Appendix 1

Review of the literature on cruise to ground effects of aircraft emissions

A number of studies (see Table A1) have highlighted the effect of full flight (or non-LTO) emissions, including those from high-altitude cruise, on surface air quality ($PM_{2.5}$ and ozone).

Tarrasón et al. (2004)[A1] found in their modelling study that aviation non-LTO emissions (i.e., above 1 km) increased maximum surface ozone over Europe by 0.4 to 0.6 ppbv and ~1% in summer and increased secondary inorganic aerosols by 0.5 to 1%, globally. They concluded that changes in surface nvPM/BC matter were negligible (<0.01%) relative to other emission sources and did not include them explicitly in model calculations.

Barrett et al. (2010)[A2] used the Goddard Earth Observing System (GEOS)-Chem CTM to show cruise-level emissions accounted for ~80% (8,000 deaths/yr) of the premature mortality impact of aviation, primarily as a result of secondary aerosol (sulphate-nitrate-ammonium) formation. The study showed that 99% of this impact was due to increases in secondary aerosol PM (and only 1% from nvPM). The study focussed on the formation of secondary aerosol particles arising from the emissions from aircraft engines at cruise and estimated ground level contributions to PM2.5. The study estimated that NO_x emissions from aircraft contributed to nitrate at ground level and also that the NO_x emissions increased the oxidative potential of the atmosphere increasing the sulphate formation from all sources. The role of background ammonia was found to be significant with peaks in $PM_{2.5}$ of up to 0.15 µg m^{-3} (as an annual average) in some areas of India and China where GEOS-Chem background ammonia concentrations were highest. The high availability of ammonia in China allowed 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 $PM_{2.5}$ is found. The modelled ammonia and $PM_{2.5}$ concentration peaks were also correlated with local peaks in population density creating the largest impact on mortality. The Barrett et al. (2010) paper uses population density and concentration response function (CRF) data to determine excess mortality rates associated with the modelled increase in $PM_{2.5}$ concentration from aircraft emissions. The results are very sensitive to population density statistics with 35% of the global 8,000 excess deaths attributed to India and China.

Lee et al (2013)[A6] used the Community Atmosphere Model with Chemistry (CAM-chem) CTM to model the impacts seasonally as well as spatially. The study found that globally, aviation emissions increased regional surface ozone by up to ~1–2 ppbv in January and 0.5 ppbv in July, with the majority of perturbations coming from cruise emissions. Emissions above landing and take-off altitudes (~1 km) increased $PM_{2.5}$ by ~0.5% (<0.2 µg m^{-3}) over the United States, Europe, and eastern Asia. In summer, the increased $PM_{2.5}$ was mainly sulphate but was not statistically significant. In winter, the additional $PM_{2.5}$ was derived mainly from ammonium nitrate and using a Student t-test (95% confidence) this was statistically significant. However, the authors concluded that this less than 1% enhancement of $PM_{2.5}$ in the boundary layer was too small to be meaningful considering the uncertainty of $PM_{2.5}$ in state-of-the-art models (e.g., uncertainty of $PM_{2.5}$ in CMAQ model is 5 µg m^{-3}). Furthermore, Lee et al. (2013)[A6] carried out an additional sensitivity simulation assuming the doubling of surface ammonia emissions which demonstrated that the aviation induced aerosol increase near the ground is highly dependent on background ammonia concentrations whose current range of uncertainty is large. Lee et al. (2013)[A6] reported results that were similar in scale and location to that of Barrett et al. (2010)[A2] and similar observations were made, such as that it is the amount of NO_x emissions from aircraft that determine the $PM_{2.5}$ perturbation at the ground rather than directly emitted aerosols from aircraft. However, in contrast to Barrett et al. (2010),[A2] Lee et al. (2013)[A6] concluded that the "*overall impact of aviation emissions on surface* $PM_{2.5}$ *is extremely small so that mortality cannot be determined from small signal with any certainty*". Lee et al. (2013)[A6] also modelled the contribution of aircraft (non-LTO and LTO) emissions to ground level ozone concentrations. They estimate a contribution of several ppb in January and 0.5 ppb in July. These results are for the short-term O_3, which overestimate the aircraft impacts since they do not account for the longer-term O_3 reduction tied to the aviation induced methane decrease that are not represented in this study. Both the total and non-LTO aircraft emissions increase boundary layer O_3 about three times more in January than in July. The largest O_3 increases in January are shown in the Eastern US (more than 2 ppb), East Asia (1.1 ppb) and Europe (1 ppb). However, considering the low background O_3 concentration in winter relative to the EPA guideline (75 ppbv as daily 8 hours maximum average concentration), Lee et al. (2013)[A6] considered that these perturbations were not important for local air quality.

Yim et al. (2015)[A7] combined global (GEOS-Chem), and regional CTM (CMAQ) : GEOS-Chem global run at 4° × 5° resolution and CMAQ with three nested regional grids: 36 km, 40.5 and 50 km resolution for US, Europe and Asia. Global average contributions of $PM_{2.5}$ and O_3 were 0.0062 µg m^{-3} and 0.6 ppbv respectively. Two peaks of PM2.5 in Northern India (0.47 µg m^{-3}) and north eastern China (0.35 µg m^{-3}), coincident with peaks in ammonia concentrations. An estimate of 16,000 excess deaths due to aviation-attributable $PM_{2.5}$ and ozone were predicted by Yim et al. (2015):[A7] 87% of these deaths from PM2.5; and with 75% attributed to non-LTO emissions. Again, the role of background ammonia led to modelled peak $PM_{2.5}$ concentrations in India and China, where population densities are greatest, similar to Barrett et al. (2010),[A2] creating a peak in predicted excess deaths. Other peaks of $PM_{2.5}$ concentration were seen close to major airports in the US where the use of regional and local dispersion modelling created finer resolution and captured of the more localized impacts of emissions, in particular LTO emissions.

Vennam et al. (2017)[A8] used the CMAQ (v5CTM and the AERO6 model to estimate the impacts of full-flight aircraft emissions on air quality, looking specifically at the sensitivity to grid resolution. The study computed seasonal aviation-attributable mass flux vertical profiles and aviation perturbations along isentropic surfaces to quantify the transport of cruise altitude emissions at the hemispheric scale. The comparison of coarse (108 × 108 km^2) and fine (36 × 36 km^2) grid resolutions in North America showed ~70 times and ~13 times higher aviation impacts for O_3 and PM2.5 in coarser domain. These differences are mainly due to the inability of the coarse resolution simulation to capture nonlinearities in chemical processes near airport locations and other urban areas.

Grobler et al. (2019)[A9] used the GEOS-Chem model as in Barrett et al. (2010)[A2] to estimate changes in air quality from LTO and non-LTO emissions but do not report changes in concentration in the paper directly. In Grobler et al. (2019)[A9] they quantify air quality impacts attributable to a marginal increase in existing emissions directly in terms of the costs of premature mortalities resulting from population exposure to fine particulate matter ($PM_{2.5}$) and tropospheric ozone using a similar approach to Barrett et al. (2010).[A2] Similar to Barrett et al. (2010),[A2] the main mortality impact is driven by increased $PM_{2.5}$ concentration from secondary aerosol particles, the increase in sulphate largely driven by the NO_x aviation emissions at cruise creating a greater oxidative potential in the atmosphere through the NO_x/O_3 photochemistry.

Jacobson et al. (2013),[A4] using a CRM (GATOR-GCMOM), found global 2006 aircraft increased surface ozone by ~0.4% (~0.05 ppbv) and surface $PM_{2.5}$ by ~0.083 µg m^{-3} as a global average. All-altitude aircraft emissions were further estimated to increase human mortality worldwide by ~620 premature deaths/year, with half due to ozone and the rest to PM2.5. The global average increase in $PM_{2.5}$ and O_3 concentrations at ground level are higher than those predicted by the CTM studies such as Barrett et al. (2010)[A2] and Yim et al. (2015).[A7] However, the estimation of excess mortalities by Jacobson et al. (2013) derived by combining current mixing ratios or concentrations predicted by the model each time step in each model grid cell with population data for each cell with relative risks was an order of magnitude lower.

Morita et al. (2014),[A10] using the NASA Goddard Institute for Space Studies (GISS) ModelE2 chemistry-climate model (here, run as a CTM), found that 2006 aviation emissions resulted in a 0.003 µg m^{-3} global increase in surface $PM_{2.5}$ (maxima in small areas of Europe, US and China with increase of >0.06 µg m^{-3} as an annual average), corresponding to 405 premature mortalities per year.

A multi-model comparison by Cameron et al. (2017),[A5] used global atmospheric computer models with standardized emission inputs, to estimate the effects of global aircraft emissions on surface air quality by tracking changes in ozone and small particles ($PM_{2.5}$). The study showed that from the CTM results aircraft all altitude emissions increase annual average near-surface ozone to a maximum of 2 ppbv with global annual averages of 0.5 ppbv or less (0.3 to 1.9% globally of background ozone which is ~12 to 32 ppbv), with qualitatively similar spatial distributions, limited mainly to the Northern Hemisphere. The absolute increase in annual average ozone concentrations varies seasonally, with higher contributions during the winter. In winter months, ambient ozone is ~5 ppbv lower than in summer months, indicating that globally, the monthly surface ozone perturbations (less than 2 ppbv) fall within the seasonal variation of the CTMs' background fields. However, Cameron et al. (2017)[A5] noted that averages, while useful for inter-model comparisons, smooth daily and regional variations that affect air quality. Annual changes in surface-level $PM_{2.5}$ of between 0.14 to 0.4% globally were shown due to secondary aerosol formation using Chemical Transport Models (CTMs). The GEOS_Chem model showed the highest contribution to global average concentration of $PM_{2.5}$ of 0.007 µg m^{-3} with maximum increases in annual average surface $PM_{2.5}$ of up to 0.15 µg m^{-3} primarily over high-traffic regions in the North American and European midlatitudes with a third peak in China. For the ModelE2 CTM a global average contribution to PM2.5 of 0.0062 µg m^{-3} was estimated with lower peak concentrations shown mainly in Europe and in western China. The third CTM (CAM5) estimated a global average contribution to $PM_{2.5}$ of 0.0034 µg m^{-3} was estimated with lower peak concentrations shown mainly in North America and Europe and both negative and positive contributions in Asia including China. The Cameron study did not compare estimates of mortalities

that are reported in a number of these studies (e.g., Barrett et al. 2010; Yim et al., 2015).[A2, A7] However, the difference in the locations of the peak concentrations at ground level from aircraft emissions estimated by the 3 CTMs in this study would likely coincide with very different population densities producing very different outcomes in terms of mortality predictions from each other.

Quadros et al. (2020)[A11] looked at the Regional Sensitivities of Air Quality and Human Health Impacts to Aviation Emissions by increasing emissions in each area in turn (North America, Europe and Asia) and calculating the increase in excess deaths arising both from an increased contribution of ozone and $PM_{2.5}$. They found that most of the increase in premature mortalities from additional aviation emissions from any of the three regions happens in Asia, both due to ozone and $PM_{2.5}$. The fact that Asia receives the largest share of health impacts despite not necessarily being the most affected region in terms of air quality from aviation emissions over other regions is due to a larger population count, which leads to higher total population exposure. Quadros et al. (2020)[A11] estimated a total of 20,300 premature deaths per annum due to $PM_{2.5}$ and 38,300 due to ozone for 2013. Quadros et al. (2020) [A11] noted that the estimated excess mortalities in their study compared to others are sensitive to the CRF values used. For comparison, the number of yearly aviation-attributable premature deaths just from $PM_{2.5}$ was estimated by Yim et al. (2015)[A7] as 13,900, considering the CRF of cardiopulmonary diseases and lung cancer from Ostro (2004)[A12]. Eastham and Barrett (2016)[A13] estimated a 9,200 increase in cardiovascular mortality due to $PM_{2.5}$ using a CRF from Hoek et al. (2013).[A14] Applying the same CRFs to the Quadros et al. (2020) [A11] study results in 9,500 (Ostro 2004)[A12] and 13,800 Hoek et al. (2013)[A14] premature deaths from $PM_{2.5}$. For ozone, using a more conservative CRF (Jerrett et al. 2009)[A15] would estimate 12,800 premature deaths, and further restricting the mortality endpoints to just chronic obstructive pulmonary disease and asthma (excluding respiratory infections) would lead to 8,400 deaths, compared to the 6,800 deaths estimated by Eastham and Barrett (2016)[A13] using this CRF.

Some further discussion on health impacts:

As noted above, some of these studies estimate excess mortalities from the modelled air quality impacts. The estimated excess mortalities predicted in these studies are sensitive to the CRF values used and the population densities. The overall excess deaths reported in these studies vary widely: 58,600 (around 20,300 from PM2.5 and 38,300 from ozone) in Quadros et al. (2020)[A11]; 16,000 (around 14,000 from $PM_{2.5}$ and 2,000 ozone) in Yim et al. (2015);[A7] 620 (half and half O_3/PM2.5) in Jacobson et al. (2013);[A4] and 405 (PM2.5) in Morita et al. (2014).[A10]

The outcomes are particularly sensitive to where the peak contributions are predicted and if they coincide with high population densities, small shifts in spatial distribution can potentially lead to large differences in outcomes. The spatial distribution of the modelled contributions is sensitive to the transport regimes in the models but also the background concentrations of pollutants such as ammonia. The population statistics clearly have high values in some areas of the world such that a very small increase in risk multiplied by a high population can create excess mortalities in the thousands, accounting for some of the large differences seen in the mortality rates reported. The different CRFs applied also create significant outcomes: Quadros et al. (2020)[A11] applied 3 different CRFs to their modelled ground level $PM_{2.5}$ contributions giving the following number of excess deaths as follows: 20,300 using the Burnett et al. (2018)[A16] CRF; 9,500 using the Ostro (2004)[A12] CRF and 13,800 using the Hoek et al. CRF (2013).[A14]

Furthermore, the CRF for $PM_{2.5}$ are generally based on epidemiological evidence using ambient measurements of $PM_{2.5}$. Thus, the $PM_{2.5}$ CRF do not differentiate between the types of $PM_{2.5}$, either the size or the chemical composition, and there is no lower threshold. The estimated excess deaths rely on the assumption that all particulate matter is equally harmful to health and that there is no threshold of concentration below which there is no effect.

High levels of $PM_{2.5}$ for some locations, as in the Six-City study,[A17] are evidence of proximity to industry or power plants. That there are health impacts from industrial pollution is no surprise, nor is it surprising that the rise in morbidity and mortality should increase with the level of pollution; the correlation between measured health outcomes and concentration of some $PM_{2.5}$ is plausible. It is plausible that the health effects appeared to be proportional to some of the concentrations, since the concentration was a measure of the closeness of the pollution source, or the quantity of pollution emitted. What is certainly not clear, however, is that the species being measured and correlated are the cause of the disease and some correlated species may be benign in the concentrations considered. In studies such as the Six-City study it now likely that the harmful substances are ultrafine particles which were not measured or for which data was not presented. However, the concentration of ultrafine particles is likely to be correlated with substance that were measured at $PM_{2.5}$. These ultrafine particles may be carbon which has a coating of toxic organics, such as polycyclic aromatic compounds and another potential hazard is metals. It is then quite misleading to conclude from a study like the Six-City study that *any*

particle, regardless of size or chemical composition, is harmful. Moreover, it is erroneous to assume that a proportionality between concentration of a substance at $PM_{2.5}$ and health impacts as in, for example, the Six-City study, can be applied to other circumstances.

Toxicological evidence suggested that the size of particles is important and that ultrafine particles (<100 nm) and their chemical composition/coating are more significant to human health.[A18-20] $PM_{2.5}$ mass concentration measurements do not reflect the contribution of these small (generally combustion generated) particles well which would be better represented by particle number measurements. Combustion particles are generally small, and modern aircraft gas turbine generated nvPM are at the lower range (around 50 nm or less). These tend not to be picked up by the mass based $PM_{2.5}$ type measurements. It is worth noting that the impact of non-LTO nvPM emissions are estimated to be low in all these studies using $PM_{2.5}$ as the metric.

Overall, the World Bank estimates[A21] that in 2019 there were 4 million excess deaths from air pollution assess on the basis of ambient $PM_{2.5}$ and a further 2.45 million from household $PM_{2.5}$. Therefore, for context, an estimate of 10,000 excess deaths from aviation-attributable emissions would represent approximately 0.16% of total excess deaths from ambient $PM_{2.5}$.

A summary of the findings from this literature are as follows:

Results from these studies are qualitatively similar in showing a marginal increase in global $PM_{2.5}$ concentration at ground level from aviation emissions (LTO and non-LTO) with similar general geographical distributions.

These studies also show that the contribution to ground level aerosol $PM_{2.5}$ from aviation emissions are largely due to non-LTO emissions.

The increase in $PM_{2.5}$ concentrations were almost all from secondary aerosol contributions (sulphate-ammonium-nitrate) with only very small, or negligible, contributions from direct aviation soot or black carbon emissions (nvPM). The relative contribution from sulphate-nitrate-ammonia varied between studies.

The range in absolute increases in $PM_{2.5}$ from aviation emissions varied by orders of magnitude in the different studies.

The additional aerosol particles ($PM_{2.5}$) at ground level from full flight aviation emissions are generally modelled through a complex set of atmospheric interactions and chemical reactions at the global scale, with some at the regional and local scale. The results are sensitive to the grid resolution used, with coarser grid resolution for the global/regional models producing higher estimates in general. Contributions from LTO emissions are higher near airports when local quality impacts are modelled using finer resolution dispersion models at these locations.

The resolution of the modelling regime is an important factor: coarser grid resolution in some of the global model studies can overestimate the contribution to ground level concentrations of $PM_{2.5}$.

Emissions of SO_x are oxidised to sulphate and NO_x emitted directly emitted from aircraft go on to form some nitrate, although sulphate dominates the aerosol component. A number of the studies also observe that the NO_x emissions are involved in photochemical reactions generating long-lived ozone which tends to increase the oxidative potential of the atmosphere allowing more sulphur (from all sources including aviation) to form sulphate and contribute to the overall $PM_{2.5}$ concentration.

The modelled interactions include aircraft-attributable HNO_3 and H_2SO_4, from NO_x and SO_x, respectively, and background NH_3 where abundant background NH_3 increases the formation of nitrate by increasing the oxidation rates.[A23]

A number of further studies, designed to estimate the impacts of sulphur levels in fuel have also estimated impacts of non-LTO emissions on ground level $PM_{2.5}$ concentrations and that ground level contributions to $PM_{2.5}$ were found to be the result of cruise-altitude NO_x, even when a zero-sulphur jet fuel is used in the modelling an increase in sulphate and nitrate $PM_{2.5}$ concentration is observed.

Where CTM studies also considered the impact of aviation emissions on ground level ozone, the impact was shown only in the northern hemisphere and the CTMs did not generally include the longer-term O_3 reduction tied to the aviation induced methane decrease.

Studies that provided the seasonal variation of ozone contributions from aviation, showed that contributions to ground level ozone from aircraft non-LTO emissions were highest in the winter months, when ambient levels of ozone are at their lowest.

Where studies used Concentration Response Functions (CRF) to estimate excess mortality from $PM_{2.5}$ and ozone, there was considerable variation in the number of excess deaths reported and also in the relative importance of each pollutant: Lim et al. (2013)[A7] showed that 85% of 16,000 excess deaths was attributed to $PM_{2.5}$; Morita et al. (2014)[A10] showed a 50/50 split for the approximately 400 excess deaths; and Quadros et al. (2020)[A11] showed that increases in aviation emissions would cause more excess deaths from ozone than $PM_{2.5}$.

The studies clearly show some similar qualitative contributions from non-LTO emissions to ground level $PM_{2.5}$ and ozone but there are differences in the scale of estimated absolute perturbations of $PM_{2.5}$ and O_3 and perhaps more importantly, there are differences in terms of the significance associated with these modelled perturbations. A number of the studies[A2, A4, A22, A10, A7] use the modelled additional concentrations to combine with population density and Concentration Response Functions (CRF) to predict additional mortality rates associated with these aircraft emission perturbations. Whereas other researchers[A6] considered that the marginal increases in $PM_{2.5}$ (and ozone) were not sufficiently substantial (<1% of background) to be meaningful, considering the uncertainty in state-of-the-art models.

Appendix A1 references and notes

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Table A.1 Concentrations at ground level due to aircraft emissions (all altitudes) from selected studies (from global models)

Study	Model & resolution	PM$_{2.5}$ µg m^{-3} or as %	Ozone ppbv or %	Excess Deaths per year	Notes
Tarrason et al., 2004[A1]	Review of CTMs	Secondary Inorganic Aerosols: 0.5–1% global increase from non-LTO	O$_3$ summer max daily 0.4–0.6 ppbv (about 1%) global increase from non-LTO	n/a	Surface ozone simulated by global CTMs can vary by ±50% between the models and is below 2 ppbv O$_3$ summer max daily 0.4–0.6 ppbv (about 1%) global increase from non-LTO SIA: 0.5–1% global increase from non-LTO
Barrett et al. (2010)[A2]	GEOS-Chem at 4° × 5°	Peak increases 0.15 µg m^{-3}, LTO+cruise Peak increases 0.03 µg m^{-3}, LTO (BC only 6 x 10^{-4} µg m^{-3}, LTO+cruise)	not reported	8000	Estimates of premature ~8,000, mortality, 80% attributable to non-LTO. Fig 1 indicates peak D concentrations of 0.15 mg m^{-3}, LTO+cruise PM2.5, and 0.03 mg m^{-3} LTO only. Fig 1 indicates peak Δ concentrations of only 6 x 10^{-4} µg m^{-3}, LTO+cruise BC.
Barrett et al. (2012)[A24]	GEOS-Chem at 4° × 5° (nested 0.5° × 0.667° within US) CMAQ (36 km × 36 km in US) p-TOMCAT	Maximum concentration magnitudes for base case conventional jet fuel (in SI fig S1) Max in Europe/China about 0.8 µg m^{-3} Mean ground-level aviation-attributable PM2.5 concentrations (SI pg17): nested GEOS-Chem (0.083 µg m^{-3}) GEOS-Chem (0.077 µg m^{-3}) CMAQ (0.068 µg m^{-3})	not reported		-9.6 × 10^{-4} µg m^{-3}–global average -4.0 to -6.0 × 10^{-3} µg m^{-3}–West US; -3.0 to -4.0 × 10^{-3} µg m^{-3}–East US -8.0 to -10.0 × 10^{-3} µg m^{-3}–North Africa, Middle East -2.0 to -3.0 × 10^{-3} µg m^{-3}–Europe

Yim et al. (2013)[A7]	GEOS-Chem CMAQ Aermod	The max annual average ground level PM2.5 concentration ($\mu g\ m^{-3}$): (a) total PM2.5: 0.114 $\mu g\ m^{-3}$; (b) BC only: 0.08 $\mu g\ m^{-3}$ and (c) nitrate only 0.008 $\mu g\ m^{-3}$.	not modelled	110	simulate European air quality at a resolution of 40.5 km, with two nested domains to simulate UK and SGB air quality at a resolution of 13.5 and 4.5 km, respectively. GEOS-Chem is applied for 2005 to provide boundary conditions to the CMAQ outermost domain. AERMOD and RDC to capture sub-grid variability. From Fig 3: BC and nitrate account for 30% and 29% of UK-wide aviation emissions-attributable PM2.5 exposure, respectively, resulting in the highest contributions compared to those of other PM species (OC: 16%; sulphate: 12%; ammonium: 13%).
Jacobson et al. (2013)[A4]	GATOR-GCMOM 4 × 5° grid (approx. 450 km × 550 km)	Annual Global Average 0.083	surface and upper tropospheric ozone by ~0.4% and ~2.5%	620 (half and half O_3/PM2.5)	Increased PM2.5 by ~83 $ng\ m^{-3}$ (0.08 $\mu g\ m^{-3}$) increased human mortality globally by ~620 (-240 to 4,770) deaths per year, with half due to O_3 and the rest to PM2.5
Lee et al. (2013)[A6]	CAM-Chem 2 × 2° grid	Average increase over Europe/China/US: <0.2 0.5%	Several ppb in January and 0.5 ppb in July Largest O_3 increases in January are shown in the Eastern US (more than 2 ppb), East Asia (1.1 ppb) and Europe (1 ppb).	too small compared to background to calculate mortalities	Cruise emissions responsible for an increase of ground PM2.5 by ~0.5% (<0.2 $\mu g\ m^{-3}$) over the United States, Europe, and eastern Asia. Emissions near cruise altitudes (9–11 km in altitude) rather than emissions during landing and take-off are responsible for most of the near ground perturbations. However, considering the low background O3 concentration in winter relative to the EPA guideline (75 ppbv as daily 8 hours maximum average concentration), these perturbations are not important for local air quality.
Morita et al. (2014)[A10]	NASA-GISS ModelE2 2 × 2.5° grid	Average: 0.003 Max values in small areas of US, China and Europe >0.06		central estimate for 2006: 405	0.003 $\mu g\ m^{-3}$ global increase in surface PM2.5 (max of > 0.06 $\mu g\ m^{-3}$ in small areas of NA, China, and Europe in plot in SI) for 2006 Aviation PM2.5 global average concentration increases to 0.018 $\mu g\ m^{-3}$ by 2050 under the ref scenario, the Tech & Op and Alt Fuel scenarios yield 0.008 $\mu g\ m^{-3}$ and 0.006 $\mu g\ m^{-3}$, respectively

Yim et al. (2015)[A7]	GEOS-Chem and CMAQ GEOS-Chem global run at 4° × 5° resolution CMAQ three nested regional grids: 36 km, 40.5 and 50 km resolution for US, Europe and Asia	Global average: 0.0062 US/Europe/Asia/other: 0.009/0.018/0.015/0.004 Two peaks of PM2.5 in Northern India (0.47 µg m^{-3}) and North-eastern China (0.35 µg m^{-3}), coincident with peaks in ammonia concentrations	Global average: 0.6 US/Europe/Asia/other: 1.1/1.0/0.9/0.5	16,000 (2100 O3 & 13900 PM2.5) PM2.5 exposure causes 87% of early deaths	increase in ground level PM2.5: 6.2 ng m^{-3} - Global, 9.0 ng m^{-3} - North America Aviation emissions result in ~16 000 early deaths each year, PM2.5 and cruise emissions cause 87% and 75% of early deaths, respectively 3.8 ng m^{-3} - Other 15.1 ng m^{-3} - Asia, 18.2 ng m^{-3} - Europe
Kapadia et al. (2016)[A22]	TOMCAT CTM with GLOMAP-mode 2.8° × 2.8° horizontal grid	Global average 0.0039 Global average (ULSF) -35.7%		3600 2580	FSC of 600 ppm result in increase of global mean surface PM2.5 concentrations by 3.9 ng m^{-3} (0.0039µg m^{-3}) and ~ 3600 (95 % CI: 1310–5890) annual premature mortalities globally; ULSF (FSC=15ppm) reduces global annual mean surface aviation-induced PM2.5 concentrations by 35.7 % and the global aviation-induced mortality rate by ~620 (95 % CI: 230–1020) mortalities per annum
Eastham and Barrett (2016)[A13]	adjoint of the GEOS-Chem chemistry-transport	not reported	ozone impacts both increases (in ground level) leading to respiratory illness and from decreases in stratospheric ozone leading to skin cancer	Respiratory (LAQ): 6,800	
Cameron et al. (2017)[A5]	5 global models; 3 CTMs NASA-GISS, fixed (CTM) CAM5 fixed (CTM) GEOS-Chem (CTM)	Annual average (monthly min/max) (fig4 0.0062 (0.004–0.008) 0.42% (0.15 µg m^{-3}) 0.0034 (0.0014–0.007) 0.21% (0.09) 0.0070 (0.0018–0.014) 0.14% (0.15 µg m^{-3})	Annual average (monthly min/max): 0.17 (0.13–0.22) 0.53% 0.48 (0.32–0.67) 1.80% 0.43 (0.27–0.65) 1.63%	n/a	Of the 3 CTMS the GEOS-Chem showed greatest areas of +0.15

Vennam et al. (2017)[A8]	CTMs CMAQv5.0.2 model and AERO6 aerosol module 180 km × 180 km grid with sensitivity case of a finer 36 km × 36 km grid	Northern Hemisphere 0.2% (mean, min-max: 0.013, 0.004–0.02 µg m^{-3}) PM2.5 0.013 µg m^{-3}–Northern Hemisphere 0.021 µg m^{-3}–North America 0.031 µg m^{-3}–Europe 0.021 µg m^{-3}–East Asia	Northern Hemisphere 1.3% (mean, min–max: 0.46, 0.3–0.5 ppbv)	n/a	The comparison of coarse (108 × 108 km^2), and fine (36 × 36 km^2) grid resolutions in NA showed ~70 times and ~13 times higher aviation impacts for O_3 and PM2.5 in coarser domain. These differences are mainly due to the inability of the coarse resolution simulation to capture nonlinearities in chemical processes near airport locations and other urban areas.
Grobler et al. (2019)[A9]	GEOS-Chem	not reported	not reported	Social costs are calculated but no details on concentrations or even premature/excess mortalities	No values of concentrations are provided but the method is the same as the Barrett et al. 2010 paper[A2] and includes many of the same authors They state that 94% of air quality impacts (which are 64% of total impacts including climate) are driven by NO$_x$.

Quadros et al. (2020)[A11]	GEOS-Chem global run at 4° × 5° resolution three nested regional grids at 0.5° × 0.625° resolution	Not clear	Not clear	Total of 20,300 (95% CI: 9,800– 40,300) premature deaths due to PM2.5 and 38,300 (21,600–57,800) due to ozone.	While total health impacts are driven largely by population densities, the air quality impacts of emissions are also driven by atmospheric conditions. Higher PM2.5 sensitivities are associated with ammonia availability (GR) and ozone sensitivity to LTO emissions is associated with the formaldehyde to NO$_y$ ratio. The same amount of emissions leads to higher PM2.5 and ozone increases, and ultimately cause an average of 45–50% more health impacts if it is emitted over Europe instead of North America or Asia. Both these numbers are highly sensitive to the choice of CRF used: Applying different CRFs to this study results in 9,500 (Ostro, 2004)[A12] and 13,800 Hoek et al. (2013)[A14] premature deaths from PM2.5. Using a more conservative CRF for ozone (Jerrett et al., 2009)[A15] yields 12,800 premature deaths, and further restricting the mortality endpoints to just chronic obstructive pulmonary disease and asthma (excluding respiratory infections) would lead to 8,400 deaths, compared to the 6,800 deaths estimated by Eastham and Barrett (2016)[A13] using this CRF.