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1 Trading Off Aircraft Fuel Burn and NO_x Emissions 2 for Optimal Climate Policy

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7
8 KEYWORDS. Aviation, Climate, NO_x, CO₂, Tradeoff, Emissions

9
10 ABSTRACT. Aviation emits pollutants that affect climate, including CO₂ and NO_x; NO_x
11 indirectly so, through the formation of tropospheric ozone and reduction of ambient methane. To
12 improve the fuel performance of engines, combustor temperatures and pressures often increase,
13 increasing NO_x emissions. Conversely, combustor modifications to reduce NO_x may increase
14 CO₂. Hence, a technology tradeoff exists, which also translates to a tradeoff between short lived
15 climate forcers and a long-lived greenhouse gas, CO₂. Moreover, the NO_x-O₃-CH₄ system
16 responds in a non-linear manner, according to both aviation emissions and background NO_x. A
17 simple climate model was modified to incorporate non-linearities parameterized from a complex
18 chemistry model. Case studies showed that for a scenario of a 20% reduction in NO_x emissions
19 the consequential CO₂ penalty of 2% actually increased the total radiative forcing (RF). For a 2%
20 fuel penalty, NO_x emissions needed to be reduced by >43% to realize an overall benefit.

21 Conversely, to ensure the fuel penalty for a 20% NO_x emission reduction did not increase overall
22 forcing, a 0.5% increase in CO₂ was found to be the ‘break even’ point. The timescales of the
23 climate effects of NO_x and CO₂ are quite different, necessitating careful analysis of proposed
24 emissions tradeoffs.

25

26 INTRODUCTION

27 Aviation is essential to international travel, and is a growing industry, with passenger traffic
28 increasing at an average of 5.3% per year since 2000. It releases anthropogenic emissions in a
29 physically and chemically complex region of the atmosphere. Aviation emissions consist
30 primarily of carbon dioxide (CO₂), nitrogen oxides (NO_x), sulfur oxides (SO_x) and soot or ‘black
31 carbon’ emissions, and small amounts of water vapour¹⁻³. The climate impacts of aviation NO_x
32 emissions are complex, since they affect the climate by contributing a positive radiative forcing
33 (RF) through the promotion of tropospheric ozone formation and a negative RF by reducing
34 methane lifetime. There are additional negative RF effects from the CH₄ lifetime reduction
35 through small reductions in background O₃ and stratospheric water vapour⁴, although the balance
36 is a net positive forcing^{2,5}. At ground level, aviation NO_x is also considered an air pollutant due
37 to its role in ozone production.

38 In 1981, ICAO adopted a first certification standard to control aircraft NO_x emissions in response
39 to concerns over the effect of NO_x emissions on surface air quality. As further NO_x stringency
40 assessments were undertaken it became apparent that the engine modifications necessary to
41 reduce NO_x resulted in a fuel burn penalty, and therefore a CO₂ penalty. Hence, it was realized
42 that a tradeoff existed between the two pollutants⁶⁻⁸.

43 A further issue arises over the timescale of the perturbations to the atmosphere; aviation NO_x
44 emissions and their associated impacts on ozone and methane contribute a short-lived climate
45 forcing to the atmosphere, whereas CO₂ release has an impact on a much longer timescale. In
46 order to understand the environmental consequences of the technology tradeoff, it is necessary to
47 model the climate impacts in some way for both NO_x and CO₂ perturbations over longer
48 timescales. Most studies of the radiative impact of aviation consider either present-day forcing,
49 or a scenario of e.g 2050 emissions^{1, 9-11}. Here, we focus on the very long term as this is not
50 normally considered and only a few studies deal with this¹²⁻¹⁴. The long-term is important as it
51 affects the choice of the mitigation options outlined here, i.e. the long-term impact of a small
52 increase in CO₂ emissions that accumulate vs shorter-term effects that reduce forcing.

53 Adding to the complexity of this, the NO_x-O₃-CH₄ atmospheric system is known to be non-
54 linear, sensitive to both the perturbing emissions being studied (i.e. aviation) and the NO_x levels
55 of the background atmosphere¹⁵⁻¹⁷. Such calculations are normally conducted with complex 3D
56 models of the atmosphere that account for this with a sophisticated chemical scheme. The
57 reduction in CH₄ lifetime, is normally calculated offline by a simplified parameterization since
58 CH₄ has a lifetime of approximately 10 – 12 years. However, model simulations for periods of
59 around 100 years are necessary to account for a significant fraction of the CO₂ emissions, usually
60 done in simplified climate models (SCMs). Previously, small perturbations of the NO_x system
61 have been treated as linear¹² (e.g. Sausen and Schumann, 2000) in SCMs. Since this is known to
62 induce inaccuracies into the computations, a new non-linear parameterization of a SCM was
63 derived from a more complex atmospheric chemistry model, MOZART-3, to model the longer-
64 term effects of aviation NO_x emissions.

65 Having demonstrated and incorporated a suitable non-linear NO_x scheme into a SCM, a series of
66 model runs were designed in order to study the tradeoff between aviation NO_x and CO₂
67 emissions over a 100 year period. Through changes in aircraft engine design and emissions
68 characteristics, the relative emissions of NO_x and CO₂ can be tuned to address specific mitigation
69 targets. From the perspective of climate change mitigation, the model runs investigate the
70 amount of NO_x reduction needed to account for any increases in CO₂ emissions and also, how
71 much additional CO₂ can be emitted before additional forcing is incurred, should NO_x emissions
72 be reduced by a set amount, in this case -20%.

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

78 METHODS

79 *Overall simulations design and modeling tools.* Comparing emissions and their climate effects in
80 some form of emission equivalence is a complex subject itself¹⁸. However, in this study, the
81 tradeoff question can be posed in a simple way in the sense of variation of RF and change in
82 global mean surface temperature (ΔT) after 100 years for constant emissions conditions over
83 some defined base case. First, the global CTM (chemistry transport model) MOZART was used
84 to investigate the linearity of the NO_x-O₃ and NO_x- CH₄ relationships in response to different
85 background conditions. The results of those model runs were then used to create a new non-
86 linear NO_x parameterization to be used in a tradeoff study.

87 The tradeoffs simulations performed with the SCM represent a parametric study, where all
88 variables are kept constant over time, beginning with a constant amount of fuel use per year. This
89 was to gauge the response of the system to a simple (constant) input, rather than being a scenario
90 study of actual projections. The constant value of fuel use was ~250 Tg per year, the
91 observational fleet value at 2012 (International Energy Agency data), background CO₂ was kept
92 constant at 404 ppm, the background value as of March 2016, thus removing the transient nature
93 of CO₂ modeling - in order to remain consistent with the constant NO_x background used in the
94 CTM runs outlined below. The global fleet emissions index for NO_x (EINO_x in g NO₂/g fuel
95 burned) was kept constant at 13, a representative fleet average. Aviation CO₂ and NO_x emissions
96 were fixed over an arbitrary 100 year simulation at ~790 Tg CO₂ (kerosene to CO₂ conversion of
97 3.16) and 3.24 Tg NO₂ (0.98 Tg N) per year respectively as a result of the constant fuel use. This
98 scenario represented the ‘base case’ where the total RF was taken to be the sum of the net NO_x
99 and CO₂ radiative forcings. Note that no ‘history’ of CO₂ emissions prior to the start year was
100 incorporated. The base case was then perturbed, the constant fuel value was changed to reflect a
101 percentage increase or decrease in CO₂ and NO_x emissions, while still remaining constant over
102 time. A common scenario from the literature suggested that a 2% fuel penalty could be incurred
103 when NO_x emissions were reduced by 20% - owing to engine modification^{7,19,20} - to determine
104 whether a net RF benefit was realized or not. The model runs then followed a logical path of
105 determining how much NO_x reduction is in fact necessary to counteract the additional 2% CO₂
106 emissions, i.e. ‘breaking even’, while ensuring that overall RF does not exceed that of the base
107 case. It is then investigated, were the situation to be reversed and NO_x reduction was held at -
108 20% below the base case, how much of CO₂/fuel penalty is allowed before forcing goes above

109 that of the base case. Sensitivity simulations were also run to understand the consequences of
110 high and low NO_x background emissions.

111 Two basic modeling tools were necessary – a sophisticated 3D CTM of the global atmosphere
112 ('MOZART' v3) and a simple climate model (SCM)(LinClim). MOZART was used to fully
113 represent the impacts of changing aircraft NO_x emissions at varying levels and backgrounds²¹,
114 the results of which were used to formulate a simplified parameterization in the LinClim SCM
115 ('LinClim', based on Sausen and Schumann, 2000), which simulated both net NO_x and CO₂
116 radiative impacts. These modeling tools are described below.

117 *Three-dimensional global chemical transport model – MOZART.* The 3D CTM MOZART
118 (Model for OZone And Related Tracers), version 3, was used to simulate the ozone burden and
119 methane lifetime change resulting from aviation NO_x emissions in this study. MOZART-3 was
120 evaluated by Kinnison et al (2007) and has been applied in several atmospheric studies²²⁻²⁵. The
121 European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data
122 for 2006 provided the meteorological fields that drive the transport of chemicals within
123 MOZART. The background emissions necessary for MOZART²⁶ represent the year 2000 and
124 were originally compiled for the IPCC AR5 report. The background data are made up of surface
125 emissions of anthropogenic activity and biomass burning, and the European Union project POET
126 (Precursors of Ozone and their Effects on Troposphere) supply the biogenic surface emissions²⁷.
127 The choice of meteorology data driving the model will affect the calculations of the NO_x/O₃/CH₄
128 impacts. Kinnison et al., (2007), when evaluating MOZART3 model performance against
129 observations of various chemical species, noted better agreement when similar ECMWF re-
130 analysis data were used vs other dynamical data. MOZART3 was also driven with ECHAM/5
131 GCM data as a test, the results from which are given in the SI. Inter-model variability is another

132 source of uncertainty in CTM modeling, in Søvde et al., (2014) MOZART3 is tested against
133 other models in its ability to model NO_x emissions²⁹, the results of that analysis are extended in
134 the SI, to show the variability of aviation NO_x responses in a small subset of CTMs and how
135 MOZART compares to other models.

136 The aim of the CTM simulations was to model how the atmosphere reacts to the release of
137 varying levels of aviation and background NO_x emissions. Although it is known that aviation
138 NO_x increases tropospheric ozone burden and reduces methane lifetime, the question arises as to
139 when this relationship becomes non-linear. The SCM LinClim previously incorporated a linear
140 scheme for NO_x - O₃ and NO_x - CH₄, such that the purpose of running iterative simulations with
141 MOZART was to determine whether a new non-linear parameterization of LinClim could be
142 formulated, and also determine the sensitivity of this non-linear response to different background
143 NO_x conditions.

144 For each simulation run on MOZART, the model was run without aircraft emissions, referred to
145 as the ‘reference run’ and then again with aircraft emissions, referred to as the ‘perturbation run’.
146 Each of these runs is preceded by a ‘spin up year’, which used the same meteorology, and
147 describes the time taken by the model for the atmospheric constituents to reach equilibrium. The
148 reference run is then subtracted from the perturbation run and the difference plotted, thus
149 showing the impact of aviation on the atmosphere. The variables for the perturbations runs are a
150 series of increasing aviation emissions, each of which was run in two different background
151 atmospheric NO_x states, described below. The spin up and either reference or perturbation run
152 constitutes a total run time of two years, which is sufficient to show the tropospheric ozone
153 response to aviation NO_x emissions²⁸ and the perturbations to methane lifetime are corrected to
154 account for its longer lifetime as described in the supplementary material.

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

165 The aviation scenarios run on MOZART-3 were generated using the REACT4C aircraft
166 emissions data set²⁹ as a starting point (from the European project – Reducing Emissions from
167 Aviation by Changing Trajectories for the benefit of Climate – ‘REACT4C’). The REACT4C
168 data were then multiplied by different factors to create several aviation emissions scenarios of
169 increased aviation activity (all with the same spatial pattern). Aviation emissions are expected to
170 grow more strongly in some regions than others, particularly the Far East/China, differential
171 growth may affect the balance of the O₃/CH₄ perturbation. However, this effect has been found
172 to be small, of the order <3% (see SI). The REACT4C emission scenarios were then modeled
173 with MOZART-3 using both the low NO_x and high NO_x background atmospheres, described
174 above.

175 Emissions of aircraft NO_x were calculated to be approximately 0.7 Tg N yr⁻¹ in the REACT4C
176 aviation emissions scenario²⁹ (2006). Emissions scenarios indicate that these emissions may
177 increase by 2050, over the range 0.8 – 5 Tg N yr⁻¹ ^{1, 9, 30-32}. The MOZART CTM was used in a

178 series of 10 simple computer simulations, scaling up the REACT4C aviation emissions over a
179 ‘realistic’ range of emissions through to beyond those currently anticipated. In addition, 7 further
180 simulations at larger incremental changes ($> 7 \text{ Tg N yr}^{-1}$) were run well beyond what might be
181 considered ‘realistic’ in order that the non-linearity of the response of the system could be
182 evaluated. In total, 17 simulations were run for the ‘high’ background NO_x emissions and a
183 further 17 simulations for the ‘low’ background NO_x emissions.

184 In order to develop a new parameterization, the RF of all the effects of aviation NO_x emissions
185 release were calculated which, in this study, comprise of short term ozone, methane, long term
186 ozone and stratospheric water vapor (SWV). We acknowledge the effects of aerosols in terms of
187 their overall radiative impact (direct and indirect) of aviation³³. Their impact on the $\text{NO}_x\text{-O}_3\text{-CH}_4$
188 systems is still not well established. Pitari et al. (2015, 2016) find a small effect that reduces the
189 net NO_x effect (it being a balance of positive and negative terms) in the aerosol providing a
190 surface for $\text{NO}_x \rightarrow \text{HNO}_3$ conversion³⁴⁻³⁵. MOZART3 does not include these terms and more
191 work is needed to better establish this effect. Short term ozone RF was calculated using monthly
192 mean ozone fields from MOZART and the Edwards-Slingo radiative transfer model, therefore
193 the relationship between ozone burden and RF is linear (see SI) that also includes a stratospheric
194 adjustment calculation (see SI), methane RF was calculated using the methodology of Hansen et
195 al., (1988)³⁶. The use of the ES code also introduces further uncertainties (see SI). The long-term
196 ozone and SWV effects are taken to be 0.5 times the methane forcing (uncertainty 60%) and 0.15
197 times the methane forcing (uncertainty 71.43%) respectively based on Myhre et al.,
198 (2013)^{4,37}(one should note that the uncertainties provided here are for global averages, not
199 specifically aviation perturbations).

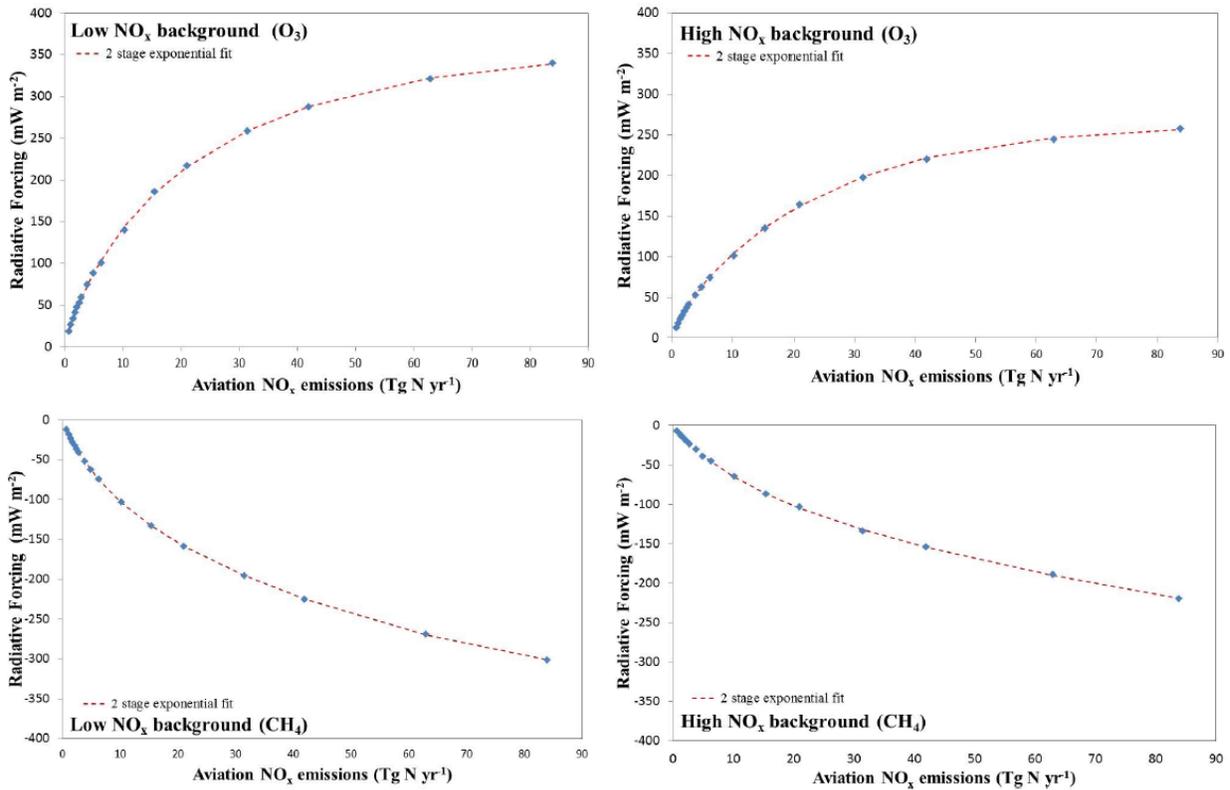
200 *The Simplified Climate Model, 'LinClim'*. LinClim was used to investigate tradeoffs in the
201 climate response between aviation NO_x and CO₂ emissions, simulations need to be performed
202 over the longer term. CTMs are computationally very expensive and demanding to run,
203 particularly when complex chemistry is involved. Simple climate models provide a way to
204 simulate future RF responses, from which climate temperature responses can be calculated while
205 running quickly and inexpensively. This type of model can run climate simulations of long
206 duration – up to hundreds of years – using input values of CO₂ and other long-lived greenhouse
207 gases generated from full general circulation model simulations and impulse response
208 functions¹².

209 LinClim is a linear climate response model that has been tailored specifically to aviation and
210 includes all the effects of aviation as outlined by the IPCC (1999)^{1,38}. The 'linearity' implied in
211 its name assumes that RF and temperature responses are small enough, and can therefore be
212 treated as linear subtractions/additions. Global aviation fuel burn is the input for LinClim and
213 from this, LinClim calculates the resulting emissions of CO₂ and NO_x using emissions indices.
214 For CO₂, this is simple, for every 1 kg of fuel burned, 3.16 kg of CO₂ is emitted. CO₂
215 concentration is then calculated using the impulse response function (IRF) from Hasselmann et
216 al., (1997)³⁹. The current carbon cycle in LinClim is based on the Maier-Reimer and Hasselmann
217 (1987)⁴⁰ model and the CO₂ RF is calculated with the function used in IPCC AR4⁴¹. For NO_x,
218 the emission index (EINO_x) of the global fleet is required. The current parameterization in
219 LinClim for calculating ozone and methane RF assumes a linear relationship between aviation
220 NO_x emissions and the resulting ozone and methane RF changes. Therefore, a new
221 parameterization, created using the results from the MOZART runs described above, was used to
222 calculate the RF from aviation NO_x emissions. This RF value was then used as an input to

223 LinClim and the corresponding temperature response from aviation net NO_x RF was calculated.
224 The temperature response formulation is based on the method described in Hasselmann et al.
225 (1993)⁴². The calculated temperature response is also dependent on the climate sensitivity
226 parameter and the lifetime of the temperature perturbation. These are tuned to LinClim's 'parent'
227 Atmosphere-Ocean General Circulation Models (AOGCMs). In this study, LinClim was tuned to
228 19 different parent models and the median temperature response was taken.

229 RESULTS

230 *Effects of aviation NO_x emissions on ozone and methane abundances.* The results of the
231 MOZART runs show that as aviation NO_x emissions increase, so does the associated global
232 ozone burden and RF (Figure 1; Figure S2). This relationship is approximately linear up to ~2 Tg
233 N yr⁻¹ of aviation NO_x emissions and shows clear non-linearity thereafter in both the low NO_x
234 and high NO_x background atmospheric states. At values of aviation NO_x emissions greater than
235 ~2 Tg N yr⁻¹ ozone formation per NO_x molecule reduces as aviation emissions increase,
236 reflecting the non-linearity of the NO_x-O₃ system¹⁵⁻¹⁷.



237
 238 **Figure 1.** The radiative forcing resulting from ozone burden (Tg O₃) (upper panels) and methane
 239 lifetime change (years) (lower panels) due to aviation NO_x emissions in the low (left hand
 240 panels) and high (right hand panel) NO_x atmospheric background states. Each point represents
 241 one of the emissions scenarios run on MOZART described in the text. The trend line shows a
 242 two-stage exponential fit of the data, which was used to create a new net NO_x RF
 243 parameterization.

244
 245 Aviation NO_x emissions result in an enhancement of OH abundance, which in turn reduces
 246 methane lifetime since OH is its principle sink term ($\text{CH}_4 + \text{OH} \rightarrow \text{CH}_3 + \text{H}_2\text{O}$). The change in
 247 methane lifetime and reduction in atmospheric abundance associated with the release of aviation
 248 NO_x thus produces a negative RF. Similar to the NO_x – O₃ relationship, the relationship between
 249 aviation NO_x emissions and methane lifetime reduction (and therefore associated RF) is

250 approximately linear until aviation NO_x emissions reach ~2 Tg N yr⁻¹ (Figure 1; Figure S2) and
251 becomes non-linear thereafter.

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

258 The emissions of NO_x used in this study represent ‘realistic’ values (the highest density of data
259 points in Figure 1 and data shown in Figure S2), through to anticipated ranges of values in future
260 scenarios, to values which are far beyond those expected. However, the purpose of using such
261 values is two-fold; firstly, to demonstrate that the response with a complex global CTM is able to
262 show the expected non-linear response and secondly, to determine at what point the production
263 of O₃ starts to saturate. Clearly, even within the range of emissions suggested in the literature (up
264 to ~5 Tg N yr⁻¹), a linear response is not expected, and such a response in a simplified model
265 would over-estimate RF and therefore temperature responses.

266 It has been established that the responses of ozone and methane to aviation NO_x emissions are
267 not linear and thus, cannot be treated as such in a parameterization for a simple climate model.

268 The results presented in Figure 1 (and Figure S2) quantify the range over which the linear
269 relationship of NO_x emissions to ozone burden and methane lifetime change is valid. It is shown
270 that both the NO_x – O₃ and NO_x – CH₄ regimes are linear up to ~2 Tg N yr⁻¹ of aviation NO_x
271 emissions and therefore, a linear regression is appropriate, however linearity ceases after 2 Tg N

272 yr^{-1} and the data are better represented by exponential fitting. These fit coefficients (Table S11)
273 can be used to calculate the RF of ozone and methane perturbations resulting from aviation NO_x
274 emissions in studies using SCMs such as LinClim.

275
276 Using the constant emissions scenario described in the methods, and keeping the EINO_x constant
277 at 13 g NO_2/kg fuel (3.9 g N/kg), the new parameterization was used to calculate the total forcing
278 from aviation NO_x emissions over 100 years (Table 1). The results show that in these simplified
279 cases, the background atmosphere determines the sign of the net NO_x forcing from aviation
280 emissions. In the high NO_x background, aviation NO_x emissions contribute a positive net forcing
281 or warming, however, in the low NO_x background, aviation NO_x emissions contribute a negative
282 net forcing, or cooling. The difference in sign is due to the fact that in lower NO_x backgrounds,
283 more OH is available for methane removal, therefore it is enhanced over ozone production in the
284 low NO_x background, compared with the high NO_x background where ozone production
285 dominates, resulting in an overall positive net forcing from NO_x . As the long-term ozone effect
286 and SWV perturbation are calculated from the methane forcing, their contribution enhances the
287 negative forcing in the low NO_x environment.

288 Table 1 also gives comparative data on the net NO_x forcing from LinClim's linear
289 parameterization and the new non-linear parameterization. While the methane forcing is
290 comparable between the two methods, the ozone forcing is overestimated by the linearized form
291 of LinClim. Although this comparison uses low NO_x values, which fall within the 'linear range'
292 of the $\text{NO}_x\text{-O}_3\text{-CH}_4$ system, they system is still inherently non-linear, and therefore the non-
293 linear regime developed here does give slightly different results.

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

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

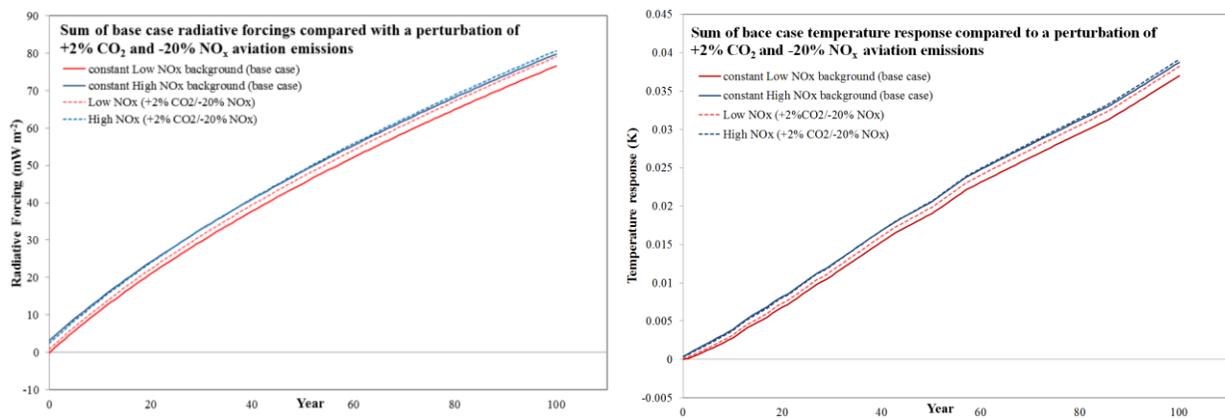
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298

299 *Tradeoff model runs using a simple climate model*

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

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



318
 319 **Figure 2.** The sum of aviation NO_x and CO₂ RF (left) and associated temperature response
 320 (right) as a result of the constant base case emissions and the initial perturbation case of -20%
 321 NO_x, +2% CO₂, both described in the text, over 100 years.

322
 323 For the low background NO_x case, the results are more complex – net NO_x emissions provide a
 324 negative RF, since methane removal dominates over ozone production. This means that any
 325 reduction in aviation NO_x emissions in the low NO_x background reduced the negative forcing,
 326 leading to an overall greater forcing. Therefore, the only way to reduce overall forcing from
 327 aviation when CO₂ emissions are increased by 2% is to, rather counter-intuitively, *increase*
 328 aviation NO_x emissions. This provides an additional negative forcing to counteract the additional
 329 positive forcing from CO₂. This is a somewhat unrealistic case in that the CO₂ penalty would

330 presumably not be incurred. It was found that aviation NO_x emissions had to be increased by
331 37% to counteract the additional RF provided by the 2% increase in CO₂ and reduce the overall
332 forcing to below that of the base case after 100 years (Table 2), and by 33% to reduce the
333 associated temperature response (Table 3). However, what this case does show is that the overall
334 impact in terms of RF and temperature does not depend solely on the technology tradeoffs, but
335 also on the background atmosphere.

336 The next model runs assume that NO_x reduction is held at 20% below the base case and it was
337 determined how much of a CO₂ penalty is permitted before total forcing increases above that of
338 the base case. It was calculated that CO₂ can only be allowed to increase by 0.5% over the base
339 case without incurring a forcing or temperature penalty over 100 years in the high NO_x
340 background. Thus, for this case in can be interpreted that any CO₂ penalty less than 0.5% will
341 yield a net climate benefit. In the low NO_x background, any reduction in NO_x emissions causes
342 an increase in overall forcing as described above. Therefore, in this scenario, the forcing is
343 increased over the base case by reducing NO_x by 20% before any CO₂ increase is considered.
344 Thus, it was determined that, should NO_x emissions be reduced by 20% in the low NO_x
345 background, CO₂ emissions would also have to be reduced by 1.5% to counteract the additional
346 forcing and temperature change incurred by the reduction in NO_x emissions over 100 years
347 (Tables 2 and 3).

348
349
350
351
352

353 **Table 2.** The percentage difference in RF for each perturbation case as compared to the base
 354 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%

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358 **Table 3.** The percentage difference in temperature change for each perturbations case as
 359 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%

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363 **DISCUSSION**

364 The results presented here provide important insights for industrial technology development and
 365 policy-making, regarding tradeoffs between different aviation emissions species. It has been
 366 found that, while there is a tradeoff between aviation NO_x and CO₂ emissions, in terms of
 367 climate change, CO₂ emissions still provide the majority of the forcing from aviation and a

368 smaller change in its emission affects the total forcing much more than an equivalent change in
369 NO_x emission. The balance of the previously well-known positive RF from ozone, and the
370 counterbalancing negative RF from reduction in methane lifetime has changed with the more
371 recent assessment of the additional negative RF terms from SWV reduction⁴, and reduction in
372 longer-term ozone⁴³. One must also consider the role of aviation NO_x as a polluter at ground
373 level, and during the landing-take off cycle, hence why its reduction from aircraft emissions is
374 desirable.

375
376 In terms of a tradeoff between different emissions, one must cautiously consider where the
377 benefit would lie in reducing one species at the expense of another. Regarding the common
378 scenario proposed in the literature, that a reduction of NO_x by 20% incurring a fuel penalty of
379 2%, while that would reduce pollution from NO_x at ground level, it was shown to be worse
380 overall in terms of total climate impact, as the additional CO₂ forcing from the fuel increase was
381 not counteracted by the reduction in NO_x emissions. In terms of the ambition of achieving a
382 climate benefit from NO_x emission reductions, we show that a fuel increase should probably be
383 avoided and our test case (20% NO_x emission reduction) showed that even an increase of 0.5%
384 fuel would yield no net climate benefit. Either much stronger NO_x emission reductions would be
385 necessary, or a condition that no fuel penalty is incurred is the best option. In any case, we show
386 that a careful environmental assessment is required. Even the cases described here may be
387 considered simplistic in terms of realism, but serve as an initial quantitative assessment of
388 tradeoffs which has so far, been absent.

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

398

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

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412 ASSOCIATED CONTENT

413 **Supporting Information.** – RF calculations, CH₄ corrections, extra information for CTM, RCP
414 explanations

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417 AUTHOR INFORMATION

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422 **Author Contributions**

423 The manuscript was written through contributions of all authors. All authors have given approval
424 to the final version of the manuscript.

425 **Notes**

426 The author declare no competing information

427

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433 ABBREVIATIONS

434 CO₂ Carbon dioxide
435 GHGs Greenhouse gases
436 ICAO International Civil Aviation Organization
437 IPCC Intergovernmental Panel on Climate Change
438 NO_x Nitrogen oxides (NO + NO₂)
439 RF Radiative Forcing

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