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CHAPTER 10

Predicted Rocket and Shuttle Effects on Stratospheric Ozone

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Contents

SCIENTIFIC SUMMARY

The exhaust products of rockets contain many substances capable of destroying ozone. Although there are over a hundred rocket launches per year worldwide, studies so far have only considered the effects of the less frequent launches of the largest rockets. Most attention has focused on the potential reductions in ozone produced by chlorine compounds from solid fuel rockets. Rockets that release or are expected to release relatively large amounts of chlorine per launch into the stratosphere include NASA's Space Shuttle (68 tons) and Titan IV (32 tons) rockets, and European Space Agency's (ESA's) Ariane–5 (57 tons).

Within a few kilometers of the exhaust trail of these rockets, local ozone may be reduced by as much as 80 percent at some heights for up to 3 hours. Since the rocket trajectory is slanted, the corresponding column ozone loss is computed to be reduced over an area of order of a few hundred square kilometers, but the depletion nowhere exceeds 10 percent. A satellite study of column ozone loss associated with several NASA Space Shuttle launches failed to detect any depletion. Local effects of similar magnitude may also be produced by the NO_x emitted by the Soviet Energy rocket. Recovery of the ozone in the wake is computed to be rapid in all cases. All but a fraction of a percent is predicted to be restored within 24 hours.

The stratospheric chlorine input from a NASA launch rate scenario of nine Space Shuttles and six Titan IV rockets per year is computed to be less than 0.25 percent of the annual stratospheric chlorine source from halocarbons in the present-day atmosphere. If the annual background source from halocarbons is reduced and/or the launch rate increases, the fractional contribution will become larger.

Steady-state model computations using the NASA scenario show increases in the middle to upper stratospheric chlorine amounts by a maximum of about 10 pptv (about 0.3 percent of a 3.3 to 3.5 ppbv background) in the northern middle and high latitudes. Independent steady-state model computations of the effect of 10 ESA Ariane–5 launches per year yield comparable maximum values, but at all latitudes. For both scenarios, corresponding decreases in ozone are computed to be less than 0.2 percent locally in the region of maximum chlorine increase, leading to changes in column ozone of much less than 0.1 percent.

It is not yet possible to quantify with confidence the effects of particulates from the exhausts, principally of Al_2O_3 from the solid-fueled rockets. However, simple steady-state estimates using the NASA scenario suggest increases of the chemically active area of stratospheric aerosols of less than 0.1 percent, so the long-term global impact is likely to be negligible.

10.1 INTRODUCTION

The major chemical effluents of either solid- or liquid-fueled rockets that can potentially perturb stratospheric ozone include chlorine compounds (HCl), nitrogen compounds (NO_x), and hydrogen compounds (H_2 and H_2O). Radicals (Cl, ClO, H, OH, HO_2, NO, and NO_2) formed directly or indirectly from rocket exhaust can cause the catalytic destruction of ozone. Other exhaust compounds that could presumably lead to ozone destruction either by direct reaction with ozone or by providing a surface for heterogeneous processes include the particulates Al_2O_3, ice, and soot.

The possible impact of the exhausts of solid-fuel rockets on the ozone layer was recognized first in the early 1970s when possible effects of supersonic civilian aircraft were also first postulated. Accordingly, they were considered as part of the Climatic Impact Assessment Program (see Hoshizaki, 1975). At that time the effects of the Space Shuttle exhausts were considered to be small; model computations led to the conclusion that (with a launch rate of 60 Space Shuttles per year) the total ozone concentrations would be reduced by about 0.25 percent in the Northern Hemisphere and by about 0.025–0.05 percent in the Southern Hemisphere with an uncertainty of about a factor of three (Potter *et al.*, 1978). Since that study, there has been new knowledge of the chemical reaction rates and changing perceptions of the role of homogeneous and heterogeneous chemical reactions. Accordingly, in this chapter we review more recent assessments. No one has yet studied the effects of the totality of launches, but the effects of the launches of the larger rockets have been assessed by Prather *et al.* (1990a,b), Karol *et al.* (1991), and Pyle and Jones (1991), as described below.

The exhaust plume, including exhausted products and heights of release, is considered in Section 10.2. The exhaust plume spreads out so effects need to be considered at various time and space scales. We loosely devise the categories of (1) local and regional and (2) global scales and consider these in Sections 10.3 and 10.4, respectively. A major uncertainty of the model simulations presented in this chapter concerns the effects of the particulates that are exhausted during rocket launches. These rocket-produced particulates are discussed in Section 10.5. Finally, conclusions are offered in Section 10.6.

10.2 THE EXHAUST PLUME

Several countries have major space launch vehicles including the U.S. (*e.g.*, Space Shuttle, Centaur, Atlas, Titan, and Delta), U.S.S.R. (*e.g.*, Energy and Proton), ESA (*e.g.*, Ariane), Japan (*e.g.*, H–1, H–2, N–2, M–5), and China (*e.g.*, Long March). Some of these launch vehicles depend on solid fuel, some depend on liquid fuel, and others rely on a combination of solid and liquid (*e.g.*, Space Shuttle). The major exhaust products of various solid and liquid systems are shown in Table 10–1.

Each Shuttle launch vehicle uses about 1,000 tons of solid propellant and about 730 tons of liquid propellant (Bennett and Hinshaw, 1991). The solid boosters exhaust their effluents of HCl, Al_2O_3, CO, CO_2, H_2, and H_2O below 50 km, whereas the exhaust products H_2O and H_2 from the main engine (based on liquid propulsion) are primarily injected above 50 km. Most of the constituents exhausted below the tropopause, typically at a height of 15 km for the launch latitudes, are washed out rapidly before they can reach the stratosphere and hence have negligible effect on the ozone layer. Thus the Shuttle exhausts approximately 68 tons of chlorine in the form of HCl per launch above the tropopause (based on Prather *et al.*, 1990a,b, with the tropopause assumed at 15 km). The comparable value for the Titan IV is 32 tons of chlorine, for Ariane–5, 57 tons (based on Pyle and Jones, 1991, with the tropopause assumed at 14 km), and for Energy, zero tons.

A projection of launches in 1991 and 2000 by the four main space agencies involved in chemical rocket launches was recently given by AIAA (1991). Although together the four main space agencies are expected to launch over a hundred rockets in each of these years, most rockets are relatively small and inject only modest amounts of substances in the stratosphere. Large amounts of stratospheric rocket effluents are injected or are expected to be injected by the Space Shuttle, Titan IV, Energy, and Ariane–5 rockets.

NASA (U.S.) is projected to launch six Space Shuttles and four Titan IV rockets in 1991 and 10 Space Shuttles and 10 Titan IV rockets in 2000. Only one launch is projected from the former Soviet Union with the use of the Energy rocket in 1991, and it is unknown how many will be launched in 2000. ESA is developing a new powerful launcher (Ariane–5),

Table 10–1 Examples of Launchers, Chemical Propulsion Systems, and Major Exhaust Products (from Table 1 of AIAA, 1991).

Country	Application	Engine/Motor	Propellant Combination	Exhaust Products
China	Long March	YF–73	O_2/H_2	H_2/H_2O
Europe	Ariane–4	HM7		
	Ariane–5	Vulcain		
U.S.	Centaur	RL10A–3–3A		
	STS	SSME		
	ALS, NLS	STME		
Japan	H–1, H–2	LE–5		
	H–2	LE–7		
U.S.S.R.	Energy	RD-0120		
U.S.	Atlas	MA–5A Sustainer	O_2/RP–1	CO, CO_2, H_2, H_2O
		MA–5A		
	Delta	RS–27A		
Japan	N–2, H–1	MB–3		
U.S.S.R.	Proton	RD–?		
	Energy	RD–170		
China	Long March	YF–22	N_2O_4/Hydrazine (Aerozine 50)	$CO, CO_2, H_2, H_2O, N_2, NO_x$
Europe	Ariane	Viking		
U.S.	Titan, Delta	AJ10–118		
	N–2 (Japan)			
	Titan	LR–91		
	Titan	LR–87		
U.S.S.R.	Proton	RD–?		
	Proton	RD–253		
Europe	Ariane–4	P9.5	Solid	$HCl, Al_2O_3, CO_2, CO, N_2, H_2, H_2O$
	Ariane–5	EAP/MPS		
U.S.	STS	RSRM		
		ASRM		
	Titan 34D	UA 1205		
	Titan IV	UA 1207		
	Titan II	Castor		
	Atlas IIAS	Castor 4A		
	Delta 6920	Castor 4A		
	Delta 7920	GEM		
Japan	N–2	Castor 2		
	H–1A	Castor 2		
	H–2	Nissan		
	MU–3S–2	M–13		
		SB–735		
		M–23		
		M–3B		
	M–5	M14		
		M24		
		M34		

which is expected to be launched later this decade. Current understanding of these rocket effluents is based on calculations using combustion chemistry. Experimental verification of the rocket effluent amounts is badly needed.

10.3 LOCAL AND REGIONAL EFFECTS

The substances emitted from rocket exhausts are initially confined to a small volume of atmosphere a few hundred meters wide extending the length of the flight path. This affected volume is then moved away from the vicinity of the launch site by the wind systems and simultaneously distorted and mixed with the surrounding air, so that the contaminated volume increases, while the concentrations of pollutants decrease. This raises the possibility that restricted areas of severely reduced columnar ozone amounts may be found downwind of launch sites for a short period after each launch.

These local and regional effects are in some ways more difficult to calculate than global effects, being very dependent on the meteorological situation prevailing at the time of launch and involving, for the timescales of a few tens of minutes to one day, small-scale mixing processes of which we have limited knowledge. Nonetheless, plausible assumptions are possible that should permit estimates to be made that indicate the order of magnitude of the reductions.

Karol *et al.* (1991) have carried out calculations of the ozone reductions that may be expected during the 24 hours following the launch of both NASA's Shuttle and the Soviet Energy rocket. They use the emissions listed in Table 10–2 and a combination of two models: a box model and a model that allows the plume to diffuse horizontally for different stages of plume-spread. The calculations were performed for two rather different exhaust scenarios for each propulsion system. In addition to gases directly emitted by the exhaust, they have also considered the possibility that nitrogen oxides are produced as a result of the mixing of hot exhaust gases with the surrounding air and that some HCl emitted by the Shuttle is converted rapidly to Cl_2. Of the total gases emitted or produced by the launch, those with significant ozone depletion potentials are listed in table 10–2 for each scenario. The effects of Al_2O_3 particles and heterogeneous chemistry are not included in this calculation.

Table 10–2 Emission scenarios used by Karol *et al.* (1991). The values are the emissions in tons into a layer with top at the height listed.

SHUTTLE	Scenario A		Scenario B	
Top of Layer (km)	HCl	NO	Cl_2	NO
4	38.0	22.0	6.1	2.5
8	22.6	13.1	3.9	1.1
16	12.6	6.7	2.6	0.8
24	10.0	3.8	1.9	0.6
32	8.9	2.2	1.2	0.4
40	8.0	1.3	0.9	0.9

ENERGY	Scenario A		Scenario B	
Top of Layer (km)	HCl	NO	Cl_2	NO
4	-	28.6	-	0.3
8	-	17.0	-	0.2
16	-	8.7	-	0.2
24	-	4.9	-	0.2
32	-	2.9	-	0.25
40	-	1.7	-	0.3

Figure 10–1 shows the calculated ozone concentration in the exhaust plume, expressed as a ratio of the initial climatological values at several heights for all scenarios. In Scenario A for the Shuttle (Figure 10–1a), 80 to 90 percent of the ozone is destroyed at all levels within a few minutes. Values stay low for about an hour (closer to 2 hours at 40 km) and then recover to be very close to their initial values by the end of the first day. In Scenario B for the Shuttle, the released chlorine products are conceived as being emitted as the more active chlorine gas rather than as hydrogen chloride, though in lesser quantities. As a result, the ozone is completely destroyed in the plume at all heights for a period (Figure 10–1b). In this scenario, the recovery is more rapid than in Scenario A at all heights except at 40 km.

These model simulations of dramatic ozone losses in the first couple of hours after launch have been corroborated by measurements taken after the launch of a different solid rocket (Titan III). The Titan III uses the same oxidizer (ammonium perchlorate) as the Space Shuttle, thus is expected to release HCl in large amounts in the exhaust plume. Ozone reductions greater than 40 percent in the exhaust trail of a Titan III solid rocket at an altitude of 18 km were observed only 13 minutes after launch (Pergament *et al.*, 1977). However, these measurements need to be repeated with modern instruments before confirmation of the theory of rapid, short-lived ozone loss in the plume.

In Scenario A for Energy (Figure 10–1c), the ozone losses are predicted to be comparable to those of the Shuttle for Scenario A, despite the lack of chlorine in the Energy emissions. For Scenario B (Figure 10–1d), however, the reductions are considerably less and the recovery more rapid. Karol *et al.* (1991) were able to show that the ozone reduction by the Shuttle depends on the form in which the chlorine is released. Substituting 10 tons of HCl to 5 tons of Cl_2 (same mass of chlorine) in Shuttle Scenario A at the 24-km level brought rapid total destruction of the ozone at that level. However, the recovery was little affected. A dependency was also demonstrated of the developments in the first two hours or so on whether the Shuttle launch is in daylight or darkness. The dependence is small for the case when the chlorine is all in the form of HCl, but large when it is in the form of Cl_2, the reductions being less than 30 percent for the nighttime case at 24 km.

According to the estimates of Karol *et al.* (1991), the areas affected by the plume are of restricted horizontal extent. The values quoted above are for the plume axis, and the effects fall off rapidly with distance from that axis. Thus, for example, at 24 km in Shuttle Scenario A the distance from the center within which the ozone is destroyed by 10 percent or more is a little over 1 km for the first hour, rising to 4 km in the next 2 hours, after which it shrinks rapidly to zero as the plume recovers to the extent that the reductions nowhere exceed 10 percent.

Aftergood (1991) suggested that there could be a significant "soft spot" or a local decrease in total ozone after a Space Shuttle launch. Since the rocket trajectories through the atmosphere are curved rather than straight up, the calculations of Karol *et al.* (1991) indicate that the maximum depletion of the total ozone column never exceeds 10 percent at any point under the Shuttle plume in the first 2 hours and subsequently falls to much smaller values. Consistent with these model computations, McPeters *et al.* (1991) found no evidence of ozone depletion in a study of TOMS images taken at varying times after eight separate Shuttle launches.

Some laboratory experiments (Gershenzon *et al.*, 1990) suggest that direct thermal decomposition of ozone may occur in high temperature jets. This phenomenon has been observed in O_2–O_3 jets for rather high ozone concentrations relative to O_2; however, the reaction may take place for atmospheric ozone concentrations at sufficiently high temperatures, such as those found in the exhaust plume. This is believed to be a rather short-term effect with recombination of the thermally decomposed products (O and O_2) occurring rapidly after mixing with cooler air.

Regional effects (1000 x 1000 km^2) due to rocket effluents have been computed [from the Cl_y (Cl, Cl_2, ClO, Cl_2O_2, HCl, HOCl, and $ClONO_2$) perturbation] due to a single Space Shuttle launch using a three-dimensional model (Prather *et al.*, 1990a,b) with a resolution of 8° latitude by 10° longitude. The Cl_y concentration at 40 km, 30°N, 70°W, can increase by a few percent 2 days after the launch, and the corresponding ozone decrease is expected to be less than 1 percent at that height. The subsequent rate at which the chlorine is dispersed depends on season, the summer atmosphere being less dispersive than the winter. After a further 6 days, the peak chlorine concentrations had fallen by a factor of 4 in the January simu-

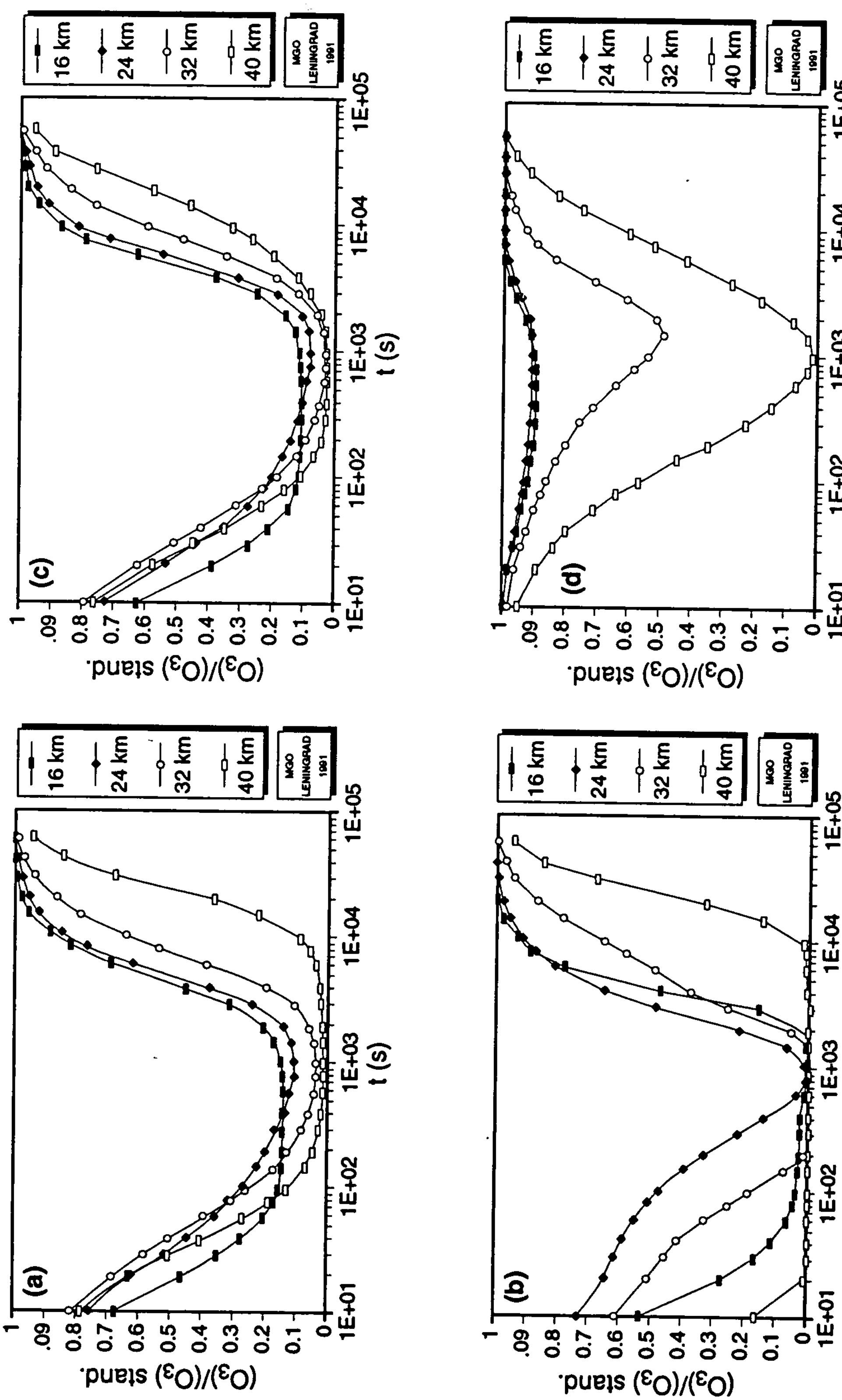

Figure 10–1 Local plume time variations in ozone due to rocket exhausts (Karol *et al.*, 1991). The vertical axis is the ozone amount expressed as a ratio of the initial (standard atmosphere) value. (a) Shuttle Scenario A (see Table 10–2); (b) Shuttle Scenario B; (c) Energy Scenario A; and (d) Energy Scenario B.

lations and a factor of 2 in the July simulations. The Cl_y emitted by the Shuttle becomes spread over all longitudes in about 30 days and is less than 0.15 percent of background levels.

In conclusion, the local plume effect of rocket exhausts has not been extensively studied, but the studies that have been undertaken indicate that rocket exhausts can lead to severe ozone loss over a restricted volume within a few kilometers of the plume axis. The corresponding total reduction of ozone column in the case of the Space Shuttle probably does not exceed 10 percent over an area the size of the TOMS field of view of 40 x 40 km^2 and is within typical natural variations some 3 hours after launch. During the subsequent few days, chlorine may remain enhanced in the upper stratosphere by a few percent, falling to a few tenths of a percent by the end of the first month. These studies have included homogeneous chemistry only and have employed a limited treatment of mixing processes that spread the plume from a scale of a few 10s of meters to the 1000 km resolved by the three-dimensional models. Further studies are needed to clarify the importance of these restrictions.

10.4 GLOBAL SCALE EFFECTS

After about a month, the effects of a given launch are spread over a sufficiently large portion of the atmosphere and diluted to the stage where they contribute less to any ozone reduction than do the remnants of the previous launches. It thus becomes necessary to consider the cumulative global-scale effect of a series of launches. A natural reference is provided by considering the steady state, which is reached when the annual average rate of increase in chlorine and other active species from exhaust plumes is balanced by the rate at which they or their derived products are removed, mostly by transfer to the troposphere followed by rain-out.

Global effects due to rocket exhausts on Cl_y and ozone concentrations, as affected by Cl_y homogeneous chemistry, have been computed by Prather *et al.* (1990a,b). The steady-state impact of nine Space Shuttles and six Titan IV launches per year on the chlorine loading was assessed with two two-dimensional models and one three-dimensional model. The increased stratospheric loading of chlorine from this U.S. launch scenario is less than 0.25 percent globally of the annual stratospheric chlorine source from halocarbons in the present-day atmosphere.

The corresponding changes in chlorine loading and ozone concentration were calculated using the two-dimensional models. The results from one of these models, the Goddard Space Flight Center (GSFC) model, are shown in Figures 10–2 and 10–3, respectively. Although there were differences of detail, the broad results of changes in chlorine concentrations were similar in all models. Cl_y in the middle to upper stratosphere is computed to increase by a maximum of about 10 pptv (about 0.3 percent of a 3.3 to 3.5 ppbv background) in the northern middle and high latitudes. Compared to the natural source of chlorine from CH_3Cl (Weisenstein *et al.*, 1991) this rocket-induced Cl_y adds about 1.7 percent to a 0.6 ppbv background.

The corresponding maximum ozone depletion was calculated to be less than 0.2 percent at 40 km in the winter hemisphere. Maximum column ozone depletion is computed to be much less than 0.1 percent for this scenario.

Using the same launch scenario, a computation of the total yearly average global stratospheric ozone depletion is found to be about 0.0065 percent (Jackman, C. H., private communication, 1991). The global effects of Space Shuttle launches have also been computed by Karol *et al.* (1991) for both scenarios listed in Table 10–2. Scaling their calculations to an equivalent nine Space Shuttle and six Titan IV launches per year gives a total global ozone depletion of 0.0072 to 0.024 percent.

Pyle and Jones (1991), using a two-dimensional model, assessed the impact of the chlorine from 10 Ariane–5 launches per year. They performed a 20-year simulation, adding the appropriate amount of chlorine for that scenario until a steady state was established in which the results repeated from one year to the next. These computations indicate an effect similar to that reported above for the Prather *et al.* (1990a,b) work on Shuttle and Titan IV launches (*e.g.*, maximum local ozone depletion is around 0.1 percent near 40 km).

In general, the modeling studies discussed above did not quantitatively evaluate the effect of effluents other than chlorine emitted from the rocket exhaust. One exception is Karol *et al.* (1991) who also included NO_x (N, NO, NO_2) injections. None of the studies considered HO_x (H, OH, HO_2), NO_x, and Cl_y in con-

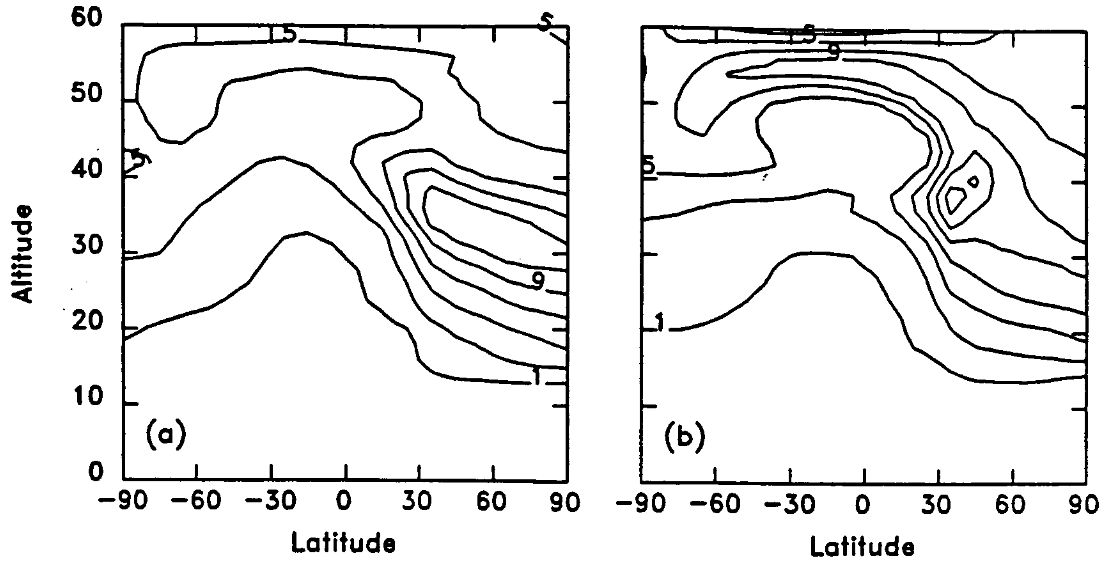

Figure 10–2 Latitude by altitude contours of the perturbation to background Cl_y levels (pptv) for the GSFC model (Prather *et al.*, 1990b) in the steady state for an annual launch scenario of nine Space Shuttles and six Titan IV rockets in (a) January and (b) July.

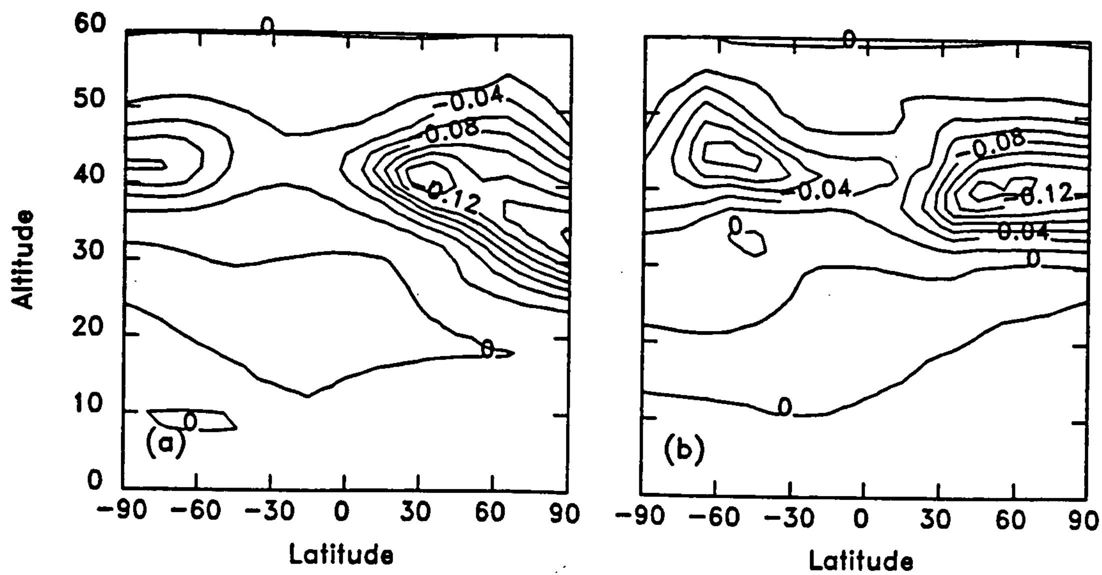

Figure 10–3 Perturbation in ozone (percent) corresponding to Figure 10–2 in (a) January and (b) July.

junction. Bennett and Hinshaw (1991) completed a calculation of the relative contributions of nine Space Shuttle and six Titan IV launches to the stratospheric burdens of the potential ozone destroyers. These were taken to be HO_x (from emitted H_2 and H_2O) and NO_x (from emitted NO) in addition to Cl_y. In this computation, NO_x was increased by 0.0014 percent (though no NO_x production from afterburning was considered), HO_x was increased by 0.0048 percent, and Cl_y was increased by 0.16 percent, all above the global background. These calculations indicate that the rocket-induced Cl_y changes should be the most significant when considering the long-term global effects on stratospheric O_3, so that the omission of other substances in the assessments reported above is not expected to affect the conclusions.

Jackman *et al.* (1991) recently completed a two-dimensional model computation on the effects of HO_x from emitted H_2 and H_2O for a hypothetical National Aerospace Plane (NASP) on stratospheric ozone. A rate of 40 launches per year results in H_2 and H_2O increases of 0.34 and 0.16 percent, respectively, at 35 km altitude and 35°N latitude. This results in an OH increase of 0.1 percent and a corresponding ozone decrease of 0.006 percent at this location. Total global column ozone impact is calculated to be a decrease of less than 0.0002 percent.

None of these calculations have included the impact of heterogeneous chemistry whether on preexisting particles or on the particles emitted in the exhaust. The latter are discussed further below. There is a need for some additional work here. However, a context for interpretation of the importance of rocket exhausts in an atmosphere containing aerosols is provided by comparing the total input of reactive chlorine into the atmosphere from rockets with the inputs from industrial sources.

10.5 EFFECTS OF PARTICULATES

Particulates in the form of Al_2O_3, soot, and ice are released to the atmosphere in chemical rocket launches. Although any chemical rocket launch releases particulates of some form into the atmosphere, most particulate measurements of rocket exhausts are associated with Space Shuttle launches. Measurements have been conducted to obtain samples of the Shuttle-exhausted aluminum oxide particles with the use of aircraft collecting filter samples during descending spiral maneuvers in the exhaust plumes. These measurements show a distribution of particles with significantly more particles below 1 μm than above 1 μm in size (Cofer *et al.*, 1985).

The first observation of Al_2O_3 particles in the stratosphere was reported by Brownlee *et al.* (1976). Zolensky *et al.* (1989) reported an order of magnitude increase in particles above 0.5 μm, which were mostly aluminum rich between 17 and 19 km from 1976 to 1984. These aluminum-bearing particles are thought to be from both the Space Shuttle launches and ablating spacecraft material, with the ablating spacecraft material predominating (Zolensky *et al.*, 1989).

The exhausted particulates may have a large local effect on the stratosphere. Recently, the effect of Al_2O_3 aerosols with a mean radius of 0.1 μm and a sticking coefficient of 5×10^{-5} has been estimated (Karol, I.L., private communication, 1991). These aerosols produce an additional 30 percent ozone depletion in the 400 to 1500 sec time period after emission. Before and after this time period, the additional depletion is mostly less than 5 percent. Since the Al_2O_3 aerosols act as condensation nuclei for sulfate in the stratosphere, it is reasoned that their stratospheric influence after the first 1500 sec will be like those of other resident aerosols.

Aerosols have been implicated in enhancing ozone decrease by chlorine species, even in the absence of polar stratospheric clouds (Hofmann and Solomon, 1989; Rodriguez *et al.*, 1991). Turco *et al.* (1982) has suggested that the Space Shuttle could increase the average ice nuclei concentration in the upper troposphere by a factor of 2. Rough estimates suggest that U.S.-launched rockets increase the global aerosol surface of the unperturbed stratosphere by about 0.1 percent (Prather *et al.*, 1990b; McDonald *et al.*, 1991), therefore, these computations indicate that the global particulate effects of these rocket-produced aerosols could be responsible for about 1/1000th of the current ozone depletion associated with heterogeneous chemistry.

10.6 CONCLUSIONS

Rocket launches can have a significant local effect on the stratosphere by reducing ozone substantially (perhaps >80 percent) within the expanding exhaust plume up to 3 hours after launch. Even when such severe reductions take place, the reduction in column ozone is probably less than 10 percent over an area a few kilometers by a few tens of kilometers and is generally much smaller. The local-plume ozone reductions decrease to near zero over the course of a day, and the regional effects are smaller than can be detected by satellite observations. Moreover, none of the atmospheric modeling studies that assume the present rate of rocket launches show a significant global impact on the ozone layer (the calculated impact is predicted to be much smaller than the effect of the solar cycle on ozone, for instance). A consideration of the other products of rocket launches that can potentially destroy ozone shows even smaller effects from those substances so far as homogeneous effects are concerned.

These modeling studies are incomplete and, because of the inherent uncertainties, may underestimate or possibly overestimate the ozone depletion expected by rockets. For instance, only one of the above studies considers the potential impact of heterogeneous chemistry. However, the total annual addition to stratospheric chlorine from rocket launches is of the order of 0.25 percent of the global annual stratospheric chlorine source from halocarbons in the present-day atmosphere, so that the global impact of rocketry is a third-order or smaller effect compared with other sources of chlorine. If the annual background source from halocarbons is reduced and/or the launch rate increases, the fractional contribution will become larger.

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