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Trading Off Aircraft Fuel Burn and NO_x Emissions for Optimal Climate Policy

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ABSTRACT. Aviation emits pollutants that affect climate, including CO_2 and NO_x; NO_x indirectly so, through the formation of tropospheric ozone and reduction of ambient methane. To improve the fuel performance of engines, combustor temperatures and pressures often increase, increasing NO_x emissions. Conversely, combustor modifications to reduce NO_x may increase CO_2. Hence, a technology tradeoff exists, which also translates to a tradeoff between short lived climate forcers and a long-lived greenhouse gas, CO_2. Moreover, the NO_x-O_3-CH_4 system responds in a non-linear manner, according to both aviation emissions and background NO_x. A simple climate model was modified to incorporate non-linearities parameterized from a complex chemistry model. Case studies showed that for a scenario of a 20% reduction in NO_x emissions the consequential CO_2 penalty of 2% actually increased the total radiative forcing (RF). For a 2% fuel penalty, NO_x emissions needed to be reduced by >43% to realize an overall benefit.

Conversely, to ensure the fuel penalty for a 20% NO_x emission reduction did not increase overall forcing, a 0.5% increase in CO_2 was found to be the 'break even' point. The timescales of the climate effects of NO_x and CO_2 are quite different, necessitating careful analysis of proposed emissions tradeoffs.

INTRODUCTION

Aviation is essential to international travel, and is a growing industry, with passenger traffic increasing at an average of 5.3% per year since 2000. It releases anthropogenic emissions in a physically and chemically complex region of the atmosphere. Aviation emissions consist primarily of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x) and soot or 'black carbon' emissions, and small amounts of water vapour[1-3]. The climate impacts of aviation NO_x emissions are complex, since they affect the climate by contributing a positive radiative forcing (RF) through the promotion of tropospheric ozone formation and a negative RF by reducing methane lifetime. There are additional negative RF effects from the CH_4 lifetime reduction through small reductions in background O_3 and stratospheric water vapour[4], although the balance is a net positive forcing [2,5]. At ground level, aviation NO_x is also considered an air pollutant due to its role in ozone production.

In 1981, ICAO adopted a first certification standard to control aircraft NO_x emissions in response to concerns over the effect of NO_x emissions on surface air quality. As further NO_x stringency assessments were undertaken it became apparent that the engine modifications necessary to reduce NO_x resulted in a fuel burn penalty, and therefore a CO_2 penalty. Hence, it was realized that a tradeoff existed between the two pollutants[6-8].

A further issue arises over the timescale of the perturbations to the atmosphere; aviation NO_x emissions and their associated impacts on ozone and methane contribute a short-lived climate forcing to the atmosphere, whereas CO_2 release has an impact on a much longer timescale. In order to understand the environmental consequences of the technology tradeoff, it is necessary to model the climate impacts in some way for both NO_x and CO_2 perturbations over longer timescales. Most studies of the radiative impact of aviation consider either present-day forcing, or a scenario of e.g 2050 emissions[1, 9-11]. Here, we focus on the very long term as this is not normally considered and only a few studies deal with this[12-14]. The long-term is important as it affects the choice of the mitigation options outlined here, i.e. the long-term impact of a small increase in CO_2 emissions that accumulate vs shorter-term effects that reduce forcing.

Adding to the complexity of this, the NO_x-O_3-CH_4 atmospheric system is known to be non-linear, sensitive to both the perturbing emissions being studied (i.e. aviation) and the NO_x levels of the background atmosphere[15-17]. Such calculations are normally conducted with complex 3D models of the atmosphere that account for this with a sophisticated chemical scheme. The reduction in CH_4 lifetime, is normally calculated offline by a simplified parameterization since CH_4 has a lifetime of approximately 10 – 12 years. However, model simulations for periods of around 100 years are necessary to account for a significant fraction of the CO_2 emissions, usually done in simplified climate models (SCMs). Previously, small perturbations of the NO_x system have been treated as linear[12] (e.g. Sausen and Schumann, 2000) in SCMs. Since this is known to induce inaccuracies into the computations, a new non-linear parameterization of a SCM was derived from a more complex atmospheric chemistry model, MOZART-3, to model the longer-term effects of aviation NO_x emissions.

Having demonstrated and incorporated a suitable non-linear NO_x scheme into a SCM, a series of model runs were designed in order to study the tradeoff between aviation NO_x and CO_2 emissions over a 100 year period. Through changes in aircraft engine design and emissions characteristics, the relative emissions of NO_x and CO_2 can be tuned to address specific mitigation targets. From the perspective of climate change mitigation, the model runs investigate the amount of NO_x reduction needed to account for any increases in CO_2 emissions and also, how much additional CO_2 can be emitted before additional forcing is incurred, should NO_x emissions be reduced by a set amount, in this case -20%.

The model runs also assess the impact of the background NO_x emission on the sign of the NO_x RF and how this impacts on a tradeoff scenario, therefore two different backgrounds NO_x levels are investigated, one to represent a near present day atmospheric composition and one to represent a background atmosphere where significant surface NO_x emissions reduction has taken place.

METHODS

Overall simulations design and modeling tools. Comparing emissions and their climate effects in some form of emission equivalence is a complex subject itself[18]. However, in this study, the tradeoff question can be posed in a simple way in the sense of variation of RF and change in global mean surface temperature (ΔT) after 100 years for constant emissions conditions over some defined base case. First, the global CTM (chemistry transport model) MOZART was used to investigate the linearity of the NO_x-O_3 and NO_x- CH_4 relationships in response to different background conditions. The results of those model runs were then used to create a new non-linear NO_x parameterization to be used in a tradeoff study.

The tradeoffs simulations performed with the SCM represent a parametric study, where all variables are kept constant over time, beginning with a constant amount of fuel use per year. This was to gauge the response of the system to a simple (constant) input, rather than being a scenario study of actual projections. The constant value of fuel use was ~250 Tg per year, the observational fleet value at 2012 (International Energy Agency data), background CO_2 was kept constant at 404 ppm, the background value as of March 2016, thus removing the transient nature of CO_2 modeling - in order to remain consistent with the constant NO_x background used in the CTM runs outlined below. The global fleet emissions index for NO_x ($EINO_x$ in g NO_2/g fuel burned) was kept constant at 13, a representative fleet average. Aviation CO_2 and NO_x emissions were fixed over an arbitrary 100 year simulation at ~790 Tg CO_2 (kerosene to CO_2 conversion of 3.16) and 3.24 Tg NO_2 (0.98 Tg N)per year respectively as a result of the constant fuel use. This scenario represented the 'base case' where the total RF was taken to be the sum of the net NO_x and CO_2 radiative forcings. Note that no 'history' of CO_2 emissions prior to the start year was incorporated. The base case was then perturbed, the constant fuel value was changed to reflect a percentage increase or decrease in CO_2 and NO_x emissions, while still remaining constant over time. A common scenario from the literature suggested that a 2% fuel penalty could be incurred when NO_x emissions were reduced by 20% - owing to engine modification[7,19,20] - to determine whether a net RF benefit was realized or not. The model runs then followed a logical path of determining how much NO_x reduction is in fact necessary to counteract the additional 2% CO_2 emissions, i.e. 'breaking even', while ensuring that overall RF does not exceed that of the base case. It is then investigated, were the situation to be reversed and NO_x reduction was held at -20% below the base case, how much of CO_2/fuel penalty is allowed before forcing goes above that of the base case. Sensitivity simulations were also run to understand the consequences of high and low NO_x background emissions.

Two basic modeling tools were necessary – a sophisticated 3D CTM of the global atmosphere (‘MOZART’ v3) and a simple climate model (SCM)(LinClim). MOZART was used to fully represent the impacts of changing aircraft NO_x emissions at varying levels and backgrounds[21], the results of which were used to formulate a simplified parameterization in the LinClim SCM (‘LinClim’, based on Sausen and Schumann, 2000), which simulated both net NO_x and CO_2 radiative impacts. These modeling tools are described below.

Three-dimensional global chemical transport model – MOZART. The 3D CTM MOZART (Model for OZone And Related Tracers), version 3, was used to simulate the ozone burden and methane lifetime change resulting from aviation NO_x emissions in this study. MOZART-3 was evaluated by Kinnison et al (2007) and has been applied in several atmospheric studies[22-25]. The European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data for 2006 provided the meteorological fields that drive the transport of chemicals within MOZART. The background emissions necessary for MOZART[26] represent the year 2000 and were originally compiled for the IPCC AR5 report. The background data are made up of surface emissions of anthropogenic activity and biomass burning, and the European Union project POET (Precursors of Ozone and their Effects on Troposphere) supply the biogenic surface emissions[27]. The choice of meteorology data driving the model will affect the calculations of the $NO_x/O_3/CH_4$ impacts. Kinnison et al., (2007), when evaluating MOZART3 model performance against observations of various chemical species, noted better agreement when similar ECMWF re-analysis data were used vs other dynamical data. MOZART3 was also driven with ECHAM/5 GCM data as a test, the results from which are given in the SI. Inter-model variability is another source of uncertainty in CTM modeling, in Søvde et al., (2014) MOZART3 is tested against other models in its ability to model NO_x emissions[29], the results of that analysis are extended in the SI, to show the variability of aviation NO_x responses in a small subset of CTMs and how MOZART compares to other models.

The aim of the CTM simulations was to model how the atmosphere reacts to the release of varying levels of aviation and background NO_x emissions. Although it is known that aviation NO_x increases tropospheric ozone burden and reduces methane lifetime, the question arises as to when this relationship becomes non-linear. The SCM LinClim previously incorporated a linear scheme for NO_x - O_3 and NO_x - CH_4, such that the purpose of running iterative simulations with MOZART was to determine whether a new non-linear parameterization of LinClim could be formulated, and also determine the sensitivity of this non-linear response to different background NO_x conditions.

For each simulation run on MOZART, the model was run without aircraft emissions, referred to as the 'reference run' and then again with aircraft emissions, referred to as the 'perturbation run'. Each of these runs is preceded by a 'spin up year', which used the same meteorology, and describes the time taken by the model for the atmospheric constituents to reach equilibrium. The reference run is then subtracted from the perturbation run and the difference plotted, thus showing the impact of aviation on the atmosphere. The variables for the perturbations runs are a series of increasing aviation emissions, each of which was run in two different background atmospheric NO_x states, described below. The spin up and either reference or perturbation run constitutes a total run time of two years, which is sufficient to show the tropospheric ozone response to aviation NO_x emissions[28] and the perturbations to methane lifetime are corrected to account for its longer lifetime as described in the supplementary material.

Ozone and methane are modeled in MOZART-3 using a constant background NO_x level. Therefore, to investigate the impact of a changing background atmosphere, two different background atmospheric NO_x scenarios (global value and spatial pattern) are used which replace those from the original background emissions inventory. The values of background NO_x emissions used here are 20.76 Tg N yr^{-1} and 44.75 Tg N yr^{-1} and were taken from the Representative Concentration Pathways (RCPs) to represent low and high levels of NO_x in the background atmosphere. The low NO_x background comes from RCP3 in the year 2100 and the high from RCP8 in the year 2020 (see SI, Figure S1). These two values were chosen to represent the highest and lowest projected range of possible background NO_x levels over the next 100 years in accordance with the RCP scenarios, thus the results are bounded in that particular range.

The aviation scenarios run on MOZART-3 were generated using the REACT4C aircraft emissions data set[29] as a starting point (from the European project – Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate – 'REACT4C'). The REACT4C data were then multiplied by different factors to create several aviation emissions scenarios of increased aviation activity (all with the same spatial pattern). Aviation emissions are expected to grow more strongly in some regions than others, particularly the Far East/China, differential growth may affect the balance of the O_3/CH_4 perturbation. However, this effect has been found to be small, of the order <3% (see SI). The REACT4C emission scenarios were then modeled with MOZART-3 using both the low NO_x and high NO_x background atmospheres, described above.

Emissions of aircraft NO_x were calculated to be approximately 0.7 Tg N yr^{-1} in the REACT4C aviation emissions scenario[29] (2006). Emissions scenarios indicate that these emissions may increase by 2050, over the range 0.8 – 5 Tg N yr^{-1} [1, 9, 30-32]. The MOZART CTM was used in a series of 10 simple computer simulations, scaling up the REACT4C aviation emissions over a 'realistic' range of emissions through to beyond those currently anticipated. In addition, 7 further simulations at larger incremental changes (> 7 Tg N yr^{-1}) were run well beyond what might be considered 'realistic' in order that the non-linearity of the response of the system could be evaluated. In total, 17 simulations were run for the 'high' background NO_x emissions and a further 17 simulations for the 'low' background NO_x emissions.

In order to develop a new parameterization, the RF of all the effects of aviation NO_x emissions release were calculated which, in this study, comprise of short term ozone, methane, long term ozone and stratospheric water vapor (SWV). We acknowledge the effects of aerosols in terms of their overall radiative impact (direct and indirect) of aviation[33]. Their impact on the NO_x-O_3-CH_4 systems is still not well established. Pitari et al. (2015, 2016) find a small effect that reduces the net NO_x effect (it being a balance of positive and negative terms) in the aerosol providing a surface for $NO_x \rightarrow HNO_3$ conversion[34-35]. MOZART3 does not include these terms and more work is needed to better establish this effect. Short term ozone RF was calculated using monthly mean ozone fields from MOZART and the Edwards-Slingo radiative transfer model, therefore the relationship between ozone burden and RF is linear (see SI) that also includes a stratospheric adjustment calculation (see SI), methane RF was calculated using the methodology of Hansen et al., (1988)[36]. The use of the ES code also introduces further uncertainties (see SI). The long-term ozone and SWV effects are taken to be 0.5 times the methane forcing (uncertainty 60%) and 0.15 times the methane forcing (uncertainty 71.43%) respectively based on Myhre et al., (2013)[4,37](one should note that the uncertainties provided here are for global averages, not specifically aviation perturbations).

The Simplified Climate Model, 'LinClim'. LinClim was used to investigate tradeoffs in the climate response between aviation NO_x and CO_2 emissions, simulations need to be performed over the longer term. CTMs are computationally very expensive and demanding to run, particularly when complex chemistry is involved. Simple climate models provide a way to simulate future RF responses, from which climate temperature responses can be calculated while running quickly and inexpensively. This type of model can run climate simulations of long duration – up to hundreds of years – using input values of CO_2 and other long-lived greenhouse gases generated from full general circulation model simulations and impulse response functions[12].

LinClim is a linear climate response model that has been tailored specifically to aviation and includes all the effects of aviation as outlined by the IPCC (1999)[1,38]. The 'linearity' implied in its name assumes that RF and temperature responses are small enough, and can therefore be treated as linear subtractions/additions. Global aviation fuel burn is the input for LinClim and from this, LinClim calculates the resulting emissions of CO_2 and NO_x using emissions indices. For CO_2, this is simple, for every 1 kg of fuel burned, 3.16 kg of CO_2 is emitted. CO_2 concentration is then calculated using the impulse response function (IRF) from Hasselmann et al., (1997)[39]. The current carbon cycle in LinClim is based on the Maier-Reimer and Hasselmann (1987)[40] model and the CO_2 RF is calculated with the function used in IPCC AR4[41]. For NO_x, the emission index ($EINO_x$) of the global fleet is required. The current parameterization in LinClim for calculating ozone and methane RF assumes a linear relationship between aviation NO_x emissions and the resulting ozone and methane RF changes. Therefore, a new parameterization, created using the results from the MOZART runs described above, was used to calculate the RF from aviation NO_x emissions. This RF value was then used as an input to

LinClim and the corresponding temperature response from aviation net NO_x RF was calculated. The temperature response formulation is based on the method described in Hasselmann et al. (1993)[42]. The calculated temperature response is also dependent on the climate sensitivity parameter and the lifetime of the temperature perturbation. These are tuned to LinClim's 'parent' Atmosphere-Ocean General Circulation Models (AOGCMs). In this study, LinClim was tuned to 19 different parent models and the median temperature response was taken.

RESULTS

Effects of aviation NO_x emissions on ozone and methane abundances. The results of the MOZART runs show that as aviation NO_x emissions increase, so does the associated global ozone burden and RF (Figure 1; Figure S2). This relationship is approximately linear up to ~2 Tg N yr^{-1} of aviation NO_x emissions and shows clear non-linearity thereafter in both the low NO_x and high NO_x background atmospheric states. At values of aviation NO_x emissions greater than ~2 Tg N yr^{-1} ozone formation per NO_x molecule reduces as aviation emissions increase, reflecting the non-linearity of the NO_x-O_3 system[15-17].

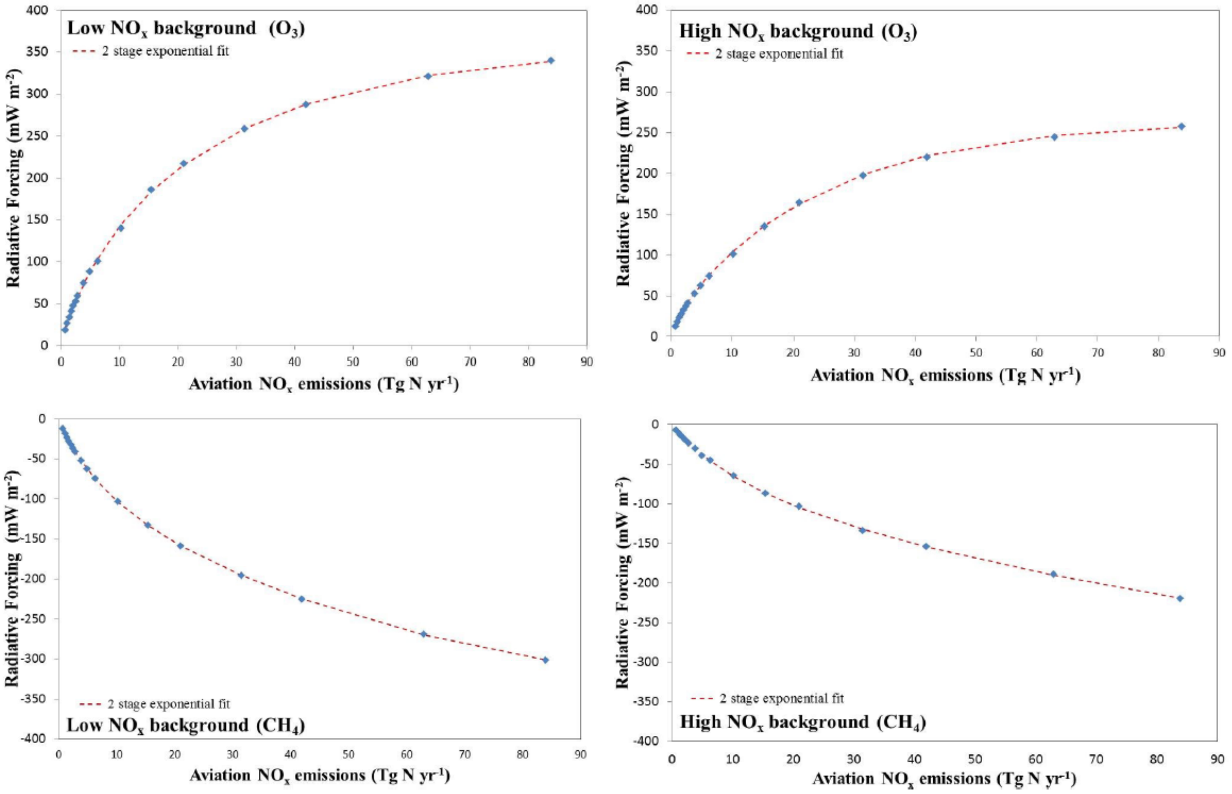

Figure 1. The radiative forcing resulting from ozone burden (Tg O_3) (upper panels) and methane lifetime change (years) (lower panels) due to aviation NO_x emissions in the low (left hand panels) and high (right hand panel) NO_x atmospheric background states. Each point represents one of the emissions scenarios run on MOZART described in the text. The trend line shows a two-stage exponential fit of the data, which was used to create a new net NO_x RF parameterization.

Aviation NO_x emissions result in an enhancement of OH abundance, which in turn reduces methane lifetime since OH is its principle sink term ($CH_4 + OH \rightarrow CH_3 + H_2O$). The change in methane lifetime and reduction in atmospheric abundance associated with the release of aviation NO_x thus produces a negative RF. Similar to the NO_x – O_3 relationship, the relationship between aviation NO_x emissions and methane lifetime reduction (and therefore associated RF) is approximately linear until aviation NO_x emissions reach ~2 Tg N yr^{-1} (Figure 1; Figure S2) and becomes non-linear thereafter.

The effects of aviation NO_x emissions on methane lifetime differ depending on the state of the background into which the emissions are released. The lifetime of methane is reduced substantially more (per NO_x molecule) in the low NO_x background scenario than the high NO_x (by an average of 50% over the range of NO_x emission values used here). The low NO_x background enables greater formation rates of ozone as described above, which in turn results in an increased concentration of OH and therefore greater decreases in methane lifetime.

The emissions of NO_x used in this study represent 'realistic' values (the highest density of data points in Figure 1 and data shown in Figure S2), through to anticipated ranges of values in future scenarios, to values which are far beyond those expected. However, the purpose of using such values is two-fold; firstly, to demonstrate that the response with a complex global CTM is able to show the expected non-linear response and secondly, to determine at what point the production of O_3 starts to saturate. Clearly, even within the range of emissions suggested in the literature (up to ~5 Tg N yr^{-1}), a linear response is not expected, and such a response in a simplified model would over-estimate RF and therefore temperature responses.

It has been established that the responses of ozone and methane to aviation NO_x emissions are not linear and thus, cannot be treated as such in a parameterization for a simple climate model. The results presented in Figure 1 (and Figure S2) quantify the range over which the linear relationship of NO_x emissions to ozone burden and methane lifetime change is valid. It is shown that both the NO_x – O_3 and NO_x – CH_4 regimes are linear up to ~2 Tg N yr^{-1} of aviation NO_x emissions and therefore, a linear regression is appropriate, however linearity ceases after 2 Tg N

yr^{-1} and the data are better represented by exponential fitting. These fit coefficients (Table SI1) can be used to calculate the RF of ozone and methane perturbations resulting from aviation NO_x emissions in studies using SCMs such as LinClim.

Using the constant emissions scenario described in the methods, and keeping the $EINO_x$ constant at 13 g NO_2/kg fuel (3.9 g N/kg), the new parameterization was used to calculate the total forcing from aviation NO_x emissions over 100 years (Table 1). The results show that in these simplified cases, the background atmosphere determines the sign of the net NO_x forcing from aviation emissions. In the high NO_x background, aviation NO_x emissions contribute a positive net forcing or warming, however, in the low NO_x background, aviation NO_x emissions contribute a negative net forcing, or cooling. The difference in sign is due to the fact that in lower NO_x backgrounds, more OH is available for methane removal, therefore it is enhanced over ozone production in the low NO_x background, compared with the high NO_x background where ozone production dominates, resulting in an overall positive net forcing from NO_x. As the long-term ozone effect and SWV perturbation are calculated from the methane forcing, their contribution enhances the negative forcing in the low NO_x environment.

Table 1 also gives comparative data on the net NO_x forcing from LinClim's linear parameterization and the new non-linear parameterization. While the methane forcing is comparable between the two methods, the ozone forcing is overestimated by the linearized form of LinClim. Although this comparison uses low NO_x values, which fall within the 'linear range' of the NO_x-O_3-CH_4 system, they system is still inherently non-linear, and therefore the non-linear regime developed here does give slightly different results.

Table 1. Radiative forcing (mW m^{-2}) resulting from aviation NO_x calculated using LinClim and the new non-linear parameterizations described in the text, when the same fuel scenario is used – as described in 'methods'.

Calculation used/forcing	**Short term O_3**	**Methane**	**Long term O_3**	**SWV**	**Total NO_x RF**
Non-linear (low NOx background)	26.80	-17.13	-8.56	-2.57	-1.468
Non-linear (high NOx background)	18.09	-9.91	-4.95	-1.48	1.745
Linear (Linclim)	28.74	-13.61	-6.80	-2.04	6.279

Tradeoff model runs using a simple climate model

Throughout these model runs, two base case scenarios were considered (Figure 2); total aviation forcing was taken as the CO_2 plus net NO_x forcing, one scenario using the low NO_x background and one the high NO_x background and the CO_2 background was set at a constant value of 404 ppm throughout (2016 value, as explained in the methods section). When the base case is perturbed by reducing NO_x emissions by 20% and increasing CO_2 emissions by 2%, total aviation forcing increases by 3.87% for the low background NO_x case, and 0.55% for the high background NO_x case after 50 years, and by 3.1% and 1.12% after 100 years (low, high NO_x backgrounds respectively). This demonstrates that for an ambition that reduces the NO_x emissions by 20%, the resultant 2% increase in CO_2 emissions (Figure 2) means that the total effect is greater than the base case – potentially inadvertently having an adverse effect on climate rather than an intended benefit. Therefore, the next step was to determine exactly how much NO_x reduction is required to reduce the total aviation forcing to below that of the base case when CO_2

emissions are assumed to increase by 2% because of the technology tradeoffs. Emissions of NO_x were incrementally reduced until the total forcing was the same as the base case. For the high background NO_x case, aviation NO_x would need to be reduced by 43% to ‘break even’ in terms of RF after 100 years, or by 38% in terms of temperature response after 100 years. The temperature response is lower due to the thermal inertia of the climate system, since the system has an additional response time over RF.

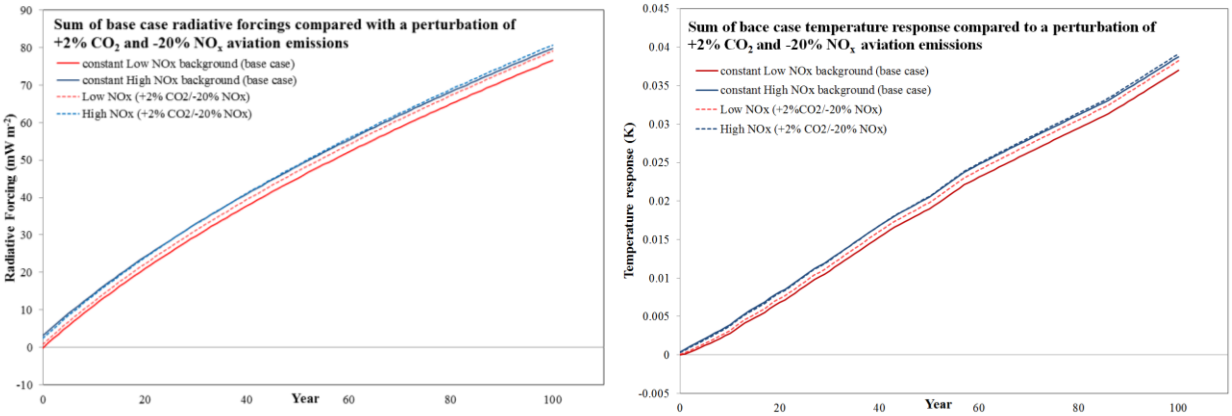

Figure 2. The sum of aviation NO_x and CO_2 RF (left) and associated temperature response (right) as a result of the constant base case emissions and the initial perturbation case of -20% NO_x, +2% CO_2, both described in the text, over 100 years.

For the low background NO_x case, the results are more complex – net NO_x emissions provide a negative RF, since methane removal dominates over ozone production. This means that any reduction in aviation NO_x emissions in the low NO_x background reduced the negative forcing, leading to an overall greater forcing. Therefore, the only way to reduce overall forcing from aviation when CO_2 emissions are increased by 2% is to, rather counter-intuitively, *increase* aviation NO_x emissions. This provides an additional negative forcing to counteract the additional positive forcing from CO_2. This is a somewhat unrealistic case in that the CO_2 penalty would presumably not be incurred. It was found that aviation NO_x emissions had to be increased by 37% to counteract the additional RF provided by the 2% increase in CO_2 and reduce the overall forcing to below that of the base case after 100 years (Table 2), and by 33% to reduce the associated temperature response (Table 3). However, what this case does show is that the overall impact in terms of RF and temperature does not depend solely on the technology tradeoffs, but also on the background atmosphere.

The next model runs assume that NO_x reduction is held at 20% below the base case and it was determined how much of a CO_2 penalty is permitted before total forcing increases above that of the base case. It was calculated that CO_2 can only be allowed to increase by 0.5% over the base case without incurring a forcing or temperature penalty over 100 years in the high NO_x background. Thus, for this case in can be interpreted that any CO_2 penalty less than 0.5% will yield a net climate benefit. In the low NO_x background, any reduction in NO_x emissions causes an increase in overall forcing as described above. Therefore, in this scenario, the forcing is increased over the base case by reducing NO_x by 20% before any CO_2 increase is considered. Thus, it was determined that, should NO_x emissions be reduced by 20% in the low NO_x background, CO_2 emissions would also have to be reduced by 1.5% to counteract the additional forcing and temperature change incurred by the reduction in NO_x emissions over 100 years (Tables 2 and 3).

Table 2. The percentage difference in RF for each perturbation case as compared to the base case.

	High NO_x background			Low NO_x background		
		50 year end point	100 year end point		50 year end point	100 year end point
	Model run	% diff from BC	% diff from BC	Model run	% diff from BC	% diff from BC
CO_2 held at +2% from BC	-25% NO_x	0.16%	0.89%	+21% NO_x	0.08%	0.87%
	-26% NO_x	0.08%	0.84%	+22% NO_x	-0.02%	0.81%
	-27% NO_x	0.0017%	0.79%	+23% NO_x	-0.11%	0.76%
	-28% NO_x	-0.08%	0.74%	+25% NO_x	-0.30%	0.65%
	-30% NO_x	-0.25%	0.64%	+30% NO_x	-0.77%	0.38%
	-40% NO_x	-1.13%	0.12%	+32% NO_x	-0.96%	0.27%
	-41% NO_x	-1.22%	0.06%	+33% NO_x	-1.05%	0.22%
	-42% NO_x	-1.31%	0.01%	+34% NO_x	-1.15%	0.16%
	-43% NO_x	-1.41%	-0.05%	+35% NO_x	-1.24%	0.11%
	-44% NO_x	-1.51%	-0.10%	+36% NO_x	-1.33%	0.052%
	-45% NO_x	-1.60%	-0.16%	+37% NO_x	-1.43%	-0.0019%
NO_x held at -20% from BC	+0.5% CO_2	-0.91%	-0.35%	-2% CO_2	-0.12%	-0.91%
	+1% CO_2	-0.42%	0.14%	-1.5% CO_2	0.39%	-0.52%
	+2% CO_2	0.55%	1.12%	-1% CO_2	0.90%	0.12%

Table 3. The percentage difference in temperature change for each perturbations case as compared to the base case.

	High NO_x background			Low NO_x background		
		50 year end point	100 year end point		50 year end point	100 year end point
	Model run	% diff from BC	% diff from BC	Model run	% diff from BC	% diff from BC
CO_2 held at +2% from BC	-20% NO_x	*0.35%*	*1.01%*	+15% NO_x	*0.44%*	*1.09%*
	-23% NO_x	*0.09%*	*0.85%*	+18% NO_x	*0.11%*	*0.90%*
	-24% NO_x	*-0.004%*	*0.80%*	+19% NO_x	*0.005%*	*0.84%*
	-25% NO_x	*-0.09%*	*0.75%*	+20% NO_x	*-0.10%*	*0.78%*
	-38% NO_x	*-1.36%*	*0.0016%*	+30% NO_x	*-1.19%*	*0.16%*
	-40% NO_x	*-1.57%*	*-0.12%*	+32% NO_x	*-1.41%*	*0.04%*
	-41% NO_x	*-1.68%*	*-0.18%*	+33% NO_x	*-1.52%*	*-0.02%*
NO_x held at -20% from BC	+0.5% CO_2	*-1.11%*	*-0.46%*	-2% CO_2	*0.16%*	*-0.76%*
	+1% CO_2	*-0.62%*	*0.03%*	-1.5% CO_2	*0.67%*	*-0.52%*
	+2% CO_2	*0.35%*	*1.01%*	-1% CO_2	*1.19%*	*0.27%*

DISCUSSION

The results presented here provide important insights for industrial technology development and policy-making, regarding tradeoffs between different aviation emissions species. It has been found that, while there is a tradeoff between aviation NO_x and CO_2 emissions, in terms of climate change, CO_2 emissions still provide the majority of the forcing from aviation and a smaller change in its emission affects the total forcing much more than an equivalent change in NO_x emission. The balance of the previously well-known positive RF from ozone, and the counterbalancing negative RF from reduction in methane lifetime has changed with the more recent assessment of the additional negative RF terms from SWV reduction[4], and reduction in longer-term ozone[43]. One must also consider the role of aviation NO_x as a polluter at ground level, and during the landing-take off cycle, hence why its reduction from aircraft emissions is desirable.

In terms of a tradeoff between different emissions, one must cautiously consider where the benefit would lie in reducing one species at the expense of another. Regarding the common scenario proposed in the literature, that a reduction of NO_x by 20% incurring a fuel penalty of 2%, while that would reduce pollution from NO_x at ground level, it was shown to be worse overall in terms of total climate impact, as the additional CO_2 forcing from the fuel increase was not counteracted by the reduction in NO_x emissions. In terms of the ambition of achieving a climate benefit from NO_x emission reductions, we show that a fuel increase should probably be avoided and our test case (20% NO_x emission reduction) showed that even an increase of 0.5% fuel would yield no net climate benefit. Either much stronger NO_x emission reductions would be necessary, or a condition that no fuel penalty is incurred is the best option. In any case, we show that a careful environmental assessment is required. Even the cases described here may be considered simplistic in terms of realism, but serve as an initial quantitative assessment of tradeoffs which has so far, been absent.

Another important consideration highlighted in this study is the effect of the background atmosphere. If background/surface NO_x emissions were to decrease, which may be likely as industries aim to cut air pollution at ground level, the net forcing from aviation NO_x emissions could result in a negative forcing, thus, aviation NO_x mitigation would not be at all beneficial in terms of climate: however, it is likely that there will be an ongoing requirement to reduce NO_x emissions at ground-level in order to reduce air pollution impacts on human health. Thus, further consideration of scenarios and test cases should be given to future work to properly assess air quality and climate impacts.

The complex interactions that have been demonstrated here show that scientific assessment and advice can assist in technology development and policy related to aircraft impacts, but it needs to be done with great care – moreover, the interactions between motivations for improving air quality and climate would benefit from extending the results to simple cost-benefit analyses. Currently, only cost-effectiveness analyses are considered in regulatory development within ICAO (International Civil Aviation Organization). As with any atmospheric modeling study, attention must be paid to the uncertainties surrounding computer simulations, the data used and the analysis of the results.

ASSOCIATED CONTENT

Supporting Information. – RF calculations, CH_4 corrections, extra information for CTM, RCP explanations

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Notes

The author declare no competing information

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ABBREVIATIONS

CO_2	Carbon dioxide
GHGs	Greenhouse gases
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
NO_x	Nitrogen oxides ($NO + NO_2$)
RF	Radiative Forcing

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