV and Atlas V, launch rates for Titan IV (counting as either Delta IV or Atlas V launches) were included for years prior to 2006 for the older 2005 prediction shown in the table. Also shown in Table 5 is the actual deposition worldwide for the years 2008, 2009, 2010, 2011, 2012, and 2013. This gives a flavor as to how deposition changes on a year-to-year basis under the current worldwide launch fleet. A new projection hasn't been added to the current report since the worldwide vehicle fleet appears to be in flux even though the 2011 prediction is currently a reasonable guess at annual emissions.

A 2009 study[1] on future environmental impact from launch vehicles predicted launch vehicle usage rates based on the cost driver to place payloads into orbit. They determined that if launch rates grew at a rate where they doubled or tripled current launch numbers every decade, then ozone destruction from launch vehicle emissions could surpass ozone destruction from worldwide release of CFCs by 2035. The study doesn't explain how such large launch rates would be sustainable given launch rate limiting issues such as the near-term sustainability of some space orbital regions due to accumulation of space debris or the added cost of space debris mitigation and remediation technologies. However, the increase in launch rates might be plausible if low-cost, high-flight-rate. reusable launch systems were developed that focused on suborbital passenger transport or freight transport rather than orbiting systems. More than 1000 flights of the various suborbital and sounding rocket versions (like the Canadian Black Brant) have occurred since their introduction in the 1960s. The Skylark suborbital rocket launched 441 times from 1957 and 2005 before retirement. Another current suborbital vehicle is the UP Aerospace, Inc. launches of Spaceloft XL. So a market for some number of these suborbital flights seems likely. There is also a growing interest in small, low-cost launchers for small satellites. The newer suborbital launch vehicles being developed (such as Spaceship 2, XCORE Lynx, and Blue Origin PM2) produce significantly more exhaust components per launch than current suborbital launch vehicles such as the Black Brant XII. The older small suborbital vehicles utilize solid rocket motors, whereas these newer larger vehicles use a variety of propellant options such as HTPB-based hybrid motors and kerosene/H_2O_2 motors. Our previous report[2,3] did not look into suborbital launch vehicles due to their small size and small amount of their emissions; however, these larger suborbital vehicles will be considered for future emissions tracking as their usage evolves in the future.

3. Environmental Effect of Emissions

In general, there are two different long-term effects from the emissions generated by the plumes of launch vehicles. There is long-term destruction of stratospheric ozone from the alumina, inorganic chlorine, and NO_x due to launch vehicle emissions. There are also long-term climate changes due to changes in the atmospheric concentration of greenhouse gases, such as stratospheric water vapor, ozone, and carbon dioxide, due to launch vehicle emissions. Both of these effects will be examined here.

3.1 Ozone Destruction

Ozone destruction in the stratosphere is primarily due to catalytic processes that derive their origins from anthropogenic emissions of compounds containing chlorine. The primary catalytic process involves inorganic chlorine.[37] Inorganic chlorine is released by launch vehicles from the burning of perchlorate-based solid rocket propellants. The alumina particulates produced from solid rocket propellants also contributes to ozone depletion.[11] Also, ozone is destroyed by NO_x catalytic processes.[11] The primary source of NO_x from launch vehicles is Russian and Chinese launch vehicles that use UDMH and N_2O_4 as propellants.

3.1.1 Stratospheric Ozone Destruction by NO_x Exhaust

Ross et al.[49] used plume and global atmospheric models to predict ozone destruction from the emissions released from Russian Proton style launch vehicles. These vehicles use hydrazine-based propellants. The primary ozone loss mechanism for the emissions from these launch vehicles is catalytic destruction from NO_x species generated in the exhaust, with water vapor making only a small contribution. They predict ten Proton launches per year should reduce the ozone by 0.00012% annually. The actual amount of NO_x produced worldwide in the stratosphere is predicted to be slightly larger than that generated by 10 Proton launches. Assuming the ozone loss scales linearly with generated NO_x concentration, then the actual average ozone loss from 2000 to 2009 has been 0.00016% annually from worldwide launches. The emissions from 2010 to 2013 are consistent with this estimate. Overall, the largest source of ozone destruction from NO_x-generated emissions in the stratosphere come from Russian and Chinese launch vehicles. The USAF contribution is significantly lower. The only launch vehicle used by the USAF that utilized hydrazine as the main stage motor propellant was the Titan IV, which has now been retired. For the past eight years, the USAF has produced on average only 0.3% of stratospheric NO_x, and the stratospheric ozone destruction annually from NO_x emissions is trivially small (0.0000005%).

3.1.2 Stratospheric Ozone Destruction by Cl_x Exhaust

Danilin et al.[16] have calculated the global decrease in ozone due to a one year cycle of vehicle launches. Their results show that for 816 tons of chlorine released as HCl in the stratosphere, there is a depletion of 0.06% of the ozone column at 60° N, while ~0.02% of the ozone column is depleted at 30° N. Table 4 shows this number is close to the current actual usage of solid motors worldwide for the years 2004 to 2013. The actual annual global concentration of accumulated inorganic chlorine for those years was 714 tons, which is similar to the average over the past 28 years, although it has recently dropped to 600 tons the past two years. It may remain lower without U.S. Space Shuttle launches. The actual ozone column lost would be 0.052% at 60° N, and 0.017% at 30° N assuming linear scaling.

Danilin et al.[56] predicted a global average annual ozone column depletion of 0.0123%. These numbers are similar to the results of Jones et al.[14] where they calculated the cumulative effect of ten Ariane 5 launches per year (550 tons deposited per year) for 20 years would be a total global ozone loss of ~0.1%. The actual deposition rate for the last 20 years was 750 tons per year, which is still similar to the number determined in the previous report of 766 tons. Scaling the ozone loss predicted by Danilin et al.[56] by the amount actually deposited gives a total ozone loss of 0.14% for the last 20 years of worldwide launches. The contribution of the USAF to the amount of worldwide inorganic chlorine deposited has averaged 23.5% for the last 20 years. However, since the retirement of Titan IV and Atlas IIAS, the USAF average contribution has dropped to 5.4% of worldwide deposition for the years 2003 to 2013. The contribution has remained low as the previous report predicted. For the next 20 years, the USAF annual contribution to ozone destruction from inorganic chlorine should be around 0.0004(3)%.

3.1.3 Stratospheric Ozone Destruction by Alumina Exhaust

Danilin et al.[56] used a 3-dimensional photochemistry and transport model to calculate the effect of alumina on global ozone. They used 1120 tons per year of alumina entering the atmosphere, which is close to the average total released by rockets from 1994 to 1998. Danilin et al. predict the total global ozone loss to be about 0.0028% per year. Ross et al. found a significant difference in the particle size distribution in the plume from the large thrust Space Shuttle and Titan IV and the plume from the smaller thrust Athena II.[57–59] The results of Ross et al. would indicate that particulate size is proportional to thrust of the solid rocket motor. For Athena II launches, Ross et al. found that 8% of the total mass was contained in particles less than a micron in size. Particulates from 0.01 μm to 1 μm are the most important to ozone depletion since only particulates of these sizes will have significant lifetimes of 1–4 years in the stratosphere. Since Athena II produces more particles less than a micron in size than Titan IV or the Space Shuttle, there is a significant increase in the surface area of the particles formed in the Athena II plume compared to the plume of the Titan IV or Space Shuttle. This would significantly impact the loss of ozone predicted previously by Danilin et al.[56] Ross et al.[52] predict that ~250 tons of alumina per year come from lower-thrust vehicles. Since the distribution of alumina size in the wake of so few solid rocket motors has been measured, the exact definition of a large- and small-thrust solid rocket motor is rather arbitrary. The Titan IV, Space Shuttle, Ariane 5, Ariane 6, SLS, and GSLV were considered large-thrust motors for this report. The average annual ozone depletion based on the results of Danilin et al.[56] scaled to include particle distributions for the exhaust from small-thrust solid rocket motors is 0.0049%.

The worldwide yearly average alumina exhaust was 1002 tons for the past 28 years, with 84–90% of the alumina coming from large-thrust vehicles. Adjusting Danilin and Ross[49,57] predictions for the actual usage rate gives an average annual ozone loss of 0.004% for the last decade. Future launch rate predictions are close to the predicted 1120 tons of Danilin et al.[56] with 1007 tons total and 170 tons coming from small-thrust vehicles in accordance with Table 5. The end of the Space Shuttle program will likely alter this in the near future. For the past two years, alumina averaged 706 tons with 37% coming from small-thrust vehicles. If this trend continues, then future ozone depletion would be affected. The USAF has launched only small-thrust solid rocket motors since 2005 because most launch vehicles used by USAF with solid motors have thrust similar to the Athena II. These motors generate a greater percentage of their particulates as small particles than the large motors in vehicles like Titan IV, thus the ozone destruction from alumina exhaust from USAF launches has only modestly decreased since 2005. The USAF average ozone destruction from alumina for the years 2006 to 2008 was 0.0005%. The average for the USAF since the retirement of Titan program is 17% higher than this number but still roughly the same as predicted in the last report. This is roughly equivalent to the amount destroyed by inorganic chlorine. Prior to the end of the Titan IV program in 2005, the USAF average annual ozone destruction from alumina was 0.0012%.

3.1.4 Stratospheric Ozone Destruction by H_2O Exhaust

Ross et al.[49] used plume and global atmospheric models to predict ozone destruction from the emissions released from Russian Proton-style launch vehicles. These vehicles use hydrazine-based propellants and the water vapor in the exhaust, resulting in only a small contribution to ozone destruction. They predict ten Proton launches per year, resulting in reducing the ozone by 0.00012% annually with 99.6% of the loss attributed to NO_x. Thus, only 0.4% of the predicted reduction in ozone is due to water vapor released by the Proton (7.2×10^{-7}% annual loss). They used a water amount of 628 tons of water vapor annually released above 15 km. The amount from all launch vehicles was about 8600 tons/yr for the past 10 years which is similar to the 8700 tons stated in the last report. Assuming the ozone loss scales linearly with generated water vapor concentration, then the actual average ozone loss from 2003 to 2013 has been 0.00001% annually from worldwide launches. The decade average has not significantly changed since the last report.

3.2 Climate Change and Radiative Forcing

Every emission from a launch vehicle has the potential to affect global climate. Some exhaust components such as carbon dioxide and stratospheric water vapor directly affect it by increasing the amount of greenhouse gases in the atmosphere. A greenhouse gas is a gas that absorbs and emits radiation within the thermal infrared range of the electromagnetic spectrum. Other exhaust components indirectly affect global climate by destroying greenhouse gas. NO_x, inorganic chlorine, and alumina in the stratosphere decrease the amount of stratospheric ozone. Stratospheric ozone is a very influential greenhouse gas in the atmosphere. Stratospheric ozone destruction significantly affects global climate. Other atmospheric greenhouse gas concentrations such as tropospheric ozone and methane are also changed by launch vehicle emissions. Other exhaust components such as alumina, sulfates, mesospheric clouds, and black carbon soot can affect the radiative balance of Earth by scattering and/or absorbing incoming radiation.

The most effective way to base the actual effect of all the cumulative exhaust components is to include launch vehicle exhaust at the altitude of emission into existing climate models. Climate modeling can predict which exhaust components the global climate is most sensitive to, as well as predict whether any exhaust components have a cumulative effect. To date, a comprehensive climate model that includes exhaust components has not been created, and climate affects of launch vehicle exhaust components can only be estimated from the current knowledge base for each component in the exhaust. This approach provides only a rough estimate of the potential for each component to influence climate.

Radiative forcing is the difference between the incoming radiation energy and the outgoing radiation energy in a given climate system. Since greenhouse gases absorb and emit infrared radiation, they can directly affect radiative forcing. For well mixed greenhouse gases such as carbon dioxide, the radiative forcing (RF) is proportional to the equilibrium climate change in terms of global mean surface temperature change.[32]

$$\Delta T_S = \lambda * RF \quad (15)$$

where λ is the climate sensitivity parameter in terms of temperature change per change in radiative power (K/W m^{-2}). Equation (15) is a simple approximation, and its exact magnitude depends on the atmospheric model used. For inhomogeneously distributed species in the atmosphere, such as ozone, λ is not constant. A positive RF means that the radiative forcing will produce an increase in global temperatures ,and a negative RF means that the radiative forcing will produce a decrease in the global temperatures.

3.2.1 Radiative Forcing of Carbon Dioxide.

The relationship between increases in atmospheric CO_2 mixing ratios and emissions has been tracked using a scaling factor known as the apparent "airborne fraction." This is defined as the ratio of the annual increase in atmospheric CO_2 to the CO_2 emissions. On decadal scales, this fraction has averaged about 60% since the 1950s. Carbon dioxide has a long atmospheric residence time, thus launch vehicle CO_2 exhaust becomes well mixed within the atmosphere. For a small perturbation in the concentrations of the atmospheric CO_2, the radiative efficiency (radiative forcing per part in million by volume in the atmosphere) is 0.01548 Wm^{-2} per ppmv.[32] Assuming worldwide emissions of 7 gigatons carbon yr^{-1} of CO_2 from all sources and an airborne fraction remaining at about 60%, Hansen and Sato predicted that the underlying long-term global atmospheric CO_2 growth rate will be about 1.9 ppm yr^{-1}, a value consistent with observations over the 1995 to 2005 decade.[60,61] This carbon emission mass ratio (7 GtC to 1.9 ppm) atmospheric concentration can be used to estimate the radiative forcing from launch vehicles. The total amount of carbon dioxide release for the last 28 years by worldwide launches was 397833 tons. The radiative forcing from worldwide launches for the last 28 years is approximately (397833 t / 7 Gt * 12g/44g * 1.9 ppm * 0.01548 W m^{-2} per ppmv) = 0.46 μW m^{-2}. The radiative forcing from USAF launches for the last 28 years is approximately 0.04 μW m^{-2}. These numbers are slightly higher than the previous report[2] but consistent with the numbers represented above.

3.2.2 Radiative Forcing of Stratospheric Water Vapor.

The lifetime of water vapor (τ) in the stratosphere is 1 to 6 years and it has a net warming effect.[32] The value six years is used here to reflect that rocket exhaust is deposited in both the lower stratosphere and also the upper stratosphere and beyond. The production rate of water vapor from a rocket motor launch is more or less instantaneous. Thus, a simple model of the cumulative effects of solid rocket launches is simply a summation of first order reactions.

$$[water_{vapor}]_t = \sum_{t_1=1985}^{t_2=2013} [water_{vapor}]_t \times e^{-\frac{t}{\tau}} \quad (16)$$

From Eq. (16) the amount of water vapor in the stratosphere from rocket launches in a given year will be the amount deposited that year plus the decayed amount from the years prior. The amount of radiative forcing from stratospheric water vapor can be estimated by small perturbations. The adjusted radiative forcing $\Delta F = f(x) - f(x_o)$ is given by the following equation:[62]

$$\Delta F = \frac{0.76}{\sqrt{1+0.01(x+x_o)}} + \frac{0.293(x+x_o)}{(1+0.046(x+x_o))} - \frac{0.76}{\sqrt{1+0.01(x_o)}} - \frac{0.293(x_o)}{(1+0.046(x_o))} \quad (17)$$

The initial water vapor concentration in ppm is x_o, and x is the small perturbation in water vapor concentration. Oinas determined a 0.12 W m^{-2} for 0.7 ppmv change in stratospheric water vapor. As of the end of 2013, there is about 62260 tons of water vapor in the stratosphere due to worldwide launches. Using a volume similar to the Ross and Sheaffer paper[71] to obtain the ppmv for water vapor yields an RF change of ~0.3 mW m^{-2} due to water vapor. This is higher than the previous report (18.2 μW m^{-2}) due to a change in the method used to convert the mass total into a ppmv of the exhaust in the stratosphere (i.e., assumptions about the density of the stratosphere and where the water vapor is likely to accumulate). As of the end of 2013, there is about 7628 tons of water vapor in the stratosphere due to USAF launches. The radiative forcing due to this water vapor is 36.8 μW m^{-2}.

Water vapor in the upper atmosphere from launch vehicles has been observed to increase mesospheric clouds, particularly in the polar region. Mesospheric clouds have been observed in the region of the summer pole over the days following launches, particularly after Space Shuttle launches, as the magnitude of the shuttle exhaust plume was larger than any other launch vehicle, and the main engines produced water vapor.[63,64]

3.2.3 Radiative Forcing of Sulfate

Sulfate aerosols, produced by oxidation of sulfur impurities in kerosene rocket fuel, tend to have a net cooling or negative radiative forcing as they scatter incoming solar radiation. The direct radiative forcing has a range of –110 W g^{-1} to –251 W g^{-1}, depending on the modeling method.[34] The value of –215 W g^{-1} was used for the modeling of aviation emissions and will be used here for better direct comparison.[65] The median global mean column burden of sulfate aerosol was derived in the Penner review by adopting an emission index for sulfur (EI) of 0.4 g of sulfur per kg of kerosene fuel and a 50% effective conversion factor from fuel-sulfur to optically active sulfate aerosols. For the burning of 47 Tg of kerosene in the stratosphere, they determined the production of 0.02 Tg of sulfur in the stratosphere. This produced a column density of sulfate of 13.5 μg m^{-2}. For the Prenner study, the radiative forcing from sulfate aerosols is then determined by taking the column density (µg m^{-2}) multiplied by –215 W g^{-1}. For aviation emissions, the radiative forcing was determined to be –0.003 W m^{-2}.

On average, launch vehicles produced 0.05 tons of sulfur over the period of 2000 to 2009. The amount of SO_x accumulated in the atmosphere would be 0.2 tons, assuming a 4-year lifetime. Using a value of –215 W g^{-1} produces an RF of –0.09 μW $m^{-2.}$ Assuming the column density scales with emission then the column density for sulfates from launch vehicle exhaust is 0.00015 μg m^{-2}. The launch vehicle exhaust radiative forcing from sulfate aerosols is then –0.03 μW m^{-2}. The radiative forcing from sulfates from USAF launch vehicles averages about –0.003 μW m^{-2}. By either determination, the RF would be negligible.

3.2.4 Radiative Forcing of Tropospheric NO_x

Determining the radiative forcing of NO_x is complicated. At lower altitudes, NO_x chemistry will increase the amount of ozone in the atmosphere and decrease the amount of methane. This means it has the potential to both increase radiative forcing by forming tropospheric ozone and decrease radiative forcing by destroying methane. Fuglestvedt et al.[66] calculated that the ozone radiative forcing per change in NO_x emission was 3.5 mW m^{-2} per TgN/yr for release of NO_x in the USA. The numbers get slightly smaller for release in other parts of the world. Ground operations causing formation of ozone is thus dependent somewhat on local atmospheric conditions. By using the results of Fuglestvedt et al., the radiative forcing from ozone formation by NO_x in the troposphere can be determined. The average annual release of NO_x in the troposphere from worldwide launches from 1985 to 2013 was 89 tons. This results in a radiative forcing for tropospheric ozone formation from worldwide launch vehicles of ($89 * 10^6$ g * 14 g/ 30g $*1*10^{-12}$ g^{-1} * 3.5 mW m^{-2}) = 0.15 μW m^{-2}. The average annual release of NO_x in the troposphere from USAF launches from the past decade was 6.1 tons. The annual radiative forcing for tropospheric ozone formation from USAF launch vehicles is 0.01 μW m^{-2}.

For Fuglestvedt et al., the CH_4 forcing per change in NO_x emission is –5 mW m^{-2} per Teragrams nitrogen/yr for release in the USA.[66] The determination for RF change due to tropospheric methane destruction from annual worldwide launches using the results of Fuglestvedt et al. is ($89 * 10^6$ g * 14 g/ 30g $*1*10^{-12}$ g^{-1} * –5 mW m^{-2}) = –0.21 μW m^{-2}. The determination for RF change due to tropospheric methane destruction from annual USAF launches using the results of Fuglestvedt et al. is -0.01 μW m^{-2}.

Launch vehicles generate NO_x throughout the troposphere. Thus, using numbers based on ground-based emissions can produce some errors, particularly for determining the RF from ozone formation.[67] Methane has a relatively long lifetime in the atmosphere. Ozone, however, is not a well-mixed gas in the troposphere. Previous determinations of the ozone formation RF based on high-flying aircraft NO_x emissions produced much larger estimates of the RF from launch vehicles. However, NO_x generation in the troposphere from non-nitrogen-carrying fuels drops off rapidly with altitude for launch vehicles. Thus, for many launch vehicles, the vast majority of the NO_x is generated near ground level. The actual RF from ozone formation in the troposphere is probably somewhat larger than that determined based on only a ground-based estimate. However, a slight increase could easily switch the magnitude of the overall effect of tropospheric NO_x release. Overall, the generation of NO_x in the troposphere probably has a slight net negative radiative forcing since the radiative forcing from ozone formation might be slightly smaller than the radiative forcing from methane destruction. All these effects are extremely small.

3.2.5 Radiative Forcing Due to Ozone Destruction from Stratospheric NO_x

Due to the difference in concentrations of trace gases in the stratosphere and in the troposphere, the NO_x that is exhausted into the stratosphere will get involved in the ClO_x-NO_x-O_3-CH_4-OH_x cycle that destroys stratospheric ozone. The loss of ozone in the stratosphere has a net cooling effect. The depletion of stratospheric ozone over the past three decades has been substantial. Between latitudes of 60°S and 60°N, it averaged about 2.6% per decade.[35] Models using observed ozone changes, but with varied methods to derive the temperature changes in the stratosphere, have obtained a radiative forcing of -0.05 W m^{-2} with a wide uncertainty range of -0.15 to $+0.05$ W m^{-2} for the years 1979 to 1998 for the ozone destruction.[68] The best estimate is from the observationally based 1979 to 1998 RF of -0.05 ± 0.05 W m^{-2} (-0.025 W m^{-2} per decade), with the uncertainty range increased to take into account ozone change prior to 1979, using the model results of Gauss et al. (2006)[78,79] as a guide. Using Ross et al.[49] determination of ozone loss from NO_x (adjusted for actual NOx released), the radiative forcing from stratospheric ozone by the NO_x exhaust from worldwide launch vehicles over the last 28 years is about (0.0016%/ 2.6% *–0.025 W m^{-2} *28 years/10 years) = –43 μW m^{-2}. The USAF produces about 2% of the stratospheric NO_x from launch vehicles. The USAF launch vehicle emissions and resulting radiative forcing contribution from ozone destruction by stratospheric NO_x is –0.86 μW m^{-2}.

3.2.6 Radiative Forcing Due to Ozone Destruction from Inorganic Chlorine

In the stratosphere, the HCl exhaust is involved in the catalytic destruction of ozone. The loss of ozone in the stratosphere has a net cooling effect. The depletion of stratospheric ozone over the past three decades has been substantial. Between latitudes of 60°S and 60°N, it averaged about 2.6% per decade.[56] Models using observed ozone changes, but with varied methods to derive the temperature changes in the stratosphere, have obtained a radiative forcing of –0.05 W m^{-2} for the years 1979 to 1998 for the ozone destruction.[68,79] Using the Danilin et al.[56] estimate (adjusted for actual Cl_x released) for ozone loss over the last 28 years, the radiative forcing from stratospheric ozone by Cl_x exhaust from worldwide launch vehicles from 1985 to 2013 year is about (0.07%/ 2.6% *–0.025 W m^{-2} *28 years/10years) = –2.0 mW m^{-2}. The USAF launch vehicle emissions and resulting radiative forcing contribution from ozone destruction for the last 28 years by stratospheric Cl_x is ~-0.56 mW m^{-2}.

3.2.7 Radiative Forcing Due to Ozone Destruction from Alumina

In the stratosphere, the alumina exhaust is involved in the catalytic destruction of ozone. The loss of ozone in the stratosphere has a net cooling effect. The depletion of stratospheric ozone over the past three decades has been substantial. Between latitudes of 60°S and 60°N, it averaged about 2.6% per decade.[56] Models using observed ozone changes, but with varied methods to derive the temperature changes in the stratosphere, have obtained a radiative forcing of –0.05 W m^{-2} for the years 1979 to 1998 for the ozone destruction.[68] Using the Ross et al.[57] estimate (adjusted for actual alumina released) for ozone loss over the last 20 years, the radiative forcing from stratospheric ozone by alumina exhaust from worldwide launch vehicles for the last 28 years is about (0.049%/ 2.6% *–0.025 W m^{-2} *28 years/10years) = –1.3 mW m^{-2}. The USAF launch vehicle emissions and resulting radiative forcing contribution from ozone destruction for the last 28 years by stratospheric alumina is ~ –0.18 mW m^{-2}.

3.2.8 Radiative Forcing Due to Ozone Destruction from Stratospheric Water Vapor

In the stratosphere, the water vapor exhaust is involved in the catalytic destruction of ozone. The loss of ozone in the stratosphere has a net cooling effect. The depletion of stratospheric ozone over the past three decades has been substantial. Between latitudes of 60°S and 60°N, it averaged about 2.6% per decade.[56] Models using observed ozone changes, but with varied methods to derive the temperature changes in the stratosphere, have obtained a radiative forcing of „0.05 W m„^{2} for the years 1979 to 1998 for the ozone destruction.[68] The radiative forcing from stratospheric ozone by water vapor exhaust from worldwide launch vehicles for the last 28 years is about (0.0001%/ 2.6% *„0.025 W m^{-2}

*28 years/10years) = –2.7 μW m^{-2}. The USAF radiative forcing contribution from stratospheric ozone by water vapor is negligible.

3.2.9 Radiative Forcing Due to Black Carbon Soot

The emissions of black carbon soot have a net warming effect on the atmosphere and were previously modeled by a global climate model.[39] The model used 75 tons/yr of black carbon for a global fleet. For the 75 ton scenario, the global RF change would be ~4 mW m^{-2}. This is close to the predicted average amount of black carbon soot generated for the past decade, 91±13 tons/yr. The USAF average for the last decade was still around 9 tons/yr, and the RF change would thus be 0.5 mW m^{-2}.

The original report's estimate for black carbon soot radiative forcing was relatively small at 0.05 μW m^{-2}.[2] This number relied on converting sooting from aviation kerosene use to kerosene use in launch vehicles. There is a relative error in this approach in that aviation fuel afterburns and has a much lower carbon sooting ratio than used for launch vehicles ~0.04 g/kg. This number was far too small. The correct sooting ratio is now used in Subsection 2.3 in the current report. This sooting ratio can be used to obtain an estimate of the radiative forcing of soot. The global mean radiative forcing to column loading of total anthropogenic black carbon is a range from approximately +1100 to +1850 W g^{-1}.[35,69] This number is generally increased to approximately +3000 W g^{-1} as a result of the higher sensitivity of the radiative forcing when the black carbon exists at higher altitudes above a greater proportion of cloudy layers.[70] (Check sentence: no conclusion.) Using a lifetime of 4 years[80] for the soot, there is ~ 400 tons from launch vehicle usage over the past 28 years, and this produces an RF of about ($400 * 10^6$ g $*5.1 * 10^{-14}$ m^{-2} * 3000 W g^{-1}) = 2.4 mW m^{-2}. This estimate is similar in magnitude to the number generated by other analysis methods described above. This means the original 2007 report clearly underestimated black carbon soot RF although the methodology would have produced a correct order of magnitude estimate had the more accurate sooting ratios been used.

3.2.10 Radiative Forcing Determined by Alternative Method

The Aerospace Corporation recently estimated RFs for black carbon soot, CO_2, H_2O, and alumina (Ross and Sheaffer[71]). The authors used a mass specific scattering or absorption factor σ (m^2/kg) of material. Such a material could be a gas or particles. While this approach is not standard, it served the purpose of estimating the order-of-magnitude of the complex phenomenon, allowing comparisons of the calculated RFs among the different emission sources. In this view, RF was treated as a linearly increasing function of the amount of material added into the atmosphere:

$$RF = I\left[\frac{2M}{3} N\, EI(j)\tau\right]\sigma_j A_{NH}^{-1}, \tag{18}$$

where M is the mean mass of propellant burn per launch, N is the annual launch rate, and EI(j) is the emission index for the exhaust product j, all of which are launch vehicle specific. The parameter σ_j is the mass-specific scattering or absorption factor for product j, and A_{NH} is the area of the northern hemisphere. *I* is the mean solar shortwave (SW) or terrestrial longwave (LW) radiation. The parameter τ is essentially the e-folding time for removal from the stratosphere, reflecting the accumulation of compounds in the stratosphere, and is assumed here equal to four years. The factor of 2/3 accounts for the fact that about one third of a rocket's total propellant burn takes place under the tropopause.

The data presented in the Ross and Sheaffer paper can be used to determine an estimate of RF changes using the current database of launch vehicles developed. They present the RF forcing due to prototypical launch vehicles in terms of mass. This can be scaled by actual launch vehicle propellant masses to estimate RF as well.

These RF rates were used to model the worldwide launch fleet by the following equation:

$$RF = mass\frac{propellant}{1000\ tons} * RF_{CO_2} + mass\frac{propellant}{1000\ tons} * RF_{\mathrm{H_2O}} + mass\frac{propellant}{1000\ tons} * RF_{\mathrm{parts}} \quad , \tag{19}$$

where the values for the various RF components come from Table 6. The particles considered in the study were alumina and soot. The total RF was then calculated for each propellant used in the launch vehicle since most launch vehicles use a combination of propellants.

Ross and Sheaffer[71] determined the RF for carbon dioxide is 3.0 µWm^{-2} for ~100 ktons over 25 years to estimate the total burden since the space age began, which is about 60% larger than the actual launch rate the past ~28 years. Scaling this gets about 1.2 µWm^{-2} for the past 25 years. This value is slightly larger than predicted above in this report but is still trivially small. Using the 100 kton number in Subsection 3.2.1 yields 1.1 µWm^{-2}, which is not unreasonably different than the 3.0 µWm^{-2} number as a rough estimate. In either method, the carbon dioxide is trivially small compared to other factors. When people talk about kerosene rockets having little atmospheric impact, they are generally thinking about carbon dioxide deposition and not black carbon soot formation.

Ross and Sheaffer[71] estimated an RF of 0.6 mWm^{-2} due to stratospheric water vapor (~70000 tons) based upon an assumed set of launch rates. Their result is similar to the number of 62260 tons determined in this report. This RF number is about twice as large as what was estimated for the RF in Subsection 3.2.2 for about the same amount of water vapor. However, their paper[71] properly states that estimates of water vapor heavily depend on accumulation and density of the air column. Ross and Sheaffer determine that the water vapor will accumulate in a complicated fashion at altitudes between 15 and 30 km. Subsection 3.2.2 now uses ~15–30 km to determine the volume of the stratosphere and assumes a well-mixed atmosphere rather than accumulation in mainly the northern hemisphere. By using a volume similar to the Ross and Sheaffer paper, the estimated number in Subsection 3.2.2 would change to ~0.3 mWm^{-2} for water vapor forcing, which is a pretty reasonable agreement for the

Table 6. Direct RF for Given Proxy Launch System Under Assumption of Constant Launch Rate of One Per Year. The RF value for hypergolic and SRM includes contribution from assumed (relatively small) soot emission.[71]

Vehicle propellant	M propellant mass (Tons)	CO_2 RF at constant launch rate (mWm^{-2})	H_2O RF at constant launch rate (mWm^{-2})	Soot RF at constant launch rate (mWm^{-2})	Alumina RF at constant launch rate (mWm^{-2})
		CO_2	H_2O	parts	parts
Hydrogen LOX	500	0.0	0.02	0.0	
Solid rocket motor	500	2×10^{-6}	0.005	0.1	0.18
Kerosene LOX	500	6×10^{-6}	0.02	0.	
Hypergolic	500	1×10^{-6}	0.001	0.06	

two methods. It certainly adds weight to the higher RF number being a reasonable assumption compared to numbers determined in the previous report that used a much larger percentage of the stratosphere.[2–4]

Ross and Sheaffer originally estimated an RF of 12. ± 2 mWm^{-2} due to soot particulates by using an estimate of launch rates. Using their numbers with actual current launch rates yields a number of 18±2 mWm^{-2}. This number is likely too large due to the relatively large sooting rates used to determine hypergolic and modern Kerosene/LOX engines as discussed in Subsection 2.3. Scaling the RF numbers in Table 6 for the soot portion of the particulates by the modern measurement of Russian kerosene engine sooting rates produces the result of ~3.3 mWm^{-2}. This value is in agreement with the two estimates in Subsection 3.2.8 in the current report. The change in RF due to assumptions in mass fraction of the kerosene engine demonstrates the need to carefully determine such mass fraction for any new engine produced. In the absence of such a determination, the most conservative estimate is reasonable.

The paper[71] includes increasing RF forcing due to alumina particulates, which is not handled anywhere else. Previously,[2] alumina particles had been treated similar to mineral dust and were assumed to have a slight negative RF due to the scattering of shortwave radiation being greater than the absorption of longwave radiation of mineral dust. However, Ross and Sheaffer demonstrated that assuming that alumina is similar to mineral dust is likely not correct, and the net effect of alumina is a positive radiative forcing. They determined an RF value for ~1200 tons of alumina accumulated a value of 4.8 mWm^{-2}. Scaling the accumulated alumina result of Danilin et al.[56] for current deposition rates and adjusting for higher percentage of smaller particulates from smaller solid rocket motors produces an accumulation of 979 tons. This is similar to the value used in reference 71 and produces a value of 3.9 $mW\,m^{-2}$.

In another review paper, Voigt et al.[76] released an overview report on the impact of rockets on the atmosphere. They summarized much of the information already included in this report. They discussed the following emissions: CO_x, H_2O, N_2, H_2, Cl_x, and alumina. The paper discusses the effect on ozone, citing many of the reports cited here. They also conclude rocket aerosol and water emissions above the troposphere also can affect the global radiation budget and mesospheric clouds but offer no estimate of that effect. They concluded that the detailed evaluation of these effects on the global scale will require models that include all relevant processes, from the Earth’s surface to the mesosphere, as discussed below.

3.2.11 Conclusion for Radiative Forcing

Table 7 has the change in radiative forcing due to the emissions from launch vehicles for the last 28 years. Carbon dioxide is only a minor contributor to the change in radiative forcing due to launch vehicles. However, due to carbon dioxide’s long atmospheric lifetime ,its continued release is cumulative, and this contribution will last thousands of years.[79] Stratospheric water vapor, soot, and alumina emissions likely cause a larger change to radiative forcing than carbon dioxide emissions, but the lifetimes of these non-well-mixed constituents in the stratosphere is relatively brief and the effects due to emissions reach and maintain a steady-state value depending on how steady the launch rate is. Given the current values of these emissions effects on the Earth’s radiative balance more effort should be used to determine these effects if/when launch rates increase. An order of magnitude increase in launch rates would start to produce significant changes. Sulfur emissions do not contribute significantly to changes in radiative forcing. All other contributions to changes in radiative forcing are dwarfed by the impact to ozone destruction, soot, and alumina particulate production. The destruction of ozone from a combination of NO_x, Cl_x, and alumina has an overall cooling effect. This effect is less understood than any other component of radiative forcing and has not been examined in any comprehensive way.

The total RF change from the year 1750 to 2013 due to anthropogenic sources was determined to be ~2.29 W m^{-2}.[68,77] The total change in RF due to launch vehicles for the last 28 years could be as high as 0.5% of this total change in RF due to anthropogenic sources or a low as –0.1%. The problem in determining this number accurately is that within the uncertainty of the negative forcing and positive forcing components, the net radiative forcing ranges from strongly positive to slightly negative. Several components in the table are not well known. If the highest values in literature are correct, the effects of ozone depletion could cause a factor of 2 to 3 more decrease in RF. Also, as demonstrated in reference 71, the RF for black carbon soot and alumina particulates could be larger than estimated here depending on future of kerosene engine designs and usage rates.

Table 7 represents an estimate of magnitude of radiative forcing from various constituents of launch vehicle exhaust. The water fraction is elevated from previous determinations due to different assumptions on accumulation in the atmosphere. However, as observed on Table 7, black carbon soot, inorganic chlorine, and alumina are clearly the exhaust components that have the most impact. This does not include unknown effects that have yet to be included in atmospheric modeling. There are known launch vehicle effects that could potentially influence radiative forcing. For instance, there is evidence that launches (at least Space Shuttle launches) affect the formation of polar mesospheric clouds.[72,63,64] However, the amount of increase of clouds and their relationship to climate change are not well known. Likely, there is both an infrared and a light-scattering component. For global aviation, several attempts have been made to estimate the impact of tropospheric contrails to radiative forcing.[73,74] Launch vehicle exhaust components, such as particulates, sulfates, and soot, can potentially influence cloud formation rates in the troposphere as well.[71,75]

Table 7. The estimates for the radiative forcing (μW m^{-2}) from different components of the exhaust from launch vehicles from 1985 to 2013. The older estimates are shown in blue. The current estimates are shown in red. The alternative determination from reference 71, shown in green, represents calculations that have been scaled based on the actual launch rates and modifications to soot mass fractions for modern Russian kerosene engines. Ref 71 scaled to actual launch rates as of 2014. The green numbers represent an estimate of current impacts and include the entire space age for components like CO_2.

	CO_2	Soot/ particulates	Alumina/ particulates	H_2O (strat)	NO_x (trop)	CH_4	NO_x (strat) (Ozone)	Sulfate (Ozone)	Cl_x (Ozone)	Alumina (Ozone)	Mesospheric clouds	H_2O (Ozone)
2012 report	0.46	4000		18.2	0.09	-0.120	-36	-0.03	-2360	-770	Not known	
Worldwide	0.46	4800		300	0.15	-0.21	-40	-0.09	-2000	-1000		-2.7
USAF	0.04	450		37	0.01	-0.01	-1	-0.003	-580	-180		
Worldwide Scaled Ref 71.	**1.2**	**3300**	**3900**	**500**								
From Ref 71	**3**	**12000**	**4800**	**600**								
Best estimate	**3-1**	**12000-3000**	**4800-4000**	**600-300**	**0.09**	**-0.120**	**-40**	**-0.09**	**-2000**	**-1000**	**Not known**	**-2.7**

3.3 The Need for Climate Modeling of Launch Vehicle Exhaust

Obviously, the best way to understand all of the influences discussed in this report is through the use of existing climate models and the incorporation of launch vehicle exhaust components into them. Launch vehicles release components in their exhaust similar to other human industrial activities; however, they release these components in atmospheric regions reached by no other industries. The transport and accumulation of components that are not well mixed in the atmosphere make a substantial difference to the estimate of their effect. The atmospheric layer of deposit, the atmospheric layer of accumulation, the transport rate, the influence on atmospheric flow, and the atmospheric chemistry can all have substantial effects on the impact of an emission, many of which are only estimated in this current report. To date, very little modeling and no total exhaust component modeling that includes chemistry has been performed. In general, launch vehicle exhaust components that have been modeled show that launch vehicles have made relatively small contribution to atmospheric changes like ozone destruction. This conclusion, however, is based on current low launch rates. At elevated launch rates, the exact composition of the fleet would greatly affect the exhaust plume components and the potential for long-term effects to the atmospheric environment. If ambitious orbital projects that require large launch rates come to fruition, full atmospheric modeling of launch vehicle exhaust plumes are going to become of interest to the community, and the assumption that launch vehicle exhaust effects on the upper atmosphere are relatively small will no longer be valid. There is no reason not to explore these questions through a more rigorous scientific approach using the most current atmospheric modeling, even if the answer is that the climate influence of launches at present is small at current low launch rates. The best method for understanding all of the potential influences launch vehicle exhaust may have is through the use of existing climate models and incorporating launch vehicle exhaust components into those models.

4. Conclusion

In contrast to earlier programs, the EEVL program has significantly impacted the environmental effect of USAF launch vehicles for the better. The primary change for the EELV program was the elimination of the Titan IV launch vehicle. This eliminated the USAF usage of large-scale solid rocket motors in the boost phase and eliminated the program's primary source of inorganic chlorine in the stratosphere. Also, the Titan IV used a hydrazine-based propellant that further contributed to ozone destruction. The current largest impact from USAF space launches is alumina produced from small launch vehicles such as Athena II, Minuteman III, Pegasus, Taurus, and Minotaur IV, V, and VI.

Ozone destruction from the formation of NO_x, alumina, and inorganic chlorine in the stratosphere continue to have a relatively small significance on environmental impact. This destruction of ozone is also likely a significant contribution to global climate change by launch vehicle emissions. Along with contributing to global climate change, ozone destruction has other negative environmental impacts. Significant changes in the ozone destruction rates from launch vehicle exhaust are likely in the future since the United States Space Shuttle program had the largest environmental footprint due to its use of large solid rocket motors in boost phase. The future Space Launch System program could be deployed with large solid rocket motors similar to those (or larger than) those on the Space Shuttle. The Europeans have begun launching VEGA and are discussing future designs of Ariane 6 as an all-solid-rocket-motor vehicle. The Chinese are also planning an all-solid-rocket-motor vehicle (the Long March 11) for use in launch-on-demand applications. European, Indian, and Japanese programs all have increased their reliance on solid rocket motors since 1985,and future vehicle designs suggest they may increase this reliance. So even though the Space Shuttle and Titan programs are now ended, the future impacts of inorganic chlorine and alumina deposition rates are not resolved. The launch rate of solid rocket motors could increase in the near future, depending on the launch rate of these internationally proposed programs.

The Russians continue to launch a fleet composed of vehicles that use hydrazine-based fuels. The Russian launch vehicle design significantly influenced the current Chinese program that uses similar vehicles. While launch rates of Russian vehicles remain steady, the Chinese launch rate continues to increase. However, the Russians have increased their use of kerosene-based launch vehicles of late and may continue to do so to decrease dependence on certain launch sites. Also, the Chinese are in the planning stages of launching kerosene/LOX vehicles. Given the above facts and the predicted increased usage of the Falcon launch vehicle family by the USA, there could also be a rise in kerosene/LOX launch vehicle launch rates in the near future. Not all of these vehicles have the sooting characteristics of the current Russian engine fleet.

The current selection of launch vehicles used worldwide suggests that worldwide space launches will continue to have a small negative impact on the ozone layer. The retirement of the shuttle has produced a small decrease in this impact, but there is nothing to suggest that future impact couldn't soon return to the impact observed during the Space Shuttle launching years due to the current vehicle designs being discussed by Europeans, USA, and China. Currently, the future impact to ozone concentrations from launch vehicle emissions is determined by scaling the results from previous computational models. The use of such scaling becomes questionable the further into the future that it is projected. This is because other ozone-depleting substances (such as CFCs) are decreasing in atmospheric concentration. Thus, the background environmental destruction rates in these computational models will need to be changed significantly thirty to fifty years in the future. Future computational models of launch vehicle emissions atmospheric impact that include more updated concentrations of these ozone-depleting substances will be needed eventually to accurately determine environmental impacts from these emissions.

The first report on our efforts to understand radiative forcing was made in 2007. Since then, better estimates and revised methods have improved accuracy of determinations and corrected errors such as the underestimate of black carbon soot impact in the original 2007 report. Still there is a limit to what can be accomplished by using the current crude approximation methods. The best way to improve the determination of the radiative forcing impact of space launches would be to utilize the current global climate models and apply them to modeling the emissions of launch vehicles. To date, very little climate modeling has been conducted that includes a comprehensive approach to the emissions from space launches. The climate effects of space launches can thus only be estimated, and significant interactions with the upper atmosphere and these emissions may not be captured by current estimates. These estimates are only of limited value, and clearly the rough estimates determined here can differ slightly from more intricate calculations such as in ref 71. To date, ozone depletion is the most comprehensively studied change due to launch vehicle emissions. Nevertheless, changes due to particulate scattering and radiative forcing, changes in upper atmospheric circulation and transport, and cloud formation should also be studied more comprehensively. Thus, particulate formation from future vehicles that plan to use hydrocarbon-based fuels (kerosene or hydrocarbon solids from hybrids or solid rocket motors) need to be included in future modeling efforts if any should arise. This may be particularly important if U.S., Russian, and Chinese kerosene engine usage increases in future vehicle designs. Given the current levels of radiative forcing, such comprehensive atmospheric modeling may at first appear to be unnecessary. However, ambitious proposed space projects, such as space tourism, would result in elevated launch rates ,and a comprehensive understanding of the impacts due to potential launch emissions on the troposphere and the upper atmosphere should be completed before such projects cause significant environmental impact. This would best align with the U.S. National Environmental Policy Act (NEPA) of 1970.

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Appendix

Table A1. Worldwide Atmospheric Deposition from Launch Vehicles as a Function of Altitude for the Years 1985 to 2013

Year	CO_2	NO_x	H_2O	Cl_x	Al_2O_3	Soot
			Troposphere			
1985	10239.71	125.14	7418.15	1294.12	1819.82	0.00
1986	7684.17	71.83	4550.20	384.75	546.27	0.00
1987	7597.22	69.48	4310.77	279.21	407.59	0.00
1988	8478.60	82.24	5104.75	454.30	645.76	0.00
1989	8152.64	99.44	5739.23	977.46	1410.73	0.00
1990	8998.88	120.23	6669.09	1333.98	1937.45	0.00
1991	6931.33	95.15	5360.53	1026.62	1460.41	0.00
1992	7716.20	112.02	6204.38	1359.05	1941.64	0.00
1993	6554.87	93.25	5234.39	1125.35	1597.77	0.00
1994	7025.22	112.92	6075.12	1346.29	1913.47	0.00
1995	5894.43	99.69	5288.76	1340.35	1910.20	0.00
1996	5841.57	105.68	5441.46	1493.48	2138.46	0.00
1997	6623.87	121.37	6213.00	1723.47	2486.00	0.00
1998	5966.26	101.87	5348.71	1382.35	1990.86	0.00
1999	5436.13	86.10	4506.48	1083.44	1589.44	0.00
2000	6313.18	100.60	5328.06	1169.18	1694.34	0.00
2001	5057.64	90.29	4667.78	1328.99	1924.38	0.00
2002	4991.65	90.18	4790.41	1130.89	1613.18	0.00
2003	3705.15	56.05	3017.11	704.81	1041.76	0.00
2004	3558.80	46.43	2633.00	414.02	628.50	0.00
2005	3958.92	57.31	3013.08	678.03	999.59	0.00
2006	4672.37	75.87	4089.12	940.15	1355.66	0.00
2007	4729.47	77.87	4094.85	936.40	1347.83	0.00
2008	5121.49	82.41	4312.53	932.79	1332.35	0.00
2009	5035.04	81.60	4526.41	1028.04	1486.62	0.00
2010	5114.22	75.64	4433.97	642.03	917.47	0.00
2011	5865.24	85.16	4885.92	925.26	1337.11	0.00
2012	5580.00	99.07	4406.80	589.32	861.39	0.00
2013	5253.46	68.36	3906.97	485.26	708.80	0.00
			Stratosphere			
1985	7673.55	26.94	5651.78	882.84	1238.78	74.76
1986	5864.26	24.76	3460.92	220.50	311.83	41.28
1987	5730.87	28.90	3159.84	87.75	128.99	36.24
1988	6411.04	29.61	3816.47	241.67	342.12	44.51
1989	6044.24	26.35	4268.92	598.12	854.69	56.44
1990	6583.65	30.69	4894.97	790.57	1136.21	66.78
1991	5104.40	25.36	4031.86	681.67	966.06	53.43
1992	5624.15	23.89	4630.30	880.61	1249.40	63.77
1993	4808.77	19.01	3945.79	763.97	1080.79	55.15
1994	5023.11	31.69	4502.86	900.24	1277.51	61.86
1995	4218.23	23.10	3909.30	888.30	1263.34	55.44
1996	4098.35	23.08	3987.92	978.10	1396.30	59.46

Year	CO_2	NO_x	H_2O	Cl_x	Al_2O_3	Soot
1997	4623.51	26.50	4516.28	1124.28	1616.30	67.07
1998	4221.36	22.16	3954.47	904.49	1296.71	56.78
1999	3838.62	22.87	3238.47	667.10	972.62	46.40
2000	4527.79	29.31	3942.98	792.93	1144.77	54.27
2001	3555.57	16.73	3429.29	882.33	1270.75	52.76
2002	3551.13	24.52	3588.09	785.35	1118.40	50.14
2003	2674.84	14.70	2220.26	448.34	660.64	32.91
2004	2611.45	17.26	2307.32	260.92	393.18	24.24
2005	2918.23	16.36	2264.95	467.23	685.83	34.63
2006	3369.24	14.93	3058.47	639.02	916.53	43.90
2007	3439.32	18.05	3468.69	648.41	929.85	44.36
2008	3698.00	24.57	3240.60	656.89	935.97	48.09
2009	3621.32	18.40	3765.65	705.32	1013.93	49.40
2010	3747.82	28.61	3720.75	449.38	638.36	38.91
2011	4321.40	23.57	4088.90	636.49	914.84	50.37
2012	4169.27	44.47	3726.41	422.27	615.71	42.51
2013	3920.63	25.06	3300.93	324.61	472.61	43.99
			Mesosphere			
1985	1398.07	4.99	1257.73	1.25	1.72	15.92
1986	1211.13	4.60	741.24	0.00	0.00	13.73
1987	1322.37	5.37	687.07	0.74	1.01	15.22
1988	1392.26	6.82	870.20	0.27	0.36	15.04
1989	1198.05	6.14	944.55	0.63	0.86	13.72
1990	1284.71	7.37	1064.95	1.62	2.29	14.84
1991	1043.36	6.29	948.51	0.84	1.22	11.51
1992	1091.06	6.24	1081.21	0.11	0.15	11.74
1993	989.39	4.93	967.36	6.66	9.27	11.79
1994	1031.54	8.26	1087.61	6.19	8.97	12.29
1995	837.35	7.06	986.80	2.88	4.19	11.27
1996	806.95	6.86	964.52	19.85	28.86	10.48
1997	895.49	7.76	1119.31	25.71	37.01	13.43
1998	953.54	6.52	1033.31	24.35	36.39	12.88
1999	940.18	6.75	878.47	30.12	44.65	14.19
2000	1117.56	8.00	1086.55	61.60	89.88	18.04
2001	741.55	4.81	880.95	36.32	52.58	12.20
2002	798.46	7.76	1031.26	67.36	97.31	13.85
2003	780.87	4.14	678.18	58.02	83.56	13.11
2004	780.66	4.14	585.82	44.34	64.70	13.65
2005	782.31	3.90	619.97	77.90	113.12	14.69
2006	862.89	4.02	921.51	81.25	117.71	15.36
2007	859.38	4.87	887.34	97.95	141.76	16.46
2008	950.25	6.23	924.12	86.76	125.22	18.03
2009	957.57	4.97	1025.12	108.02	156.94	18.69
2010	899.47	7.21	949.68	41.29	60.82	12.98
2011	1139.44	6.70	1120.60	88.89	129.55	19.59
2012	1239.45	10.56	1096.30	111.68	162.16	22.24
2013	1342.30	7.40	978.75	77.36	112.09	25.54
			Thermosphere			
1985	5800.58	25.73	8909.83	5.49	8.79	63.88
1986	5161.24	24.02	4111.71	3.78	5.97	55.81
1987	5407.21	29.61	3018.47	8.24	13.35	59.73
1988	5676.04	32.24	4581.05	5.68	9.13	63.77
1989	4845.64	27.74	6031.36	11.01	17.72	53.27

Year	CO_2	NO_x	H_2O	Cl_x	Al_2O_3	Soot
1990	5190.36	29.58	6889.73	17.78	28.09	56.77
1991	3988.58	25.14	6298.37	3.71	5.61	44.47
1992	4313.46	23.18	7714.90	9.82	14.95	46.77
1993	3810.86	18.98	6756.66	6.46	9.65	41.57
1994	4073.40	32.82	7562.09	10.82	17.08	44.90
1995	3637.33	23.92	7212.42	7.87	11.46	39.88
1996	3161.02	25.30	7058.08	8.28	12.79	34.43
1997	3556.22	28.56	8091.35	16.22	24.75	39.22
1998	3351.95	24.01	7138.20	18.78	29.60	37.55
1999	3477.14	26.99	5221.34	22.26	34.51	39.27
2000	4056.46	38.22	6753.59	14.85	23.35	45.04
2001	2619.90	20.48	6051.77	12.41	19.33	29.25
2002	2597.08	31.10	6612.88	11.91	16.71	28.17
2003	2212.23	18.11	3143.62	15.77	22.70	24.83
2004	2657.26	21.92	2300.18	8.62	13.96	29.48
2005	2341.10	23.31	3126.25	10.18	14.90	26.39
2006	2451.07	21.24	5053.81	13.79	20.09	27.58
2007	2447.71	24.96	4939.30	12.17	17.73	27.06
2008	2719.98	30.73	5371.98	12.29	17.51	29.94
2009	2714.62	27.20	5463.48	11.15	16.98	30.51
2010	2862.40	30.04	4952.89	11.05	17.57	31.29
2011	3260.13	27.11	5667.80	17.49	27.14	37.26
2012	3515.83	42.21	4422.84	9.75	15.04	39.26
2013	3725.80	0.00	3730.94	23.93	36.99	46.05

Table A2. Active Launch Vehicles and the Main Engines Used on First Stage

Vehicle	Booster Stage Engine	First Stage Engine	Second Stage Engine
China			
Kaitouzhe-1		Solid	Solid
Long March 2		Hypergolic	Hypergolic
Long March 4		Hypergolic	Hypergolic
Long March-5 3	LOx/Kerosene	LOx/Kerosene	LOx/Kerosene
Long March-5 5	LOx/Kerosene	LOx/Hydrogen	LOx/Hydrogen
Long March-11		Solid	Solid
Russian			
Cyclone 4		Hypergolic	Hypergolic
DNEPR-1		Hypergolic	Hypergolic
Proton		Hypergolic	Hypergolic
Rockot		Hypergolic	Hypergolic
Soyuz	LOx/Kerosene	LOx/Kerosene	LOx/Kerosene
Strela		Hypergolic	Hypergolic
Zenit-3SL		LOx/Kerosene	LOx/Kerosene
Israel			
Shavit-1		Solid	Solid
South Korea			
KSLV		LOx/Kerosene	Solid
Iran			
Safir		Hypergolic	Hypergolic
Europe			
Ariane 5	Solid	LOx/Hydrogen	
Ariane 6		Solid	Solid

Vehicle	Booster Stage Engine	First Stage Engine	Second Stage Engine
Soyuz ESA	LOx/Kerosene	LOx/Kerosene	LOx/Kerosene
VEGA		Solid	Solid
Japan			
H IIA	Solid	LOx/Hydrogen	LOx/Hydrogen
H IIB	Solid	LOx/Hydrogen	LOx/Hydrogen
Epsilon		Solid	Solid
North Korea			
Unha-3		Hypergolic	Hypergolic
INDIA			
PSLV	Solid	Solid	Hypergolic
GSLV	Hypergolic	Solid	Hypergolic
GSLV MK3	Hypergolic	Solid	LOx/Hydrogen
U.S.A.			
Atlas V	Solid	LOx/Kerosene	LOx/Hydrogen
Delta 4M	Solid	LOx/Hydrogen	LOx/Hydrogen
Delta 4H		LOx/Hydrogen	LOx/Hydrogen
Falcon 9 v1.1		LOx/Kerosene	LOx/Kerosene
Falcon 9 H		LOx/Kerosene	LOx/Kerosene
Minotaur		Solid	Solid
Minotaur IV		Solid	Solid
Minotaur V		Solid	Solid
Minotaur VI		Solid	Solid
Pegasus XL		Solid	Solid
Vehicle		First Stage Engine	
Super Strypi		Solid	Solid
Spaceship two		Hybrid	
Antares		LOx/Kerosene	Solid
Space Launch Systems	Solid	LOx/Hydrogen	
South Africa			
Cheetah-1		LOx/Kerosene	

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