

# Global Mortality Attributable to Aircraft Cruise Emissions

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Received April 23, 2010. Revised manuscript received  
 August 2, 2010. Accepted August 19, 2010.

Aircraft emissions impact human health through degradation of air quality. The majority of previous analyses of air quality impacts from aviation have considered only landing and takeoff emissions. We show that aircraft cruise emissions impact human health over a hemispheric scale and provide the first estimate of premature mortalities attributable to aircraft emissions globally. We estimate ~8000 premature mortalities per year are attributable to aircraft cruise emissions. This represents ~80% of the total impact of aviation (where the total includes the effects of landing and takeoff emissions), and ~1% of air quality-related premature mortalities from all sources. However, we note that the impact of landing and takeoff emissions is likely to be under-resolved. Secondary  $\text{H}_2\text{SO}_4$ – $\text{HNO}_3$ – $\text{NH}_3$  aerosols are found to dominate mortality impacts. Due to the altitude and region of the atmosphere at which aircraft emissions are deposited, the extent of transboundary air pollution is particularly strong. For example, we describe how strong zonal westerly winds aloft, the mean meridional circulation around 30–60°N, interaction of aircraft-attributable aerosol precursors with background ammonia, and high population densities in combination give rise to an estimated ~3500 premature mortalities per year in China and India combined, despite their relatively small current share of aircraft emissions. Subsidence of aviation-attributable aerosol and aerosol precursors occurs predominantly around the dry subtropical ridge, which results in reduced wet removal of aviation-attributable aerosol. It is also found that aircraft  $\text{NO}_x$  emissions serve to increase oxidation of nonaviation  $\text{SO}_2$ , thereby further increasing the air quality impacts of aviation. We recommend that cruise emissions be explicitly considered in the development of policies, technologies and operational procedures designed to mitigate the air quality impacts of air transportation.

## Introduction

Aviation currently accounts for approximately 3% of annual fossil fuel energy usage (1) and has been forecast to grow at an average of 5% per annum until 2027 (2). While climate perturbations attributable to aircraft emissions have been extensively studied (3, 4), the impact of aviation on air quality and human health globally has not been reported.

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Current regulatory practice is to neglect the effects of aircraft cruise emissions on surface air quality (5, 6). Only landing and takeoff cycle (LTO) emissions—conventionally up to an altitude of 3000 ft or approximately 1 km—are generally accounted for. This corresponds to a typical planetary boundary layer height, within which pollutants mix rapidly. However, recent regional modeling work indicates that cruise emissions may contribute a significant fraction of aircraft-accountable ground-level pollutant concentrations on a regional scale (7).

We report simulation results indicating that aircraft cruise emissions are implicated in increased premature mortality on a hemispheric scale. Furthermore, meridional and zonal circulation patterns at cruise altitudes displace impacts from flight paths by several thousand kilometers. Our approach is to use a recent aircraft emissions inventory, a global chemistry–transport model, population density and disease statistics, and concentration–response functions derived from epidemiological studies to assess the impact of aircraft emissions globally on premature mortality. Parametric uncertainties in aircraft emissions and concentration–response functions are propagated throughout the analysis, along with estimates of modeling uncertainty.

## Materials and Methods

Fuel burn and emissions inventories were based on the U.S. Federal Aviation Administration's AEDT/SAGE tool (8), which has been evaluated and its uncertainty quantitatively assessed (9). AEDT/SAGE calculates aircraft fuel burn in 2006 at 188 Tg, which we estimate to be accurate to  $\pm 5\%$  overall and  $\pm 25\%$  for LTO operations. The global average emissions index (emitted pollutant mass per fuel burn mass) for oxides of nitrogen is  $\text{EI NO}_x$  as  $\text{NO}_2 = 13.8 \text{ g/kg-fuel} \pm 25\%$ . Current evidence suggests that the globally averaged aviation fuel sulfur concentration is in the range 400–800 ppm (10, 11). Significant regional and interannual variability exists, but at the present time insufficient fuel survey data is available to support regionally differentiated fuel sulfur concentration specifications. We assumed a fleet average fuel sulfur concentration of  $600 \pm 200 \text{ ppm}$ , which corresponds to  $\text{EI SO}_x$  as  $\text{SO}_2 = 1.2 \pm 0.4 \text{ g/kg-fuel}$ . Nominal black carbon (BC) and particulate organic carbon (OC) emissions indices were estimated at  $\text{EI BC} = 0.04 \text{ g/kg-fuel}$  and  $\text{EI OC} = 0.02 \text{ g/kg-fuel}$ , respectively. Uncertainties in BC and OC emissions are discussed in the Supporting Information (SI). Primary sulfate aerosol emissions were estimated by assuming a nominal conversion efficiency of  $\epsilon = 2\%$  from fuel sulfur to  $\text{S}^{\text{VI}}$ , with a range of  $\epsilon = 0.5$ –6%. LTO particulate matter emissions indices were based on the First Order Approximation version 3 (12). Emissions indices with associated uncertainty ranges are summarized in Table 1.

The global three-dimensional, coupled oxidant–aerosol model, GEOS-Chem, was chosen for this study (13). It is driven by assimilated meteorological observations from the Goddard

**TABLE 1. Fleet Averaged Emissions Indices Used in Current Assessment by Emitted Species**

EI (g/kg)	low	nominal	high
$\text{NO}_x$ as $\text{NO}_2$	10.4	13.8	17.3
$\text{SO}_x$ as $\text{SO}_2$	0.8	1.2	1.6
BC	0.01	0.04	0.2
$\text{S}^{\text{VI}}$ as $\text{H}_2\text{SO}_4$	0.01	0.04	0.15
OC	0.01	0.02	0.6

Earth Observing System and has been extensively applied and evaluated. GEOS-Chem has been used to study the intercontinental transport of aerosols and aerosol precursors (14–19) and in a recent air quality mortality assessment for shipping (20). A model sharing substantially common code for photochemistry, emissions and deposition was applied for the 1999 IPCC Special Report on Aviation and the Global Atmosphere (3). A detailed wet deposition scheme is included, which has been constrained by observations (21). BC, OC and  $\text{H}_2\text{SO}_4\text{--HNO}_3\text{--NH}_3$  aerosols are simulated (18).

Epidemiological studies indicate that long-term population exposure to fine particulate matter with an aerodynamic diameter less than  $2.5\text{ }\mu\text{m}$  ( $\text{PM}_{2.5}$ ) is associated with increased risk of health impacts including premature mortality (22–28). Although associations between other pollutants and premature mortality have been found, a relatively strong evidence base exists for  $\text{PM}_{2.5}$  as the exposure metric that is most consistently and independently associated with premature mortality and other health effects. No exposure threshold is likely to exist for  $\text{PM}_{2.5}$  (28).

Concentration–response functions relate baseline pollutant concentrations and baseline health incidence rates to expected changes in incidence rates. Concentration–response functions and confidence intervals were based on the World Health Organization (WHO) guideline method (28). Premature mortalities caused by lung cancer and cardiopulmonary diseases due to long-term exposure to aviation-attributable  $\text{PM}_{2.5}$  were considered for adults over age 30. Global population density data derived primarily from national censuses (29) and WHO disease statistics aggregated on the WHO subregion level were used in the analysis. An unquantified uncertainty is the potential differential toxicity of the PM modeled, which is important to the extent that aviation-attributable PM differs in chemical composition and size relative to the polluted urban air upon which epidemiological concentration–response functions are derived. We note that the PM precursor pollutants emitted from aviation are not different than those emitted from other combustion sources. This implies that the impacts of secondary  $\text{H}_2\text{SO}_4\text{--HNO}_3\text{--NH}_3$  aerosols are comparable to nonaviation sources assuming no differential toxicity among secondary PM species.

Results from 50 GEOS-Chem integrations of 15 months duration are reported herein. A set of simulations was used to represent the range of uncertain parametric inputs. Coupling between primary sulfate aerosol emissions and  $\text{SO}_2$  emissions was accounted for through the fuel sulfur to  $\text{S}^{\text{VI}}$  conversion efficiency. Results of simulations were used to construct a multidimensional interpolation (covering fuel burn, EI  $\text{NO}_x$ , EI  $\text{SO}_x$ ,  $\epsilon$ , EI BC, and EI OC), through which input probability density functions were passed to produce probabilistic outputs of population exposure. Additional simulations captured the impact of LTO emissions only, European cruise emissions, North American cruise emissions, and South-East Asian cruise emissions. The role of aircraft  $\text{NO}_x$  emissions in oxidizing nonaviation  $\text{SO}_2$  was explored with a set of simulations at different aviation fuel sulfur concentrations (0, 200, 400, 600, and 800 ppm) and with aircraft  $\text{NO}_x$  emissions at their nominal value, perturbed by  $\pm 25\%$ , and set to zero. Two different aerosol thermodynamic equilibrium codes were employed. Sensitivity simulations were conducted to quantify the influence of uncertainty in background ammonia and selection of meteorological year. Further details are given in the SI.

## Results and Discussion

We first discuss results from simulations with all uncertain parameters at their nominal values. Figure 1 shows aircraft fuel burn, and separately, ground-level perturbations in BC

only and all  $\text{PM}_{2.5}$  (BC, OC, sulfate, nitrate, and ammonium) due to aircraft emissions. LTO-only and full flight (LTO+Cruise) fuel burn and air quality impacts are shown in the right and left columns, respectively.

Aircraft-attributable BC is formed during combustion; as such, transport and removal processes are most relevant when considering ground-level BC perturbations. In the case of LTO emissions and ground-level BC perturbations, Figure 1 (right column) show a strong spatial correlation, although impacts are visibly displaced to the east due to prevailing ground-level westerly winds at midlatitudes. Considering all aircraft emissions [Figure 1 (left column)], impacts are dispersed throughout  $30\text{--}60^\circ\text{N}$  and to the east of peak emissions by  $\sim 10\text{ }000\text{ km}$ .

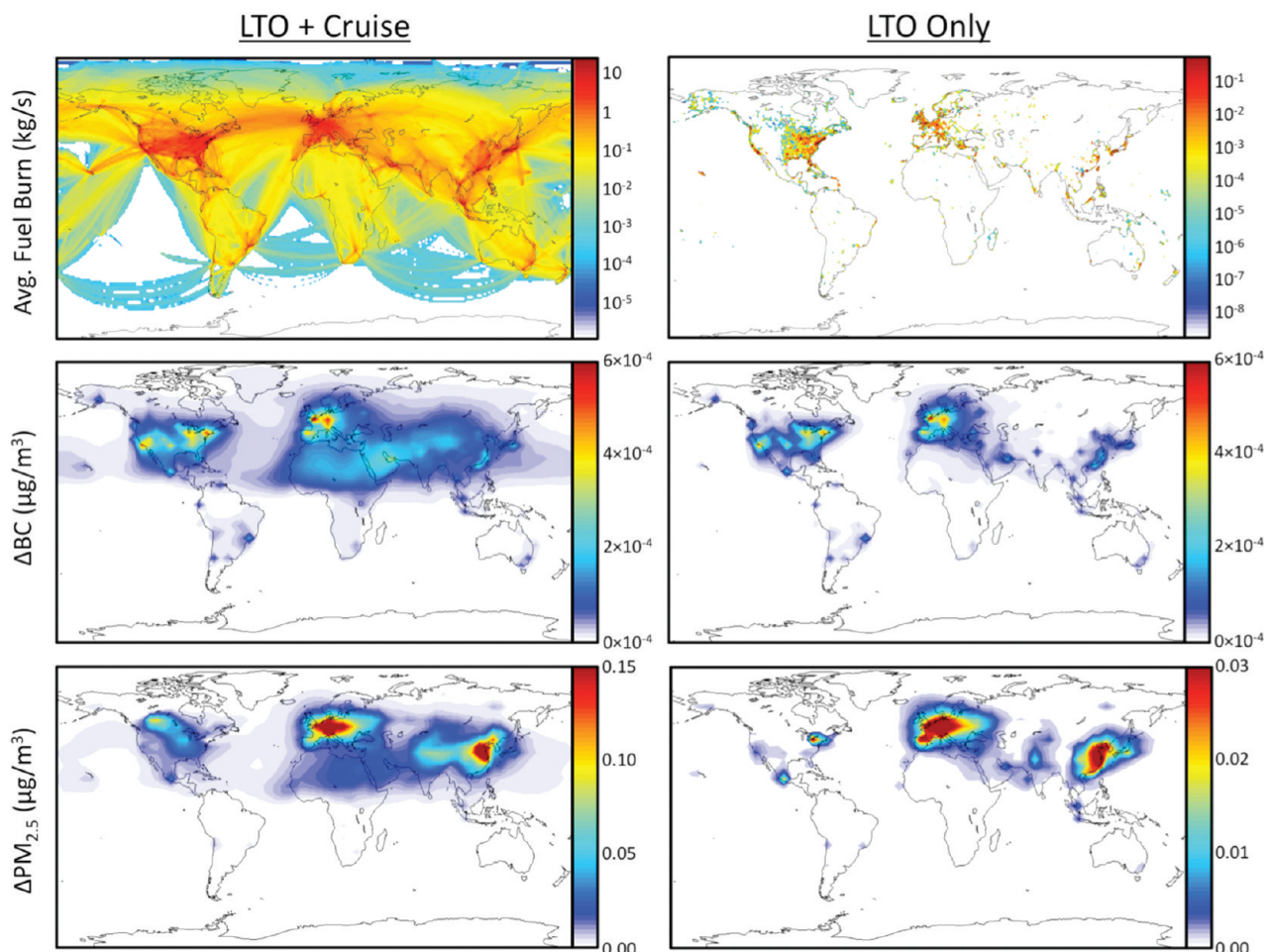
Features of the mean circulation of the atmosphere that contribute to this are depicted in Figure 2, which shows mean meridional streamlines and zonal mean winds as a function of altitude. It can be seen that the peak in zonal westerly winds occurs at about  $35^\circ\text{N}$  and 270 hPa (9.5 km), which corresponds closely to the latitude of peak aircraft emissions and typical cruise altitudes. A large fraction of aircraft emissions are thus injected at a latitude and altitude where pollutants are transported east at greater than 15 m/s on average, resulting in longitudinally displaced ground-level impacts.

Peak aircraft emissions occur in the upper part of the Ferrel cell—a thermally indirect midlatitude meridional circulation—which can be characterized in an average sense by air masses at  $\sim 40^\circ\text{N}$  and cruise altitudes moving south to  $\sim 30^\circ\text{N}$  before descending toward ground-level. Subsiding air masses at  $\sim 30^\circ\text{N}$  may be entrained into the Hadley circulation and so continue further south past  $20^\circ\text{N}$ , or be entrained into surface southerlies. While upwelling regions transferring polluted air masses from the lower to free troposphere experience efficient wet scavenging of aerosol, subsiding air masses transporting pollution from cruise altitudes to the lower troposphere are not associated with rapid aerosol removal. The typical aircraft pollution transport path depicted in Figure 2 thus provides for a low-removal rate path for aerosol. The mean fuel burn-weighted flight latitude is  $34^\circ\text{N}$ , while the mean aviation BC perturbation latitude is  $28^\circ\text{N}$ , i.e. a 600 km southerly shift. Moreover, as can be seen in Figure 2, there is a 900 km southerly shift between the mean cruise emissions latitude and the center-of-mass of surface  $\Delta\text{BC}$  impacts.  $\Delta\text{BC}$  is approximately symmetric around the subtropical ridge.

Figures 1 and 2 show that  $\text{PM}_{2.5}$  perturbations do not penetrate the intertropical convergence zone (ITCZ), where strong convective activity occurs. Impacts of LTO emissions (Figure 1) do not extend as far south due to prevailing northerly surface winds and faster removal rates in the lower atmosphere.

Aviation-attributable ground-level  $\text{PM}_{2.5}$  consists largely of primary particulate matter (BC and OC), and secondary sulfate-ammonium-nitrate aerosols formed through reaction with aircraft-attributable  $\text{HNO}_3$  and  $\text{H}_2\text{SO}_4$ , from  $\text{NO}_x$  and  $\text{SO}_x$ , respectively, and background  $\text{NH}_3$ . In regions with available  $\text{NH}_3$ , aqueous then solid phase ammonium concentrations increase until all sulfate is neutralized. If  $\text{NH}_3$  is still available, aerosol nitrate begins to form. Aerosol liquid water responds nonlinearly over these regimes. On a global basis, 99% of population-weighted aircraft attributable  $\text{PM}_{2.5}$  is secondary sulfate-ammonium-nitrate aerosol and 1% is primary particulate matter.

Figure 3 shows speciated plots of the ground-level  $\text{PM}_{2.5}$  perturbation due to aviation. These constitute the components of aviation-attributable  $\text{PM}_{2.5}$  with the exception of secondary organic aerosols (see the SI). The influence of the lack of available ammonia over the Sahara can be seen: nitrate formation is suppressed in this region, with only (acidic)



**FIGURE 1.** Global plots for and LTO (0–1 km) and full flight (LTO + Cruise) operations: vertically summed average fuel burn (kg/s per  $1^\circ \times 1^\circ$ ); ground-level BC perturbation ( $\mu\text{g}/\text{m}^3$ ); and ground-level total  $\text{PM}_{2.5}$  perturbation ( $\mu\text{g}/\text{m}^3$ ) attributable to aviation.

sulfate formation occurring. Note that the OC pattern is on account of the nominal assumption of low OC cruise emissions relative to LTO, which are spatially variable depending on aircraft age and type.

Applying the WHO concentration–response functions, disease statistics, population density data, and GEOS-Chem modeling results, we estimate a global total of 9970 premature mortalities per year due to aircraft emissions (given 2001–2 meteorology). Premature mortalities per year for selected countries are: Canada, 67; China, 1890; Ethiopia, 43; France, 380; Germany, 545; India, 1640; Iran, 76; Spain, 189; United Kingdom, 362; and United States, 458. LTO emissions account for 20% of the total premature mortalities attributable to aviation globally, however this is likely a lower bound due to the global model resolution. We estimate that LTO impacts are underestimated by a factor of 2 in the U.S. by comparing results from a GEOS-Chem simulation with high ( $\sim 36$  km) resolution CMAQ simulations of the impact of U.S. LTO operations (30). While noting that the underestimate of LTO impacts is likely lower in other countries that receive a relatively higher fraction of transboundary pollution from aircraft, applying this factor globally leads to an estimate of LTO emissions being responsible for  $\sim 30\%$  of aviation-attributable premature mortalities. This is discussed in the SI.

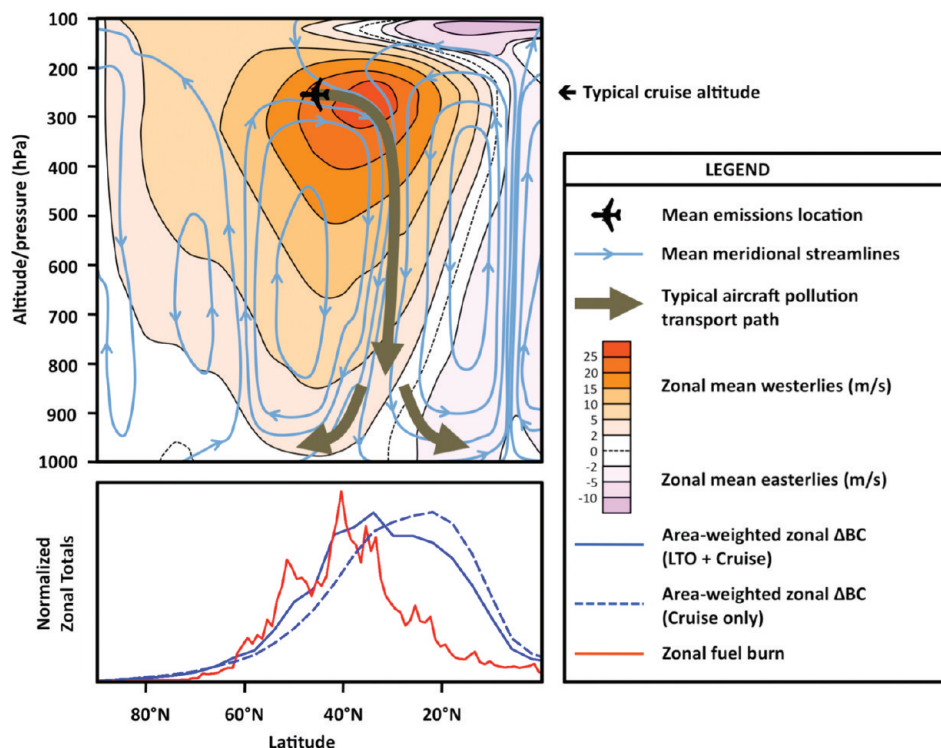
Impacts due to cruise emissions from specific regions were considered. Figure 4 shows the perturbation in surface BC concentrations due to emissions only from Europe (EUR), North America (NA) and South-East Asia (SEA), respectively, which illustrates the impact of strong zonal westerlies at cruise altitudes and meridional transport for EUR and NA emissions. In the case of SEA emissions, which occur in the subtropics

with prevailing easterly winds and upwelling air, the majority of the impacts are to the west. EUR, NA, and SEA emissions account for 34%, 34%, and 29% of global aviation-attributable premature mortalities, respectively, accounting for 97% of the total mortalities. Results differed by less than 1% when regional attribution was calculated by subtracting aircraft emissions from EUR, NA, and SEA with all other aircraft emissions present.

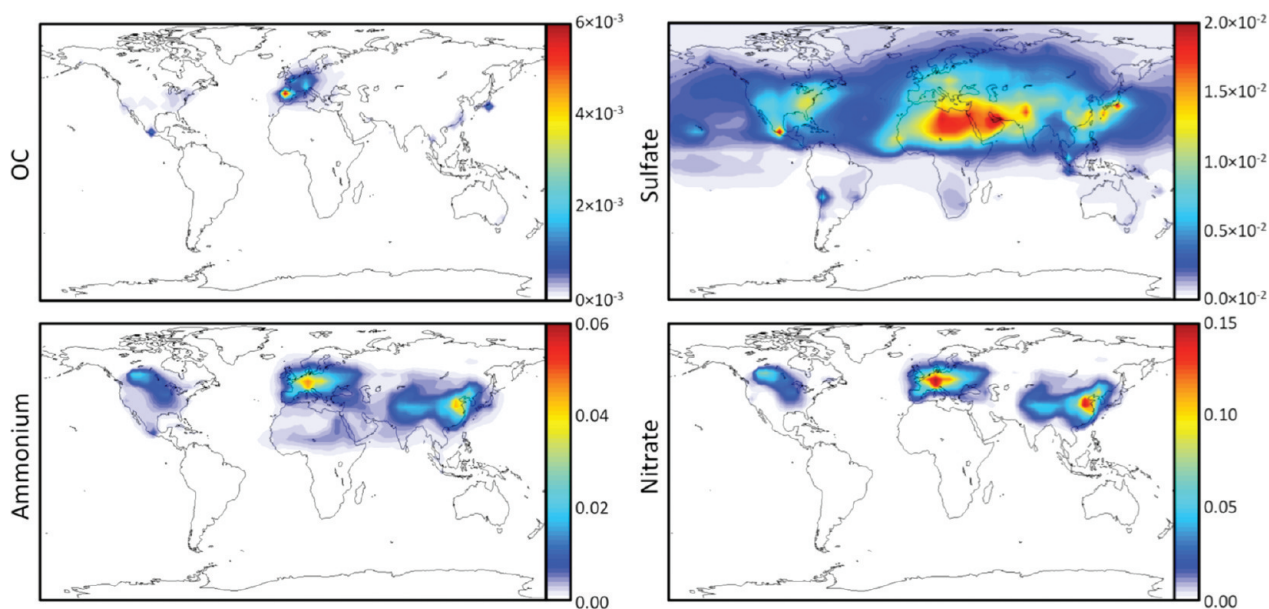
Figure 1 shows a local peak  $\text{PM}_{2.5}$  concentration in China. The global background ammonia concentration as calculated by GEOS-Chem is shown in Figure 5. Peak ammonia concentrations and emissions occur in China (31). The high availability of ammonia in China allows for efficient conversion of aerosol precursors transported from the north and west into secondary aerosol. The country with the second highest available ammonia is India, particularly in the north, where again a peak in aircraft-attributable  $\text{PM}_{2.5}$  is found. These ammonia and  $\text{PM}_{2.5}$  concentration peaks are also correlated with local peaks in population density (29). Vertically integrated aircraft fuel burn over India and China account for 2% and 8% of global fuel burn, respectively, while their combined share of global aviation-attributable premature mortalities is 35%.

The role of aircraft  $\text{NO}_x$  emissions in producing ozone in the upper troposphere and lower stratosphere (UT/LS) has been extensively studied in a climate context (4). We show here that aircraft  $\text{NO}_x$  emissions are not only responsible for increased surface nitrate concentrations, but also for increased sulfate concentrations. This is because aircraft  $\text{NO}_x$  emissions increase the oxidizing capacity of the atmosphere, which increases oxidation of (nonaviation)  $\text{SO}_2$  to sulfate.





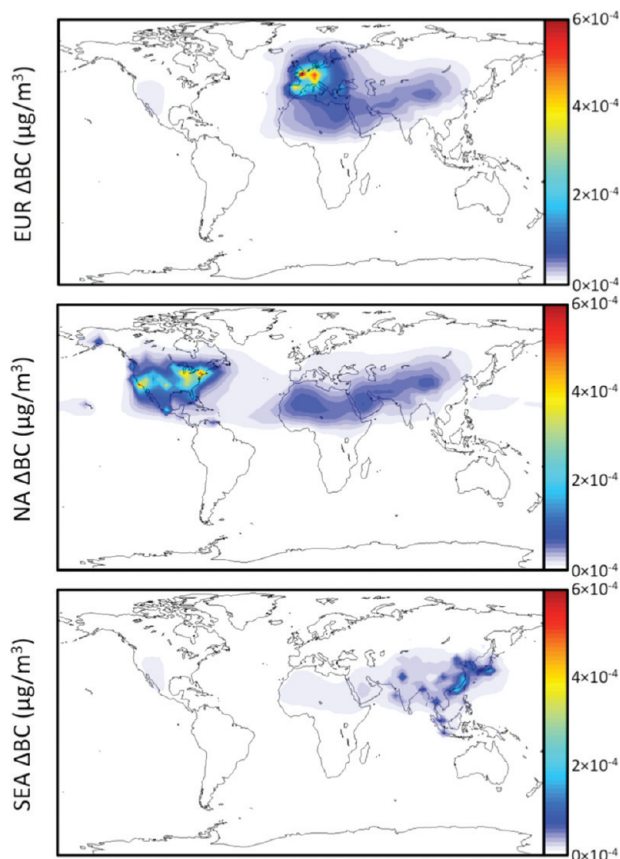
**FIGURE 2.** The upper panel shows mean meridional streamlines in light blue (i.e., contours of constant stream-function). The polar, Ferrel, and Hadley cells can be seen from left-to-right. A significant fraction of aircraft fly in the upper part of the Ferrel cell. Also shown in the upper panel is the mean zonal wind speed. At typical cruise altitudes, the latitudes of peak aircraft emissions are in a region of strong zonal westerlies, allowing for rapid transport of pollutants to the east. The lower panel shows normalized zonal fuel burn, and normalized ground-level area-weighted  $\Delta BC$  attributable to all aviation emissions and cruise-only emissions (the cruise-only zonal fuel burn is approximately equal to LTO + cruise zonal fuel burn).  $\Delta BC$  is weighted by zonal area to be proportional to the total aviation attributable BC mass in the surface layer. There is an overall mean southerly shift of 600 km from emissions to  $\Delta BC$  impact, or 900 km if only cruise emissions are considered. The green arrows indicate the overall transport path for aircraft-attributable aerosol and aerosol precursors, with the ground-level aviation BC perturbation being nearly symmetric about the subtropical ridge.



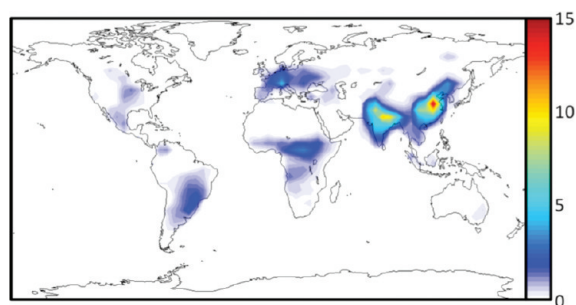
**FIGURE 3.** Speciated ground-level  $PM_{2.5}$  perturbation ( $\mu g/m^3$ ) due to aviation. (The BC perturbation is given in Figure 1.)

Unger et al. described the link between ozone precursor emissions and sulfate concentrations (32). Specifically, increased  $NO_x$  emissions result in increased ozone, which yields increased OH for (predominantly) gas phase oxidation of  $SO_2$  to sulfate. We note that  $NO_x$  emissions in the UT/LS result in greater ozone production than the same emissions at the surface level (4).

In order to investigate the relationship between aircraft  $NO_x$  emissions and surface sulfate loading, GEOS-Chem integrations were performed perturbing aircraft  $NO_x$  emissions by  $\pm 25\%$  and varying aviation fuel sulfur concentrations (which are directly proportional to  $SO_x$  emissions) over 0–800 ppm. Results are given in Figure 6, which shows the change in the average surface sulfate concentration attributable to



**FIGURE 4.** Perturbation in the ground-level BC concentration ( $\mu\text{g}/\text{m}^3$ ) attributable to aircraft emissions from only from EUR ( $25^\circ\text{W}, 38^\circ\text{N} - 30^\circ\text{E}, 70^\circ\text{N}$ ), NA ( $165^\circ\text{W}, 10^\circ\text{N} - 50^\circ\text{W}, 38^\circ\text{N}$ ) and SEA ( $65^\circ\text{E}, 6^\circ\text{S}$  to  $150^\circ\text{E}, 54^\circ\text{N}$ ), respectively.



**FIGURE 5.** The background ground-level  $\text{NH}_3$  concentration ( $\mu\text{g}/\text{m}^3$ ).

aviation as a function of the assumed aviation fuel sulfur concentration. We find that at the nominal assumed level of aircraft  $\text{NO}_x$  emissions and fuel sulfur concentration (600 ppm), more than half of aviation-attributable sulfate at the surface is associated with aircraft  $\text{NO}_x$  emissions and not with aircraft  $\text{SO}_x$  emissions. This can be discerned from Figure 6 by noting that the upper solid line does not intersect the origin when aircraft  $\text{NO}_x$  emissions are included; the vertical offset between the two solid lines in the plot represents the sulfate attributable to aircraft  $\text{NO}_x$  emissions, while the increase to the right is due to increasing fuel sulfur concentration.

The regional distribution of the role of aircraft  $\text{NO}_x$  emissions increasing the oxidation of background (non-aviation)  $\text{SO}_2$  and DMS to sulfate is depicted in Figure 7, where a 0 ppm aviation fuel sulfur concentration has been assumed. (Surface DMS loading decreased by  $\sim 0.01 \mu\text{g}/\text{m}^3$  over the northern Pacific and Atlantic oceans.) It can be seen that the latitude band of increased ozone due to aviation gives rise

to a corresponding increase in sulfate, except that this increase is magnified in regions of high background  $\text{SO}_2$  emissions.

Accounting for parametric uncertainty in emissions, concentration–response functions and estimated modeling uncertainties and biases (discussed in the SI), our expected number of premature mortalities per year due to aviation is 12 600, with a 95% confidence interval of 6000–19 900. We find that the single largest contributor to uncertainty is the concentration–response function, followed by estimated modeling uncertainty. EI  $\text{NO}_x$  is the third most significant contributor, while uncertainty in fuel sulfur to  $\text{S}^{\text{VI}}$  conversion efficiency has a negligible (less than 1%) effect on estimates.

We note additional sources of uncertainty that were addressed with sensitivity simulations or considered qualitatively. Formation of  $\text{H}_2\text{SO}_4\text{--HNO}_3\text{--NH}_3$  aerosols is sensitive to background  $\text{NH}_3$  emissions. Sensitivity simulations perturbing ammonia emissions by +30% and –30% (discussed in the SI) resulted in global mortalities changing by +10% and –15%, respectively, with changes concentrated in regions of highest ammonia emissions. A sensitivity simulation based on a different year (2006) and an updated meteorological data product resulted in aviation-attributable mortalities increasing by 21% relative to the base period (spanning 2001–2002). A further year (2007) with the same updated meteorological product resulted in a relative change in aviation-attributable mortalities of +5%. We also note that under-resolution of LTO impacts by a global atmospheric model (discussed in the SI) may increase the total mortalities attributable to LTO emissions from  $\sim 20\%$  to  $\sim 30\%$  or more.

We have shown that  $\sim 8000$  premature mortalities (or on the order of 60 000 life years lost) per year are attributable to aircraft cruise emissions worldwide. This can be compared with a recent analysis for shipping by Corbett et al., which estimates  $\sim 60\,000$  mortalities per year attributable to that sector (20). The quantity of fuel burned by the two sectors is similar, but the fuel sulfur concentration of marine bunker fuel is an order of magnitude higher (8, 20). Corbett et al. found their premature mortality estimate for California was  $\sim 3$  times higher than a previous analysis by the California Air Resources Board that excluded the effects of ships more than 24 nm from the shoreline, although other differences in modeling may have contributed to this. We note that the methods used in the present study are comparable to those used in the shipping study—both applied GEOS-Chem and the same WHO concentration–response functions (although in a more aggregate form in Corbett et al.). The World Health Organization estimates that globally 0.8 million premature mortalities per year are due to anthropogenic air pollution (26). Our estimates for aviation-attributable mortalities represent less than 1% of this figure.

Liu et al. (33) estimated globally  $\sim 90\,000$  premature deaths are due to intercontinental transport of  $\text{PM}_{2.5}$  and its precursors. While aviation accounts for  $\sim 1\%$  of total air quality-related premature mortalities, it is equivalent to  $\sim 10\%$  of intercontinental impacts. Precise quantitative comparison of aviation’s “efficiency” of exporting pollution relative to other sources on a like-for-like basis requires further work. However, our calculations indicate that some countries are net exporters of aircraft pollution and some are net importers. For example, the United States incurs  $\sim 7$  times fewer mortalities than would be expected based on its aviation fuel burn alone, while India incurs  $\sim 7$  times more mortalities than would be expected by scaling total global aviation mortalities by its fraction of aviation fuel burn (see the SI).

The air quality impacts of aviation are uniquely influenced by mean features of the general circulation, which serve to reduce the correlation between countries responsible for the majority of emissions, and populations exposed to the largest health risk perturbations. A key implication of our results is

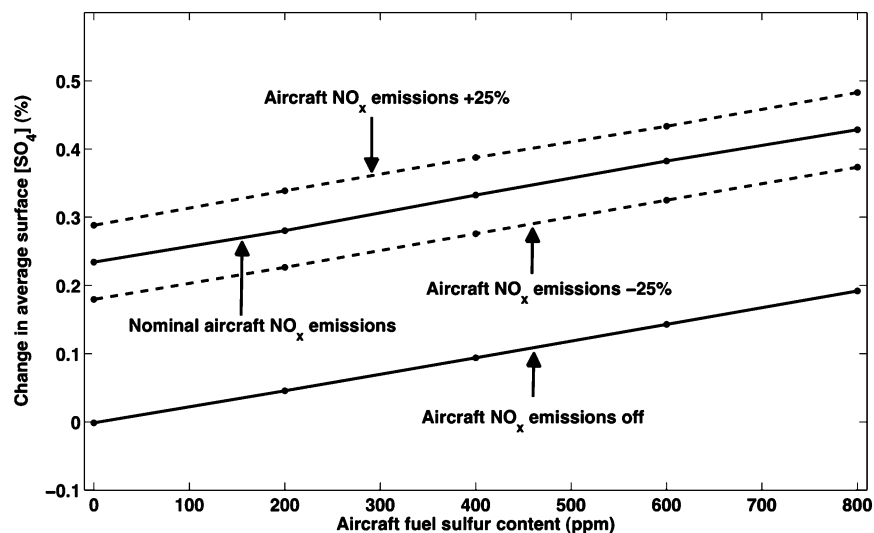


FIGURE 6. Change in average surface sulfate loading as a function of aircraft  $\text{NO}_x$  and  $\text{SO}_x$  emissions.

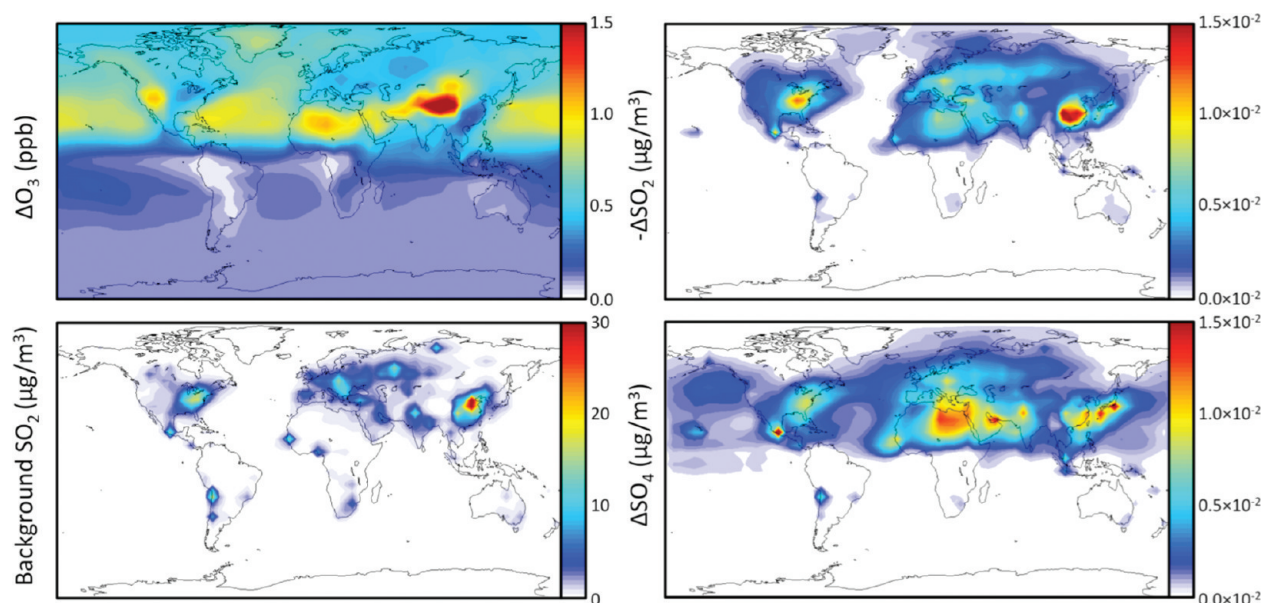


FIGURE 7. Decrease in the ground-level  $\text{SO}_2$  concentration and the increase in the ground-level sulfate and ozone concentrations attributable to aircraft emissions. For these figures, a 0 ppm aviation fuel sulfur concentration has been assumed. The background  $\text{SO}_2$  concentration is also shown. It can be seen that aviation increases surface sulfate loading most where it increases ozone (e.g., over the Pacific Ocean) and/or in regions where the background  $\text{SO}_2$  concentration is high (e.g., on the Eastern Seaboard of the U.S.). We also note that over oceans increased oxidation of DMS occurs.

that future policy analyses of the air quality impacts of aviation should account for cruise emissions. Consideration of the LTO phase in isolation when compiling emissions inventories for air quality purposes may miss the majority of the health-relevant emissions. Because aircraft operational and technological factors that control cruise emissions are different from those that set LTO emissions, it is important that development of new technologies, operational procedures, and policies designed to mitigate environmental impacts of air transportation explicitly address cruise operations. Furthermore, as aviation is estimated to contribute  $55 \text{ mWm}^{-2}$  (3.5%, with an uncertainty range of 1.3–10%) of present-day radiative forcing of the climate (4), the present analysis provides a case for the cobenefits of emissions mitigation in the aviation sector.

### Acknowledgments

UK Research Councils EPSRC and NERC funded this work. The U.S. Federal Aviation Administration and U.S. Depart-

ment of Transportation Volpe Center provided aircraft emissions inventories used in this study.

### Supporting Information Available

Further discussion, analyses and results. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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ES101325R