The 2003 North American electrical blackout: An accidental experiment in atmospheric chemistry

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[1] The August 2003 North American electrical blackout provided a unique opportunity to quantify directly the contribution of power plants to regional haze and O_3. Airborne observations over central Pennsylvania on August 15, 2003, ~24 h into the blackout, revealed large reductions in SO_2 (>90%), O_3 (~50%), and light scattered by particles (~70%) relative to measurements outside the blackout region and over the same location when power plants were operating normally. CO and light absorbing particles were unaffected. Low level O_3 decreased by ~38 ppbv and the visual range increased by >40 km. This clean air benefit was realized over much of the eastern U.S. Reported SO_2 and NO_x emissions from upwind power plants were down to 34 and 20% of normal, respectively. The improvement in air quality provides evidence that transported emissions from power plants hundreds of km upwind play a dominant role in regional haze and O_3 production. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 6620 Public Issues: Science policy. **Citation:** Marufu, L. T., B. F. Taubman, B. Bloomer, C. A. Piety, B. G. Doddridge, J. W. Stehr, and R. R. Dickerson (2004), The 2003 North American electrical blackout: An accidental experiment in atmospheric chemistry, *Geophys. Res. Lett.*, *31*, L13106, doi:10.1029/2004GL019771.

1. Introduction

[2] The August 2003 electrical blackout that affected over 100 power plants in the northeastern U.S. and southeastern Canada provided a unique opportunity to evaluate the contribution of power plant emissions to regional haze and ozone (O_3). The impact of transported point source pollution on regional air quality depends on emissions, meteorology, and non-linear chemical responses. So far, quantification of the impacts has been based on multi-year measurement and modeling studies [e.g., *Solomon et al.*, 2000] and results of long-term emissions reduction scenarios [*Malm et al.*, 2002]. This paper presents results of direct measurements of the effect of power plant emissions reductions on regional air quality with all other factors held relatively constant.

[3] Fossil fuel burning power plants account for more than half of electrical energy production in the U.S., but also ~22% of the nitrogen oxides ($NO_x = NO + NO_2$) and ~69% of the sulfur dioxide (SO_2) emissions [*United States Environmental Protection Agency* (*U.S. EPA*), 2003a]. NO_x combines with volatile organic compounds (VOCs) in the presence of sunlight to produce O_3, the principal component of photochemical smog. SO_2 may be oxidized to produce sulfate (SO_4^{2-}), the primary constituent of $PM_{2.5}$ (particles with diameters ≤ 2.5 μm) in the northeastern U.S. [*Malm et al.*, 2000]. In summertime, under high pressure with westerly transport, emissions of NO_x and SO_2 in the northeastern U.S. induce severe smog and haze events, primarily comprised of O_3 and sulfate-dominated fine particles [*Ryan et al.*, 1998; *Sistla et al.*, 2001; *Taubman et al.*, 2004a]. Both pollutants have been linked to adverse health effects, degradation of the environment, and global climate change [*McClellan*, 2002; *Gent et al.*, 2003; *U.S. EPA*, 2003b; *Houghton et al.*, 2001].

[4] Airborne measurements were made over Maryland and Virginia (outside the blackout area) and Pennsylvania (in the center of the blackout area) on August 15, 2003, ~24 h into the blackout. The results are compared to those from the previous summer in the same location and under similar meteorological conditions when upwind power plants were operating normally. Emissions data are examined in conjunction with back trajectories to quantify the contribution of power plants to the observed air quality. Results help quantify the impact of reduced SO_2 and NO_x emission on air quality in the northeast U.S.

2. Sampling Platform

[5] A light aircraft outfitted for atmospheric research was used as the sampling platform. Ozone, CO, and SO_2 mixing ratios were measured using Thermo Environmental Instruments analyzers. Sub-micrometer particle counts were determined using a MetOne 9012 optical particle counter. Particle light scattering at 450, 550, and 700 nm was measured using a TSI 3563 integrating nephelometer. Particle light absorption at 565 nm was quantified with a Particle/Soot Absorption Photometer. For full details of instruments used, see *Taubman et al.* [2004b].

3. Results and Discussion

[6] Two flights were conducted on August 15, 2003. During the first flight, three vertical spirals (surface-3 km) were performed over Luray (38.70°N, 78.48°W) and Winchester (39.15°N, 78.15°W) in Virginia and Cumberland, Maryland (39.60°N, 78.70°W) at ~14:00, 15:00, and

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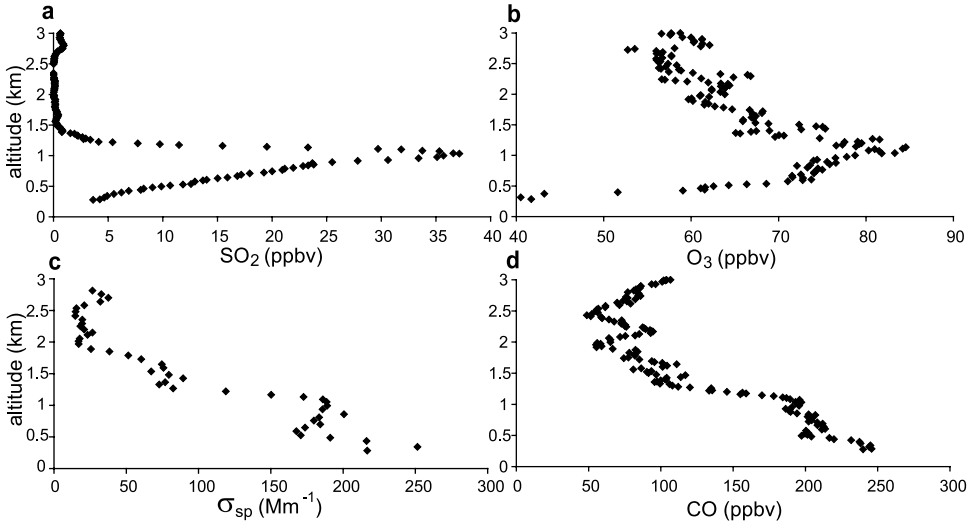

Figure 1. Running 1 min mean SO_2 mixing ratios (a); 10 s O_3 mixing ratios (b); particle light scattering at 550 nm (c); and running 1 min mean CO mixing ratios (d) over Luray, Virginia (outside blackout area) at 1400 UTC (10:00 LST) 15 Aug, 2003.

15:30 UTC, respectively. Two spirals were performed over Selinsgrove, Pennsylvania (40.82°N, 76.86°W) at ~19:00 and 20:00 UTC during the second flight.

[7] The morning spirals (outside the blackout region) revealed trace gas mixing ratios and particle properties typical of those routinely observed on previous flights [*Dickerson et al.*, 1995; *Ryan et al.*, 1998; *Taubman et al.*, 2004a]. Observations over Luray, for example, show maxima in SO_2 and O_3 mixing ratios in a thin layer at ~1 km MSL (Figures 1a and 1b). A corresponding peak in particle light scattering was also seen at this altitude; but values increased again below 500 m MSL (Figure 1c), corresponding to a maximum in CO (Figure 1d). These observations indicate a stable nocturnal boundary layer with a maximum depth of 500 m MSL. Above this altitude, NO_x and SO_2 from power plants produced O_3 and SO_4^{2-}, respectively, which were transported in the residual layer. Below 500 m, the pollution was most likely of local origin. Particles observed in the nocturnal boundary layer may have been largely organics, the products of vehicle exhaust and home heating and cooking, which can scatter visible light efficiently [*Malm et al.*, 1994].

[8] Observations from the afternoon flight were different. Spirals over Selinsgrove, Pennsylvania revealed very little O_3, SO_2, and PM relative to the morning flight and areas to the south (Figures 2a–2c). CO concentrations were within 0.5σ of the 1992 median August and September values over Baltimore, Maryland and vicinity [*Dickerson et al.*, 1995], and remained fairly constant throughout the afternoon, apparently only varying with altitude (Figure 2d). Linear regressions between O_3 and SO_2 measured during the flight showed that O_3 over Selinsgrove was not correlated with SO_2 ($r = 0.13$), while it was elsewhere ($r = 0.80$). Observations over Selinsgrove are consistent with reductions in power plant emissions but no corresponding changes in vehicle emissions.

[9] To investigate whether the improvement in air quality over Selinsgrove was due to reductions in upwind power

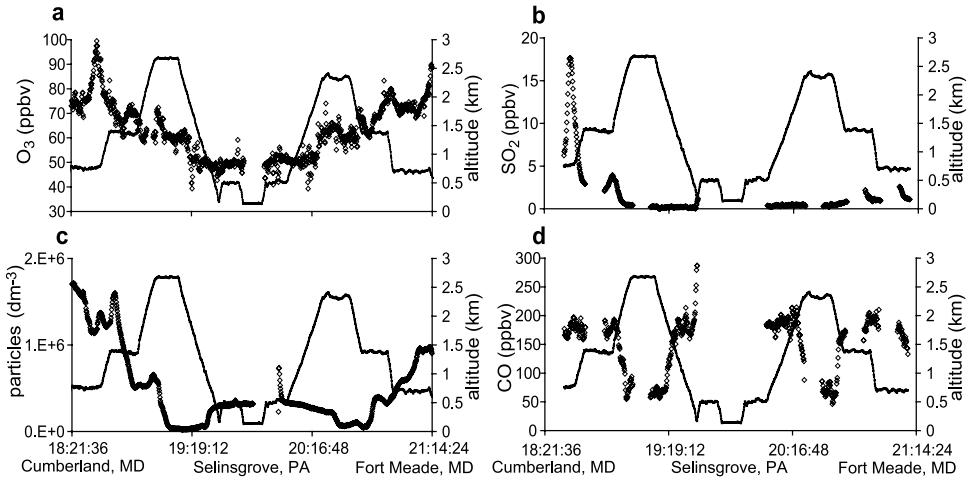

Figure 2. Second flight on August 15, 2003 showing altitude (solid black lines), time (UTC), as well as takeoff, landing and spiral locations. Open diamonds represent 10 s O_3 mixing ratios (a); running 1 min mean SO_2 mixing ratios (b); sub-micrometer particle counts (c); and running 1 min mean CO mixing ratios (d).

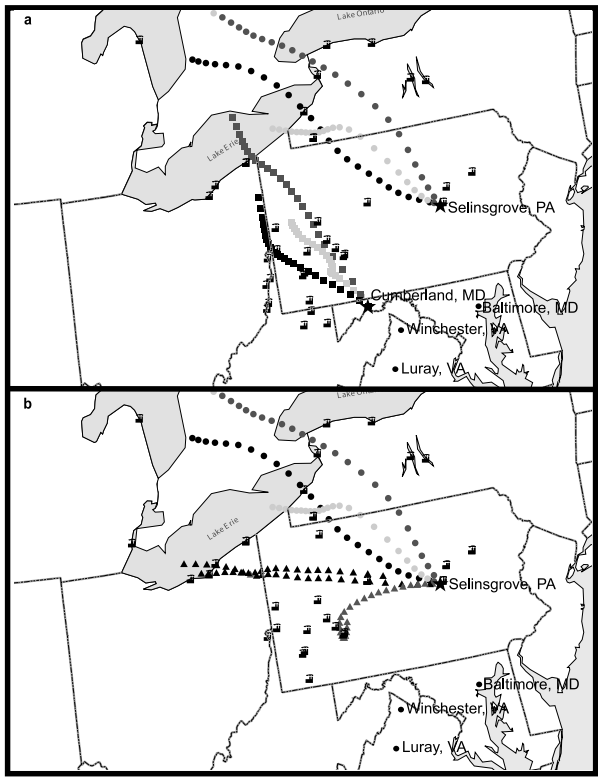

Figure 3. Map of northeastern U.S. showing modeled back trajectories (24 h) from Cumberland, MD and Selinsgrove, PA on 15 Aug, 2003 at 1500 and 2000 UTC, respectively (a); and Selinsgrove, PA on 15 Aug, 2003 (circles) and on 4 Aug, 2002 (triangles) at 2000 and 2100 UTC, respectively (b). Light gray represents 0–500 m, dark gray 500–1500 m, and black 1500–2500 m AGL. Icons represent power plants that fall within trajectory buffers regardless of size or extent of down scaling during the blackout.

plant emissions, 24 h backward trajectories were run from Selinsgrove at 500, 1500, and 2500 m AGL using the NOAA ARL HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Version 4) (R. R. Draxler and G. D. Rolph, HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website, http://www.arl.noaa.gov/ready/hysplit4.html, NOAA Air Resources Laboratory, Silver Spring, Md., 2003) and EDAS meteorological fields (Figure 3a). A 100 km wide swath was then assigned to the trajectory paths to account for uncertainties. Hourly NO_x and SO_2 emissions data (Nabors, K., personal communication, 2003) for U.S. power plants falling within the swaths were integrated over the 24 h period preceding the measurements (Table 1). This enabled the pairing of upwind emissions data with wind trajectory analyses. A large source of uncertainty in this approach is the lack of emissions data from Canada.

[10] For comparison, the same back trajectory and emissions procedure was followed for Selinsgrove, PA on August 4, 2002 (prior to blackout), and Cumberland, MD on August 15, 2003 (out of blackout area). On August 4, 2002, Selinsgrove was under similar synoptic patterns as on August 15, 2003. Regional mean surface temperatures were ~33°C on both days and wind speeds and directions were similar (Figure 3b). This analysis yielded large differences in upwind power plant emissions (Table 1). SO_2 and NO_x emissions upwind of Selinsgrove on August 15, 2003 were reduced to 34% and 20% of normal and to 34% and 25% of that observed upwind of Cumberland, respectively (Table 1).

[11] The impact of this emissions disparity on downwind air quality is illustrated in Figure 4. Near surface SO_2, O_3, and light scattered by particles measured over Selinsgrove in 2003 were reduced by >90%, ~50%, and ~70%, respectively, relative to 2002 observations (Figures 4a–4c). Defining visual range as the 98% extinction point, the reduction in aerosol extinction corresponds to an increase in visual range of >40 km. The concomitant decreases in SO_2 and particle light scattering suggest that improvements in visibility resulted directly from reduced power plant SO_2 emissions. Reductions in O_3, apparently the result of decreased NO_x emissions, were greatest near the surface (~38 ppbv) and fell off at higher altitudes where large-scale processes play a more dominant role in the O_3 budget. As with CO concentrations, however, light absorption by particles shows a less dramatic difference (Figure 4d). In fact, absorption was higher in 2003 than in 2002, suggesting little or no reduction in vehicle emissions during the blackout relative to typical values. The single scattering albedo was 0.95 on the normal day, but fell to 0.85 during the blackout. Electricity generation produces very little CO or absorbing aerosols; instead, they are mainly emitted by vehicles that continued to operate during the blackout. No discernible changes in road vehicular traffic activity could be observed near or upwind of the study area during the blackout (D. Szekeres, Traffic counts data, Pennsylvania Department of Transportation (PDOT), Bureau of Planning and Research, personal communication, 2004).

[12] Forward trajectories (not shown) run from Selinsgrove reach Baltimore, Philadelphia, and New York, depending on the altitude. Thus, the improvement in air quality depicted in Figure 4 was experienced over several major eastern cities. This is corroborated by the fact that O_3 concentrations in Maryland were forecasted to be 125 ppbv

Table 1. 24 h Integrated SO_2 and NO_x Emissions From Upwind Power Plants That Fall Within Back Trajectory Source Regions for Selinsgrove on 15 Aug, 2003 and 4 Aug, 2002 (Normal Day), and Cumberland on 15 Aug, 2003 (Outside Blackout Area)[a]

	Selinsgrove 15 Aug, 2003	Selinsgrove 4 Aug, 2002	Cumberland 15 Aug, 2003	Emissions Reduction Upwind of Selinsgrove on 15 Aug, 2003 Relative to:	
	Blackout Day	Normal Day	Blackout Day	Selinsgrove on 4 Aug, 2002	Cumberland on 15 Aug, 2003
SO_2 tons/day	2424.1	7227.9	7033.9	66%	66%
NO_x tons/day	309.2	1565.0	1219.9	80%	75%

[a]Also shown are percentage emissions reductions upwind of Selinsgrove on 15 Aug, 2003 relative to 4 Aug, 2002 and Cumberland on 15 Aug, 2003.

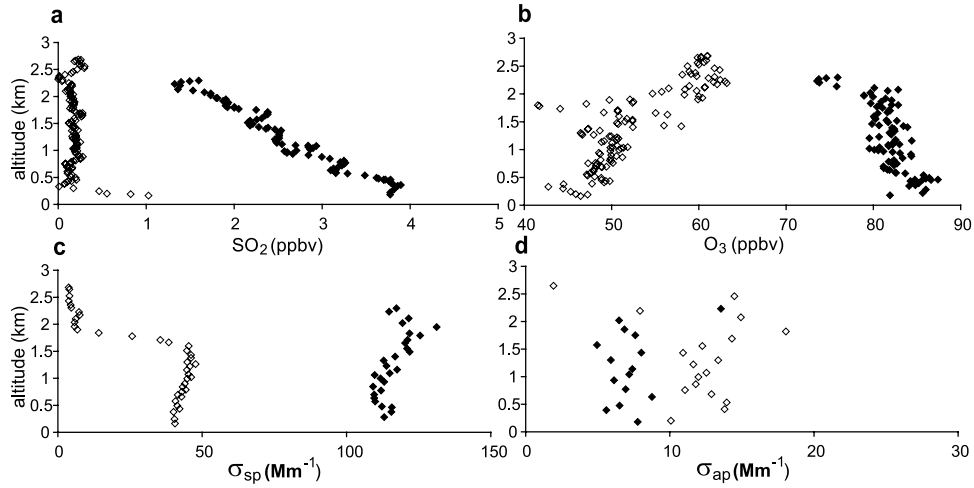

Figure 4. Comparison of running 1 min mean SO_2 mixing ratios (a); 10 s O_3 mixing ratios (b); particle light scattering at 550 nm (c); and particle light absorption at 565 nm (d) measured on 15 Aug, 2003 (open diamonds) and 4 Aug, 2002 (filled diamonds) over Selinsgrove, Pennsylvania.

but reached only 90 ppbv (Maryland Department of Environment, 2003, http://www.mde.state.md.us/Air/air_quality/ozone_forecast.asp). Because the RMS forecast error is 10 ppbv, we attribute the bulk of this overestimation to reduced power plant emissions.

4. Conclusions

[13] Airborne measurements made over central Pennsylvania on August 15, 2003, ~24 hours into one of the largest electrical blackouts in North American history, showed large reductions in SO_2 (>90%), O_3 (~50%), and light scattered by particles (~70%) relative to observations over western Maryland earlier in the day and over the same location the year before. This translated into a reduction in low level O_3 of ~38 ppbv and an improvement in visual range of >40 km. Forward trajectories show that these improvements in air quality benefited much of the eastern U.S. CO and particle light absorption values did not change much, however, suggesting that vehicle emissions were largely unaffected during the blackout. Reported power plant SO_2 and NO_x emissions upwind of central Pennsylvania on August 15, 2003 were 34% and 20% of normal, respectively. Thus, the decreases in SO_2, O_3, and particle light scattering appear to be predominantly due to reductions in power plant emissions hundreds of km upwind of the study area. The observed reductions exceed expectation based on estimated relative contribution of power plants to these pollutants and their precursors (NO_x ~22%, SO_2 ~69% and PM ~8%) [*U.S. EPA*, 2003a]. The dramatic improvement in air quality during the blackout may result from underestimation of emissions from power plants, inaccurate representation of power plant effluent in emission models or unaccounted for atmospheric chemical reaction(s). These unique observations will provide a resource for determining whether air quality models can accurately reproduce the contributions of specific pollution sources to regional air quality.

[14] **Acknowledgment.** This work was supported by the Maryland Department of Environment (MDE).

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