

## Potential climate impact of black carbon emitted by rockets

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[1] A new type of hydrocarbon rocket engine is expected to power a fleet of suborbital rockets for commercial and scientific purposes in coming decades. A global climate model predicts that emissions from a fleet of 1000 launches per year of suborbital rockets would create a persistent layer of black carbon particles in the northern stratosphere that could cause potentially significant changes in the global atmospheric circulation and distributions of ozone and temperature. Tropical stratospheric ozone abundances are predicted to change as much as 1%, while polar ozone changes by up to 6%. Polar surface temperatures change as much as one degree K regionally with significant impacts on polar sea ice fractions. After one decade of continuous launches, globally averaged radiative forcing from the black carbon would exceed the forcing from the emitted CO<sub>2</sub> by a factor of about 10<sup>5</sup> and would be comparable to the radiative forcing estimated from current subsonic aviation. **Citation:** Ross, M., M. Mills, and D. Toohey (2010), Potential climate impact of black carbon emitted by rockets, *Geophys. Res. Lett.*, 37, L24810, doi:10.1029/2010GL044548.

### 1. Introduction and Motivation

[2] Surging investments in new rockets and spacecraft and new applications for these vehicles foretell that the number of launches and variety of rocket engines will increase in coming decades [Ziliotto, 2010]. One type of new launch market is suborbital spaceflight, with plans for many hundreds, perhaps thousands, of space tourism and scientific research flights annually. The new so-called “hybrid” rocket engine, which oxidizes a solid synthetic hydrocarbon (HC) fuel with N<sub>2</sub>O, is the chosen propellant for a number of the suborbital space-ships that will be flying soon [Chandler, 2007]. While the stratospheric emissions from a single suborbital rocket will be small compared to an orbital rocket, total suborbital fleet emissions could become comparable to present day rocket emissions within a decade. It is of interest therefore to consider what impact these rockets could have on stratospheric ozone and global climate.

[3] Rocket emissions have been studied previously [World Meteorological Organization (WMO), 2002], primarily within the context of chemical ozone loss caused by solid rocket motors that emit chlorine and alumina particles. None of the previous studies considered how rocket emissions might alter the radiative balance of the atmosphere. Particles emitted by

rockets, on the other hand, might be expected to modify radiation fluxes in the stratosphere and have not been previously studied in this context. Particles emitted by rockets include alumina, metallic debris, and soot or black carbon (BC) particulate, in variable amounts depending on the engine and altitude.

[4] BC is known to modify the radiative properties of the atmosphere because it efficiently absorbs solar shortwave radiation [Balkanski *et al.*, 2010; Crutzen, 2006]. The atmosphere may be particularly sensitive to BC emitted by HC-fueled rockets because they emit several orders of magnitude more BC (per unit propellant) than aircraft, directly into the upper stratosphere from fixed sites. Thus rocket BC has much longer lifetime and larger steady state stratospheric burden, at greater altitude, than aircraft burning the same amount of fuel. We estimate the globally averaged steady state direct radiative forcing (RF) from a uniformly distributed stratosphere black carbon layer from rockets as

$$RF = \frac{\tau \sigma_m F_s (1 + A) N P EI_{BC}}{S} \quad (1)$$

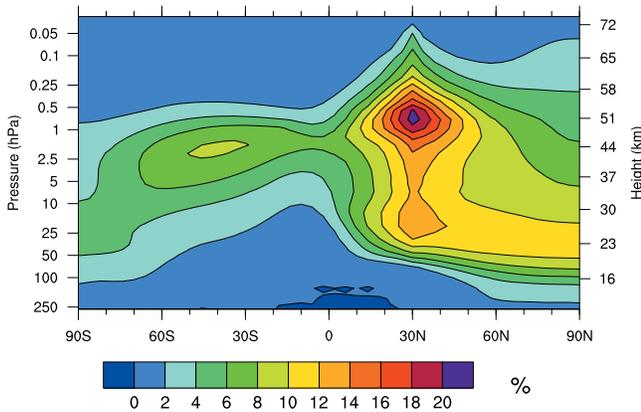
where  $\sigma_m$  is the BC mass specific absorption efficiency,  $F_s$  is mean solar SW flux,  $\tau$  is stratospheric lifetime,  $A$  is Earth albedo,  $N$  is number of launches per year,  $P$  is propellant burned in the stratosphere per launch,  $EI_{BC}$  is the rocket soot emission index, and  $S$  is Earth’s surface area. For 0.1  $\mu\text{m}$  BC particles  $\sigma_m$  equals  $9 \text{ m}^2 \text{ g}^{-1}$  [Zhang *et al.*, 2008] and using values of  $EI_{BC}$ ,  $N$ , and  $P$  expected for the suborbital rocket fleet (discussed below), we find RF equals  $43 \text{ mWm}^{-2}$ , much larger than BC forcing from current aviation and comparable to BC forcing from the global road transport sector [Balkanski *et al.*, 2010] and net forcing associated with the global air transport [Grewe *et al.*, 2007]. The estimated rocket RF is large enough to motivate a more detailed look at the problem of rocket BC emissions using a detailed global climate model (GCM) to study changes in global patterns of circulation and climate and the distribution of important trace species, such as ozone.

[5] We report the result of a GCM simulation of the Earth’s response to a layer of stratospheric BC that could be generated by a particular type of HC-fueled rocket system. There are two main types of BC-emitting rocket engines, one burning kerosene and liquid oxygen and another (“hybrid”) burning solid HC (e.g. synthetic rubber or plastic) and N<sub>2</sub>O [Sutton and Biblarz, 2010]. Currently, HC rockets are mainly kerosene-fueled but the hybrid has various technical and economic advantages and could, according to various development plans become a significant fraction of all rocket activities by 2020. Hybrids are of special interest because they likely have larger BC emission index ( $EI_{BC}$ ) than kerosene rockets and are of most interest to the nascent suborbital “space tourism” portion of the space industry, a potentially

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**Figure 1.** Thirty-year-average percent enhancement in BC loading relative to background calculated for the assumed scenario of continuous rocket launches, following 10 years of model spin-up.

fast-growing segment of the space transportation sector [Crouch *et al.*, 2009].

## 2. Model Description

[6] We model the response of the Earth system to rocket BC emissions using the Whole Atmosphere Community Climate Model, Version 3 (WACCM3). WACCM3 is a comprehensive model that simulates the chemical, dynamical and radiative coupling of the atmosphere between the surface and  $\sim 145$  km [Garcia *et al.*, 2007] and has been used in a wide variety of applications to investigate the response of the global Earth system to natural and human produced changes in atmospheric composition and radiation [Garcia and Randel, 2008; Tilmes *et al.*, 2009]. WACCM3 was recently coupled with the Community Aerosol and Radiation Model for Atmospheres (CARMA), a three-dimensional microphysics package adapted for the treatment of BC aerosol to study the global effects of stratospheric soot loading from fires ignited by a nuclear conflict [Mills *et al.*, 2008]. For this calculation, we adopt the treatment of BC developed for the nuclear conflict investigation by Mills *et al.* [2008], a log-normal distribution centered on  $0.1 \mu\text{m}$  diameter with  $\sigma_m$  equal  $9 \text{ m}^2 \text{ g}^{-1}$  (at  $0.6 \mu\text{m}$ ). Because of a lack of in situ measurements, the microphysical properties of rocket BC are poorly understood and we acknowledge significant uncertainties concerning size distributions, surface coatings, coagulation rates, and aging tendencies. However, our representation is broadly consistent with rocket BC characteristics derived from engine combustion models and plume remote sensing [Simmons, 2000]. We coupled a slab ocean and simple sea ice model, controlled only by heat and moisture fluxes, [e.g., Tilmes *et al.*, 2009] to WACCM3 in order to calculate surface temperature and ice fraction changes. We include only the radiative effects of BC and do not consider any chemically active (i.e.  $\text{H}_2\text{O}$ ,  $\text{HO}_x$ , and  $\text{NO}_x$ ) gaseous species in the exhaust; these could modify the results reported here.

[7] Based on detailed plans for space tourism and science flights using suborbital hybrid rockets [Sanderson, 2010], we assume  $N$  equals 1000 launches per year and  $P$  equals  $10^4$  kg propellant per launch.  $\text{EI}_{\text{BC}}$  for kerosene engines is 20–40  $\text{g kg}^{-1}$ , depending on engine model and altitude [Byun and

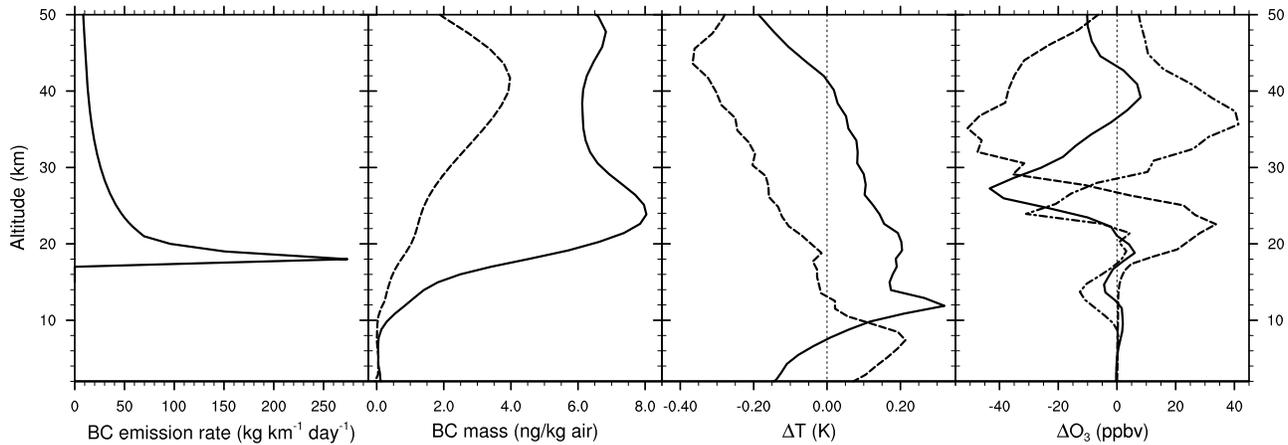
Back, 2007].  $\text{EI}_{\text{BC}}$  for hybrid engines is expected to be larger than for kerosene engines because of lower carbon particulate oxidation rates in the hot plume [Sutton and Biblarz, 2010; Simmons, 2000]. Accordingly, we assume hybrid rocket  $\text{EI}_{\text{BC}}$  equals  $60 \text{ g kg}^{-1}$  while noting it is a provisional, though plausible, value. The annual stratospheric BC emission for our scenario equals 600 metric tons (t). This compares to 5000 t emitted by subsonic aircraft into the troposphere [Balkanski *et al.*, 2010] and 500 t emitted into the lower stratosphere by hypothetical supersonic transport fleets [Lee *et al.*, 2009]. Currently, the global fleet of orbital kerosene rockets ( $N \sim 25 \text{ yr}^{-1}$  and  $P \sim 10^5 \text{ kg}$ ) emits  $\sim 75$  t of BC into the stratosphere, so our scenario could coarsely be interpreted as an order of magnitude increase in kerosene orbital launches, with no hybrids. This might come about, for example, if large kerosene rockets were developed for ambitious space exploration goals. In any case, given the lack of detailed knowledge of the microphysical properties of rocket BC and unknown growth rate of the space transport sector, we cannot place a formal uncertainty on our scenario. We assume a vertical distribution of BC emission that would be typical for a suborbital rocket air launched at 16 km, with burnout at 70 km, shown in Figure 2a. The BC is injected at  $33^\circ\text{N}$ ,  $107^\circ\text{W}$ , near a potential launch site for high flight rate suborbital rockets.

[8] Two 40-year climate simulations were carried out: (a) a control case and (b) a case that includes the rocket BC scenario. Ignoring the first ten years for model spin-up and numerical convergence, we calculate the 30-year average atmospheres for the two cases and compare them. Formal significant statistical differences were determined using the Student's *t*-test; a difference is considered significant at the 95% confidence level. In the interest of simplicity, these initial rocket BC simulations do not account for expected future increases in (greenhouse gases) GHGs or decreases in ozone depleting halogens. Relaxing these constraints should not greatly affect our main conclusions, though future models should examine how changes in stratospheric composition from rocket emissions might interact with changes in GHGs, stratospheric chlorine, and background BC.

## 3. Results and Discussion

[9] Figure 1 shows the calculated distribution of the BC enhancement due to the rockets after the simulation reaches a quasi-steady state. The annually averaged total stratospheric loading is 2600 t, 4.4 times the annual emission. The load is mostly carried in a thin persistent northern hemisphere (NH) BC layer between  $25^\circ\text{N}$ – $45^\circ\text{N}$ . Only 20% of the steady state BC load is in the southern hemisphere (SH), so the layer maintains a strong hemispherical asymmetry (see Animation S1 of the auxiliary material).<sup>1</sup> Whereas natural aerosol injections into the stratosphere (e.g., volcanoes or surface fires) are episodic and decay within a few years, the continuous nature of rocket emissions means that the rocket stratospheric BC layer becomes a constant, asymmetric feature of Earth's atmosphere for as long as the launches continue. Figure 2b shows the vertical distribution of the BC layer, with a peak enhancement of 8 ng per kg of air at 25 km, above the main part of the emission. In comparison, the BC loading of a fleet

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2010GL044548.



**Figure 2.** Vertical distribution of zonally averaged (a) rocket BC emission, (b) steady state annually averaged BC loading at 45–60°N (solid) and 45–60°S (dashed), (c) annually averaged change in temperature at 60–75°N (solid) and 40–60°S (dashed), and (d), change in ozone mixing ratio in DJF at 45–60°N (solid), 15°S–15°N (dashed), and 45–60°S (dot-dashed).

of future supersonic aircraft is predicted to reach 0.8 ng per kg of air at an altitude of 16 km [e. g. *Grewe et al.*, 2007].

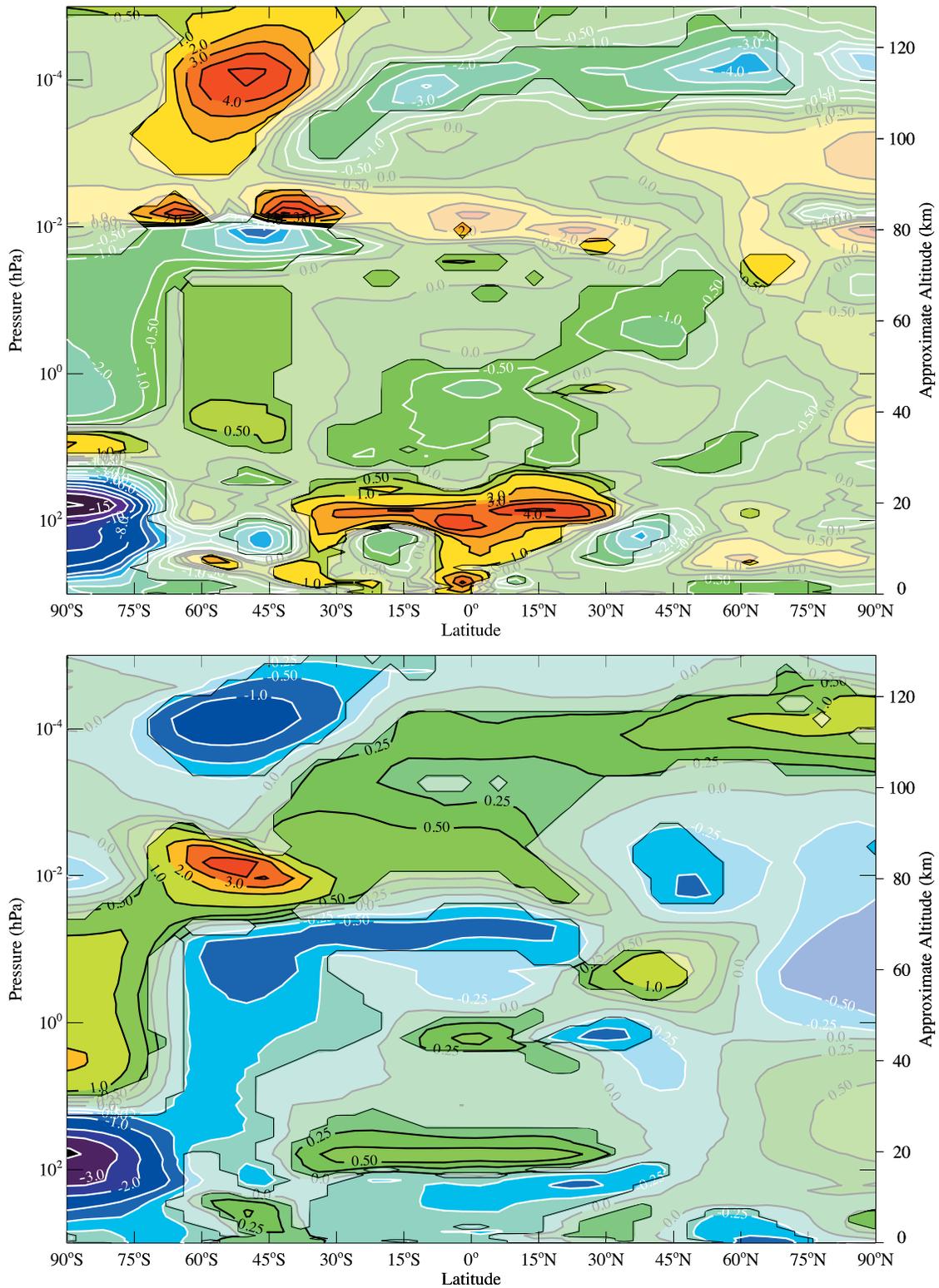
[10] Figure 3 shows the model change in zonally averaged ozone concentration and temperature. Ozone declines in the tropics and subtropics by up to several percent, depending on season and location. These changes are exceptional in that they are comparable to present day ozone depletion there due to chlorofluorocarbons (CFCs) and other compounds restricted by the Montreal Protocol [*WMO*, 2006]. Ozone is predicted to change by 5–6% in the high mid-latitudes and polar regions, particularly over the Antarctic. This is comparable to the observed high-latitude ozone response to CFCs so that the rocket BC will influence ozone recovery, at least at the poles. The change in annually averaged global total ozone is small (0.1%) and not statistically significant, suggesting that dynamical and chemical processes that may be responsible for the large regional changes offset each other globally. Alternatively, dynamical processes alone might dominate the ozone response. Support for the latter notion is found in a positive correlation between ozone and temperature changes in the tropical stratosphere (Figure 3 and Figure S1 in Text S1 of auxiliary material), opposite of climate–ozone connections mediated by the temperature dependence of ozone chemistry reaction rates [*WMO*, 2006]. On the other hand, the changes in polar ozone positively correlate with temperature change, suggesting transport dominates over chemical processes there. Further model studies will be required to fully understand the issue.

[11] Importantly, the global pattern of ozone changes displayed by the model – tropical decrease and high-latitude increase – is characteristic of an acceleration of the global Brewer-Dobson (BD) circulation seen in other studies of climate forcing by GHGs [*Garcia and Randel*, 2008; *Tilmes et al.*, 2009]. In these cases, strengthening BD circulation increases the rate of ozone transport out of the tropical source region and toward high latitudes. Although the exact model mechanisms that enhance the BD circulation have yet to be fully understood, it is thought that changes in the middle atmosphere thermal and wind structure modify the wave propagation characteristics of the stratosphere, changing the global pattern of momentum transport [*Calvo and Garcia*, 2009]. With the rocket BC, model zonal winds decrease by

$\sim 2 \text{ m s}^{-1}$  in the high latitude middle stratosphere, a similar pattern to GCMs with increased GHG concentrations (see Figure S2 in Text S1 of the auxiliary material).

[12] While the global response to the rocket BC emission resembles a GHG response (strengthened BD circulation), Figure 2 shows a key difference from GHG cases with respect to heating. For the rocket emission case, the annual zonal mean temperature in the BC layer increases by 0.2 K, a feature absent in the southern hemisphere. Because little BC is transported into the SH, thermal forcing there is nil and the associated temperature changes are small. Previous models have shown that small hemispherical asymmetries in thermal forcing can cause relatively large changes in the BD circulation [*Lindzen and Hou*, 1988] and this sensitivity may help explain the disproportionately large magnitude of the model response to relatively small amounts of rocket BC. Further numerical experiments with this and other climate models will help reveal the mechanisms for these changes and the relative sensitivity of the climate system to soot emitted by rockets versus GHG emissions by those same rockets.

[13] The predicted changes in circulation and distribution of radiatively important species have significant consequences for regional patterns of surface temperatures and climate. Figure 3b shows the predicted change in the NH winter temperature distribution. South polar stratospheric temperatures increase by  $\sim 2 \text{ K}$  during the austral summer and remain elevated by  $>1 \text{ K}$  throughout the year (Figure S1 in Text S1 of auxiliary material.) While it is beyond the scope of this paper to explore all of the details of the perturbed thermal and kinetic energy flows, model diagnostics indicate that movement of the subtropical jets and regional changes in cloudiness, albedo, oceanic heat content, and longwave atmospheric transmissivity all contribute. Model SH extratropical regional RF  $\sim 0.1 \text{ W m}^{-2}$ , generally consistent with the earlier estimate of the globally averaged RF. Figures 2c and 3b show that the NH mid-latitude surface cools by a few tenths K in some seasons, consistent with the reduction in solar intensity beneath the shading BC layer above. Taken together, these results clearly demonstrate that the accumulation of BC from the modeled suborbital rocket fleet launched 1000 times per year (or orbital rocket equivalent) will influence global climate about as much as the world’s fleet of



**Figure 3.** Change in calculated 30-year zonally averaged distribution of (a) ozone concentration (%) and (b) temperature (K) in DJF due to the prescribed BC emission. Dark (high contrast) regions show a change significant at the 95% level.

subsonic aircraft [Lee *et al.*, 2009]. The details of the changes caused by aircraft and rockets will certainly differ, but rocket emissions on this scale clearly cross a threshold to be considered a human-influenced climate impact of global importance.

[14] A number of potentially important earth system changes associated with the rocket BC-induced circulation changes are predicted by the model. We take special note of perturbations to model polar sea ice amounts in both hemispheres. Through ice-albedo feedback, sea ice serves a critical role in the Earth's climate system and biosphere. Observed losses of north polar summer sea ice exceed model predictions [Serreze *et al.*, 2009; Screen and Simmonds, 2010], indicating a greater sensitivity to RF changes than is currently understood. In our model, total sea ice coverage changes in both hemispheres by significant amounts. Antarctic sea ice area changes by 5% or more, generally consistent with the polar temperature changes. Arctic ice shows much smaller changes, less than 5% seasonally, and no significant secular change.

[15] Overall, these results should not be taken as a precise forecast of the climate response to a specific launch rate of a specific rocket type. Rather, the simulation should be taken as a gauge of the large sensitivity of the atmosphere to a persistent stratospheric BC layer caused by HC-fueled rockets, for which suborbital hybrids are a particular, though not exclusive, concern. The results clearly indicate areas for further investigation such as considering the gaseous components of HC rocket emissions (emitted H<sub>2</sub>O, for example, will also accumulate in the stratosphere), including reactions on BC surfaces (that may offset or exacerbate the response reported here), investigating the non-linearity of the response with respect to launch rate, and determining the relative importance of launch site location. Most importantly, an ensemble of GCMs should be applied to determine the sensitivity of the response to model specific assumptions and parameterizations.

[16] Particulate emissions from rockets have historically been considered short-lived, but this is so only in the sense that they wash out from the stratosphere within a decade of stopping launches. As long as HC rocket launches continue, the associated BC load effectively acts as a GHG with disproportionately large warming potential, one that far exceeds that of CO<sub>2</sub> emitted by the rockets. Assuming EI<sub>CO<sub>2</sub></sub> of 300 g kg<sup>-1</sup>, we estimate that after one decade of suborbital hybrid rocket launches at the assumed rate, RF from the accumulated BC for these 10,000 launches will exceed RF from the associated CO<sub>2</sub> emissions by a factor of about 10<sup>5</sup>. As long as the launch rate is maintained, the CO<sub>2</sub> climate forcing for this fleet would be minuscule compared to the BC forcing. Accordingly, assessments of climate forcing for passenger and cargo rockets that consider only CO<sub>2</sub> emissions [Fawkes, 2007] underestimate rockets' contribution to climate change by many orders of magnitude.

#### 4. Summary

[17] We have performed the first model of global change caused by particles emitted by rockets. The model predicts that the climate and ozone impacts of BC soot emissions from planned air-launched suborbital (space tourism and scientific) launches are likely to be significant regionally, possibly comparable to the impact of present day global aviation

and CFCs. Absorption of solar radiation in a BC layer that accumulates over several years of launching causes changes in the global atmospheric circulation that resemble the global scope of BD circulation changes caused by increasing GHGs, ozone recovery, and geoengineering schemes based on stratospheric particles. We estimate that for HC-fueled rockets, the climate impact of BC soot emissions dominates over CO<sub>2</sub> emissions by a factor of about 10<sup>5</sup>, for as long as the launches continue. The strong response likely results from unique altitude, persistence, and asymmetric nature of the rocket-produced BC soot layer. Further sensitivity and ensemble studies and measurement of emissions from HC-fueled rockets are required to verify and provide confidence in our results. Our result, if confirmed, could have important climate and ozone related regulatory or economic implications for HC-fueled rockets [Ross *et al.*, 2009].

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