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[1] We report on the production and transport of the 0.4 Tg of nitric oxide generated in the Siberian upper troposphere by the 1908 Tunguska object. The simulation uses a three-dimensional chemistry and transport model of the global troposphere. We find that much of the nitric oxide forms nitric acid that deposits downwind of the blast site within the first month, with no severe damage to the ecosystem caused by acid rain. Ozone and OH are totally scavenged locally soon after the impact, then they increase respectively by up to 30% and 200% during the first weeks. The total deposition below the explosion is simulated within a factor of 2 of that indicated by an analysis of peat samples. Considering the details of the model this may be the first reasonable calculation on the acid deposition distribution, and could help in locating interesting sites for future peat samples collection. *INDEX TERMS:* 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 1630 Global Change: Impact phenomena. **Citation:** Curci, G., G. Visconti, D. J. Jacob, and M. J. Evans (2004), Tropospheric fate of Tunguska generated nitrogen oxides, *Geophys. Res. Lett.*, *31*, L06123, doi:10.1029/2003GL019184.

1. Introduction

[2] On the morning of 30 June 1908 a tremendous explosion occurred in the skies above Tunguska River basin, Siberia (61°N, 102°E). The 2200 km^2 area of forest around the explosion site was blown flat and about 170 km away a sun-like fireball was seen in the daytime cloudless sky [*Krinov*, 1966]. The cause of such explosion was the breakup of a 30 m stony meteorite at an altitude of about 9 km [*Chyba et al.*, 1993, hereinafter referred to as C93].

[3] *Park* [1978] first suggested that both the passage through the atmosphere and the final explosion of an asteroid would produce an enormous amount of NO via thermochemical reactions of N_2 and O_2 due to high temperatures reached in shocked air (2200–2700°C). The nitric oxide subsequently would form acids that deposit to the ground as acid rain.

[4] The atmospheric impact of the meteorite depends to a large degree on whether it was a low density body or a stony meteorite. Calculations of *Turco et al.* [1982, hereinafter referred to as T82] rely on the assumption that the impactor was a rare very low density comet having an initial kinetic energy of $\sim 10^{18}$ J. In this context, NO is efficiently produced almost uniformly through the mesosphere and the stratosphere because of gradual ablation of the body during atmospheric entry, and just 1% of the energy is released in the terminal low-altitude blast. Using a 1-D photochemical model, T82 predicted that the 30 Tg of NO produced should have left traces in Arctic and Antarctic ice cores; however no detectable signal related to the predicted perturbations has been found [*Rocchia et al.*, 1990; *Rasmussen et al.*, 1984]. The fate of the NO produced in the troposphere by the explosion is not discussed by the same authors. In a later study that uses a more accurate aerodynamic model, C93 found that Tunguska explosion at ~9 km is fully compatible with the entry of a more common stony asteroid that would release all its energy in the vicinity of the blast point. If so, the Tunguska object would have released a negligible amount of NO in the middle atmosphere, while it would have produced NO efficiently just in a narrow altitude range near the explosion point. A lower density body, like a comet, would disintegrate much higher in the atmosphere.

[5] In this work we take advantage of a state-of-the-art chemistry-transport model to analyze how the atmosphere reacts to a sudden injection of a large amount of NO in the upper troposphere, how long it takes for the atmosphere to recover and what is the spatial range affected by the acid deposition. The NO source we adopt is compatible with a Tunguska-scale event as prefigured by C93. Although the origin of the Tunguska object is still debated, the stony asteroid theory is the most widely accepted and there is general agreement both on the height range and on the order of magnitude of the final explosion energy [*Vasilyev*, 1998], that are key parameters in the present study. In section 2 we give a brief description of the model used and we explain how we set up simulations. We discuss results in section 3, and we summarize our findings in section 4.

2. Simulations Set Up

2.1. Model Description

[6] Our simulations use version 5.05.03 of the GEOS-CHEM global 3-D model of tropospheric chemistry (http://www-as.harvard.edu/chemistry/trop/geos) driven by assimilated meteorological data from the NASA Goddard Earth Observing System (GEOS-3). The GEOS-3 data have a 1° × 1° resolution in the horizontal and 48 sigma-pressure levels extending from 0 to 80 km. The horizontal resolution is degraded here to 4° latitude × 5° longitude for computational expediency in GEOS-CHEM. A sensitivity simulation that uses a 2° × 2.5° horizontal resolution has also been run. The simulations include a detailed ozone-NO_x-hydrocarbons mechanism with about 80 species and 300 reactions (*Bey et al.* [2001], including updates described at the above web site). The wet deposition scheme for soluble gases and aerosols is as presented by *Liu et al.* [2001]. Dry deposition

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is computed with a standard resistance-in-series scheme [*Wesely*, 1989] as described by *Wang et al.* [1998]. The oxidants-aerosols coupling is described by R. J. Park et al. (Natural and transboundary pollution influences on sulfate-nitrate-ammonium aerosols in the United States: Implications for policy, submitted to *Journal of Geophysical Research*, 2003).

[7] In the present study we are not attempting to exactly tune the model to a 1908 atmosphere, mainly for two reasons: (1) considering that we are focusing on the effect of a large regional perturbation on top of the atmospheric background, the exact definition of the background is of little importance, so we use present day emissions for trace gases and (2) we do not have reliable meteorological data from 1908. Lacking data on the actual 1908 meteorology, we repeat simulations for three different years for which GEOS-3 data are available to us (1998, 2000 and 2001) and average the results. Of the three years, only the 1998 has an uncommon feature of interannual variability, namely a signature of the 1997–98 El Niño that induces a little (~5%) increase of the zonal wind at Northern midlatitudes.

2.2. NO Production Calculations

[8] The Tunguska explosion released in the atmosphere $4.2–17.0 \times 10^{16}$ J of energy, with a most probable value of about 5×10^{16} J [*Vasilyev*, 1998], that is about 60 times the energy of the Hiroshima A-bomb [*Ben-Menahem*, 1975]. Nearly all the energy was deposited in the altitude range between 12 and 5 km [*Chyba et al.*, 1993]. According to *Zahnle* [1990, Figure 3] the NO production efficiency for a 5×10^{16} J impact is about 1.5×10^{17} molec NO/J, yielding 7.5×10^{33} NO molecules that is 0.4 Tg of nitric oxide. Notably, this is the same order of magnitude reported by *Rasmussen et al.* [1984], who estimated an upper limit for NO production of 0.6 Tg from Greenland ice samples. This result is also consistent with calculations by T82 who estimated a 42 eV energy requirement to produce a single NO molecule in a Tunguska-like event. Since 1 eV $=1.6 \times 10^{-19}$ J they obtain the same NO production efficiency of 1.5×10^{17} molec NO/J.

[9] In the present study we are focusing on the tropospheric fate of shock-generated NO_x and for the sake of simplicity we assume that all 0.4 Tg of NO are produced within the troposphere and only in the region of maximum energy release (above 5 km). We also assume that the nitrogen is initially released over an horizontal area smaller than a model grid-box area, $\sim 1.1 \times 10^5$ km^2 and $\sim 2.8 \times 10^4$ km^2 for the lower and higher grid resolution respectively. Considering that the area of the seared forest is $\sim 2.2 \times 10^3$ km^2 and that a 700–800 K temperature is enough to burn trees [*Kring and Durda*, 2002] we argue that the >2000 K core of shocked-air did not spread beyond the burnt area.

[10] We start our perturbed simulations distributing 7.5×10^{33} molecules of NO along the column of grid boxes corresponding to the impact site (61°N, 102°E) in an altitude range extending from 5 km to the tropopause, located approximately at 8 km in July. Considering an approximate air density of $\sim 1 \times 10^{19}$ molec cm^{-3} and a total shocked volume of 2.5×10^{20} cm^3 and 6.3×10^{19} cm^3 for the lower and higher resolution model respectively, we have local NO mixing ratios of 3 ppmv and 12 ppmv, respectively. Comparison with unperturbed atmosphere is made against standard model runs covering the same time period. We do not consider injection of other trace gases such as water vapor, carbon dioxide, ammonia that are expected for a cometary body [*Turco et al.*, 1982] but not for a stony meteorite. We do not also address possible perturbations to atmospheric circulation from pressure and temperature shock waves, again because of the lack of the necessary data.

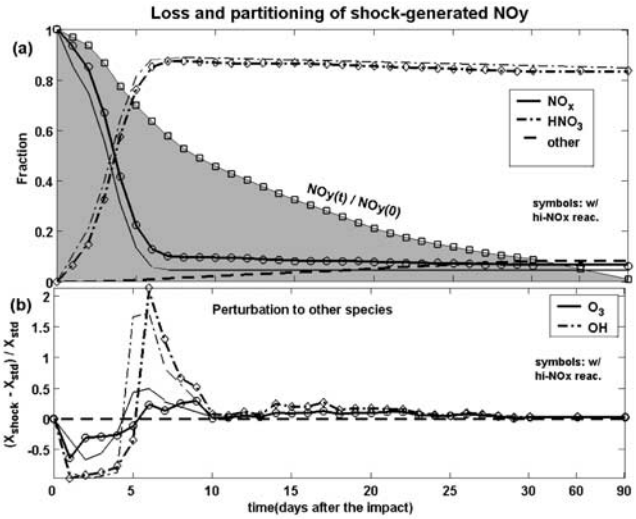

Figure 1. (a) Shaded area: globally integrated fraction of the initial shock-generated nitrogen still in the atmosphere. Thick lines: partitioning of shock-generated NO_y in the low resolution model. Symbols: calculations with high-NO_x chemistry. Thin lines: calculations with the high resolution model with high-NO_x chemistry. (b) Percent differences of ozone and OH mixing ratios in standard and perturbed model at a representative location downwind of the explosion. X = mixing ratio. Line thickness and symbols have the same meaning as in (a).

3. Results

[11] Figure 1a shows fractions of asteroidal nitrogen lost during the first three months of simulation (shaded area). We calculated total budget of nitrogen compounds both in perturbed and unperturbed run; from the differences we estimated the fraction of molecules due to explosion still contained in the atmosphere. During the first month 87% of that nitrogen is lost to the ground, and much of the residual is lost during the second month. The tropospheric NO_x perturbation could be considered exhausted after three months. The other lines in Figure 1a show how the partitioning among nitrogen compounds evolves. At the beginning of the simulation, all the shock-generated nitrogen is in NO_x form (thick solid line), then it rapidly converts to HNO_3 (thick dash-dotted line) on a time scale of about 5 days. The other species play a minor role. We also calculated the number of molecules lost in each individual process (not shown): the main sink is wet removal of HNO_3, followed in importance by dry removal of HNO_3. Deposition of other nitrogen containing compounds is negligible.

[12] The symbols superimposed to lines in Figure 1 show timeseries obtained from model runs that, in addition to the standard mechanism, use certain reactions potentially effective at high-NO_x levels [e.g., *Kasting and Ackerman*, 1985]. These reactions should accelerate the conversion of NO_x to acids. However, they do not display a significative impact on the loss and partitioning of NO_y in these simulations.

[13] Close to the lines representative of NO_x and HNO_3 timeseries in Figure 1a we show thinner lines representative of timeseries from the high resolution model. The model include also the high-NO_x reactions just mentioned. As can be seen, there is a quicker and more efficient conversion of nitrogen oxides to acids. Indeed, the conversion proceeds half a day in advance with respect to the lower resolution model and higher fractions of HNO_3 are reached. The higher initial mixing ratios account for half of the difference and the high-NO_x reactions account for the other half.

[14] Other species in the atmosphere are slightly affected on a monthly mean basis by the sudden injection of NO_x. Figure 1b show percent differences of tropospheric O_3 and OH from perturbed run with O_3 and OH from control run, at a representative location 2000 km to the east of the blast site at 5 km altitude. The timeseries is relative to midday conditions. Ozone and OH are almost completely scavenged by NO_x during the first 3–4 days. After that they increase locally respectively by up to 30% and 200%, when increased NO_x start to catalyze production of ozone rather than scavenging it. When NO_x is almost totally converted to nitric acid the effect vanishes. The monthly mean hemispherical burden does not change by more than a few percent for both species. During the second month the perturbation is largely negligible. Consequently, carbon monoxide and methane perturbations are not expected to have left significant traces (e.g., in Greenland ice cores). Timeseries from the high resolution model with high-NO_x reactions (thinner lines) display a similar amplitude of the perturbation. However, the positive maximum occurs earlier because of the faster consumption of NO_x.

[15] Figure 2 shows how nitric acid formed after the impact is spatially redistributed when lost to the ground in the lower resolution model simulation. Each panel show the integrated deposition over an increased time period. In a large area to the north and to the south-east of the impact site up to 8 kg of N per km^2 fall as acid rain transported by the prevailing westerlies, while just below the explosion about 2 kg N/km^2 are deposited. This acid deposition impulse takes place basically during the first month. In the following weeks there is still enough HNO_3 left to affect much of the Northern Hemisphere with the deposition of shock-generated nitrogen.

[16] We compare our results with peat samples analysis by *Kolesnikov et al.* [1998, hereinafter referred to as K98], who, looking at nitrogen isotopic anomalies, estimated that about 2×10^6 kg of nitrogen from acid rain fell over the 2200 km^2 area around the explosion epicenter. This translates in a local surface density of ~900 kg N/km^2. We remark that the grid-box area in our 4° × 5° simulation is ~1.1×10^5 km^2, that is 50 times larger than the area considered by K98. To get the same surface density as reported by K98 over an entire grid-box would require ~10^8 kg N, or ~50% of the total 2×10^8 kg N initially injected. But, as we have seen in Figure 1a, half of the NO_x source is converted to HNO_3 only after 3–4 days, enough time for the plume to travel for thousands of km away of the blast site. With the 2° × 2.5° model we get a deposition increase of a 3–4 factor near the Tunguska basin with respect to the low resolution model. To get the ~900 kg N/km^2 over a single ~2.8×10^4 km^2 grid-box we would need ~2.5×10^7 kg N (~12% of the total), a quantity achievable in about 1 day (Figure 1a, thinner lines). At the bottom of Figure 2 we also show a colorbar scaled with the total quantity of nitrogen deposited in a single model grid-box. In the box below the explosion about 3×10^5 kg N are collected, or 7 times less than the quantity claimed by K98 only for the area of the forest. Notably, with the higher resolution model we obtain ~1×10^6, a value within a factor of 2 of the K98 value.

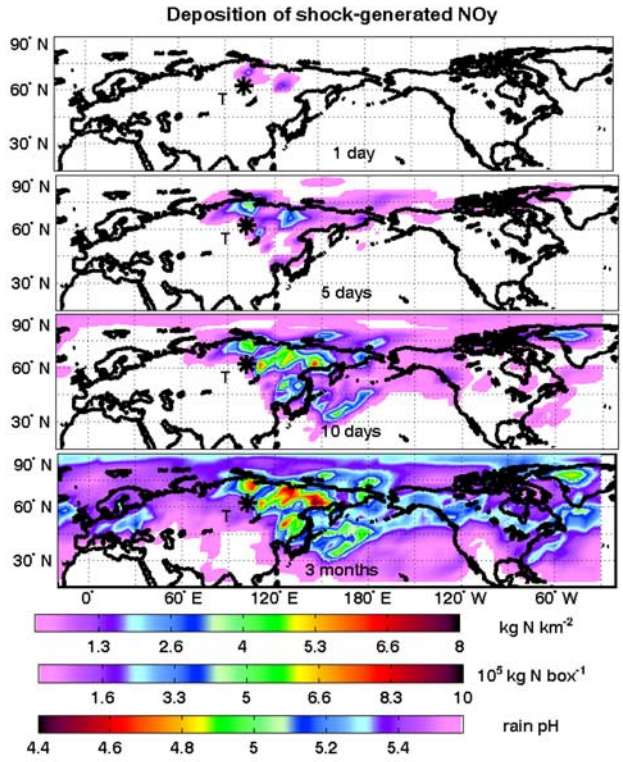

Figure 2. Integrated surface density of shock-generated nitrogen deposited to the ground over several time periods. Blast site is marked by a star. The T indicates the position of the Tomsk sampling site described in K98. Please refer to the text for colorbars explanation.

[17] Possible explanations for the discrepancy between modelled and K98 deposition include: 1) model resolution, 2) interannual variations in precipitation, 3) explosion generated atmospheric perturbations, 4) uncertainty in the magnitude and vertical extent of the shock-generated NO, and 5) representation errors in the K98 calculations. The low resolution of the model basically prevents us from comparing the deposition per unit area. The reconstruction of the 1908 precipitations pattern and of the atmospheric perturbation are complicated by the lack of observations and are beyond the scope of this paper. We carried out two sensitivity simulations, one distributing the shock-generated NO from the ground to the tropopause and the other releasing 10 times more NO. Below the explosion point

we get a +30% and a × 6 deposition, respectively. We also argue that there could be a flaw in calculations by K98, because they extrapolated the total deposition of nitrogen from samples collected very close to the explosion point and assuming that they are representative of a vast area that could have been subjected to a very inhomogeneous acid deposition.

[18] Apart from deposition at the impact site, our simulations suggest that shock-generated NO_y could have left traces over an area much larger than the seared forest (Figure 2) and peat samples analysis could reveal similar, although less pronounced, structures as those found below the explosion point. K98 also remarked that peat samples 2000 km south-west of the impact site near Tomsk (denoted by a T in Figure 2) do not show prominent features correlated to acid rain deposition. If our simulated distribution is correct, Tomsk site would have been outside the main deposition zone, thus explaining lack of evidence for strong acid deposition as near the impact.

[19] Figure 2 also shows how the shock-produced HNO_3 can induce a rain pH as low as 4.4 in regions downwind of the explosion, when nitrate prevails in acid deposition (see the last colorbar at the bottom of Figure 2). The rain pH is calculated by dividing the HNO_3 flux by the water precipitation flux, which give us the HNO_3 concentration in the rain. Considering that such values of rain pH are, if not higher than, comparable to those in modern industrial areas, it is not likely that such deposition would severely damage the ecosystem because of the short duration of the perturbation. Also in the above mentioned ×10 simulation we obtain rain pHs no lower than 3.5.

4. Conclusions

[20] We assume that about 0.4 Tg of nitric oxide was produced in the upper troposphere after the Tunguska body explosion. This is the same order of magnitude of the upper limit of 0.6 Tg experimentally estimated by *Rasmussen et al.* [1984]. A vast area downwind of the impact site would have been subjected to moderate acid rain episodes mainly during the following month, because of the fast conversion of NO to nitric acid. Three months after the impact the perturbation completely fades out. Our study shows a reduction of the atmospheric effects with respect to previous model calculation by T82 basically because our estimate relies on an improved study on the nature of Tunguska body [*Chyba et al.*, 1993], that is it most likely a less energetic stony asteroid and not a low density comet. The energy released is about 100 times less in our case and NO production is peaked in the upper troposphere and not distributed in mesosphere and stratosphere as in T82.

[21] The low resolution of the model prevents us from comparing the deposition density over the area below the explosion point with the analysis of peat samples by K98. However, the high-resolution simulation gets within a factor of 2 of the K98 total deposition value. Our model suggests that peat samples analysis over the vast area to the north and to the south-east of the impact site (Figure 2), where no samples have been collected so far, would reveal nitrogen isotopic anomalies similar to those found near the impact site.

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