Nitrogen oxides emitted from aircraft engines alter the chemistry of the atmosphere, perturbing the greenhouse gases methane (CH₄) and ozone (O₃). We quantify uncertainties in radiative forcing (RF) due to short-lived increases in O₃, long-lived decreases in CH₄ and O₃, and their net effect, using the ensemble of published models and a factor decomposition of each forcing. The decomposition captures major features of the ensemble, and also shows which processes drive the total uncertainty in several climate metrics. Aviation-specific factors drive most of the uncertainty for the short-lived O₃ and long-lived CH₄ RFs, but a nonaviation factor dominates for long-lived O₃. The model ensemble shows strong anticorrelation between the short-lived and long-lived RF perturbations (R² = 0.87). Uncertainty in the net RF is highly sensitive to this correlation. We reproduce the correlation and ensemble spread in one model, showing that processes controlling the background tropospheric abundance of nitrogen oxides are likely responsible for the modeling uncertainty in climate impacts from aviation.

We analyze aviation NOx RF from the ensemble of all published studies since the IPCC aviation assessment (15), which synthesized earlier work. Fig. 1 shows each RF estimate from the last 12 y, broken down into its short-lived and long-lived O₃ and CH₄ components. These estimates come from diverse models, including CTMs (7, 10–12, 18–21) and coupled chemistry–climate general circulation models (GCCMs) (7, 15, 19–21). They are based on a wide range of scenarios for aviation and other emissions. Studies find little evidence for nonlinearity of the atmospheric response to aviation emissions over the range 0.4 to 1.3 Tg(N) a⁻¹ used in the ensemble here (7, 18), so we normalize all results to 1 Tg(N) a⁻¹ from aviation.

The RF values in Fig. 1 and throughout this work are the steady-state responses to aviation NOx emissions. Most studies calculate these by the difference between two steady-state simulations with differing aviation NOx emissions (7, 18–21). Three studies report 100-year integrated RF responses to pulse emissions of aviation NOx (10–12), which are comparable to the steady-state response because the integration time is much longer than the CH₄ perturbation lifetime (10–15 y). The latter studies use pulse durations between 1 mo and 1 y, which could conceivably increase the spread of RF estimates, but we find their results to be within the envelope of RF from steady-state simulations. Our ensemble statistics would not change by excluding them. We exclude one recent aviation study (22) because it results derive from the same model simulations as another included study (21) and another because of its different experimental design (23). Stated RFs are based on composition changes in the troposphere and do not include stratospheric response, although some studies also include the lower stratosphere, where aviation NOx also increases O₃.

Author contributions: C.D.H. and M.J.P. designed research; C.D.H. and Q.T. performed research; C.D.H., Q.T., and M.J.P. analyzed data; and C.D.H. and M.J.P. wrote the paper. The authors declare no conflict of interest.

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time of CH$_4$ always less than predicted at steady state due to the decadal life-time of short-lived O$_3$ abundance and larger ozone production efficiency (7, 18, 19). None of the three RF estimates in Fig. 1 exhibit any trends over the time of publication. Likewise, their spread has not changed over a decade of model development. We find no clear differences among the steady-state RF estimates in Fig. 1, and the greenhouse effect is similar to the upper tropospheric NOx feedback factor ($f_{\text{CH}_4}$), which prolongs the lifetime of CH$_4$ perturbations (16), and $d/O_3$ is the O$_3$ component of the long-lived CH$_4$ perturbation (26). Note that the product of the first three terms on the right-hand sides of Eqs. 3 and 4 equals the steady-state response of CH$_4$ abundance to aviation emissions (14).

Table 1 reviews the best estimates and one-sigma uncertainties (68% confidence interval) of each factor in Eqs. 2–4, including the values adopted in this work. Atmospheric measurements provide no direct constraints on these factors. Although the range of models does not encompass all potential uncertainties and errors, it does in this case provide a large ensemble.

Only two of the factors—$d/O_3$ and $dL_{\text{CH}_4}/dE$—require model simulations specific to aviation to derive their values and uncertainties, although $dF/d/O_3$ is also somewhat dependent on the aviation perturbation (see below). The values adopted here for $d/O_3$ and $dL_{\text{CH}_4}/dE$ encompass recent estimates based on model ensembles (19, 20), but exclude values from IPCC (15) that were based on early CTMs, which had coarse resolution at aircraft altitudes, and were not supported by subsequent studies. The poorly understood sources of model differences in these terms are discussed below, but likely involve the range of NO$_x$:NO$_2$ and OH:HO$_2$ ratios and background NOx abundances across the models.

The remaining factors can be estimated from general literature on atmospheric composition and climate, without requiring model studies or calculations specific to aviation. The O$_3$ response to long-lived CH$_4$ changes, here $d/O_3/d/CH_4 = 3.5 \pm 1.0$ DU/(ppmCH$_4$)$^{-1}$, can be calculated from models (17, this work) and is qualitatively supported by numerous studies showing that the increase in mean tropospheric O$_3$ since the preindustrial era is partially due to the increase in CH$_4$ (16). Our estimated range for the CH$_4$ feedback factor ($f_{\text{CH}_4} = 1.4 \pm 0.1$) includes values from models with widely varying chemical mechanisms (16, 17, this work). The final terms involve mapping the changes in greenhouse gases, as in the prior section. In this section we present an alternative method for determining the uncertainty of aviation impacts based on decomposing the RF into its key factors. We use literature review and expert judgment to assess the uncertainty in each factor and propagate these to the uncertainty in RF. Many of the factors can be derived from the general climate forcing literature and do not require model simulations that are specific to aviation. A major advantage of this approach is that we can identify the dominant sources of uncertainty.

The steady-state, global mean RF from aviation NOx emissions ($F$) can be broken into components due to the short-lived O$_3$ response ($F_{\text{short O}_3}$), and the long-lived CH$_4$ and O$_3$ responses ($F_{\text{long CH}_4}$, and $F_{\text{long O}_3}$, respectively):

$$F = F_{\text{short O}_3} + F_{\text{long CH}_4} + F_{\text{long O}_3} \ .$$

These components can in turn be factorized into key terms summarizing the chemical interactions between NOx, O$_3$, and CH$_4$, including their feedbacks:

$$F_{\text{short O}_3} = (d/O_3)_{\text{short}}/dE) (dF/d/O_3) \ .$$

$$F_{\text{long CH}_4} = (dL_{\text{CH}_4}/dE) f_{\text{CH}_4} (dF/d/CH_4) \ .$$

$$F_{\text{long O}_3} = (dL_{\text{O}_3}/dE) f_{\text{O}_3} (dF/d/O_3) \ .$$

where $d/O_3$ is the short-lived O$_3$ response to aviation NOx emissions ($E$) and $dL_{\text{CH}_4}/dE$ is the accompanying relative change in CH$_4$ lifetime, $dF/d/O_3$ and $dF/d/CH_4$ are the RF efficiencies of tropospheric O$_3$ and CH$_4$, $f_{\text{CH}_4} = 1.78$ ppm is the global mean CH$_4$ abundance, $f_{\text{CH}_4}$ is the feedback factor, which prolongs the lifetime of CH$_4$ perturbations (16), and $d/O_3$ is the O$_3$ component of the long-lived CH$_4$ perturbation (26). Note that the product of the first three terms on the right-hand sides of Eqs. 3 and 4 equals the steady-state response of CH$_4$ abundance to aviation emissions (14).

RF Uncertainty from Factor Decomposition

Past efforts to quantify the uncertainty in the climate impacts of aviation NOx have relied primarily on ensembles of model simulations, as in the prior section. In this section we present an alternative method for determining the uncertainty of aviation impacts based on decomposing the RF into its key factors. We use literature review and expert judgment to assess the uncertainty in each factor and propagate these to the uncertainty in RF. Many of the factors can be derived from the general climate forcing literature and do not require model simulations that are specific to aviation. A major advantage of this approach is that we can identify the dominant sources of uncertainty.

The steady-state, global mean RF from aviation NOx emissions ($F$) can be broken into components due to the short-lived O$_3$ response ($F_{\text{short O}_3}$), and the long-lived CH$_4$ and O$_3$ responses ($F_{\text{long CH}_4}$, and $F_{\text{long O}_3}$, respectively):

$$F = F_{\text{short O}_3} + F_{\text{long CH}_4} + F_{\text{long O}_3} \ ,$$

These components can in turn be factorized into key terms summarizing the chemical interactions between NOx, O$_3$, and CH$_4$, including their feedbacks:

$$F_{\text{short O}_3} = (d/O_3)_{\text{short}}/dE) (dF/d/O_3) \ .$$

$$F_{\text{long CH}_4} = (dL_{\text{CH}_4}/dE) f_{\text{CH}_4} (dF/d/CH_4) \ .$$

$$F_{\text{long O}_3} = (dL_{\text{O}_3}/dE) f_{\text{O}_3} (dF/d/O_3) \ .$$

where $d/O_3$ is the short-lived O$_3$ response to aviation NOx emissions ($E$) and $dL_{\text{CH}_4}/dE$ is the accompanying relative change in CH$_4$ lifetime, $dF/d/O_3$ and $dF/d/CH_4$ are the RF efficiencies of tropospheric O$_3$ and CH$_4$, $f_{\text{CH}_4} = 1.78$ ppm is the global mean CH$_4$ abundance, $f_{\text{CH}_4}$ is the feedback factor, which prolongs the lifetime of CH$_4$ perturbations (16), and $d/O_3$ is the O$_3$ component of the long-lived CH$_4$ perturbation (26). Note that the product of the first three terms on the right-hand sides of Eqs. 3 and 4 equals the steady-state response of CH$_4$ abundance to aviation emissions (14).

Table 1 reviews the best estimates and one-sigma uncertainties (68% confidence interval) of each factor in Eqs. 2–4, including the values adopted in this work. Atmospheric measurements provide no direct constraints on these factors. Although the range of models does not encompass all potential uncertainties and errors, it does in this case provide a large ensemble.

Only two of the factors—$d/O_3$ and $dL_{\text{CH}_4}/dE$—require model simulations specific to aviation to derive their values and uncertainties, although $dF/d/O_3$ is also somewhat dependent on the aviation perturbation (see below). The values adopted here for $d/O_3$ and $dL_{\text{CH}_4}/dE$ encompass recent estimates based on model ensembles (19, 20), but exclude values from IPCC (15) that were based on early CTMs, which had coarse resolution at aircraft altitudes, and were not supported by subsequent studies. The poorly understood sources of model differences in these terms are discussed below, but likely involve the range of NO$_x$:NO$_2$ and OH:HO$_2$ ratios and background NOx abundances across the models.

The remaining factors can be estimated from general literature on atmospheric composition and climate, without requiring model studies or calculations specific to aviation. The O$_3$ response to long-lived CH$_4$ changes, here $d/O_3/d/CH_4 = 3.5 \pm 1.0$ DU/(ppmCH$_4$)$^{-1}$, can be calculated from models (17, this work) and is qualitatively supported by numerous studies showing that the increase in mean tropospheric O$_3$ since the preindustrial era is partially due to the increase in CH$_4$ (16). Our estimated range for the CH$_4$ feedback factor ($f_{\text{CH}_4} = 1.4 \pm 0.1$) includes values from models with widely varying chemical mechanisms (16, 17, this work). The final terms involve mapping the changes in green-
house gas composition to RF. For CH₄ perturbations, which are globally uniform, the RF efficiency, \( dF/d[CH_4] \) = 370 mW m⁻² ppm [ppm (CH₄)]⁻¹, is relatively well-known and nearly constant across all models (27). For O₃ perturbations, the RF is less well-known because the perturbation patterns themselves vary significantly between models. The RF efficiency may also differ between the short-lived and long-lived O₃ responses because they have different spatial and temporal distributions, but we adopt one value here, \( dF/d[O_3] \) = 36 ± 8 mW m⁻² DU [O₃]⁻¹, because the range derived from aviation-specific model tests (7) overlaps that from studies of the preindustrial to present-day changes in O₃ RF (28–30).

Table 2 shows the values and uncertainties of all RF components obtained by propagating the adopted values in Table 1 through Eqs. 1–4. For simplicity, the uncertainty calculations here assume that all factors are uncorrelated, which is reasonable for the individual O₃ and CH₄ RF components, but not for their sum, as we discuss in the next section. Each one of the RF estimates derived from the factor decomposition agrees with the model ensemble estimate within its 68% confidence intervals. Furthermore, neglecting net RF for the moment, the uncertainties of each RF component derived from the factor decomposition are comparable to the standard deviations of the model ensemble. This level of agreement illustrates the usefulness of the factor decomposition method, which might be extended to RF of aviation contrails by considering factors such as flight paths, likelihood of ice supersaturation, and rates of ice sedimentation and evaporation, among others, but such an analysis is beyond the scope of this work.

An additional benefit of the factor decomposition, which is not available from the model ensemble approach, is that we can easily determine which of the terms contributes most to uncertainty in RF. For the short-lived O₃ response, uncertainties in \( d[O_3]_{short}/dE \) and \( dF/d[O_3] \) contribute roughly equally to the uncertainty in

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**Table 1. Factors governing the climate impact of aviation NOx emissions**

<table>
<thead>
<tr>
<th>Factor, unit</th>
<th>Value</th>
<th>Uncertainty*</th>
<th>Source*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d[O_3]_{short}/dE )</td>
<td>0.9 ± 25%</td>
<td>(15)</td>
<td></td>
</tr>
<tr>
<td>DU [O₃]</td>
<td>0.6 ± 15%</td>
<td>(19)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.51 ± 36%</td>
<td>(20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.74</td>
<td>UCI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.60 ± 0.15</td>
<td>Adopted</td>
<td></td>
</tr>
<tr>
<td>( dL_{CH4}/dE )</td>
<td>-2.4 ± 20%</td>
<td>(15)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.8 ± 36%</td>
<td>(19)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.55 ± 38%</td>
<td>(20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.7</td>
<td>UCI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.7 ± 0.35</td>
<td>Adopted</td>
<td></td>
</tr>
<tr>
<td>( f_{CH4} )</td>
<td>1.38 ± 0.05</td>
<td>(16)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.52</td>
<td>UCI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.40 ± 0.10</td>
<td>Adopted</td>
<td></td>
</tr>
<tr>
<td>( d[O_3]/d[CH4] )</td>
<td>3.7 ± 0.8</td>
<td>(16)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>(17)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5 ± 1.0</td>
<td>Adopted</td>
<td></td>
</tr>
<tr>
<td>( dF/d[CH4] )</td>
<td>370 ± 7.2%</td>
<td>(27)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>370 ± 7.2%</td>
<td>Adopted</td>
<td></td>
</tr>
<tr>
<td>( dF/d[O_3] )</td>
<td>38</td>
<td>(28)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>(29)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>420</td>
<td>± 12</td>
<td>(30)</td>
</tr>
<tr>
<td></td>
<td>36 ± 6</td>
<td>(7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>36 ± 8</td>
<td>Adopted</td>
<td></td>
</tr>
</tbody>
</table>

DU, Dobson unit.
*Stated uncertainties are one standard deviation (68% confidence interval).
†UCI values are from the UCI CTM used in this work. Adopted values are used throughout this analysis.
‡Model standard deviation is <25% without the single outlier model.
§RF calculated for preindustrial to present changes in tropospheric O₃, not aviation-specific pattern.

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**Table 2. Steady-state RF (mW m⁻²) from aviation NOx emissions, 1 Tg(N) a⁻¹**

<table>
<thead>
<tr>
<th>RF term</th>
<th>Factored decomposition*</th>
<th>Model ensemble†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-lived O₃</td>
<td>+21.6 ± 7.2</td>
<td>+27.3 ± 9.7</td>
</tr>
<tr>
<td>Long-lived CH₄</td>
<td>-15.7 ± 3.6</td>
<td>-16.1 ± 5.6</td>
</tr>
<tr>
<td>Long-lived O₃</td>
<td>-5.3 ± 2.2</td>
<td>-6.6 ± 3.3</td>
</tr>
<tr>
<td>Net</td>
<td>+0.6 ± 8.3</td>
<td>+4.5 ± 4.5</td>
</tr>
</tbody>
</table>

*Calculated from Eqs. 1–4 with factor values given in Table 1, assuming that all factors are uncorrelated. Stated uncertainties are one standard deviation (68% confidence interval).
†Calculated from models shown in Figs. 1 and 2. Stated uncertainties are one standard deviation.
‡Accounting for correlations due to all common factors in Eqs. 2–4 reduces the uncertainty to ±8.1 mW m⁻².

For the long-lived CH₄ response, however, the uncertainty in \( dL_{CH4}/dE \) causes about 80% of the uncertainty in \( F_{long,CH4} \). In both of these cases, the dominant uncertainty originates in factors that require aviation-specific studies. In contrast, for the long-lived O₃ response, almost 50% of the variance in \( F_{long,CH4} \) originates in the \( d[CH_4]/d[O_3] \) term, which reflects uncertainty in the global response of O₃ to CH₄ perturbations and is not a unique response to aviation emissions. The \( dL_{CH4}/dE \) and \( dF/d[O_3] \) uncertainties explain most of the remaining variance of long-lived O₃ RF.

**Correlation of RF Components and its Causes**

Fig. 2 shows the ensemble of net RF across the models. For three early studies that did not calculate \( F_{long,CH4} \), we fill in values by scaling the reported \( F_{long,CH4} \):

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**Fig. 2.** Steady-state net RF (mW m⁻²) caused by aviation NOx emissions. Values are scaled to 1 Tg(N) a⁻¹. See Fig. 1 caption for the key to multimodel papers. An asterisk (*) indicates that the long-lived O₃ RF was obtained using Eq. 5. The mean and standard deviation is given.
The net RF from aviation NOx for the model ensemble is $+4.5 \pm 4.5 \text{ mW m}^{-2}$ for emissions of 1 Tg(N) a$^{-1}$. Although 17 of the 21 net RF estimates are positive, the 68% confidence interval includes zero. This range is similar to those in recent studies that use a subset of the models analyzed here [e.g., $+4.3 \pm 3.4$ (20), $-0.3$ to $+6.0$ (31)].

The net RF derived from the factor decomposition is $+0.6 \text{ mW m}^{-2}$. If we naively assume no correlation among the RF components, then its one-sigma range is $+0.6 \pm 8.3 \text{ mW m}^{-2}$, which encompasses the ensemble-based estimate and likewise spans zero. However, this assumption of no correlation gives an uncertainty in the net RF that is nearly twice as large as the spread in models, despite the similarity of standard deviations for each RF component found above. This discrepancy persists if we account for correlations due to common factors in Eqs. 2-4 (uncertainty reduces to $\pm 8.1 \text{ mW m}^{-2}$). The ensemble-derived standard deviation of net RF is also much smaller than would be expected if the variance of each of the ensemble-derived component RFs were independent (expected $\pm 11.6 \text{ mW m}^{-2}$), implying that there are important correlations between the components.

Fig. 3 shows that short-lived O$_3$ RF and long-lived CH$_4$ RF are strongly correlated in the model ensemble ($R^2 = 0.79$), which has previously been assumed but not strongly correlated (15). In the absence of quantitative data, earlier work assumed 100% anticorrelation between the O$_3$ and CH$_4$ RF components, but recognized that this assumption would give confidence intervals for net aviation NOx RF that are too small (22). For example, if we assume 100% anticorrelation, instead of the actual 79%, between the positive and negative RF components from the model ensemble, the inferred uncertainty in net RF would be $\pm 0.8 \text{ mW m}^{-2}$, which is one-fifth of the actual ensemble variation. Assuming the same with the factor decomposition, we would expect net RF uncertainty of $\pm 1.4 \text{ mW m}^{-2}$, which is one-third of the ensemble variation. Using a subset of the model ensemble studied here, Myhre et al. (7) found that the largest net aviation NOx RF occurred in models with the largest ratio of initial O$_3$ column change to fractional CH$_4$ lifetime change and the full ensemble also supports this conclusion.

![Graph showing steady-state RF (mW m$^{-2}$) from short-lived O$_3$ versus long-lived CH$_4$ caused by aviation NOx emissions. Values are scaled to 1 Tg(N) a$^{-1}$. Model data (black diamonds) and their mean (gray circle) are from Fig. 1. UCI CTM sensitivity studies show change relative to the mean: lightning NOx emissions (4 Tg(N) a$^{-1}$) reduced 50% (L-NOx2), surface NOx emissions (45 Tg(N) a$^{-1}$) reduced 50% (S-NOx2), convective fluxes reduced 50% (convection/2), kinetics favoring O$_3$ production (kinetics), and a previous model version. Long-lived CH$_4$ RF here excludes the impact on stratospheric water vapor.]

To assess the causes of correlation between the RF components, we test the sensitivity of the University of California, Irvine (UCI) CTM to processes and parameters that likely reflect important differences among the models in the ensemble, similar to an earlier study of global O$_3$ and CH$_4$ budgets (32). Hoor et al. (20) describe the base CTM configuration (version 5.6). RF changes in the sensitivity tests are overlaid on Fig. 3 based on factor changes given in Table S1. Large and similar changes in both short-lived O$_3$ and long-lived CH$_4$ RF components come from halving either convective fluxes or surface NOx emissions [originally 45 Tg(N) a$^{-1}$]. Both increase the aviation RF due to short-lived O$_3$ and decrease the (negative) RF due to long-lived CH$_4$ by 3 to 8 mW m$^{-2}$ each. Halving the lightning NOx source [originally 4 Tg(N) a$^{-1}$] similarly shifts both aviation RF components in the same direction as the first perturbations but by less than 2 mW m$^{-2}$, possibly because most lightning occurs in the tropics far from the major flight routes. Considering the export efficiency of surface NOx to the free troposphere is 5–20% (33, 34), the changes to $\frac{d(O_3)}{dF}$, $\frac{d(L-NOx)}{dF}$, and RF per unit change to fractional CH$_4$ lifetime change to fractional CH$_4$ lifetime change and the full ensemble also supports this conclusion.

Fig. 3. Steady-state RF (mW m$^{-2}$) from short-lived O$_3$ versus long-lived CH$_4$ caused by aviation NOx emissions. Values are scaled to 1 Tg(N) a$^{-1}$. Model data (black diamonds) and their mean (gray circle) are from Fig. 1. UCI CTM sensitivity studies show change relative to the mean: lightning NOx emissions (4 Tg(N) a$^{-1}$) reduced 50% (L-NOx2), surface NOx emissions (45 Tg(N) a$^{-1}$) reduced 50% (S-NOx2), convective fluxes reduced 50% (convection/2), kinetics favoring O$_3$ production (kinetics), and a previous model version. Long-lived CH$_4$ RF here excludes the impact on stratospheric water vapor.

Conclusions

RF of aviation NOx emissions is often evaluated through a model ensemble approach where the standard deviation of the ensemble is used as a measure of the uncertainty. From published results, we show that one important metric, steady-state RF, has not changed much in value or uncertainty with model and emission developments over the last decade. Overall, published work suggests that the steady-state, net RF is $+4.5 \pm 4.5 \text{ mW m}^{-2}$ for aviation NOx emissions of 1 Tg(N) a$^{-1}$, which is consistent with recent studies using a subset of the models analyzed here. Other important RFs from aviation include CO$_2$, contrails, and induced cirrus. Current CO$_2$ forcing is about $+28 \text{ mW m}^{-2}$ for 2005 (22), but not in steady state. Contrail and cirrus RFs are typically estimated to be positive $[-33 \text{ mW m}^{-2}$ (22)] although some recent studies find larger positive and negative cirrus effects $[-140$ to
+120 mW m⁻² (36, 37)]. These steady-state contrail and cirrus RF estimates should be increased by about 15% to compare with the 1 Tg(N)⁻¹ values used here.

The GWP allows for direct comparison of aviation emissions of NOx with those of CO₂. From the model ensemble here, the net RF from 1 Tg(N) aviation emission pulse integrated over 100 y is +4.5 mW m⁻² and that of 1 Tg of CO₂ is 0.087 mW m⁻² (derived from ref. 27). Thus, the ensemble-derived GWP of aviation NOx (as N) itself is at least 52 ± 52. If we had included the additional cooling attributed to CH₄-driven changes in stratospheric water vapor (7), then this number would be closer to zero, but the uncertainty would increase. Similar 100-year GWP ranges were derived by Fuglestvedt et al., (31) (–2 to 71) and Myhre et al., (7) (–21 to 67), although the latter included the stratospheric water vapor effect. Given aviation CO₂:NOx emission ratios of 800:1 by mass of N (7, 22), the 100-year integrated RF from aviation NOx is about 7% ± 7% of that from aviation CO₂.

Using a complementary approach, we factor the aviation NOx RF into its key terms and assess the best value and uncertainty of those terms, many of which reflect basic knowledge of atmospheric chemistry and RF and are not specific to aviation. The three component RF values and their uncertainties propagated from the factor decomposition, assuming no correlations among the factors, agree with the ensemble mean values and standard deviations. This second method identifies those terms largely responsible for the overall uncertainty and thus can be used to guide research priorities. For example, aviation-specific terms drive most of the uncertainty for the short-lived O₃ and long-lived CH₄ RFs. —RFs—RFs—for for long-lived O₃, RFs—RFs—RFs—for those terms, many of which reflect basic knowledge of atmospheric chemistry and their application to changing emissions and climate.

ACKNOWLEDGMENTS. We thank the European Union Quantify project (Robert Sausen) and the UK Omega project (David Lee) for their inspiring workshops on aircraft routing, aviation, and the climate at which this work was spawned. Ivar Ibsen, Joyce Penner, and two reviewers provided helpful comments. This research has been supported by National Aeronautics and Space Administration Grants NNG06GB84G and NNX08AR25G, the US National Science Foundation Grant ATM-0550234, and the Kavli Foundation.


Table S1. Response of climate-relevant factors in model sensitivity tests

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value*</th>
<th>Met</th>
<th>L-NOx</th>
<th>Conv</th>
<th>S-NOx</th>
<th>S-CO</th>
<th>Kinetics</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d(O_3)/dE$</td>
<td>0.60 ± 0.15</td>
<td>−0.01</td>
<td>+0.05</td>
<td>+0.21</td>
<td>+0.19</td>
<td>−0.23</td>
<td>+0.07</td>
<td>−0.07</td>
</tr>
<tr>
<td>$dLCH_4/dE$</td>
<td>−1.7 ± 0.3</td>
<td>+0.03</td>
<td>−0.12</td>
<td>−0.32</td>
<td>−0.56</td>
<td>+0.10</td>
<td>−0.02</td>
<td>+0.37</td>
</tr>
<tr>
<td>$F_{short O_3}$</td>
<td>21.6 ± 7.2</td>
<td>−0.36</td>
<td>+1.8</td>
<td>+7.6</td>
<td>+6.8</td>
<td>−8.28</td>
<td>+2.5</td>
<td>−2.5</td>
</tr>
<tr>
<td>$F_{long CH_4}$</td>
<td>−15.7 ± 3.6</td>
<td>+0.28</td>
<td>−1.1</td>
<td>−3.0</td>
<td>−5.2</td>
<td>+0.92</td>
<td>−0.18</td>
<td>+3.4</td>
</tr>
</tbody>
</table>

Units are same as given in Table 1.

*Adopted value and standard deviation from Tables 1 and 2.

Sensitivity tests involve the following changes to the University of California, Irvine chemistry-transport model (CTM): Met, use 2004 meteorology instead of 2005; L-NOx, decrease lightning NOx emissions (4 Tg(N) a⁻¹) by 50%; Conv, reduce convective updraft and downdraft fluxes by 50%; S-NOx, reduce surface NOx emissions (45 Tg(N) a⁻¹) by 50%; S-CO, reduce surface CO emissions (983 Tg(CO) a⁻¹) by 50%; Kinetics, rates coefficients pushed to upper limit of uncertainty (1) in favor of O₃ production from NOx (HO₂ + NO, +15%; NO + O₂, −10%; HO₂ + O₃, −15%); Version, use CTM version 5.4 instead of 5.6.