Marginal Climate and Air Quality Costs of Aviation Emissions

Supplementary Information

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SI.1. Methods

SI.1.1. Emissions Data for the year 2015

Emissions for a full year of aviation operations in the year 2015 in the full flight, Landing and Take Off (LTO), and cruise flight phases are listed in Table SI.1, Table SI.2 and Table SI.3 respectively. In all three tables global, as well as, regional emissions totals are presented.

Fuel burn, nitrogen oxides (NOₓ), hydrocarbons (HC), carbon monoxide (CO), black carbon (BC), and organic carbon (OC), and non-methane volatile organic compounds (NMVOC) emissions are derived using U.S. Federal Aviation Administration (FAA)’s Aviation Environmental Design Tool (AEDT) (Wilkerson et al 2010). Sulfur emissions are based on an assumed fuel sulfur content of 600 ppm by mass, while carbon dioxide (CO₂) and water vapor (H₂O) emissions are based on emissions indices of EI_{CO₂} = 3.155 kg/kg and EI_{H₂O} = 1.233 kg/kg respectively, consistent with the ACCRI phase two report (Brasseur et al 2016).

Table SI.1: Full Flight AEDT Emissions

|                           | Global | USA      | North America | Europe | Southeast Asia |
|---------------------------|--------|----------|---------------|--------|----------------|
| Fuel-Burn (Tg Fuel)       | 240    | 40.1     | 66.2          | 49.9   | 63.9           |
| NOₓ (Tg NOₓ as NO₂)      | 3.60   | 0.559    | 0.890         | 0.751  | 0.990          |
| NMVOC (Gg NMVOC)          | 37.6   | 10.35    | 14.39         | 8.47   | 7.84           |
| CO (Gg CO)                | 595    | 134      | 190           | 135    | 147            |
| BC (Gg BC)                | 8.68   | 1.47     | 2.32          | 1.81   | 2.31           |
| OC (Gg OC)                | 3.44   | 0.567    | 0.905         | 0.720  | 0.902          |
| SOₓ (Gg S)                | 144    | 24.1     | 39.7          | 29.9   | 38.3           |
| CO₂ (Tg CO₂)              | 757    | 127      | 209           | 157    | 202            |
| H₂O (Tg H₂O)              | 296    | 49.4     | 81.6          | 61.5   | 78.8           |

Table SI.2: Landing and Take-off AEDT Emissions

|                           | Global | USA      | North America | Europe | Southeast Asia |
|---------------------------|--------|----------|---------------|--------|----------------|
| Fuel-Burn (Tg Fuel)       | 20.3   | 4.53     | 6.10          | 4.95   | 5.99           |
| NOₓ (Tg NOₓ as NO₂)      | 0.308  | 0.0650   | 0.0849        | 0.0783 | 0.0932         |
| NMVOC (Gg NMVOC)          | 11.9   | 4.01     | 5.37          | 2.68   | 2.22           |
| CO (Gg CO)                | 166    | 42.2     | 56.5          | 40.0   | 42.3           |
| BC (Gg BC)                | 1.00   | 0.228    | 0.318         | 0.233  | 0.281          |
| OC (Gg OC)                | 0.147  | 0.0336   | 0.0485        | 0.0445 | 0.0329         |
| SOₓ (Gg S)                | 12.2   | 2.72     | 3.66          | 2.97   | 3.59           |
| CO₂ (Tg CO₂)              | 64.0   | 14.3     | 19.2          | 15.6   | 18.9           |
| H₂O (Tg H₂O)              | 25.0   | 5.59     | 7.52          | 6.10   | 7.39           |
|                        | Global | USA    | North America | Europe | Southeast Asia |
|------------------------|--------|--------|---------------|--------|----------------|
| Fuel-Burn (Tg Fuel)    | 220    | 35.6   | 60.1          | 45.0   | 57.9           |
| NOx (Tg NOx as NO2)    | 3.29   | 0.494  | 0.805         | 0.673  | 0.897          |
| NMVOC (Gg NMVOC)       | 25.8   | 6.34   | 9.03          | 5.78   | 5.62           |
| CO (Gg CO)             | 429    | 91     | 134           | 95     | 104            |
| BC (Gg BC)             | 7.68   | 1.24   | 2.00          | 1.58   | 2.03           |
| OC (Gg OC)             | 3.29   | 0.534  | 0.856         | 0.675  | 0.869          |
| SOx (Gg S)             | 132    | 21.4   | 36.1          | 27.0   | 34.7           |
| CO2 (Tg CO2)           | 694    | 112    | 190           | 142    | 183            |
| H2O (Tg H2O)           | 271    | 43.9   | 74.1          | 55.5   | 71.4           |

### SI.1.2. Climate Modeling: APMT-Impacts Climate

To compute the climate impact, the reduced order climate model, Aviation environmental Portfolio Management Tool - Impacts Climate (APMT-IC) V24b is applied. APMT-IC is a reduced order climate modeling tool, specifically developed for policy analysis in a cost benefit framework. APMT-IC captures both the physical and socio-economic impacts of aviation on global climate change, as well as the associated uncertainties.

This section presents an overview of the methods and assumptions used in APMT-IC V24b. For a historical perspective, prior literature can be consulted, including the earliest documented version of APMT-IC (V1) (Marais et al 2008) as well as later versions by Mahashabde (2009) (V14), Wolfe (2012) (V21) and Wolfe (2015) (V23).

The APMT-IC model has been developed as a Simple Climate Model (SCM) capable of estimating the impact of aircraft emissions on the climate and quantifying the uncertainties associated with these impacts. Aviation’s impacts are estimated in terms of Radiative Forcing (RF), which is a measure of changes in the global energy budget, changes in global average surface temperatures, and by monetizing the impacts due to health, welfare, and ecological costs associated with these temperature changes. The monetary impacts are estimated using damage functions on a year-by-year basis before the overall long-term monetized impact is computed using the Net Present Value (NPV) concept. An overview of the code architecture and the primary input assumptions used are shown in Figure SI.1. The modeling approach is presented in the following sections. Where parts of the current version of APMT-IC has remained unchanged from previous versions, the model description closely follows that of prior descriptions.
The modeling outline in the following sections follows the same structure as presented in Figure SI.1. Section SI.1.2.1 describes the input files, Section SI.1.2.2 and SI.1.2.3 describe the CO\textsubscript{2} and short-lived climate forcer radiative forcing, Section SI.1.2.5 describes the temperature change model, and Section SI.1.2.6 describes the monetized socio economic impact.

**SI.1.2.1. Input Emissions**

APMT-IC takes inputs in the form of annual total fuel-burn, CO\textsubscript{2}, and NO\textsubscript{x} emissions for the time period over which the impacts and/or a policy are analyzed. For the purpose of this study, APMT-IC is run for an emissions pulse of $10^6$ kg fuel burn in the year 2015. CO\textsubscript{2}, and NO\textsubscript{x} emissions are specified using the derived emissions indices in Brasseur et al (2016). Impacts due to the short-lived forcers are derived by calculating the costs of each climate forcer associated with $10^6$ kg fuel burn. Cost per unit of emissions species is found by normalizing the cost of each climate forcer by their respective average precursor emission associated with $10^6$ kg of fuel burn.

**SI.1.2.2. CO\textsubscript{2} Radiative Forcing Impact**

CO\textsubscript{2} is one of the primary drivers of climate change and is responsible for roughly half of aviation’s climate impact (Lee et al 2009). Compared to the non-CO\textsubscript{2} impacts (see Section SI.1.2.3), CO\textsubscript{2} has a long atmospheric lifetime and we expect over 20% of today’s CO\textsubscript{2} emissions to remain in the environment for the next 1000 years (Joos et al 2013). As such the
CO₂ model must consider the long-lasting, integrated climate impact of CO₂. Therefore, APMT-IC models 800 years following an emissions scenario.

The impact of CO₂ emissions is estimated using the three main modeling steps as developed by Hasselmann et al (1997), Sausen and Schumann (2000), and Shine et al (2005). These steps include (i) modeling the change in atmospheric CO₂ concentrations due to the added emissions, (ii) using a logarithmic radiative transfer function to calculate the radiative forcing, and (iii) calculating the temperature response. In addition, the aviation CO₂ impact is non-linearly dependent on the changes in non-aviation CO₂ emissions. These non-aviation source CO₂ emissions and their impacts are referred to as background impacts. To capture the impact of these background emissions, APMT-IC calculates both the background and aviation CO₂ impacts. These modeling steps are described in the following sections.

**Atmospheric CO₂ Concentration**

The fraction of annual CO₂ emissions remaining in the environment at a specified number of years following an emission pulse can be estimated using an Impulse Response Function (IRF). APMT-IC models CO₂ using a sum of IRFs in a convolution approach.

In APMT-IC V24, the CO₂ modelling method has been updated to capture nonlinear impacts of background anthropogenic CO₂ levels on the atmospheric removal rate of aviation CO₂.

Background anthropogenic CO₂ emissions scenarios are taken from the Representative Concentration Pathways (RCP) as provided by the Intergovernmental Panel on Climate Change (IPCC). The four pathways developed in the RCPs represent future emissions projections from a larger set of scenarios in the literature (van Vuuren et al 2011), spanning the range of expected radiative forcing values for 2100. These scenarios were further extended to include emissions projections up to the year 2500 (Meinshausen et al 2011b). CO₂ concentrations for each RCP scenario are also included in the scenario data set. These CO₂ concentrations were derived using the Model for Greenhouse-gas Induced Climate Change (MAGICC6), which is a model capable of capturing the non-linear carbon cycle feedbacks (Meinshausen et al 2011a).

To calculate the aviation CO₂ contribution, we compute multiple IRFs using MAGICC6. Figure SI.2 outlines the process for deriving these IRFs. For a more detailed analysis on how IRFs can be derived, we refer to Joos et al (2013).
Figure SI.2: Impulse Response Function Calculation

Figure SI.3 shows the different APMT-IC IRFs. For the time period between 2010 and 2100, IRFs are calculated at a 10-year emissions resolution for each of the four RCP scenarios. Between 2100 and 2500, a 100-year emissions resolution is applied. RCP emissions are defined to 2500 (Meinshausen et al 2011b) only. As such, IRF behavior after 2500 has been extrapolated using an exponential function.

For an emission in any of the years in between the MAGICC6 IRFs, a linear interpolation between the preceding and immediately following available years is used. To illustrate, to model the impact of emissions occurring in 2024, APMT-IC uses an IRF constructed by linearly interpolating between the 2020 and 2030 IRFs.

Figure SI.3: Impulse Response Functions for Different Background RCP CO₂ levels
**CO₂ Radiative Forcing**

The CO₂ RF, a measure of the net change in the Earth’s energy balance due to a CO₂ emission, is modeled using the radiative transfer function included in the IPCC 5th Assessment Report (Myhre et al 1998, 2013). This radiative transfer function is written as

\[
RF_{CO₂}(t) = RF_{x2CO₂} \cdot \log_2 \frac{X_{CO₂(1750)} + \Delta X_{CO₂(t)}}{X_{CO₂(1750)}}, \tag{Eq 1}
\]

where \(X\) represents the mixing ratio in ppm and \(X_{CO₂(1750)}\) represents the pre-industrial era mixing ratio of 278ppm (IPCC 2013). \(RF_{x2CO₂}\) represents the radiative forcing expected from a doubling of CO₂.

The logarithmic dependence of radiative forcing on CO₂ concentration represents a non-linearity, where larger background CO₂ concentrations lead to lower aviation related CO₂ radiative forcing. To capture this non-linearity, APMT-IC models CO₂ radiative forcing using a marginal impact approach, where aviation’s CO₂ RF is estimated by first calculating the total anthropogenic CO₂ RF and then subtracting the total anthropogenic CO₂ RF without aviation emissions. Mathematically this can be written as

\[
RF(\text{Aviation CO}_₂) = RF(\text{Total Anthropogenic CO}_₂) - RF(\text{Total Anthropogenic CO}_₂ - \text{Aviation CO}_₂) \tag{Eq 2}
\]

Background RCP concentration data, obtained from RCP database (van Vuuren et al 2011), is loaded from a lookup table inside APMT-IC. Furthermore, Eq 1 has been found to differ from complex simulation projections by up to 5% (Prather et al 2012, Aamaas et al 2013). To account for the uncertainty associated with the IRF and the RF calculations, a uniform uncertainty of 10% is applied to this calculation.

**SI.1.2.3. Non-CO₂ Radiative Forcing Impact**

In addition to the CO₂ impacts, aviation’s climate impacts are also driven by non-CO₂ impacts, with literature estimating the non-CO₂ impact of aviation to account for between 0.4 and 3.7 times the impact of aviation CO₂ on a per unit of fuel burn basis (Dorbian et al 2011). In order to quantify the non-CO₂ impacts within APMT-IC, reduced order methods are used. In this section we first discuss how radiative impacts from BC, sulfates, nitrate aerosols, water, as well as contrails are modeled, followed by discussion of how the indirect NOx impact of ozone and methane is modeled.

Impacts due to BC, sulfates, nitrate aerosols, water, and contrails are assumed to last less than one year after emissions. In light of the short lifetime of these species, it is assumed these species’ radiative forcing impact to scale linearly with emissions in the year they are emitted.
The method for quantifying these impacts was developed by Sausen and Schumann (2000) and extended by Sausen et al (2005). Mathematically it can be written as

\[ RF_{\text{short},j}(t) = \frac{Q(t)}{Q(t = t_{\text{ref}})} RF_{\text{short},j}(t = t_{\text{ref}}) \]  

Eq 3

where, \( RF_{\text{short},j} \) represents the radiative forcing of species \( j \). \( Q(t) \) represents the emissions quantity, which is modeled in APMT-IC to scale with fuel burn for BC, sulfates, water, and contrails. For nitrates, \( Q(t) \) is the specified NO\(_x\) emissions.

The current implementation in the APMT-IC code uses the year 2006 fuel burn as the reference \( Q(t = t_{\text{ref}}) \) and the associated short lived forcer RF from 2006, supplied by research conducted by the Aviation Climate Change and Research Initiative (ACCRI) (Brasseur et al 2016). The initiative used a multi-model and multi-team approach consisting of 10 teams, with a total of 47 researchers, from 23 institutions worldwide. For the modeling effort, teams all used the same set of speciated gridded aviation emissions from AEDT for the year 2006 to compute speciated radiative forcing estimates. Some of these results were also published as stand-alone papers.

The following paragraphs give an overview of the ACCRI research by presenting the models used to derived the radiative forcing estimates that are included in the current version of APMT-IC.

NASA’s Goddard Institute for Space Studies Model E2 (GISS-E2), a General Circulation Model (GCM) was used to find radiative impacts of 0.6 mW/m\(^2\) for black carbon, 1.3 mW/m\(^2\) for direct water vapor emissions, -7+/−2 mW/m\(^2\) for sulfate and -4.0+/−1 mW/m\(^2\) for nitrate aerosols (Unger et al 2013). Another GCM, the Goddard Chemistry Climate Model (GEOSCCM) was used to calculate the impact due to changes in stratospheric water vapor and found 2.0 mW/m\(^2\). A Chemical Transport Model (CTM), the Community Atmosphere Model, version 5 (CAM5), was used to find the radiative impact due to black carbon of 1.0 mW/m\(^2\), and sulfate aerosols of -3.0 mW/m\(^2\). Integrated Global System Modeling framework (IGSM), which is a model of intermediate complexity, found the radiative impact of -4.4 mW/m\(^2\) due to sulfate aerosols and -7.5 mW/m\(^2\) for nitrate aerosols.

The radiative impacts of contrails are the net impact of the interaction with both shortwave and longwave radiation. Chen and Gettelman (2013) applied the CAM5 climate model, and found contrail radiative forcing of 12.4 mW/m\(^2\). Schumann and Graff (Schumann and Graf 2013) used a combination of contrail cirrus prediction model (CoCiP) (Schumann 2012) and diurnal trends derived from observations of Meteosat infrared data and flight records spanning over eight years (Graf et al 2012). They find contrail-cirrus RF of 50 mW/m\(^2\) (uncertainty range 40–80 mW/m\(^2\)). The radiative impact of linear contrails, which are young contrails, are much easier to identify visually. The radiative impact of linear contrails was quantified by Spangenberg et al (2013)
using satellite data. They found 5.7 mW/m² for flight operations in 2006. Minnis et al (2013) identified and tracked contrails in satellite observations, and found that the cloud coverage due to contrail-cirrus is 3.5 times larger than for linear contrails alone. When combined with representative optical depth and effective crystal diameter, these two studies lead to an approximate overall contrail-cirrus impact of 51.3 mW/m².

These contrail radiative impacts agree with previous literature finding between 10-80 mW/m² for emissions in 2005 (Stordal et al 2005, Lee et al 2009) and 31 mW/m² based on AERO2K air traffic inventory for the year 2002 using the ECHAM4 climate model (Burkhardt and Kärcher 2011).

Table SI.4 summarizes the reference RF and reference fuel burn for each species, and uncertainty distribution used by APMT-IC based on the Brasseur et al (2016) data. Monte Carlo uncertainty distributions, are derived following a simplified rule. If three or more RF values are available in Brasseur et al (2016), APMT-IC V24b uses a triangular distribution to model the RF distribution for that short-lived forcer. The distribution’s minimum value is set to the minimum value from Brasseur et al (2016), and similarly the distribution maximum value is set to the maximum RF value from Brasseur et al (2016). The mid value for the triangular distribution is found by taking the mean of the RF values presented in Brasseur et al (2016) for a particular short-lived forcer. If only two RF values are presented in Brasseur et al (2016), APMT-IC V24b uses a uniform uncertainty distribution, once again where the distribution upper and lower bounds correspond to the bounding RF values in Brasseur et al (2016).

Table SI.4: Values used for the short-lived, non-CO2 impacts based on Brasseur et al (2016).

| Species                 | RF_{short,j} [mW/m²] |
|-------------------------|-----------------------|
| BC                      | 0.6, 1 (Uniform)      |
| Sulfates                | -9, -4.8, -3 (Triangular) |
| Water                   | 1.3, 2 (Uniform)      |
| Contrain-cirrus         | 12.4, 37.9, 80 (Triangular) |
| Nitrate Aerosols        | -7.5, -3 (Uniform)    |
| RF_{2×CO2}              | 3.5, 3.7, 4.2 (Triangular) |
| Reference Year Fuel Burn| 188.1 Tg              |
| Reference Year NO\textsubscript{x} emissions | 2.67 Tg NO\textsubscript{x} as NO\textsubscript{2} |

The climate impacts due to NO\textsubscript{x}, not only include the nitrate cooling pathway included in Table SI.4, but also includes indirect ozone and methane warming and cooling pathways. These ozone-methane impacts occur on time scales of less than one year and on the atmospheric the lifetime of methane. As such, these lifetimes are also considered when modeling these indirect impacts in APMT-IC.
As described in Mahashabde (2009), to capture the timescales of these impacts, APMT-IC uses an Absolute Global Warming Potential (AGWP) approach, where AGWP for species \( x \) is defined as

\[
AGWP_{TH,x} = \int_0^{TH} RF_x \, dt \quad \text{Eq 4}
\]

Firstly, an emission of \( NO_x \) leads to an increase in the tropospheric ozone concentrations. Ozone is a strong warming climate forcer (Myhre et al 2013), with a short atmospheric lifetime and its impacts are assumed to last for a single year. Therefore, the AGWP\(_{100} \) for this forcer is the same as the RF in the first year following 1 kg of emission. In this description, this pathway is referred to as the \( NO_x-O_3 \) short impact, and it is modeled using the AGWP and the specified \( NO_x \) emissions. Mathematically the radiative forcing is derived as

\[
RF_{NO_x-O_3,\text{short}}(t = 1) = Q_{NO_x}(t) \cdot AGWP_{NO_x-O_3,\text{short}} \quad \text{Eq 5}
\]

Secondly, \( NO_x \) emissions lead to decrease of atmospheric methane due to a \( NO_x \) related increase in the hydroxyl radical, which reacts with \( CH_4 \) to reduce the \( CH_4 \) background concentrations. Methane is a strong climate forcer, and this decrease leads to a cooling impact. This process, referred to as the \( NO_x-CH_4 \) long impact, occurs over the atmospheric lifetime of methane of 10-12 years. To model this impact, APMT-IC uses the AGWP to compute the RF in the first year after emissions using

\[
RF_{NO_x-CH_4,\text{long}}(t = 0) = \frac{AGWP_{100,NO_x-CH_4,\text{long}}}{\int_0^{100} e^{-\frac{t}{\tau}} \, dt} \quad \text{Eq 6}
\]

where \( \tau \) is appropriate e-folding timescale. After the \( RF_{NO_x-CH_4,\text{long}}(t = 0) \) has been computed, the impact in each year is quantified using an appropriate e-folding timescale \( \tau \) as presented in Eq 7.

\[
RF_{NO_x-CH_4,\text{long}}(t) = Q_{NO_x}(t) \cdot RF_{NO_x-CH_4,\text{long}}(t = 0) \cdot e^{-\frac{t}{\tau}} \quad \text{Eq 7}
\]

Thirdly, \( NO_x \) emissions result in a long-term reduction in \( O_3 \) concentrations, referred to as the \( NO_x-O_3 \) long impact. The OH radical discussed for \( NO_x-CH_4 \) long impacts also leads to the production of the hydroperoxyl radical, \( HO_2 \), which reacts with \( O_3 \) to reduce the ozone concentration over a timescale of 10-12 years. This effect is modeled using Eq 8 and Eq 9.

\[
RF_{NO_x-O_3,\text{long}}(t = 0) = \frac{AGWP_{100,NO_x-O_3,\text{long}}}{\int_0^{100} e^{-\frac{t}{\tau}} \, dt} \quad \text{Eq 8}
\]

\[
RF_{NO_x-O_3,\text{long}}(t) = Q_{NO_x}(t) \cdot RF_{NO_x-O_3,\text{long}}(t = 0) \cdot e^{-\frac{t}{\tau}} \quad \text{Eq 9}
\]
The AGWP and timescale values are shown in Table SI.5. These values are taken from Stevenson et al (2004); Wild et al (2001) and Hoor et al (2009), and capture the uncertainty bounds of more comprehensive reviews of aviation NOx impacts (Holmes et al 2011). For a single Monte Carlo run, APMT-IC takes AGWP values ($AGWP_{NOx-O_3,short}$, $AGWP_{NOx-CH_4,Long}$, $AGWP_{NOx-O_3,Long}$) and an associated exponential decay timescale, $\tau$, from one of the three sources. For example, if it selects the $AGWP_{NOx-O_3,short}$ value from Stevenson et al (2004), the remaining RF values and the timescale are also be selected from Stevenson et al (2004). This is because each of the three NOx impacts are dependent upon one other and the models used to estimate them.

Table SI.5: AGWP and timescale values used to model the NOx related ozone and methane impacts. AGWP is measured in units of $\frac{W \cdot yr}{m^2 \cdot g \cdot NOx} \times 10^{-15}$. Discrete uniform uncertainty distribution is discussed in the text.

| Decay Timescale [yr] | AGWP<sub>100</sub> CH<sub>4</sub> (long) | AGWP<sub>100</sub> O<sub>3</sub> (long) | AGWP<sub>100</sub> O<sub>3</sub> (short) |
|----------------------|---------------------------------|---------------------------------|---------------------------------|
| Stevenson et al (2004) | 11.5                            | -4.2                            | -0.95                           | 5.06                           |
| Wild et al (2001)     | 11.8                            | -4.6                            | -1.5                            | 7.9                            |
| Hoor et al (2009)     | 10.7                            | -4.3                            | -1.8                            | 7.4                            |

Finally, we note that a NOx related cooling climate impact also results from a methane related reduction in stratospheric water vapor. APMT-IC does not explicitly model this impact as part of the NOx contributions, although it is partially included in the stratospheric water vapor listed in Table SI.4.

SI.1.2.4. Breaking down climate impacts by flight phase

APMT-IC provides estimates for the climate impact of full flight emissions. For the current paper, we are also interested in the impact in broken down by flight phase. This section discusses how this breakdown of climate impacts is calculated for each of the emissions species considered.

Firstly, we consider the CO<sub>2</sub> impact. CO<sub>2</sub> not only undergoes few chemical interactions in the atmosphere, but also has long atmospheric lifetime (~20-1000 years). Both these factors contribute to a uniform long-term radiative impact, irrespective of emissions region and emissions altitude. As a result, the social cost of carbon remains the same regardless of emissions altitude and we do not include any adjustments to break down CO<sub>2</sub> impact by flight phase.

Secondly, we consider the short-lived forcer impacts contrail-cirrus and stratospheric water vapor, which are modeled using the results presented in Brasseur et al (2016). Because these two impacts exclusively occur due to high altitude emissions, the full impact from Brasseur et al (2016) was attributed to the cruise flight phase.
Third, we calculate the impact of black carbon, sulfates, and nitrates in LTO by scaling the emissions and radiative forcing estimates presented in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) to aviation LTO emissions. Aviation LTO and cruise emissions are taken from AEDT and are presented in Table S1.6.

Table S1.6: Full Fleet AEDT emissions for year 2006

|                      | Full Flight | LTO  | Cruise | Notes                                      |
|----------------------|-------------|------|--------|--------------------------------------------|
| Fuel-Burn (Tg)       | 188         | 22.3 | 166    | ACCRI & AEDT                               |
| NOx (Tg as NO2)      | 2.66        | 0.275| 2.38   | ACCRI & AEDT                               |
| BC* (Gg)             | 5.96        | 0.88 | 5.08   | ACCRI & AEDT                               |
| SOx (Tg SO2)         | 0.226       | 0.027| 0.199  | Fuel sulfur content of 600mg/kg            |
| CO2 (Tg)             | 593.1       | 70.4 | 523.7  | $\text{EICO}_2 = 3.155\text{kg/kg}$        |
| H2O (Tg)             | 231.8       | 27.5 | 204.7  | $\text{EIH}_2O = 1.233\text{kg/kg}$        |

* For the BC emissions, ACCRI (Brasseur et al 2016) and AEDT gave different emission for full flight. ACCRI reported 5.91 Gg while AEDT reports 6.81 Gg. Because our BC RF values are derived using ACCRI emissions, we use the full flight emissions from ACCRI in our analysis, and break down the LTO and cruise emissions using the LTO-Cruise emissions ratios from AEDT.

Using the aviation emissions presented in Table S1.6, the mean cruise radiative impact is found by finding the difference between full flight radiative impact (Brasseur et al 2016) and the LTO radiative impact over a year of operations. Because cruise accounts for 90% of full flight emissions, the cruise impact uncertainty is taken to match the full flight uncertainty in Brasseur et al (2016). Table S1.7 summarizes the LTO and cruise radiative impact for nitrate, black carbon, and sulfates, over a year of aviation operations.

Table S1.7: LTO and Cruise Radiative Forcing for Nitrates, Sulfates, and Black Carbon over a year of aviation emissions in 2006.

|                      | LTO Radiative Impact | Cruise Radiative Impact |
|----------------------|-----------------------|-------------------------|
|                      | Mid Value             | Lower Bound             | Upper Bound             | Mid Value | Lower Bound | Upper Bound |
| Nitrates (mW/(m² yr))| -0.21                 | -0.58                   | -0.059                  | -5.5      | -6.7        | -2.7        |
| Black Carbon (mW/m² yr)| 0.042                   | 0.0052                   | 0.087                   | 0.76      | 0.56        | 0.96        |
| Sulfates (mW/m² yr)  | -0.099                | -0.14                   | -0.052                  | -4.70     | -8.90       | -2.90       |
Fourth, as discussed in Section SI.1.2.3, NO\textsubscript{x} impacts of short term ozone, and longer term methane and ozone are modelled using the Absolute Global Warming Potential (AGWP) results of Stevenson et al (2004), Wild et al (2001) and Hoor et al (2009). Of these three reports, only Wild et al (2001) presented AGWPs for both aviation as well as ground emissions. Therefore, we quantify the climate LTO NO\textsubscript{x} ozone, long-term methane, and long-term ozone impacts using the radiative forcing estimates for ground emissions of NO\textsubscript{x} from Wild et al (2001).

To quantify the cruise climate impact of NO\textsubscript{x} emissions we use emissions scaled results from Wild et al (2001). Wild et al (2001) found the impact per unit ground NO\textsubscript{x} emissions was 10% of the impact per unit of full flight NO\textsubscript{x} emissions. In addition, the LTO emissions only account for 10.3% of the full flight emissions. As such LTO NO\textsubscript{x} emissions only account for 1% of the overall climate NO\textsubscript{x} impact. Therefore, cruise NO\textsubscript{x} emissions account for 99% of the overall NO\textsubscript{x} climate impact. To ensure LTO and Cruise radiative impacts add up to the full flight radiative impacts, the AGWP from Stevenson et al (2004), Wild et al (2001) and Hoor et al (2009) are scaled by a constant factor. To illustrate mathematically

\[
AGWP_{\text{Cruise}} \cdot E_{\text{Cruise}} = AGWP_{\text{FF}} \cdot E_{\text{FF}} - AGWP_{\text{LTO}} \cdot E_{\text{LTO}}
\]

\[\text{Eq 10}\]

Where AGWP\textsubscript{x} represents the AGWP as discussed in Section SI.1.2.3, E\textsubscript{FF} represents the full flight emissions, and E\textsubscript{LTO} represents the LTO emissions. Using emissions fractions presented in Table SI.6 (10.3% NO\textsubscript{x} emissions in LTO), and the fact that NO\textsubscript{x} ground emissions AGWP values are 10% of full flight, Eq 10 is rewritten as

\[
AGWP_{\text{Cruise}} = \frac{AGWP_{\text{FF}} \cdot E_{\text{FF}} - 0.0103 \cdot 0.01 \cdot AGWP_{\text{FF}} \cdot E_{\text{FF}}}{(1 - 0.0103) \cdot E_{\text{FF}}}
\]

\[\text{Eq 11}\]

\[
AGWP_{\text{Cruise}} = 1.1 \cdot AGWP_{\text{FF}}
\]

\[\text{Eq 12}\]

Finally, because the break down of climate impacts by flight phase, depend on the full flight radiative data, the full flight damage estimates should be treated as the more reliable metric.

**SI.1.2.5. Temperature Response Model**

While RF provides useful information on the climate impacts of aviation emissions, policy makers may require more information to be able to compare short-lived impacts relative to longer term impacts. A climate metric based on temperature change facilitates such a comparison. A large integrated earth-atmospheric-ocean model could be used to estimate temperature change. However, these models are too computationally expensive to evaluate a large number of policy scenarios. To facilitate the comparison of many policy options, 1-box or
2-box models that simulate the mixed ocean layer and the deep ocean have been used within APMT-IC. These models incorporate the relevant physics to model the impact of RF changes on the temperatures of the atmosphere and ocean, and are fast enough to rapidly analyze many policy scenarios. Wolfe (2012) tested three models including: (i) a model developed by Shine et al (2005), which was originally implemented in APMT-IC, (ii) the Raper-Wigley model (Raper et al 2001, Wigley and Schlesinger 1985) and (iii) the CICERO model (Berntsen and Fuglestvedt 2008, Schneider and Thompson 1981). The CICERO model was found to more closely approximate the 100 year temperature response for a variety of scenarios as presented by the IPCC (Wolfe 2012) and was subsequently implemented in APMT-IC. In this section, an overview of the CICERO model is provided.

The original versions of the climate model incorporated the temperature response model developed in Shine et al (2005). This used the climate sensitivity to estimate the change in the atmosphere/mixed layer temperature. The CICERO model advances this framework by modeling the temperature response of the deep oceans, $T_2$, in addition to that of the atmosphere/mixed layer ocean, $T_1$. The deep ocean temperature is an important addition as this helps simulate the long-term response of the ocean as a heat sink. The equations used are shown in Eqs. 11 and 12.

$$\frac{\partial T_1}{\partial t} = \frac{RF(t)}{C_1} - \frac{T_1}{\tau} - \alpha_1(T_1 - T_2)$$  \hspace{1cm} Eq 13

$$\frac{\partial T_2}{\partial t} = \alpha_2(T_1 - T_2)$$  \hspace{1cm} Eq 14

To understand the physics modeled within these equations, we describe each term on the Right-Hand Side (RHS) separately. The first term in Eq. 11, $\frac{RF(t)}{C_1}$, represents the rate of temperature change due to the estimated radiative forcing, where $C_1$ is the effective heat capacity of the atmosphere/mixed-ocean layer. The heat capacity indicates how much energy is required to result in a temperature change of the atmosphere. The second part of the RHS in Eq 13, $\frac{T_1}{\tau}$, captures the equilibrium temperature due to the radiative forcing given the feedbacks in the climate system. The final term, which is reciprocated in Eq 14, represents the exchange of heat between the deep oceans and the atmosphere/mixed-layer ocean. The coefficients $\alpha_1$, and $\alpha_2$, are computed by

$$\alpha_1 = \frac{c_w}{C_1} \left( F + \frac{K_z \rho}{\Delta z} \right)$$ \hspace{1cm} Eq 15

$$\alpha_2 = \frac{c_w}{C_2} \left( F + \frac{K_z \rho}{\Delta z} \right)$$ \hspace{1cm} Eq 16

where $c_w$ is the specific heat of liquid water, $F$ is the advective mass flux of water from the boundary layer to deep ocean (assumed constant), $K_z$ is the turbulent diffusion coefficient for
mixing between the mixed ocean layer and the deep ocean, $\rho$ is the density of water, $\Delta z$ is the mixing depth for turbulent mixing of heat and $C_2$ is the heat capacity of the deep ocean.

The $\tau$ parameter in Eq 13 is computed through

$$\tau = C_1 \lambda = C_1 \frac{\Delta T_{x2CO_2}}{RF_{x2CO_2}} \tag{Eq 17}$$

where $RF_{x2CO_2}$ and $\Delta T_{x2CO_2}$ are the radiative forcing and temperature change due to a doubling of CO$_2$ respectively.

$\Delta T_{x2CO_2}$ is known as the equilibrium climate sensitivity (ECS), and determines the temperature reached at equilibrium. The IPCC estimated two thirds of the ECS probability distribution to fall between 2K and 4.5K, but mentioned that larger values could not be excluded (Roe and Baker 2007). Following recent peer reviewed social cost of carbon estimates (US Government 2016) which used the Roe and Baker (2007) uncertainty distribution, APMT-IC V24b also uses the Roe and Baker (2007) ESC uncertainty distribution. The Roe and Baker (2007) ECS is derived through

$$\Delta T_{x2CO_2} = \frac{\Delta T_{x2CO_2,0}}{1 - f} \tag{Eq 18}$$

where $\Delta T_{x2CO_2,0}$ is the climate sensitivity in the absence of climate feedback effects (estimated be 1.2K (Roe and Baker, 2007)), and $f$ is the normally distributed feedback factor, which represents the uncertainty of the climate feedbacks effects. Calibrating the Roe and Baker ECS distribution to the IAWG SCC parameters, resulted in a mean feedback factor of 0.618 and a standard deviation of 0.185. In line with the IAWG SCC, the ECS distribution was truncated at 10K.

By comparing the values used by Berntsen and Fuglestvedt (2008) to other estimates, expected values as well as uncertainty ranges for each of the other temperature model parameters were derived. These values are tabulated in Table 5. We note here that these uncertainty ranges do not necessarily reflect physical ambiguity, but the modeling uncertainty associated with the underlying models. For example, the range of $\Delta z$ values represents the various approaches to representing diffusive heat transfer with more complex models.

Table SI.8: Values used for the temperature response model. Triangular uncertainty distributions were used, unless otherwise stated.

| $\Delta T_{x2CO_2}$ [K] | Values and Distribution  |
|------------------------|--------------------------|
|                        | Roe and Baker (2007)*    |
| $RF_{x2CO_2}$ [W/m$^2$] | 3.5, 3.7, 4.2            |
| $c_w$ [J/K/kg $\times 10^3$] | 4.2 (constant) |
As with the CO₂ modeling, where both the background and the aviation contributions were computed, APMT-IC also calculates both the aviation temperature change, and the background temperature change. Previous versions of APMT-IC computed the background temperature changes using the background CO₂ RF values, and the temperature model discussed in this section. However, using the CO₂ background RF to compute background temperature change, does not include the contribution of other background climate forcers, such as N₂O, CH₄, and aerosols. Therefore, MAGICC6 was used to create lookup tables for background temperature change for each of the RCP scenarios in APMT-IC V24.

To ensure consistency within a Monte Carlo draw, the background temperature and aviation temperature change uncertainty are paired. For instance, a high relative background temperature change should also result in a high relative aviation temperature change. This correlation is significant, because background temperature change affects the magnitude of the damages. Therefore, the lookup table generated for MAGICC6 was generated for the largest contributor of temperature change, different ECS values (1.5K, 2K, 3K, 3.5K, 4K, 5K, 6K) and each RCP scenario. For each Monte Carlo draw, APMT-IC linearly interpolates the background temperature change from the MAGICC6 lookup table. Figure SI.4 shows the APMT-IC V24b background temperature change for different RCP scenarios, along with the 5th IPCC Coupled Model Intercomparison Project (CMIP5) temperature estimates.

\[ C_1 \ [J/K/m^2 \times 10^8] = 1.791, 3.13, 4.48 \]
\[ C_2 \ [J/K/m^2 \times 10^{10}] = 0.63, 1.26, 2.52 \]
\[ F \ [kg/m^2/s \times 10^{-4}] = 0.62, 1.23, 2.46 \]
\[ K_z \ [m^2/s \times 10^{-5}] = 4.4, 10 \quad \text{uniform} \]
\[ \rho \ [kg/m^3] = 1000 \quad \text{constant} \]
\[ \Delta z \ [m] = 500, 1000, 2000 \]

*aCalibrated to the Interagency Working Group on Social Cost of Carbon (US Government 2016)*
The above temperature model was derived to model temperature changes caused by the horizontal and vertical radiative distribution of CO₂ in the atmosphere. Climate efficacies have been introduced to adjust CO₂ induced temperature change models for temperature change due to a variety of short-lived climate forcers. Efficacy is defined as the ratio of the climate sensitivity parameter for a given forcing agent to that for a given change in CO₂ (Hansen et al 2005). However, for aviation, these climate efficacy values are still associated with large uncertainties as very few studies exist (Lund et al 2017). Wuebbles et al (2010) argue that “too few climate models have assessed aviation efficacies to justify their use in policy”. For the radiative efficacy, we use values of unity with no uncertainty distribution. This is in-line with Fuglestvedt et al (2010) who also used values of one. Furthermore, if more literature becomes available with climate efficacies, the paper results can be adjusted for different values of efficacy after the fact, as long as the aviation impact remains small enough to remain in a quasi linear regime of the damage function described in the next section.

SI.1.2.6. Physical and Monetary Damage Model

There are three major steps for quantifying the monetary damages in terms of the Net Present Value (NPV). Firstly, damage functions are used to estimate the climate impacts due to a temperature change as a percentage of GDP. The dollar values of these damages are quantified

Figure SI.4: Background Temperature Change, with APMT-IC Uncertainty based on Roe and Baker (2007). The shaded regions indicate the [33,67] percentile range and the solid line indicates the mean temperature change. The skewed distribution is driven by the distribution of the ECS.
using GDP forecasts. Finally, the NPV of damages is calculated by discounting future damages to social costs today.

The framework for damage functions was developed in the Dynamic Integrated model of Climate and the Economy (DICE) (Nordhaus and Boyer 2000), where climate damages were estimated as a percentage of GDP due to predicted changes in temperature. Nordhaus and Boyer based their assessment of damages on valuations of climate impact estimates in six major categories: agriculture, sea level rise, health, human settlements and ecosystems, other market sections affected by climate change, and non-market impact. They also account for the possibility of catastrophic climate change impacts, and add 25% for any sectors not quantified by their damages estimations.

Estimates of the damages as a percentage of GDP are calculated using Eq 19, which incorporates both a linear sum and a quadratic sum of the temperature change to allow for the non-linearities in quantifying the climate damages.

\[ D_k(t) = \frac{a_{1,k} \Delta T(t) + a_{2,k} \Delta T(t)^2}{1 + a_{1,k} \Delta T(t) + a_{2,k} \Delta T(t)^2} \]  

Eq 19

In Eq 19, \( \Delta T \) is the temperature increase relative to preindustrial levels. The damage function requires two coefficients to be estimated, \( a_{1,k} \) and \( a_{2,k} \). APMT-IC V24b damage function coefficients are taken from Nordhaus (2017). Table 6 tabulates the parameter values. The coefficients are assumed to be normally distributed with standard deviation, \( \sigma \).

| Coefficient | Values |
|-------------|--------|
| \( a_{1,k} \) \[ fraction \( \frac{GDP}{K} \] \( \times 10^{-3} \) | 0 |
| \( a_{2,k} \) \[ fraction \( \frac{GDP}{K^2} \] \( \times 10^{-3} \) | 2.36 |
| \( \sigma \) [fraction GDP] \( \times 10^{-3} \) | 1.18 |

Table SI.9: Values used within the damage functions as developed by (Nordhaus and Boyer 2000).

To convert the climate damages from a percentage of GDP to monetized estimates, the result from Eq 19 is multiplied by forecasts of GDP. GDP projections are provided by the OECD global reference Shared Socio-economic Pathways (SSPs) (Dellink et al 2017). The SSPs allow for the development of a range of forecasts or “story-lines” based on a society’s ability to mitigate or adapt to the impacts of climate change. Figure SI.5 presents the GDP forecasts for the five representative SSP scenarios (Dellink et al 2017). The SSP scenarios are defined in 2005 USD-values. APMT-IC uses the World Bank GDP deflator to adjust the price levels.
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SI.1.2.7. Scaling Contrail Impact by Emission

In line with the purpose of this paper, results are presented on a per mass of emissions basis. However, contrail formation is driven by multiple characteristics of aircraft emissions and it is not immediately clear by which emission the contrail-cirrus impact should be normalized.

In line with current literature, we present the contrail-cirrus impact normalized by a unit of fuel burn and additionally we also present the contrail-cirrus costs normalized by flight km (Lund et al 2017, Fuglestvedt et al 2010, Dorbian et al 2011). However, for constant fuel burn, factors such as the (i) role of soot; (ii) dependence on the water vapor emissions factor through changes in fuel type; (iii) strong spatial and temporal dependence resulting from relative humidity patterns, cloud cover, and time of day; (iv) increase in contrail formation likelihood with increased engine efficiency; or (v) dependence on size of the aircraft all influence the contrail-cirrus impact. Although literature has qualitatively described the impact of each of these properties on contrails (Caiazzo et al 2017, Schumann 2000), the quantification of the scaling on a global scale remains an open research question.

Therefore, the normalized contrail-cirrus cost metrics, as presented in this paper, are not applicable to evaluate flight scenarios departing from current emissions patterns. To illustrate this, we discuss the qualitative impact of each of these factors.

Firstly, increases in the particulate matter number emissions are expected to increase the contrail lifetime as well as their instantaneous radiative impact. When a contrail forms, water vapor condenses on particles in the exhaust plume. The more particles are available, the more ice
crystals form. For the same volume of emitted water, the ice crystals will be smaller, leading to an increase in the instantaneous contrail radiative impact, because the smaller ice crystals collectively have a larger surface area. In addition, the lower crystal mass slows down settling into the lower and warmer parts of the atmosphere where they would evaporate. This leads to an increased contrail lifetime and a higher instantaneous radiative impact integrated over the contrail lifetime.

Secondly, increases in water vapor emissions per unit of fuel energy leads to a non-linear increase in contrail formation. This is because, when the water vapor mass per unit of energy increases, the exhaust plume will contain larger amounts of water vapor compared to the energy in the exhaust plume. As a result, there is a greater range of conditions when the exhaust plume can become ice supersaturated as it mixes with the ambient air and cools down, leading to increased contrail formation as the water vapor emissions index increases. However, as long as the same type of fuel is used, contrail impacts are expected to scale linearly with water vapor emissions all other factors remaining the same.

Third, contrail impacts vary by time and location of emissions. Contrails form and persist when the local ambient conditions are ice supersaturated. These cold and wet conditions do not occur uniformly across the globe. For instance, they have higher prevalence in the extra tropics than in the tropics at flight altitude (Irvine and Shine 2015). Subsequent radiative impacts depend on how much heat is trapped, and how much incoming light is reflected back into space. The contribution of contrails to additional light reflected back into space (cooling impact) increases when contrails are present over dark surfaces, during the day, and at locations with high solar radiation incidence angles. The heat trapped by contrails increases with local humidity, because contrails take up water vapor from the surrounding atmosphere. Therefore, contrails occurring in the tropics are likely to have higher warming impact, due to the high local humidity (Lund et al 2017, Burkhardt and Kärcher 2011).

Fourth, contrail formation increases with an increase in engine efficiency. Aircraft engines that are more efficient extract more energy from a unit of fuel burn. As a result, the exhaust gas is cooler. As such, there is a greater range of conditions where exhaust plume can become ice supersaturated as it mixes and cools. While we scale the contrail-cirrus impact by fuel burn, changes in engine efficiency would result in an opposite scaling. To illustrate, if engine efficiency increases, contrail formation increases, but fuel burn decreases. For this reason, we additionally present results normalized by flight distance. Although normalization by flight distance is still subject to the reverse impact scaling of the increase in contrail formation, it is not additionally subject to the decrease in fuel burn, leading to a slightly more robust contrail scaling metric, than scaling by fuel burn alone (Fuglestvedt et al 2010, Lund et al 2017).
Finally, the contrail impact per unit of fuel is likely reduced for larger aircraft. Once contrails have formed, they also cause water already present in the environment to condense, thereby increasing the water mass of the contrail. As such, the contrail water mass, and subsequent radiative impact is in part due to the aircraft water vapor emissions, and in part due water vapor in the environment. Larger aircraft likely burn more fuel per flight km, and as a result, may have a smaller contrail impact per unit fuel burn than smaller aircraft.

Therefore, we conclude, that the particulate matter number emissions index, water vapor per unit of fuel energy, time and location, engine efficiency, and aircraft size all influence contrail-cirrus impact scaling to emissions. Consequently, contrail-cirrus metrics normalized by fuel burn or flight distance are not adequate to evaluate flight scenarios significantly different to present day emissions and conditions. Results presented in this paper, normalized by fuel burn and flight distance, represent current state of the literature, but further research into the contrail-cirrus scaling impact of these factors would be necessary before these cost metrics could be applied to emissions scenarios departing from present day conditions.

SI.1.3. Air Quality Modeling and Uncertainty Quantification

SI.1.3.1. Air Quality Modeling

The air quality impact is modeled using the GEOS-Chem Adjoint model, originally developed by Henze et al (2007) and collaboratively updated since\(^1\). Details specific to our use of the GEOS-Chem adjoint model are presented in this section. Uncertainty quantification of our air quality results is discussed in Section SI.1.3.2.

Using GEOS-Chem, sensitivities of cost to unit emissions are calculated on a global 4° × 5° model resolution (latitude × longitude) and 47 vertical hybrid sigma-eta pressure levels extending from the surface to 0.01 hPa. Global anthropogenic emissions in GEOS-Chem are from the EDGAR 4.3.1 global emissions inventories, which is overwritten by regional emissions where available (e.g. EPA National Emissions Inventory (NEI) 2011 for the US). Sensitivities are computed using GEOS5 global assimilated meteorological data from the Global Modeling and Assimilation Office (GMAO) at the NASA Goddard Space Flight Center for 2009.

Within the sensitivity calculation, the GEOS-Chem atmospheric modeling is combined with population data and epidemiological data to find the number of mortalities. Population data is obtained from the year-2015 Landscan dataset (Oak Ridge National Laboratory 2015). Epidemiological data, in the form of concentration response functions are implemented as per Hoek et al (2013) and Jerrett et al (2009) for PM\(_{2.5}\) and ozone respectively.

\(^1\) For the GEOS-Chem Adjoint community wiki see [http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_Adjoint](http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_Adjoint)
To determine number of mortalities, both these concentrations response functions require baseline disease incidence as well as the population fraction over 30 years of age, which we obtain by country from the World Health Organization (WHO 2018).

Mathematically, the number of mortalities in each grid cell due to emissions in another grid cell, can be written as

\[ \Delta \text{Premature Mortalities}_{x,j,i,p} = I_{\text{Baseline},i} \left( 1 - e^{-\beta_p \Delta \chi_{x,j,i,p}} \right) \times Pop_{>30,i} \times \text{Population}_i \]  

\[ \text{Eq 20} \]

where \( \text{Population}_i \) represents the population in grid cell \( i \), \( I_{\text{Baseline},i} \) and \( Pop_{>30,i} \) respectively represent the country specific baseline disease incidence and population fraction over the age of 30. \( \Delta \chi_{x,j,i,p} \) represents the change of ground level concentration of pollutant \( p \), PM\(_{2.5}\) or ozone in grid cell \( i \), due to emissions of species \( x \), in grid cell \( j \). \( \beta_p \) represents a parameter derived for pollutant \( p \), from the concentration response function’s parameters and is defined by

\[ \beta_p = \frac{\ln RR_{\text{lit},p}}{\Delta \chi_{\text{lit},p}} \]  

\[ \text{Eq 21} \]

Where \( RR_{\text{lit},p} \) is the increased risk of premature mortality, given some change in concentration \( \Delta \chi_{\text{lit},p} \) of pollutant \( p \). Both \( RR_{\text{lit},p} \) and \( \Delta \chi_{\text{lit},p} \) are used as published in Hoek et al (2013) and Jerrett et al (2009) PM\(_{2.5}\) and ozone respectively.

However, due to the computational costs of running the adjoint method, Eq 20 is linearized using the first term of the Taylor series expansion as shown in Eq 23.

\[ \Delta \text{Premature Mortalities}_{x,j,i,p} = I_{\text{Baseline},i} \beta_p \Delta \chi_{x,j,i,p} \times Pop_{>30,i} \times \text{Population}_i \]  

\[ \text{Eq 22} \]

The number of mortalities are monetized using a country-specific value of statistical life (VSL), calculated consistent with Barrett et al (2012). These VSL values are based on the 1990 EPA value, which was derived from a meta-study. The central estimate is \( 4.8 \times 10^6 \) USD [year 1990 USD] (US EPA 2014). To translate the year-1990 US VSL to country-specific values for the Year \( t_v \) at price levels of Year \( t_p \), Eq (24) is used:

\[ VSL_{\text{Country},t_v,t_p} = VSL_{\text{US},1990,1990} \left( \frac{\text{real. GDP}_{\text{Country},t_v}}{\text{real. GDP}_{\text{US},1990}} \right)^\varepsilon \frac{\text{GDP deflator}_{t_p}}{\text{GDP deflator}_{1990}} \]  

\[ \text{Eq 23} \]

where \( \varepsilon \) is the income elasticity of VSL.

To adjust price levels, the GDP deflator is obtained from the Federal Reserve Economic Data as the Gross Domestic Product Implicit Price Deflator. Multiplying the year-1990 VSL obtained
from the EPA with the change in GDP deflator relative to its year-1990 value yields the year-
1990 VSL for a specific target price year. With this simplification, the country specific VSL at
year 2015 price levels can then be written as shown in Eq. (25).

\[
V_{US,t_4,2015} = V_{US,1990,2015} \left( \frac{\text{real. GDP}_{\text{Country},2015}}{\text{real. GDP}_{US,1990}} \right)^\varepsilon
\]

Eq 24

In Eq. (24) and Eq. (25), we follow US EPA (2016) and Robinson & Hammitt (2015) and use a
central estimate for the income elasticity of VSL at 0.7. Consistent with Barrett et al (2012), we
further use Worldbank GDP per capita data for 2015 in PPP for the income based VSL
adjustment.

The sum of damages due to a unit of emissions in a grid cell, also referred to as sensitivities, are
calculated using Eq. (26).

\[
\text{Damages}_{x,j,p} = \sum_{i=\text{Grid Cells}} V_{\text{country},i} \times \Delta \text{Premature Mortalities}_{x,j,i,p}
\]

Eq 25

where for each grid cell \( j \), the global damage due to a unit increase of emission of species \( x \), is
calculated for both PM\(_{2.5}\) and ozone.

Gridded AEDT emissions (Sect. SI.1.1) are used to calculate overall global damages attributable
to each aviation emission specie. The impact per unit of emissions is found by dividing the total
impact aviation attributable impact by the total emission. Mathematically, written as

\[
\text{Damages Per Unit Emissions}_{x,p} = \frac{\sum_j \text{Damages}_{x,j,p} \times \text{Emissions}_{x,j}}{\sum_j \text{Emissions}_{x,j}}
\]

Eq 26

This process is repeated for both PM\(_{2.5}\) and ozone, and overall air quality damages are found as
the sum of these respective impacts.

Overall damages are taken as the sum of the damages resulting from population exposure of
PM\(_{2.5}\) and ozone, written as

\[
\text{Damages Per Unit Emissions}_{x,\text{overall}} = \text{Damages Per Unit Emissions}_{x,\text{PM}_{2.5}} + \text{Damages Per Unit Emissions}_{x,\text{ozone}}
\]

Eq 27

Results are also derived for globally averaged VSL, in which case, a globally averaged VSL of
3.81 million 2015 USD is used. This VSL is derived using a population weighted GDP per capita
in PPP, and income elasticity of 0.7, consistent with country specific VSL assumptions.
SI.1.3.2. Air quality impact uncertainty quantification

This subsection discusses uncertainty quantification of air quality impact. In our uncertainty quantification we assume the uncertainty associated with $I_{\text{Baseline},i}$, $Pop_{>30,i}$, and Population$_i$ to be much smaller than the uncertainty associated with the US VSL in 1990, income elasticity $\varepsilon$, the $R_{\text{lit},p}$ values, and the model output uncertainty $\Delta x_{x,j,i,p}$. Therefore, we only quantify uncertainty resulting from these factors. We use a coupled Monte Carlo simulation with 100,000 simulations to determine the uncertainty range. More details are discussed below.

Substituting Eq 22 and Eq 24 into Eq 26, leads to Eq 29.

$$\text{Damages Per Unit Emissions}_{x,p} = \frac{I_{\text{Baseline},i}}{\sum_j \text{Emissions}_{x,j}} \times \text{VSL}_{US,1990,2015} \times \beta_p \times \Delta x_{x,j,i,p} \times A_p(\varepsilon)$$  \hspace{1cm} Eq 28

Where $A(\varepsilon)$ is given by

$$A_p(\varepsilon) = \left(\sum_j \text{Emissions}_{x,j} \times \sum_{i=\text{Grid Cells}} \left(\frac{\text{real.GDP}_{\text{Country},2015}}{\text{real.GDP}_{p,cUS,1990}}\right)^\varepsilon \times Pop_{>30,i} \times \text{Population}_i\right)$$

The uncertainty associated with (i) $\text{VSL}_{US,1990,2015}$, (ii) $\beta_p$, (iii) $\varepsilon$, (iv) $\Delta x_{x,j,i,0_4}$ and (v) $\Delta x_{x,j,i,PM_{2.5}}$ can now be combined to find overall uncertainty by using a coupled Monte Carlo simulation, using the following uncertainty assumptions:

(i) For the uncertainty associated with $\text{VSL}_{US,1990,2015}$, we follow the EPA guideline as outlined in US EPA (2014). The central estimate is given as $4.8 \times 10^6$ USD [year 1990] and the associated uncertainty follows a Weibull distribution with a scale factor of 5.32 and shape factor of 1.51 (US EPA 2014).

(ii) For the uncertainty associated with $\beta_p$ we use the $R_{\text{lit},p}$ uncertainty distributions as presented in Hoek et al (2013) and Jerrett et al (2009) and compute the distribution of $\beta_p$. Summary of the CRF values are presented in Table SI.10

(iii) The uncertainty associated with $A_p(\varepsilon)$ is driven by the uncertainty in the income elasticity $\varepsilon$. For $\varepsilon$, we follow US EPA (2016) and Robinson & Hammitt (2015) who used a central estimate of 0.7 with reasonable bounds between 0.1 and 1.4. We change the lower reasonable bound to 0 to reflect VSL adjustment as price-level-based adjustment only. We then compute adjoint sensitivity matrices for $\varepsilon$ equal to 0, 0.7, and 1.4. The adjoint calculation does not keep track of where impacts occur, and as such, the uncertainty distribution of $A_p$ is unknown. We therefore assume a
triangular distribution where the bounds and mid value are given by $A_p(0), A_p(0.7), A_p(1.4)$.

(iv) The uncertainty associated with the changes in ozone concentration at ground level ($\Delta \chi_{x,i,o_3}$) is derived from an inter-model comparison of changes in ground-level concentration due to aviation emissions (Cameron et al 2017). The GEOS-Chem ozone response (0.43 ppbv) differed by less than 5% to the multi-model mean of 0.41 ppbv, while the standard deviation between the models was 20% of the mean. Using this result as guidance, we add a multiplicative uncertainty to ozone concentration. This distribution has a triangular distribution with a central value of one and a standard deviation of 0.2. This triangular distribution has a minimum, mid, and maximum value of 0.5, 1, 1.5 respectively.

(v) The upper bound of uncertainty associated with the changes in PM$_{2.5}$ concentration at ground level ($\Delta \chi_{x,i,PM_{2.5}}$) is derived from the aviation inter-model comparison (Cameron et al 2017), where the GEOS-Chem average ground-level PM$_{2.5}$ concentration due to aviation emissions, is half of that reported by the other two CTM models$^2$. The lower bound of uncertainty is set by comparisons between in situ concentration measurements and GEOS-Chem output for all-source emissions, where studies have found GEOS-Chem over estimates the annual average nitrate PM$_{2.5}$ by up to 2.8 times over most of the US (Heald et al 2012, Walker et al 2012). Using these two results, we add a multiplicative uncertainty to the PM$_{2.5}$ concentration with a triangular distribution with a minimum value of 0.36, an upper bound of 2, and a mean value of one.

This process is completed for both the PM$_{2.5}$ and ozone impacts. Because the same value of $\varepsilon$ are present in both $A_{PM_{2.5}}(\varepsilon)$ and $A_{O_3}(\varepsilon)$, the Monte Carlo simulation, treats $A_{PM_{2.5}}(\varepsilon)$ and $A_{O_3}(\varepsilon)$ as correlated variables. This is written mathematically as

$$\text{Damages} = \frac{I_{\text{Baseline},i}}{\sum_j Emissions_{x,j} \times VSL_{US,1990,2015}} \times (\beta_{PM_{2.5}} \times \Delta \chi_{x,i,PM_{2.5}} \times A_{PM_{2.5}}(\varepsilon) + \beta_{O_3} \times \Delta \chi_{x,i,O_3} \times A_{O_3}(\varepsilon)) \quad \text{Eq 29}$$

We report 5$^{th}$ and 95$^{th}$ percentile values in results tables in Section SI.2.2 of and Section 3 of the main manuscript, and a discussion of output sensitivity to each of these uncertain variables is presented in Section SI.2.6.2.

$^2$ Due to the large stochastic variability included in the outputs of coupled Climate Response Models (CRMs), we only include the output from the Chemical Transport Models (CTM) and uncoupled runs of the Climate Response Models (CRM) reported in Cameron et al (2017).
Table SI.10: CRF Relative Risk uncertainty distribution values

| CRF                        | Relative risk triangular distribution (LB, Mid, UB) | Concentration increment $\Delta \chi_{\text{lit,}p}$ |
|---------------------------|-----------------------------------------------------|-----------------------------------------------------|
| Ozone (Jerrett et al 2009) | 1.0014, 1.04, 1.0786                                 | 10 ppb                                              |
| PM$_{2.5}$ (Hoek et al 2013) | 1.0335, 1.11, 1.1752                                 | 10 $\mu$g/m$^3$                                    |
SI.2. Results

SI.2.1. Intermediate Climate results

SI.2.1.1. Global Warming Potential

Absolute Global Warming Potential (AGWP) is defined as the integrated radiative forcing \((RF)\) on a set time horizon \((TH)\), following 1 kg of an emission of a species \(X\). Mathematically it can be written as

\[
AGWP_X = \int_0^{TH} RF_X \, dt,
\]

where \(TH\) is the time horizon, and \(RF\) is the radiative forcing caused by 1 kg of the climate forcer \(X\). The Global Warming Potential (GWP) of an emission species serves as a comparison of how that species compares to the radiative impact of CO\(_2\). The GWP can be found by normalizing the AGWP of species \(X\), by the AGWP of CO\(_2\). Mathematically it is written as

\[
GWP_X = \frac{AGWP_X}{AGWP_{CO_2}}.
\]

Table SI.11 presents GWP values derived from this study. Both the AGWP\(_X\) and the AGWP\(_{CO_2}\) are computed using APMT-IC. The GWP values for NO\(_x\) are based on 1 kg emission of NO\(_x\) as NO\(_2\), while the sulfur impact us based on 1 kg emission of SO\(_x\) as S, and 1 kg fuel burn for contrail-cirrus. These values are calculated using a Monte Carlo simulation, where the GWP for each run is calculated individually, and the GWP mean, and the 5\(^{th}\) and 95\(^{th}\) percentiles are found using the Monte Carlo set.

|                     | 20 Years     | 50 Years     | 100 Years    | 500 Years     |
|---------------------|--------------|--------------|--------------|--------------|
| NO\(_x\): CH\(_4\)  | -150 (-180, -130) | -90 (-100, -76) | -54 (-63, -45) | -14 (-16, -12) |
| NO\(_x\): O\(_3\) Long | -49 (-70, -29) | -29 (-41, -18) | -17 (-24, -11) | -4.5 (-6.3, -2.7) |
| NO\(_x\): O\(_3\) Short | 280 (190, 360) | 140 (95, 180) | 83 (56, 110) | 21 (14, 28) |
| NO\(_x\): Nitrate Aerosols | -82 (-120, -49) | -41 (-59, -25) | -24 (-35, -14) | -6.2 (-8.9, -3.7) |
| NO\(_x\): Total     | 1.1 (-72, 64) | -19 (-54, 11) | -12 (-33, 5.2) | -3 (-8.4, 1.3) |
| Contrail-Cirrus     | 9.6 (4.7, 15) | 4.8 (2.4, 7.6) | 2.8 (1.4, 4.5) | 0.73 (0.36, 1.2) |
| Sulfur Impact       | -2100 (-2900, -1300) | -1000 (-1500, -680) | -610 (-870, -400) | -160 (-220, -100) |
| BC                  | 5600 (4200, 7100) | 2800 (2100, 3500) | 1600 (1200, 2100) | 430 (320, 540) |
| H\(_2\)O            | 0.3 (0.23, 0.37) | 0.15 (0.12, 0.18) | 0.087 (0.068, 0.11) | 0.023 (0.018, 0.028) |
SI.2.1.2. Temperature Potential

Absolute Temperature Potential (ATP) is defined as the surface temperature change ($\Delta T(t)$) at a given time, following 1 kg of an emission of a species $X$ at $t = 0$. Mathematically it can be written as

$$\text{ATP}_X = \Delta T(t)$$

The Temperature Potential (TP) of an emission species serves as a comparison of how that species compares to the temperature response after an emission of the same amount of CO$_2$. The TP can be found by normalizing the ATP$_X$ of species $X$, by the ATP$_{CO_2}$ of CO$_2$. Mathematically it is written as

$$\text{TP}_X = \frac{\text{ATP}_X}{\text{ATP}_{CO_2}}$$

Table SI.12 presents TP values derived in this study. Both the ATP$_X$ and the ATP$_{CO_2}$ are computed using APMT-IC. The TP values for NO$_x$ is based on 1 kg emission of NO$_x$ as NO$_2$, while the sulfur impact us based on 1 kg emission of SO$_x$ as S, and 1 kg fuel burn for contrail-cirrus. These values are calculated using a Monte Carlo simulation, where the TP for each run is calculated individually, and the TP mean, and the 5th and 95th percentiles are found using the Monte Carlo set.

Table SI.12: Temperature Potential of Aviation Emissions. Results presented as mean (5th percentile, 95th percentile)

|                | 20 Years     | 50 Years     | 100 Years    | 500 Years    |
|----------------|--------------|--------------|--------------|--------------|
| NO$_x$: CH$_4$| -110 (-130, -84) | -16 (-23, -10) | -5 (-9.1, -2.1) | -2.8 (-4.7, -1.5) |
| NO$_x$: O$_3$ Long | -34 (-49, -20) | -5.1 (-8, -2.7) | -1.6 (-3.2, -0.59) | -0.92 (-1.7, -0.39) |
| NO$_x$: O$_3$ Short | 29 (4.8, 79) | 7.6 (2.7, 15) | 7.4 (2.8, 14) | 4.3 (2, 7.6) |
| NO$_x$: Nitrate Aerosols | -8.5 (-23, -1.3) | -2.2 (-4.5, -0.74) | -2.1 (-4.3, -0.76) | -1.3 (-2.3, -0.54) |
| NO$_x$: Total | -120 (-140, -97) | -15 (-22, -11) | -1.3 (-3.7, 0.053) | -0.66 (-2, 0.2) |
| Contrail-Cirrus | 1.0 (0.14, 2.8) | 0.26 (0.079, 0.56) | 0.25 (0.081, 0.53) | 0.15 (0.056, 0.29) |
| Sulfur Impact | -220 (-580, -34) | -55 (-110, -19) | -54 (-110, -20) | -32 (-57, -14) |
| BC | 580 (96, 1500) | 150 (56, 300) | 150 (58, 280) | 86 (43, 150) |
| H$_2$O | 0.031 (0.0052, 0.082) | 0.008 (0.003, 0.016) | 0.0077 (0.0031, 0.015) | 0.0045 (0.0023, 0.0077) |
### SI.2.2. Reduced Order Cost Results – Full tables

#### Table SI.13: Full Flight Results

|                  | Climate                  | Air Quality               | 2% Disc. Rate | 2.5% Disc. Rate | 3% Disc. Rate | 5% Disc. Rate | 7% Disc. Rate | 3% Disc. Rate | 3% Disc. Rate |
|------------------|---------------------------|---------------------------|---------------|----------------|---------------|---------------|---------------|---------------|---------------|
|                  |                           |                           | $/tonne CO₂   | $/tonne HC     | $/tonne H₂O   | $/tonne NO₂   | $/tonne NOₓ   | Country Specific VSL | Global Average VSL |
| CO₂              | [$/tonne CO₂]             |                           | 95            | 260            | 110           | 82            | N/A           | N/A           | N/A           |
|                  |                           |                           | (14, 250)     | (9.3, 160)     | (6.7, 120)    | (2.7, 44)     | (1.5, 23)     | N/A           | N/A           |
| NOₓ: CH₄        | [$/tonne NOₓ as NO₂]     |                           | -2600         | -2200          | -2000         | -1300         | -960          | N/A           | N/A           |
|                  |                           |                           | (-7000, -370) | (-5900, -330)  | (-5100, -290) | (-3300, -210) | (-2400, -150) | N/A           | N/A           |
| NOₓ: O₃ Short   | [$/tonne NOₓ as NO₂]     |                           | 2900          | 2600           | 2400          | 1900          | 1700          | N/A           | N/A           |
|                  |                           |                           | (380, 8200)   | (350, 7100)    | (330, 6500)   | (280, 5000)   | (260, 4300)   | N/A           | N/A           |
| NOₓ: O₃ Long    | [$/tonne NOₓ as NO₂]     |                           | -850          | -730           | -640          | -430          | -310          | N/A           | N/A           |
|                  |                           |                           | (-2300, -110) | (-2000, -96)   | (-1700, -85)  | (-1100, -60)  | (-800, -45)   | N/A           | N/A           |
| NOₓ: Nitrate Aerosols | [$/tonne NOₓ as NO₂] |                           | -850          | -760           | -690          | -560          | -490          | N/A           | N/A           |
|                  |                           |                           | (-2400, -110) | (-2100, -99)   | (-1900, -93)  | (-1500, -80)  | (-1300, -72)  | N/A           | N/A           |
| NOₓ: Total      | [$/tonne NOₓ as NO₂]     |                           | -1400         | -1100          | -910          | -360          | -66           | 23000         | 22000         |
|                  |                           |                           | (-3700, -190) | (-3000, -150)  | (-2500, -120) | (-1200, 22)   | (-620, 340)   | (3500, 72000)  | (3400, 7100)  |
| Contrail-Cirrus | [$/tonne Fuel Burn]     |                           | 100           | 89             | 82            | 66            | 58            | N/A           | N/A           |
|                  |                           |                           | (12, 290)     | (11, 250)      | (10, 230)     | (8.7, 180)    | (7.8, 150)    | N/A           | N/A           |
|                  | [$/Flight km]            |                           | 0.28          | 0.25           | 0.23          | 0.19          | 0.16          | N/A           | N/A           |
|                  |                           |                           | (0.028, 0.81) | (0.03, 0.7)    | (0.028, 0.64) | (0.024, 0.5)  | (0.022, 0.43) | N/A           | N/A           |
| Fuel Sulfur     | [$/tonne S]              |                           | -21000        | -19000         | -18000        | -14000        | -12000        | 30000         | 31000         |
|                  |                           |                           | (-60000, -2800)| (-52000, -2500)| (-47000, -2400)| (-37000, -2100)| (-31000, -1900)| (47000, 100000)| (48000, 110000)|
| BC              | [$/tonne BC]             |                           | 58000         | 52000          | 47000         | 39000         | 34000         | 14000         | 12000         |
|                  |                           |                           | (7800, 160000)| (7200, 140000)| (6800, 130000)| (5900, 98000) | (5300, 83000) | (1800, 44000) | (1600, 41000) |
| H₂O             | [$/tonne H₂O]            |                           | 95            | 62             | 45            | 17            | 1.8           | 0             | 0             |
|                  |                           |                           | (14, 250)     | (9.3, 160)     | (6.7, 120)    | (2.7, 44)     | (0.28, 4.4)   | (0, 0)        | (0, 0)        |
| NMVOC           | [$/tonne HC]             |                           | N/A           | N/A            | N/A           | N/A           | N/A           | 7700          | 5200          |
|                  |                           |                           | N/A           | N/A            | N/A           | N/A           | N/A           | (1100, 2100)  | (830, 17000)  |
| CO              | [$/tonne CO]             |                           | N/A           | N/A            | N/A           | N/A           | N/A           | 290           | 230           |
|                  |                           |                           | N/A           | N/A            | N/A           | N/A           | N/A           | (43, 860)     | (36, 770)     |
| OC              | [$/tonne OC]             |                           | N/A           | N/A            | N/A           | N/A           | N/A           | 11000         | 9800          |
|                  |                           |                           | N/A           | N/A            | N/A           | N/A           | N/A           | (1500, 37000) | (1400, 34000) |
| Total           | [$/tonne Fuel Burn]     |                           | 370           | 260            | 200           | 110           | 82            | 360           | 350           |
|                  |                           |                           | (53, 990)     | (38, 700)      | (30, 530)     | (16, 290)     | (12, 210)     | (56, 1200)    | (55, 1100)    |
Table SI.14: Cruise Results with Uncertainty

|                | Climate | Air Quality |
|----------------|---------|-------------|
|                | 2% Disc. Rate | 2.5% Disc. Rate | 3% Disc. Rate | 5% Disc. Rate | 7% Disc. Rate | 3% Disc. Rate | 3% Disc. Rate |
|                | Country Specific | VSL | Global Average | VSL |
| CO₂            | [$/tonne CO₂] | 95 | (14, 250) | 62 | (9.3, 160) | 45 | (6.7, 120) | 17 | (2.7, 44) | 9.4 | (1.5, 23) | N/A | N/A |
| NOₓ: CH₄       | [$/tonne NOₓ as NO₂] | (-7800, -420) | (-6600, -370) | (-5700, -330) | (-3700, -230) | (-2600, -170) | N/A | N/A |
| NOₓ: O₃ Short  | [$/tonne NOₓ as NO₂] | (-3300) | (-2900) | (-2700) | (-2200) | (-1900) | (-1300, -73) | N/A | N/A |
| NOₓ: O₃ Long   | [$/tonne NOₓ as NO₂] | (-950) | (-810) | (-720) | (-480) | (-900, -50) | N/A | N/A |
| NOₓ Aerosols   | [$/tonne NOₓ as NO₂] | (-860) | (-760) | (-700) | (-570) | (-500) | N/A | N/A |
| NOₓ: Total     | [$/tonne NOₓ as NO₂] | (-1400) | (-1200) | (-940) | (-340) | (-20) | (3300, 69000) | (3400, 70000) |
| Contrail-Cirrus| [$/tonne Fuel Burn] | 110 | (13, 320) | 100 | (12, 280) | 92 | (11, 260) | 75 | (9.8, 200) | 66 | (8.9, 170) | N/A | N/A |
| Fuel Sulfur    | [$/tonne S] | -24000 | (-67000, -3100) | -21000 | (-58000, -2800) | -20000 | (-53000, -2700) | -16000 | (-41000, -2300) | -14000 | (-35000, -2100) | 30000 | 32000 |
| BC             | [$/tonne BC] | 64000 | (8600, 180000) | 57000 | (8000, 150000) | 52000 | (7500, 140000) | 43000 | (6500, 110000) | 37000 | (5800, 92000) | 7000 | 7200 |
| H₂O            | [$/tonne H₂O] | 3.5 | (0.48, 9.6) | 3.1 | (0.44, 8.4) | 2.8 | (0.41, 7.5) | 2.3 | (0.36, 5.9) | 2 | (0.32, 5) | N/A | N/A |
| NMVOC          | [$/tonne HC] | N/A | N/A | N/A | N/A | N/A | (360, 7300) | (340, 7000) |
| CO             | [$/tonne CO] | N/A | N/A | N/A | N/A | N/A | (31, 630) | (28, 610) |
| OC             | [$/tonne OC] | N/A | N/A | N/A | N/A | N/A | (7000) | (7200) |
| Total          | [$/tonne Fuel Burn] | 380 | (54, 1000) | 270 | (39, 720) | 210 | (31, 560) | 120 | (18, 310) | 90 | (13, 230) | 340 | 340 |
Table SI.15: Landing and Take-off Results with Uncertainty

|                | 2% Disc. Rate | 2.5% Disc. Rate | 3% Disc. Rate | 5% Disc. Rate | 7% Disc. Rate |
|----------------|---------------|-----------------|---------------|---------------|---------------|
| Climate        |               |                 |               |               |               |
| CO₂ [$/tonne CO₂] | 95            | 63              | 45            | 17            | 9.5           |
| NOₓ: CH₄ [$/tonne NOₓ as NO₂] | -550 | -470            | -410          | -270          | -200          |
| NOₓ: O₃ Short [$/tonne NOₓ as NO₂] | 390 | 350             | 320           | 260           | 230           |
| NOₓ: O₃ Long [$/tonne NOₓ as NO₂] | -180 | -160            | -140          | -91           | -66           |
| NOₓ: Nitrate Aerosols [$/tonne NOₓ as NO₂] | -440 | -400            | -360          | -300          | -260          |
| NOₓ: Total [$/tonne NOₓ as NO₂] | -780 | -670            | -590          | -400          | -290          |
| Contrain-Cirrus [$/tonne Fuel Burn] | 0             | 0               | 0             | 0             | N/A           |
| Fuel Sulfur [$/tonne S] | -3200 | -2800           | -2600         | -2100         | -1800         |
| BC [$/tonne BC] | 22000 | 20000           | 18000         | 15000         | 13000         |
| H₂O [$/tonne H₂O] | 0             | 0               | 0             | 0             | N/A           |
| NMVOC [$/tonne HC] | N/A           | N/A             | N/A           | N/A           | N/A           |
| CO [$/tonne CO] | N/A           | N/A             | N/A           | N/A           | N/A           |
| OC [$/tonne OC] | N/A           | N/A             | N/A           | N/A           | N/A           |
| Total [$/tonne Fuel Burn] | 290           | 190             | 130           | 49            | 26            |

Air Quality

|                | 3% Disc. Rate | 3% Disc. Rate |
|----------------|---------------|---------------|
| Climate        | Country Specific VSL | Global Average VSL |
| CO₂            | N/A           | N/A           |
| NOₓ: CH₄       | N/A           | N/A           |
| NOₓ: O₃ Short  | N/A           | N/A           |
| NOₓ: O₃ Long   | N/A           | N/A           |
| NOₓ: Nitrate Aerosols | N/A        | N/A           |
| NOₓ: Total     | N/A           | N/A           |
| Contrain-Cirrus | N/A         | N/A           |
| Fuel Sulfur    | 37000         | 26000         |
| BC             | 66000         | 45000         |
| H₂O            | 24000         | 160000        |
| NMVOC          | 32000         | 24000         |
| CO             | 66000         | 45000         |
| OC             | 43000         | 34000         |
| Total          | 590           | 430           |
### Table S.I.16: Regional Full Flight Results (3% Discount Rate)

|                  | Country Specific VSL | Global Average VSL |
|------------------|-----------------------|--------------------|
|                  | Asia-Pacific | European | North American | USA | Asia-Pacific | European | North American | USA |
| NO₂ [$/tonne NO₂ as NO₂] | 21000 | 34000 | 23000 | 24000 | (3300, 71000) | (5200, 100000) | (3500, 72000) | (3700, 75000) | (3500, 73000) | (4500, 95000) | (3300, 70000) | (3400, 71000) |
| Fuel Sulfur [$/tonne S] | 26000 | 43000 | 30000 | 32000 | (4000, 90000) | (6500, 140000) | (4700, 100000) | (4900, 110000) | (4300, 95000) | (6300, 140000) | (4700, 100000) | (4900, 110000) |
| BC [$/tonne BC] | 15000 | 25000 | 12000 | 14000 | (2000, 52000) | (3200, 75000) | (1600, 37000) | (1900, 43000) | (2200, 34000) | (2500, 62000) | (1200, 30000) | (1300, 32000) |
| NMVOC [$/tonne HC] | 6400 | 20000 | 4100 | 4400 | (950, 20000) | (2700, 54000) | (620, 12000) | (660, 13000) | (970, 20000) | (1700, 37000) | (480, 9900) | (500, 10000) |
| CO [$/tonne CO] | 260 | 500 | 260 | 270 | (38, 860) | (73, 1400) | (39, 790) | (41, 830) | (37, 850) | (53, 1100) | (32, 700) | (33, 720) |
| OC [$/tonne OC] | 9600 | 22000 | 10000 | 11000 | (1300, 34000) | (2900, 68000) | (1400, 33000) | (1600, 36000) | (1400, 35000) | (2300, 57000) | (1100, 28000) | (1200, 30000) |
| Total [$/tonne Fuel Burn] | 350 | 550 | 330 | 350 | (53, 1200) | (83, 1700) | (51, 1000) | (55, 1100) | (57, 1200) | (73, 1500) | (48, 1000) | (51, 1100) |

### Table S.I.17: Regional Cruise Results (3% Discount Rate)

|                  | Country Specific VSL | Global Average VSL |
|------------------|-----------------------|--------------------|
|                  | Asia-Pacific | European | North American | USA | Asia-Pacific | European | North American | USA |
| NO₂ [$/tonne NO₂ as NO₂] | 19000 | 31000 | 23000 | 24000 | (3000, 62000) | (4700, 96000) | (3600, 75000) | (3800, 78000) | (3000, 65000) | (4400, 93000) | (3600, 74000) | (3700, 77000) |
| Fuel Sulfur [$/tonne S] | 25000 | 42000 | 31000 | 33000 | (3900, 87000) | (6400, 140000) | (4800, 110000) | (5100, 110000) | (4100, 91000) | (6400, 140000) | (5000, 110000) | (5300, 120000) |
| BC [$/tonne BC] | 5700 | 11000 | 7200 | 7400 | (790, 20000) | (1500, 38000) | (1000, 25000) | (1000, 26000) | (860, 22000) | (1500, 38000) | (1000, 25000) | (1000, 26000) |
| NMVOC [$/tonne HC] | 2000 | 3200 | 2400 | 2400 | (300, 6300) | (490, 9800) | (370, 7400) | (370, 7500) | (300, 6300) | (440, 9100) | (340, 7100) | (340, 7200) |
| CO [$/tonne CO] | 180 | 270 | 220 | 220 | (27, 580) | (40, 820) | (33, 680) | (34, 690) | (26, 570) | (35, 760) | (30, 640) | (30, 650) |
| OC [$/tonne OC] | 5700 | 11000 | 7200 | 7400 | (790, 20000) | (1500, 38000) | (1000, 25000) | (1000, 26000) | (860, 22000) | (1500, 38000) | (1000, 25000) | (1000, 26000) |
| Total [$/tonne Fuel Burn] | 310 | 480 | 330 | 360 | (48, 1000) | (74, 1500) | (52, 1100) | (56, 1200) | (51, 1100) | (70, 1500) | (51, 1100) | (55, 1100) |
Table SI.18: Regional Landing and Take-off Results (3% Discount Rate)

|                | Country Specific VSL | Global Average VSL |
|----------------|----------------------|--------------------|
|                | Asia-Pacific | European | North American | USA         | Asia-Pacific | European | North American | USA         |
| NO\textsubscript{x} as NO\textsubscript{2} [$/tonne NO\textsubscript{x}] | 44000        | 67000     | 18000          | 20000       | 46000        | 35000     | 8300           | 8900         |
| (6400, 150000) | (8600, 180000)      | (2500, 48000)      | (2800, 53000)   | (7100, 160000) | (5100, 120000) | (1300, 27000) | (1400, 29000) |
| Fuel Sulfur [$/tonne S] | 37000        | 52000     | 20000          | 24000       | 38000        | 32000     | 8700           | 10000        |
| (5000, 130000) | (6600, 150000)      | (2600, 57000)      | (3000, 66000)   | (5400, 130000) | (4400, 110000) | (1300, 30000) | (1400, 35000) |
| BC [$/tonne BC] | 83000        | 120000    | 41000          | 50000       | 82000        | 64000     | 16000          | 19000        |
| (11000, 280000) | (14000, 320000)    | (5000, 110000)     | (6000, 140000)  | (12000, 290000) | (9000, 220000) | (2300, 56000) | (2700, 67000) |
| NMVOC [$/tonne HC] | 18000        | 56000     | 7400           | 8000        | 170000       | 29000     | 4500           | 4700         |
| (2600, 55000) | (7400, 150000)      | (1000, 20000)      | (1100, 21000)   | (2700, 55000) | (4400, 97000) | (700, 15000) | (740, 15000)  |
| CO [$/tonne CO] | 480          | 1100      | 380            | 400         | 450          | 600       | 250            | 260          |
| (63, 1600) | (150, 2800)       | (54, 1100)        | (56, 1100)      | (62, 1600) | (95, 2000) | (38, 830) | (39, 860) |
| OC [$/tonne OC] | 110000      | 190000    | 60000          | 76000       | 110000       | 100000    | 23000          | 29000        |
| (15000, 380000) | (23000, 530000)    | (7200, 170000)     | (9100, 210000)  | (16000, 390000) | (14000, 360000) | (3300, 82000) | (4100, 100000) |
| Total [$/tonne Fuel Burn] | 720          | 1100      | 280            | 320         | 760          | 600       | 130            | 140          |
| (100, 2400) | (150, 3100)       | (39, 730)        | (44, 830)       | (120, 2600) | (88, 2100) | (20, 420) | (22, 470) |

### SI.2.2.1. Air Quality Discount Rate Adjustments

As indicated, the air quality presented in Table SI.13 to Table SI.18 are derived using a 3% discount rate. Air quality results can be adjusted for a 2% and 7% discount rates by multiplying these above air quality results by 1.0311 and 0.9007 respectively. These differences are caused by the cessation lag between exposure and mortalities.
### SI.2.2.2. CAQSC cost of fuel burn

**Table SI.19: CAQSC cost of fuel burn in different flight phases (USD/Tonne Fuel Burn in 2015) (3% discount rate)**

|                | Landing and Take-off | Cruise | Full Flight |
|----------------|----------------------|--------|-------------|
|                | Climate  | Air Quality | Total  | Climate  | Air Quality | Total  | Climate  | Air Quality | Total  |
| CO₂            | 140      | N/A         | 140    | 140      | N/A         | 140    | 140      | N/A         | 140    |
|                | (21, 370)| (21, 370)   | (21, 370) | (21, 370)| (21, 370)   | (21, 370) | (21, 370)| (21, 370)   | (21, 370) |
| NOₓ            | -9       | 560         | 550    | -14      | 320         | 300    | -14      | 340         | 330    |
|                | (-24, -1.2)| (79, 1600) | (70, 1600)| (-38, -1.9)| (50, 1000) | (35, 1000)| (-37, -1.8)| (52, 1100) | (38, 1100) |
| Contrail-Cirrus*| 0       | 0           | 0      | 92       | N/A         | 92     | 82       | N/A         | 82     |
|                |          | (11, 260)   | (11, 260) |          | (11, 260)   | (11, 260) |          | (10, 230)   | (10, 230) |
| Fuel Sulfur    | -1.6     | 19          | 18     | -12      | 18          | 6.3    | -11      | 18          | 7.6    |
|                | (-4.2, -0.22)| (2.6, 59) | (0.92, 58)| (-32, -1.6)| (2.8, 62) | (-18, 52)| (-28, -1.4)| (2.8, 62) | (-15, 53) |
| BC             | 0.89     | 3.2         | 4.1    | 1.8      | 0.25        | 2.1    | 1.7      | 0.5         | 2.2    |
|                | (0.096, 2.6)| (0.42, 9.6)| (0.98, 11)| (0.26, 4.9)| (0.034, 0.87)| (0.48, 5.2)| (0.25, 4.5)| (0.067, 1.6)| (0.6, 5.3)|
| H₂O            | 0        | 0           | 0      | 3.5      | N/A         | 3.5    | 3.1      | N/A         | 3.1    |
|                |          | (0.51, 9.3) | (0.51, 9.3)|          | (0.45, 8.2) | (0.45, 8.2) |          | (0.17, 3.4) | (0.17, 3.4) |
| NMVOC          | 11       | N/A         | 11     | 0.27     | 0.27        | 0.27   | N/A      | 1.2         | 1.2    |
|                | (1.6, 31)| (1.6, 31)   |          | (0.042, 0.85)| (0.042, 0.85)|          | (0.17, 3.4)| (0.17, 3.4) |          |
| CO             | N/A      | 4.3         | 4.3    | 0.39     | 0.39        | 0.39   | N/A      | 0.72        | 0.72   |
|                |          | (0.62, 12)  | (0.62, 12)|          | (0.06, 1.2) | (0.06, 1.2)|          | (0.11, 2.1) | (0.11, 2.1)|
| OC             | N/A      | 0.77        | 0.77   | 0.11     | 0.11        | 0.11   | N/A      | 0.16        | 0.16   |
|                |          | (0.098, 2.2)| (0.098, 2.2)|          | (0.015, 0.37)| (0.015, 0.37)|          | (0.022, 0.53)| (0.022, 0.53)|
| Total Cost     | 130      | 590         | 730    | 210      | 340         | 550    | 200      | 360         | 560    |
|                | (20, 340)| (84, 1700)  | (180, 1900)| (31, 560)| (53, 1100)  | (170, 1400)| (30, 530)| (56, 1200)  | (180, 1400)|
| Compartment       | Climate  | Air Quality | Total | Climate  | Air Quality | Total |
|-------------------|----------|-------------|-------|----------|-------------|-------|
| $\text{CO}_2$     | 300      | N/A         | 300   | (44, 790)| N/A         | 30    |
| $\text{NO}_x$     | -21      | 350         | 330   | (-55, -2.9)| 310         | 300   |
| Contrail-Cirrus*  | 100      | N/A         | 100   | (12, 290)| N/A         | 58    |
| Fuel Sulfur       | -13      | 19          | 5.9   | (-36, -1.7)| 16          | 8.9   |
| BC                | 2.1      | 0.51        | 2.6   | (0.28, 5.8)| 0.45        | 1.7   |
| $\text{H}_2\text{O}$ | 3.8  | N/A         | 3.8   | (0.52, 10)| (0.35, 5.4)| 2.2   |
| NMVOC             | N/A      | 1.2         | 1.2   | N/A      | 1.1         | 1.1   |
| CO                | N/A      | 0.74        | 0.74  | N/A      | 0.65        | 0.65  |
| OC                | N/A      | 0.17        | 0.17  | N/A      | 0.15        | 0.15  |
| Total Cost        | 370      | 370         | 740   | 82       | 320         | 410   |
SI.2.2.3. Global LTO Comparison to Literature (Shindell 2015)

We compare our LTO results to Shindell (2015), who presented climate and air quality cost of emissions at ground level.

Table SI.21 presents our LTO results for climate and air quality alongside those given by Shindell. We compare our climate results to only Climate damages which Shindell calculated using a damage function approach, excluding the additional health and regional climate damages also given by Shindell.

We find that almost all of Shindell’s results fall within our 5th and 95th percentile range. The only exception is the climate damages associated with NOx emission, for which our calculated impact exceeds the impact calculated by Shindell by an order of magnitude. However, the air quality costs per unit NOx are consistent, and are two orders of magnitude greater than our calculated climate costs. As a result, we find a consistent total impact per unit NOx.

In addition, although Shindell’s results fall within our uncertainty bounds, there are still large differences in the estimated mean values. We estimate air quality impacts for fuel sulfur and emitted black carbon which are one third and one half, respectively, of those given by Shindell. The difference in fuel sulfur impact could be due to differences in marginal and average damage approaches (see SI.2.5). Shindell determined average damages using total annual mortalities, total speciated global emissions, and the fractional contribution of each species to estimate the average cost due to one unit of emission. However, we compute marginal air quality impacts using the adjoint of the GEOS-Chem chemistry transport model. This captures behavior such as the low (or even negative) sensitivity of total particulate matter to sulfur emissions under certain atmospheric chemical conditions (Seinfeld and Pandis 2016), which could result in a lower marginal impact compared to the average impact.

The difference in BC results is likely a result of the large grid cells used in the present study as discussed in Sec 2.3, which we expect will lead to underestimation of the black carbon impact (Arunachalam et al 2011, Li et al 2016, Thompson et al 2014, Fenech et al 2018, Barrett et al 2010). Shindell’s values, which are based on higher resolution measurements, still remain within the uncertainty bounds of the present study.
Table SI.21: Comparison to Shindell (2015)

|                  | Climate 3% Discount Rate | Climate 5% Discount Rate | Air Quality |
|------------------|--------------------------|--------------------------|-------------|
|                  | Shindell | Present Study | Shindell | Present Study | Shindell | Present Study |
| CO₂ [$/tonne CO₂] | 36.2     | 45 (6.7, 120) | 11.3     | 17 (2.7, 44)  | 0.0       | N/A           |
| NOₓ [$/tonne NO₂] | -75.7    | -590 (-1600, -81) | -19.3    | -400 (-1100, -55) | 23043.6  | 26000 (4000, 89000) |
| Sulfur Impact [$/tonne S] | -3164.2 | -2600 (-7000, -360) | -2034.1  | -2100 (-5500, -310) | 74584.7  | 24000 (3400, 85000) |
| BC [$/tonne BC]  | 22601.4  | 18000 (2000, 52000) | 14690.9  | 15000 (1700, 41000) | 70064.4  | 45000 (6300, 160000) |
| CO [$/tonne CO]  | 101.7    | N/A                      | 47.5     | N/A                      | 271.2    | 360 (56, 1200) |
| OC [$/tonne OC]  | -3164.2  | N/A                      | -2034.1  | N/A                      | 57633.6  | 66000 (9200, 230000) |

For consistency, the Shindell (2015) values in above table have been adjusted for mass units (from per tonne N to tonne NO₂ and from tonne SO₂ to tonne S) and dollar values were also adjusted from 2007 USD to 2015 USD.

SI.2.2.4. Regional Air Quality Comparison to Literature

We compare the US based LTO findings to the results by Penn et al (2017), who quantify the annual mortalities resulting from aviation emissions at 66 major US airports. Penn et al (2017) estimated that these emissions result in 100 mortalities annually, accounting for 85% of all LTO related mortalities in the US. Monetizing these deaths using the global average VSL of 3.8 million USD, and combining with US LTO fuel burn of \(4.53 \times 10^6\) tonnes, results in normalized damages of 99 $/Tonne US LTO fuel burn, which is within our uncertainty bounds of 24 to 450 $/tonne US LTO fuel burn for a globally averaged VSL.

When comparing our PM\(_{2.5}\) LTO US metrics to Dorbian et al (2011), we find our fuel sulfur and NOₓ results fall within their uncertainty range, while our BC and OC cost results falls below the Dorbian et al (2011) uncertainty range. BC and OC contribute to direct PM\(_{2.5}\) formation, and as such our lower values are likely due to the impact of using large grid cells.

SI.2.2.5. Climate Yearly Growth of Metrics

The magnitude of climate damages per unit of emission increases with time, given the middle of the road RCP 4.5 and SSP 1 scenarios used in this study. These growth rates are calculated by using APMT-IC to calculate the marginal costs per unit of emissions for emissions pulses in
2025, 2035, 2045, and 2055 for each discount rate. Subsequently a growth rate $r$ is calculated for each forcer by using the derived cost data to perform a least-squares fit to the functional form of Eq 30.

$$NPV_{t=2015+\Delta t} = NPV_{2015}(1 + r)^{\Delta t}$$

Eq 30

In this equation, $NPV_{2015}$ represents the marginal climate cost in 2015 and $NPV_{t=2015+\Delta t}$ represents the marginal climate costs due to an emissions pulse $\Delta t$ years after 2015.

Table S1.22 shows the derived annual growth rate for each species under three different discount rates. These growth rates can be used along with Eq 30 to adjust the climate cost metrics presented in Section S1.2.2 for emissions in future years. To calculate the impact of future emissions of NO\textsubscript{x}, the impact of the individual NO\textsubscript{x} components must be computed individually, and summed for the overall NO\textsubscript{x} impact.

|                      | 2% Discount Rate | 3% Discount Rate | 7% Discount Rate |
|----------------------|------------------|------------------|------------------|
| CO\textsubscript{2}  | 1.6%             | 2.1%             | 3.2%             |
| NO\textsubscript{x}: CH\textsubscript{4} | 3.5%             | 3.8%             | 4.3%             |
| NO\textsubscript{x}: O\textsubscript{3} Short | 4.3%             | 4.7%             | 5.0%             |
| NO\textsubscript{x}: O\textsubscript{3} Long | 3.5%             | 3.8%             | 4.3%             |
| NO\textsubscript{x}: Nitrate Aerosols | 4.3%             | 4.7%             | 5.0%             |
| Contrail Cirrus      | 4.3%             | 4.7%             | 5.0%             |
| Sulfates             | 4.3%             | 4.7%             | 5.0%             |
| Black Carbon         | 4.3%             | 4.7%             | 5.0%             |
| H\textsubbox{2}O     | 4.3%             | 4.7%             | 5.0%             |

The growth rates in Table S1.22 show increasing marginal costs of emissions pulses in future years. This observed increase in the magnitude of marginal costs is driven by three factors. The first is a combination of increasing background temperature change under the RCP 4.5 scenario and the non-linear DICE damage function. As background temperature change increases, total damages increase approximately quadratically (see Eq 19). As a result, the same amount of marginal temperature change will result in higher marginal damages as time passes, because of background temperature change increases. Secondly global GDP increases with time under SSP 1 scenario. Because damages are computed as a fraction of global GDP, as the GDP increases, so do the calculated damages, even if the temperature change remains constant. Third, for CO\textsubscript{2}, the accumulation of CO\textsubscript{2} in the atmosphere with time under the RCP 4.5 scenario leads to slower
removal of a marginal pulse of CO₂. This leads to more warming and more subsequent damage per unit of marginal CO₂ as time increases.

**SI.2.2.6. Sensitivity to RCP and SSP Scenario**

Climate results presented in Section SI.2.1 to SI.2.5 were derived using RCP 4.5 and SSP 1 scenarios, which both represent middle of the road scenarios. Sensitivity to alternative scenarios is evaluated by computing climate results for alternative emissions and socio-economic scenarios, such as low and high RCP and SSP scenarios.

Table SI.23 presents changes to results under RCP 2.6 and RCP 8.5, representing low and high background emissions scenarios respectively. Higher background CO₂ emissions lead to longer lasting aviation CO₂, in turn which leads to a decrease in the radiative forcing due to an extra unit of CO₂, however, increased background emissions also increases the background temperature change, which increases the marginal climate damages. On net, an increase in background emissions leads to an increase in damages for a warming forcer, and an increase in benefit for cooling forcers as illustrated by Table SI.23.

Table SI.24 presents changes to results under SSP 3 and SSP 5 scenarios representing low and high socio-economic scenarios respectively.

*Table SI.23: Climate model Sensitivity to RCP Scenario*

|                      | RCP 2.6 (Low Emission Scenario) | RCP 8.5 (High Emission Scenario) |
|----------------------|---------------------------------|----------------------------------|
|                      | 2% DR  | 3% DR  | 7% DR  | 2% DR  | 3% DR  | 7% DR  |
| CO₂                  | -25%   | -18%   | -7%    | 11%    | 14%    | 9%     |
| NOₓ: CH₄             | -10%   | -7%    | -3%    | 17%    | 12%    | 7%     |
| NOₓ: O₃ Short       | -7%    | -3%    | 0%     | 13%    | 8%     | 3%     |
| NOₓ: O₃ Long        | -10%   | -7%    | -3%    | 17%    | 12%    | 7%     |
| NOₓ: Nitrate Aerosols| -7%    | -3%    | 0%     | 13%    | 8%     | 3%     |
| NOₓ: Total          | -15%   | -15%   | -58%   | 22%    | 21%    | 75%    |
| Contrail-Cirrus      | -7%    | -3%    | 0%     | 13%    | 8%     | 3%     |
| Sulfur Impact        | -7%    | -3%    | 0%     | 13%    | 8%     | 3%     |
| BC                   | -7%    | -3%    | 0%     | 13%    | 8%     | 3%     |
| H₂O                  | -7%    | -3%    | 0%     | 13%    | 8%     | 3%     |
| Total                | -21%   | -13%   | -2%    | 11%    | 11%    | 4%     |

*Table SI.24: Climate model Sensitivity to SSP Scenario*

|                      | SSP 3 (Low Socio-Economic Scenario) | SSP 5 (High Socio-Economic Scenario) |
|----------------------|------------------------------------|--------------------------------------|
|                      | 2% DR    | 3% DR    | 7% DR    | 2% DR    | 3% DR    | 7% DR    |
| CO₂                  | -42%     | -39%     | -23%     | 79%      | 53%      | 19%      |
SI.2.3. CO₂ Equivalent Climate Results per Unit of Fuel Burn

In this section, cost metrics are presented on a CO₂ equivalent per unit of fuel burn basis, in the form of a Net Present Value (NPV) ratio. The NPV ratios are calculated using the mathematical expression

\[
\text{NPV Ratio} = \frac{\text{NPV}_{X,\text{per unit fuel burn}}}{\text{NPV}_{\text{CO}_2,\text{per unit fuel burn}}} \quad \text{Eq 31}
\]

where \(\text{NPV}_{X,\text{per unit fuel burn}}\) represents the climate cost or benefit of emissions species \(X\) per unit of fuel burn, and \(\text{NPV}_{\text{CO}_2,\text{per unit fuel burn}}\) represents the climate cost/benefit of CO₂ for a unit of fuel burn. Therefore, these ratios represent the relative importance of each of the short-lived climate forcers to the importance of CO₂ for each unit of fuel burn.

In this study, these results are derived by applying Eq 31 to each Monte Carlo simulation, and then the mean, and 5th and 95th percentile values are found from the set of 100,000 Monte Carlo simulations. Table SI.25 presents the results for the mean, 5th and 95th percentile of the NPV ratios.

|                     | 2% Discount Rate | 3% Discount Rate | 7% Discount Rate |
|---------------------|------------------|------------------|------------------|
| CO₂                 | 1.00             | 1.00             | 1.00             |
|                     | (1.00, 1.00)     | (1.00, 1.00)     | (1.00, 1.00)     |
| NOx                 | -0.07            | -0.09            | -0.03            |
|                     | (-0.10, -0.04)   | (-0.15, -0.05)   | (-0.24, 0.14)    |
| Contrails*          | 0.33             | 0.58             | 1.95             |
|                     | (0.16, 0.53)     | (0.28, 0.92)     | (0.96, 3.08)     |
| Fuel Sulfur         | -0.04            | -0.07            | -0.25            |
|                     | (-0.06, -0.03)   | (-0.11, -0.05)   | (-0.36, -0.16)   |
| BC                  | 0.01             | 0.01             | 0.04             |
|                     | (0.00, 0.01)     | (0.01, 0.01)     | (0.03, 0.05)     |
These metrics correspond to the metrics presented in Table 2 in Dorbian et al (2011). However, low and high results in Dorbian et al (2011) are presented for low and high lens assumptions, and not by Monte Carlo Simulation.

For ease of comparison, the results presented in Dorbian et al (2011) are presented in Table SI.26. The Dorbian et al (2011) contrail and the total fuel burn results fall within our contrail uncertainty range, however NO\textsubscript{x}, fuel sulfur, BC, H\textsubscript{2}O fall outside our uncertainty range. Both Dorbian et al (2011) and the present study were derived using the same climate model (APMT-IC).

Table SI.26: Cost Metrics presented in Dorbian et al (2011) on a CO\textsubscript{2} equivalent per unit of fuel burn basis. The values between the brackets represent model assumptions for low and high climate damages for both the numerator (the short-lived climate forcer) and the denominator (CO\textsubscript{2}).

|         | 2% Discount Rate | 3% Discount Rate | 7% Discount Rate |
|---------|------------------|------------------|------------------|
| CO\textsubscript{2} | 1.00 (1.00, 1.00) | 1.00 (1.00, 1.00) | 1.00 (1.00, 1.00) |
| NO\textsubscript{x} | -0.03 (-0.05, -0.03) | -0.03 (-0.06, -0.03) | 0.18 (0.07, 0.15) |
| Contrails* | 0.42 (0.1, 0.56) | 0.74 (0.19, 1.06) | 2.28 (0.62, 3.56) |
| Fuel Sulfur | -0.11 (-0.27, -0.01) | -0.2 (-0.51, -0.01) | -0.61 (-1.65, -0.03) |
| BC | 0.08 (0.01, 0.14) | 0.14 (0.01, 0.25) | 0.43 (0.03, 0.85) |
| H\textsubscript{2}O | 0.07 (0.00, 0.13) | 0.13 (0.01, 0.25) | 0.41 (0.02, 0.83) |
| Total Fuel Burn | 1.4 (0.8, 1.8) | 1.8 (0.6, 2.5) | 3.7 (0.1, 6.4) |

* Contrails includes contrail-cirrus

The differences in results can be explained by changes in short-lived climate forcer uncertainty distributions. Table SI.27 shows the radiative forcing estimates for aviation used in the present study, as well as in Dorbian et al (2011). Changes in these estimates are due updated radiative
estimates derived by the ACCRI phase two research initiative (Brasseur et al 2016). Results for the overall total fuel burn remains the similar because it is driven by the largest cost contributors, CO\(_2\) and contrails, for which the uncertainty distributions have remained stable.

Table SI.27: Comparison of RF Uncertainty Distributions

| Forcer                          | Present study | Dorbian et al (2011) |
|---------------------------------|---------------|----------------------|
|                                 | Based on Brasseur et al (2016) |                      |
| Contrails (and Contrail Cirrus) | 37.9 (12.4 to 80) | 33, (12.5 to 86.7)   |
| Fuel Sulfur                     | -4.8 (-3 to -9) | -4.8, (-0.79 to -29.3) |
| BC                              | 0.6 to 1 (Uniform Distribution) | 3.4 (0.56 to 20.7)   |
| H\(_2\)O                        | 1.3 to 2 (Uniform Distribution) | 2.8 (0.39 to 20.3)   |
| Nitrates (One of four indirect NO\(_x\) impacts included in the climate model) | -7.5 to -3 (Uniform Distribution) | Not included |

SI.2.4. Results – Percentage PM\(_{2.5}\) vs Ozone Impact

Table SI.28 presents the percentage of the total air quality impact arising from the PM\(_{2.5}\) emission to impact pathway. The remainder of the impact arises from the population exposure to ozone.

In all flight phases, and for all species except CO, we find the PM\(_{2.5}\) impact pathway the largest contributor to costs. Per unit fuel burn we find the PM\(_{2.5}\) impact pathway to be responsible for 63% of the overall costs in full flight, similar to Eastham and Barrett (2016) who find an overall percentage of 58% mortalities from PM\(_{2.5}\), and the remainder from ozone related impacts. In the LTO flight phase we find the PM\(_{2.5}\) impact pathway to be responsible for 80% of the impact, and 60% in cruise.

Table SI.28: PM\(_{2.5}\) Impact as a percentage of overall impact.

|                  | Full Flight | LTO   | Cruise |
|------------------|-------------|-------|--------|
| NO\(_x\)         | 62%         | 80%   | 59%    |
| Sulfur Impact    | 80%         | 98%   | 79%    |
| BC               | 100%        | 100%  | 100%   |
| NMVOC            | 67%         | 71%   | 53%    |
| CO               | 39%         | 39%   | 38%    |
| OC               | 100%        | 100%  | 100%   |
SI.2.5. Marginal and Average Costs

Due to non-linearities involved in both climate and air quality impacts, the marginal cost, which is the cost due to an additional unit of emission, differs from the average cost of a unit of anthropogenic emission. In line with the purpose of this paper, we present marginal cost metrics, which are applicable to evaluate the impact of marginal emissions interventions. However, this approach is not appropriate when quantifying aviation’s contribution to the total anthropogenic damages. To illustrate, we present an example based on the climate damage function.

The climate results are derived using a nonlinear damage function defined by Nordhaus (2017). Using this damage function, total damages due to anthropogenic emissions is calculated using Eq 32.

\[
D(\Delta T_{all}) = \frac{a\Delta T_{all}^2}{a\Delta T_{all}^2 + 1}
\]

Eq 32

Where $\Delta T_{all}$ is the temperature increase from preindustrial conditions and $a$ represents the damage function coefficient defined as discussed in Section SI.1.2.6.

The damages due to an average unit of background emission can be calculated by attributing a portion of the total damages to the unit of background emissions, for instance on a CO$_2$ equivalent emissions basis, or on a temperature change basis.

In contrast, the damages due to an additional unit of emissions, i.e. marginal damages, are estimated using

\[
D_{Marginal}(\Delta T_{all}, \Delta T) = D(\Delta T_{all}) - D(\Delta T_{all} - \Delta T)
\]

Eq 33

While the marginal approach remains valid to evaluate the impact of emissions interventions, it would not accurately capture the total damages due to anthropogenic emissions if each sector is treated individually. Or put differently, if this same marginal approach (Eq 33) is used to calculate the impacts from all sectors individually, the damages from the sum of all the sectors will not be equal to the total damages as calculated with Eq 32.

For climate, we expect the marginal damages per unit temperature change to be larger than the total damages per unit temperature change, due to the quadratic nature of the non-linear damage function for the range of $\Delta T_{all}$ considered under the RCP scenarios ($\Delta T_{all} < 10$ °C).
To quantify this, we can find the ratio of marginal damages per unit of temperature increase ($\Delta T$) to the average damages per unit of temperature increase from preindustrial conditions ($\Delta T_{all}$). Mathematically this can be written as

$$\text{Ratio} = \frac{D_{\text{Marginal}}(\Delta T_{all}, \Delta T)}{D(\Delta T_{all})/\Delta T_{all}}$$

Eq 34

By substituting the damage function (Eq 32) and recognizing that for infinitesimal temperature increases, the numerator can be written as the derivative of the damage function, the ratio becomes

$$\text{Ratio} = \frac{2}{a \Delta T_{all}^2 + 1}$$

Eq 35

For small all-source temperature increases, the marginal climate damages per unit of temperature change is subsequently approximately double the damages for an average unit of background temperature change. Under RCP 4.5 emissions scenario, total temperature increases are predicted to be between 1 and 5 °C and $a = 0.00236$ fraction $\frac{\text{GDP}}{\text{°C}^2}$. Therefore, the ratio of marginal to total is expected to be between 1.9 and 2.

This analysis is greatly simplified by the analytical climate damage function. However, for the air quality impacts, numerically derived using GEOS-Chem, an analytical damage function is not available and it is not clear how the marginal damages differ from the average damages without performing multiple additional numerical simulations.

**SI.2.6. Monte Carlo Convergence and Sensitivity Study**

**SI.2.6.1. Convergence**

The climate and air quality impact distributions are computed using quasi-random Monte Carlo simulations. Uncertain parameter draws are selected using a Sobol sequence. The relative standard error of the sample mean is used to quantify convergence. It is defined as

$$\delta_{\text{StError}} = \frac{\sigma}{\sqrt{N} \cdot \mu}$$

Eq 36

where $\sigma$ indicates the output standard deviation, $N$ indicates the number of Monte Carlo simulations, and $\mu$ indicates the output mean. For the purpose of this work we consider a relative standard error of the sample mean less than 1% to be converged.
Eq 36, a result of the central limit theorem, can only be applied under the condition of a finite population variance. Finite population variance can be verified by indicating the variance of variance reduces as the number of samples increase. Figure SI.6 shows the variance of variance for the climate and air quality total fuel burn metrics as the number of Monte Carlo simulations increase. The figure is generated by running the climate and air quality models 1000 times for the number of samples indicated on the x-axis. These plots show that the variance converges as the number of samples increases. Therefore, the central limit theorem, and Eq 36 are expected to remain valid.

In this study, we used 100,000 draws. At this number of draws, the relative standard error of the sample mean is less than 0.5% for both the climate and air quality results, indicating a satisfactory level of convergence.

![Figure SI.6: Variance of variance of (a) climate and (b) air quality model outputs](image)

**SI.2.6.2. Sensitivity to Uncertain Variables**

To calculate the contribution to variance of each uncertain input variable, we estimate total effect indices. These indices indicate the fractional contribution of each uncertain input variable to the output variability, both through its direct (first-order) contribution, as well as through its interaction with other variables.

Mathematically, the total effect index can be written as

\[
S_{T_1} = 1 - \frac{V[E(Y|E_{-1})]}{V(Y)}
\]

*Eq 37*
Method

Total effect indices are estimated using Saltelli’s method (Saltelli et al 2008). Derivation steps are outlined below following the description in Saltelli (2008).

We define two matrices, A and B, which each includes a set of input variables suitable for one Monte Carlo simulation. This leads to two \((N, k)\) matrices of random numbers, where \(N\) is the number of members included in the Monte Carlo simulation, and \(k\) represents the number of uncertain variables considered. Furthermore, we define the matrix \(C_i\), which is the matrix B, with one column (i.e. values for the uncertain input variable \(i\)) replaced with the values from matrix A for the same uncertain input variable \(i\).

Then we use our climate or air quality Monte Carlo simulation code to compute the output for \(f(A), f(B)\) and \(f(C_i)\), where \(f\) indicates the climate or air quality damage quantification for the given inputs. This leads to the set of column vectors

\[
\begin{align*}
y_A &= f(A) \\
y_B &= f(B) \\
y_{C_i} &= f(C_i)
\end{align*}
\]

These column vectors are used then used to derive the \(S_{T_i}\), for input variable \(i\), using the formula

\[
S_{T_i} = 1 - \frac{y_B^T \cdot y_{C_i} - f_0^2}{y_A^T \cdot y_A - f_0^2}
\]

Where \(T\) indicates the transpose, and \(f_0\) represents the output mean

\[
f_0 = \frac{1}{N} \sum_{j=1}^{N} y_A
\]

Using this method, the \(S_{T_i}\)s are only approximate, because these values are based on Monte Carlo simulation. To ensure adequate convergence, we use a sobol’ set with \(N=100,000\) to draw the initial \((N, 2k)\) matrix for the climate results, and for air quality we use \(1,000,000\) members to derive this sensitivity study.

Results

Table SI.29 and Table SI.30 present the total effect indices for air quality and climate respectively. We find that the largest contributors to output uncertainty in the overall sensitivity of climate impact per unit of fuel burn are (i) climate sensitivity and (ii) the climate damage function, with total effect indices of 0.66 and 0.43 respectively. The indices of all other uncertain variables are below 0.04.

For air quality, we find the uncertainty in the VSL\(_{1990}\) to be the largest contributor to the overall uncertainty, with a total-effect index of 0.83. Income elasticity has a total-effect index of 0.13, while the concentration response function has indices of less than 0.06 or less.
When calculated analytically these indices sum to one for a purely additive model, but can exceed one if interaction effects exist. For the climate model, the sum over all the total-effect indices is 1.16, while for air quality the sum is 1.15. This indicates significant effect interaction for both models.

Table SI.29: Estimates of the total order sensitivity indices computed using Saltelli’s method (Saltelli et al 2008) method for air quality impact per unit of fuel burn

| Variable                              | Reference to distribution definition | Total Effect Index (STi) |
|---------------------------------------|-------------------------------------|-------------------------|
| VSL Elasticity                        | Section SI.1.3                      | 0.12                    |
| PM$_{2.5}$ CRF                        | Section SI.1.3 & Table SI.10        | 0.07                    |
| O$_3$ CRF                             | Section SI.1.3 & Table SI.10        | 0.05                    |
| VSL 1990                              | Section SI.1.3                      | 0.77                    |
| GEOS-Chem Uncertainty – PM$_{2.5}$    | Section SI.1.3                      | 0.13                    |
| GEOS-Chem Uncertainty – O$_3$         | Section SI.1.3                      | 0.02                    |
| Total                                 |                                      | 1.15                    |

Table SI.30: Estimates of the total order sensitivity indices computed using Saltelli’s method (Saltelli et al 2008) method for climate impact per unit of fuel burn

| Variable                              | Reference to distribution definition | Total Effect Index (STi) |
|---------------------------------------|-------------------------------------|-------------------------|
| CO$_2$ RF model                       | Section SI.1.2.2                    | 0.00                    |
| NO$_x$ Model                          | Section SI.1.2.3 & Table SI.5       | 0.00                    |
| RF Contrails                          | Section SI.1.2.3 & Table SI.4       | 0.04                    |
| RF Sulfates                           | Section SI.1.2.3 & Table SI.4       | 0.00                    |
| RF BC                                 | Section SI.1.2.3 & Table SI.4       | 0.00                    |
| RF H$_2$O                             | Section SI.1.2.3 & Table SI.4       | 0.00                    |
| RF Nitrate                            | Section SI.1.2.3 & Table SI.4       | 0.00                    |
| RF Doubling CO$_2$                    | Section SI.1.2.3 & Table SI.4       | 0.00                    |
| Heat Capacity of Ocean Mixed-layer    | Section SI.1.2.5 & Table SI.8       | 0.00                    |
| Climate Sensitivity                   | Section SI.1.2.5 & Table SI.8       | 0.66                    |
| Temp model Diffusion Coef             | Section SI.1.2.5 & Table SI.8       | 0.00                    |
| Temp model Advection Coef             | Section SI.1.2.5 & Table SI.8       | 0.01                    |
| Heat Capacity of Deep Ocean           | Section SI.1.2.5 & Table SI.8       | 0.00                    |
| Ocean Turbulent Mixing Depth          | Section SI.1.2.5 & Table SI.8       | 0.01                    |
| DICE Damage Function                  | Section SI.1.2.6 & Table SI.9       | 0.43                    |
| Total                                 |                                      | 1.16                    |
Monte Carlo Uncertainty Data Availability

To ensure accurate use of uncertainty estimates, the full Monte Carlo data sets for Table SI.13 to Table SI.18 are also made available as described in the “data availability statement” in the main text of the paper. These estimates are applicable to determine the uncertainty ranges for emissions scenarios, as presented in Section 3.4 of the main text.

A CSV file is provided for each column in Table SI.13 to Table SI.18. The CSV files include the ordered members of the Monte Carlo simulation, for instance the first row of each CSV file corresponds to the same Monte Carlo member. While these data sets are to be used for uncertainty estimates, central estimates can be derived using the central estimates from Table SI.13 to Table SI.18.

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