# Mitigating future aviation $CO_2$ emissions – "timing is everything"


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**Abstract:** In this report, we analyse and rank the most effective mitigation options for international aviation emissions of $CO_2$, using objective science-based metrics of the climate impacts of the $CO_2$ emissions; 'radiative forcing', and 'global mean temperature response', quantified in terms of reductions over a business-as-usual (BAU) base-case. Simple calculations of emissions over time, or by a given point in time, cannot provide an analysis of the climate impacts of mitigation measures because of the complex accumulative nature of $CO_2$ in the atmosphere. This report provides such an objective analysis of the climate impacts of scenarios of mitigation measures. Twenty-three incremental mitigation scenarios for aviation $CO_2$ emissions were analysed for their reductions in radiative forcing/temperature response by 2050 over a BAU aviation technology/operational improvements scenario (scenario 'S2'). The mitigation measures included five levels of technology/operational improvements, three levels of biofuel market penetration, and two levels of geographical coverage of an emissions trading system. Sensitivities were addressed by analysing three aviation growth scenarios against four background scenarios of global $CO_2$ emissions – i.e. emissions from all other sectors/countries – (the so-called 'Representative Concentration Pathways' scenarios). In addition, the median temperature responses were calculated from 20 global climate models parameterizations. These combinations of analysis and sensitivities provided a total of 11,520 model simulations. This exhaustive analysis provided a robust ranking of aviation mitigation options and quantification of the relative benefits of the different mitigation responses in terms of their impact on climate. The mitigation measures considered included: technological and operational improvements, introduction of biofuels, and actual and potential market-based mechanisms (here – emissions trading systems) over the BAU technology/operational (S2) improvements scenario.

A clear picture emerged of the European Emissions Trading Scheme (EU-ETS) for aviation providing the largest single incremental improvement in radiative forcing and temperature response by 2050 of ~15% (range 12 to 17%) over BAU (S2). The next largest single potential contributor, as a measure, to reductions in aviation $CO_2$ radiative forcing by 2050 was a maximum feasible reductions (MFR[1]) scenario of reductions in aviation $CO_2$ emissions from technological and operational improvements (scenario 'S5') over BAU (S2), of 6.4% (range 6.1 to 6.9%). The additional introduction of "*likely*" levels of biofuels[2] over BAU (S2) gave the smallest reduction, as a single measure, in aviation $CO_2$ radiative forcing by 2050 over BAU scenario S2 of 1.1% (range 1.0 to 1.2%). By combining MFR technology/operational improvements (S5) with biofuels at "*speculative*" levels, reduced aviation $CO_2$ radiative forcing over BAU (S2) by 9% (range 8.3 to 9.6%). Combining all possible measures – MFR technology/operations, "speculative" biofuels, and the EU-ETS, reduced aviation $CO_2$ RF by 19.5% (range 16.1 to 21.5%) over BAU (S2). Even if total aviation is analysed (domestic plus international), the same rank order is still found, the EU-ETS for aviation offering a 16.2% (range 12.8 to 18%) reduction in aviation $CO_2$ radiative forcing by 2050 over BAU scenario S2, with no additional improvements in technology/operations.

In addition, a hypothetical system for a global emissions trading system starting in 2012 based on international departing flights was analysed for international aviation; such a system offered a


[1] What are taken here as being Maximum Feasible Reductions in technological and operational improvements were noted by (MODTF/FESG, 2009) as being "*...sensitivity study that goes beyond the improvements based on industry-based recommendations".*

[2] The levels of biofuels were taken from the analysis of the UK Committee on Climate Change (2009), in which they were labeled "*likely*", "*optimistic*", and "*speculative*".

30.1% (range 24.1 to 33.4%) reduction in aviation $CO_2$ radiative forcing by 2050 over the BAU (S2) scenario, and a 32.4% (range 26.3 to 35.8%) reduction for total aviation. Temperature reduction potentials followed the same rank order as radiative forcing. Sensitivity analyses showed that the relative reductions in aviation $CO_2$ radiative forcing are somewhat dependent on the aviation growth scenario but rank order does not change, and are independent of background RCP scenarios (which embrace both 'high emission' and a '2°C-like' background $CO_2$ scenarios). The reason that the ETS options result in such marked radiative forcing reductions, is their inherent ability to achieve emission reductions quickly, which is vital when considering the effectiveness of any $CO_2$ mitigation action, because of the accumulative nature of $CO_2$ in the atmosphere. The *timing* as to when reductions in $CO_2$ emissions occur matters – not just the achievement of an emissions goal by some future date.

# 1 Introduction

## 1.1 Context and key concepts

Aviation emissions represent a small but significant and increasing fraction of global annual $CO_2$ emissions, being ~2.3% in 2005 (Lee et al., 2009). The international fraction of aviation emissions is approximately 62% of total civil aviation $CO_2$ emissions, however, international aviation emissions are not accounted for under international policy. If this international fraction of aviation emissions of $CO_2$ were 'a country', they would be the ~17th largest emitter of $CO_2$ in 2010, using global emissions data from CDIAC (Boden et al., 2013).

Emissions of $CO_2$ represent the largest driver of 'global warming', and the effect or 'impact' of greenhouse gas (GHG) emissions is usually quantified in terms of 'radiative forcing' (RF). Radiative forcing is a metric that is widely used in the scientific community and by the Intergovernmental Panel on Climate Change (IPCC) to place the effects of different GHGs and climate-forcing agents on a common scale that allows a ranking of effect or impact to a date, and is measured in watts per square metre. The larger the magnitude of RF for a given GHG etc., the greater the warming effect. The total RF from all GHGs, forcing agents and effects[3] in 2005 was +1.6 (+0.6 to +2.4) W $m^{-2}$ and has resulted in a change in global mean surface temperature of 0.74 (0.56 to 0.92) degrees Celsius (IPCC, 2007).

Radiative forcing is defined as the energy imbalance at the top of the atmosphere relative to pre-industrialization (taken as 1750), and is used since many climate modelling experiments have shown that there is a proportionality between RF and global mean surface temperature change ($\Delta T$), multiplied by some constant (the 'climate sensitivity parameter', $\lambda$) i.e.

$$RF \approx \lambda \Delta T$$

The RF metric is used since it puts diverse physical phenomena that affect climate on a common scale (see footnote 2).

'Climate change' is, however, more than changes in global mean surface temperature: it may include changes in wind and precipitation patterns, increases in frequency of extreme weather events, sea-level rise etc. However, the change in global mean surface

[3] Not all effects on climate arise from GHGs. Positive (warming) and negative (cooling) RF effects may arise from diverse physical phenomena including, for example, changes in cloud coverage, aerosol abundance, reflectivity (albedo) of the earth's surface, changes in solar radiation etc.

temperature is often taken as a first-order indicator of climate change. Local or regional changes in temperature can be larger than the global mean change.

In this work, we focus on the impacts of $CO_2$ emissions from aviation, although its associated emissions of $NO_x$, particles, and water vapour also give rise to both positive and negative RFs that are larger, in total, than the RF from aviation's historical $CO_2$ emissions alone (IPCC, 1999; Lee et al., 2009). Given that aviation is a sector that is highly dependent on liquid fossil fuels, and is growing globally at a rate faster than GDP and faster than fuel-efficiency improvements (IPCC, 1999), there is a strong interest in reducing its $CO_2$ emissions.

In terms of policy, aviation $CO_2$ emissions are split into 'international' and 'domestic' fractions. Currently, reduction or limitation of international aviation $CO_2$ emissions, are to be dealt with through the International Civil Aviation Organization (ICAO) under Article 2.2 of the Kyoto Protocol. The ICAO, and the sector itself has set a number of goals and targets that have been analysed in terms of future compliance, or otherwise, by Lee et al. (2013) who examined the contributions to mitigation of technology and operational improvements (Anon., 2010), rates of biofuel uptake (from the UK Committee on Climate Change, 2009), and the existing EU-Emissions Trading Scheme.

Whilst the outcome of the 'Gap Report' (Lee et al., 2013) was clear in terms of the effectiveness of various emission mitigation options compared with 'goals' by 2050 as a target date, an emission *rate* in 2050 does not provide a clear and unequivocal ranking of the environmental effectiveness of a mitigation strategy in terms of the *impacts* of the $CO_2$ emissions, nor the relative effectiveness of these strategies. This is because of the long lifetime(s) of $CO_2$ in the atmosphere. In essence, when considering an emission target by a certain future date, the profile or trajectory over time is more important than the final emission rate at some target date. Put simply, it is the *cumulative emissions* that are important to some real effect on climate (Allen et al., 2010).

In this work, we go the next step from the 'Gap Report' (Lee et al., 2013) and quantify the $CO_2$ emission reductions from various mitigation options in terms of RF and change in global mean temperature to rank and quantify the effectiveness, in terms of these metrics, of the various mitigation options of technology and operational improvements, biofuel utilization, and the EU-ETS. In addition, we analyse the effectiveness of a hypothetical global emissions trading scheme for aviation, where from 2012 all international departing flights (including the EU-ETS) are incorporated into such a system.

# 2 Methodology

## 2.1 Overall calculation methodology

If one considers the pathway between emissions of $CO_2$ and its eventual temperature response, one may formulate a schema such as is illustrated in Figure 1.

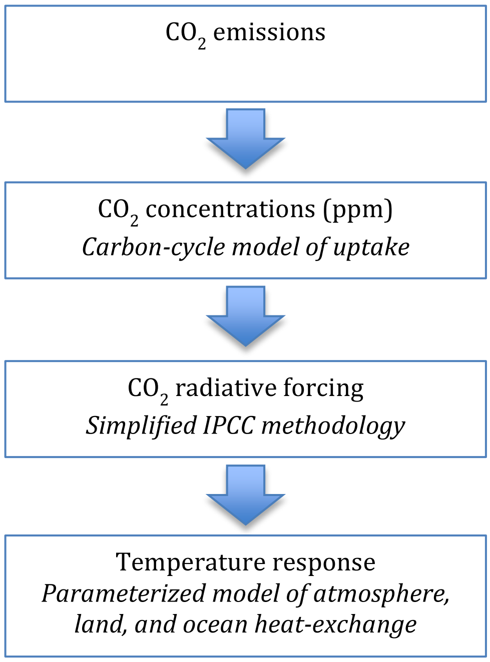



*Figure 1. Schema of how the earth-atmosphere system responds to emissions of $CO_2$.*

As outlined in Figure 1, emissions of $CO_2$ are converted to concentrations of $CO_2$ in the atmosphere (expressed in parts per million, ppm) via a carbon cycle model. The resultant $CO_2$ concentrations may then be used to calculate the $CO_2$ RF response via some simplified expression, as used by the IPCC and others. Finally, the changes in global mean surface temperature from the RF are calculated, using a climate response model. These steps are described in more detail in Appendix 1.

## 2.2 Background $CO_2$ emissions data for projections

One of the most influential components in calculation of aviation $CO_2$ RF, other than overall aviation emissions, in absolute terms, is the background emission scenario assumed. This is because the $CO_2$ RF response is non-linear. Thus, for the same aviation emissions, a different RF will result, depending on the other (background) $CO_2$ emissions assumed. For this analysis, like many other contemporary climate scenario analyses, including those for the IPCC Fifth Assessment Report, the so-called 'Representative Concentration Pathways' (RCPs) are used. The RCPs are described in more detail by Moss et al. (2010) and Meinshausen et al. (2011). The RCPs represent "*one of many possible scenarios that would lead to a specific radiative forcing characteristics*" (Moss et al., 2010). The pathways describe the concentration levels and also the trajectory to reach the target RF levels at specific point in time. These "*plausible pathways*" consist of harmonized emissions from Integrated Assessment Models and the resulting concentration projections with climate feedback for all major anthropogenic GHGs and can be used in climate research (Meinshausen et al., 2011).

The RCPs used were: RCP3-PD (peak at ~3 W $m^{-2}$ before 2100 and then declines), RCP4.5 (~4.5 $Wm^{-2}$ at stabilization after 2100), RCP6 (~6 W $m^{-2}$ at stabilization after 2100) and RCP8.5 (>8.5 W $m^{-2}$ in 2100), and these are shown in terms of $CO_2$ concentrations and the underlying emissions profiles over time (to 2050) in Figure 2.

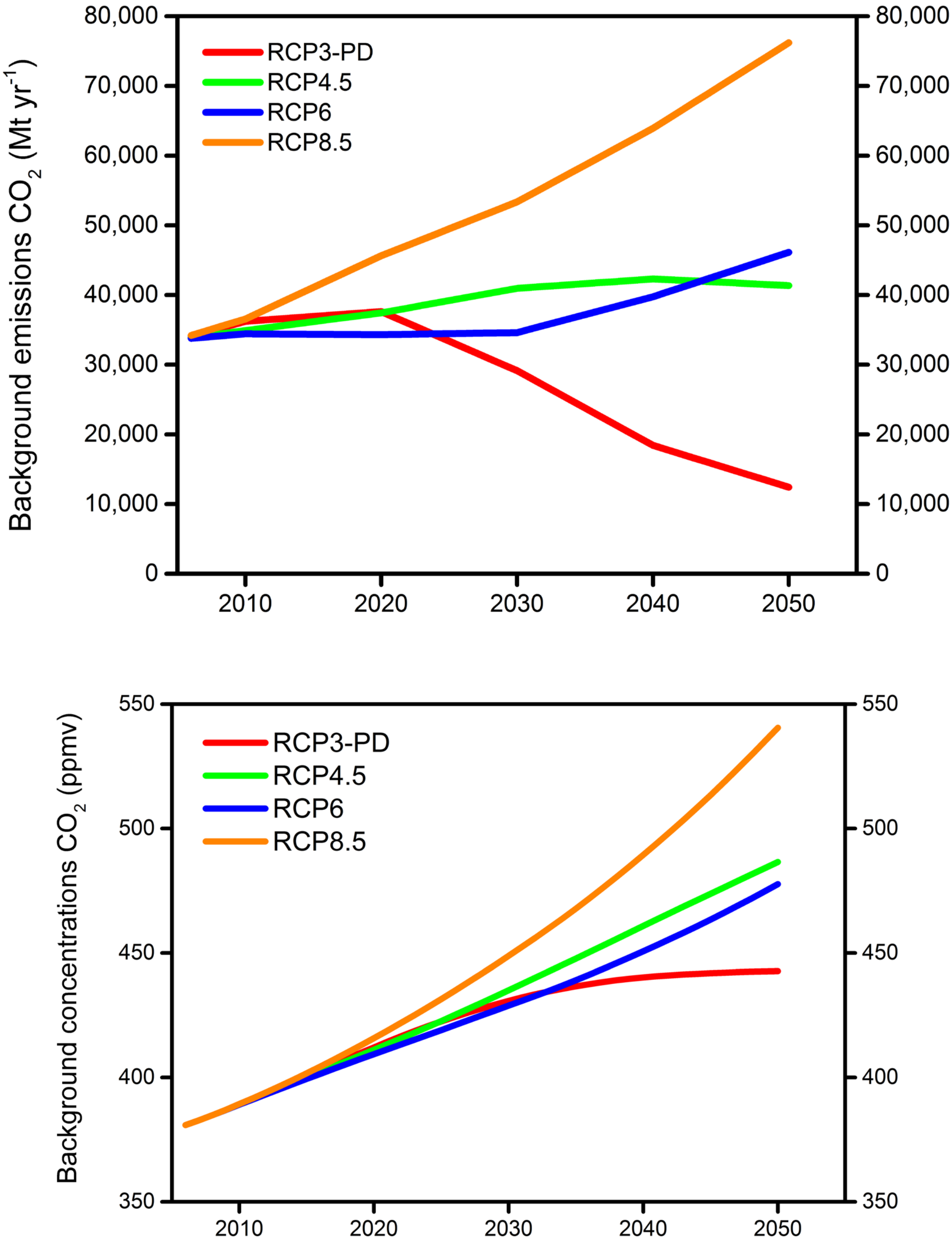



*Figure 2. Emissions (upper panel) and concentrations (lower panel) of $CO_2$ according to RCPs 3-PD, 4.5, 6, and 8.5.*

## 2.3 Aviation $CO_2$ emissions data

The key component to this work is the assumed aviation $CO_2$ emissions. In order to calculate the $CO_2$ RF/$\Delta T$ response, it is necessary to know *historical* emissions, since that is how $CO_2$ RF is effectively defined – the RF response at some point in time, which because of the long lifetime(s) of $CO_2$ requires historical emissions data. For these calculations, we use historical aviation $CO_2$ emission data between 1940 and 1970 from Sausen and Schumann (2000) and an updated time series from Lee et al. (2009) between 1970 and 2005 from International Energy Agency statistics of global kerosene usage. For 2006 we use the global civil $CO_2$ emissions estimate of MODTF/FESG (2009), which is a comprehensive multi-model calculation of global civil aviation emissions from a bottom-up inventory that includes all city-pair routes and modelled aircraft-specific emissions.

For future years, we utilize a number of data sources and evaluations to calculate baseline emissions, and emissions reductions to 2050 resulting from various mitigation strategies. The emissions calculations are documented in detail by Lee et al. (2013) but in essence, the following sources of data/assumptions are used.

*Traffic growth scenarios*: three basic traffic scenarios of low, central, and high growth projections are taken from the ICAO-CAEP Forecasting and Economic Support Group, as documented by MODTF/FESG (2009). The emissions calculations from the 'Aviation Gap Report' (Lee et al., 2013) were updated to include time-series of the low and high growth rates of aviation traffic from MODTF/FESG (2009) and are shown for international aviation emissions against various aviation 'goals' in Figure 3. These data were used in the calculations made for this study, along with the corresponding 'total' (i.e. domestic plus international) aviation $CO_2$ emissions.

*Technological and operational emissions reductions*: a range of technological and operational efficiency gain scenarios are taken from ICAO-CAEP work, as documented by MODTF/FESG (2009) labelled 'S1' through to 'S5' (see Table 2.1), in which we assume that 'S2' represents a business-as-usual (BAU) projection of development of technological and operational efficiency emission reductions (Lee et al., 2013).

*Biofuel availability and life-cycle reductions*: biofuel availability and the effective emissions reductions are essentially highly speculative because of the immaturity of the technology and market. Moreover, there are few assessments of potential global availability under various assumptions. We use the assessment of the UK Committee on Climate Change (CCC, 2009), which has a comprehensive and transparent analysis underlying it.

*Regional MBM (EU-ETS)*: this is a relatively simple mitigation option to calculate, and it is based on the commencement of the extension to the EU-ETS to aviation in 2012, and the resultant emissions savings to 2020 under the policy, which includes EU domestic emissions, intra-EU international departing emissions, and non-EU international arriving and departing emissions. We extend the current cap and keep the geographical scope of the scheme constant to 2050.

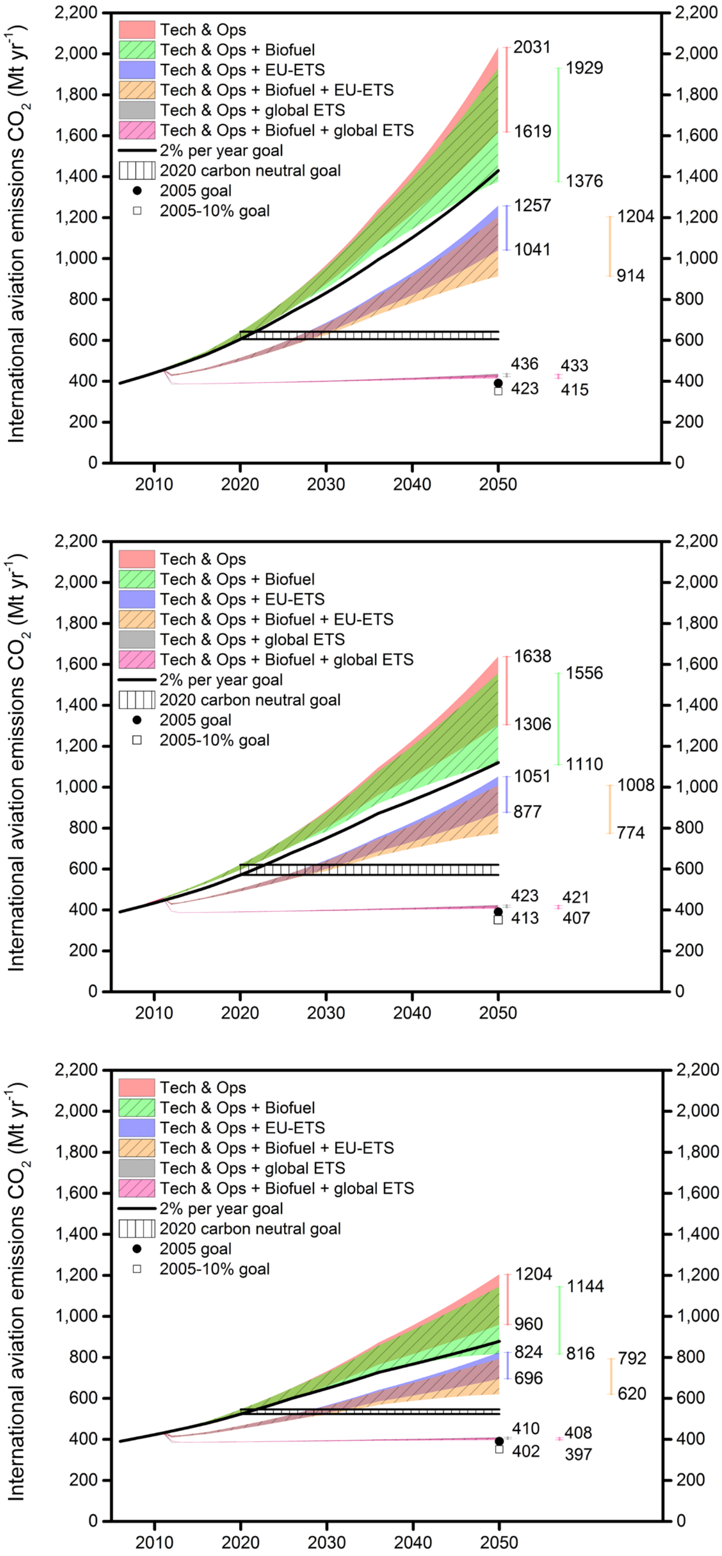
*Global MBM (Global ETS)*: in this work, we add to the 'Gap Report' work, by analysing a hypothetical global emissions-trading system based upon international departures starting in 2012 and subsuming the EU-ETS. We make no assumptions over domestic policies other than for the EU states (which already have a scheme), and it uses a cap identical to the EU-ETS. For the 'international' calculations, the reduction arising from

the cap (of 95% of 2006 emissions) is applied to international traffic; for the 'total' aviation emissions calculations, international flights, and domestic EU flights are included.

In both the Regional MBM (the EU-ETS for aviation) and the hypothetical Global MBM (Global ETS), it is assumed that $CO_2$ savings from permit purchases above the cap level are made elsewhere, i.e. from other sectors, and are 100% effective in terms of carbon-saving. We also account in both schemes for a small (3.2%) reduction in demand (Faber et al., 2007) arising from increased ticket prices (see Lee et al., 2013).

*Table 2.1. Overview of mitigation response and assumptions*

| Type of response | Assumptions | Reference/notes |
|---|---|---|
| **Technology & operations** | | MDG/FESG (2009) |
| 'S2' | Low aircraft technology and moderate operational improvements | |
| 'S3' | Moderate aircraft technology and operational improvements | |
| 'S4' | Advanced technology and operational improvements | |
| 'S5' | Optimistic technology and operational improvements | "*…sensitivity study that goes beyond the improvements based on industry-based recommendations*" |
| **Biofuels** | | CCC (2009) |
| "*likely*" | 10% by 2050, 50% life-cycle efficiency | Applied to S2 (Lee et al., 2013) |
| "*optimistic*" | 20% by 2050, 50% life-cycle efficiency | Applied to S3, S4 (Lee et al., 2013) |
| "*speculative*" | 30% by 2050, 50% life-cycle efficiency | Applied to S5 (Lee et al., 2013) |
| **Regional MBM** | | European Commission |
| EU-ETS | Starts 2012 with cap of 97% mean emissions 2004–2006, 2013 cap 95%; scheme continues as planned until 2020 and continued at same cap level until 2050 | 2020–2050 continuation, Lee et al. (2013) |
| **Global ETS** | | |
| International only | All international departing flights subsuming EU domestic flights, starting 2012 at a 97% cap, with a 95% cap commencing 2013, continuing to 2050. The cap is based on 2006 global international departing flights | This work |




High growth

Central growth

Low growth

*Figure 3. International aviation emissions of $CO_2$ and mitigation potential relative to various goals (left hand column), data shown indicated for 2050 values (high, central, low scenarios, from top to bottom). Note that the '2005 emissions goal' (and 10% reduction on that) are "by 2050", so no emissions pathway over time is defined, cf. the 2% per year fuel efficiency goal, and the 2020 carbon-neutral goal of ICAO (Lee et al., 2013).*

## 2.4 Analytical methodology to quantify RF and $\Delta T$ benefits

The primary purpose of this study is to quantify the benefits of different mitigation strategies in terms of RF and $\Delta T$, i.e. 'climate impacts', in order to set out a clear and unambiguous analysis of what the best mitigation opportunities are that minimize aviation's $CO_2$ climate impact.

As outlined in Section 1, quantification of emission *rates* by a particular year alone cannot quantify 'best' environmental outcomes, since $CO_2$ accumulates in the atmosphere, so that it is the emissions trajectory or the integrated emissions over a period of time that determine environmental impact (Allen et al., 2009). Moreover, this study is a policy-analysis, and relates principally to international emissions, although total emissions are also of interest from a contextual point of view, and critical for quantification of the contribution of the international fraction.

Thus, given that the motivation is to look at the benefits of emissions mitigation strategies for *international* aviation, this presents an analytical problem in the calculation of RF and $\Delta T$. This is because both these metrics are defined by the total history of aviation, where the beginning of 'significant' aviation is taken as 1940 (IPCC, 1999; Sausen and Schumann, 2000). Unfortunately, data do not exist for the split of domestic vs. international aviation emissions prior to the 1990s, so a method was developed by which the benefits of different mitigation strategies were calculated for international aviation between 2006, the 'baseline year' and 2050. The emissions calculations for 2006 to 2050 include a split of international and domestic emissions by mitigation strategy by growth scenarios. Thus, in order to calculate RF and $\Delta T$ reductions, they must be against a 'baseline'. The technology/operations scenario 'S2' was selected, which approximates to a projection of business-as-usual improvements (Lee et al, 2013). However, as mentioned, a historical estimation of the international split is not available, thus the *savings* in impact are calculated from an incremental mitigation strategy over a baseline to the international fraction of emissions only, and this is subtracted from the total (international plus domestic emissions).

Taking as a simple worked example, the total S2 emissions in 2050 for the central growth scenario are 2,504 Tg[4] $CO_2$ and the international emissions for S2 are 1,638 Tg $CO_2$ (Lee et al., 2013). The incremental mitigation scenario S3 for international emissions in 2050 is 1,527 Tg $CO_2$. Thus, the international savings (for 2050) for S3 over S2 are calculated as 2,504–(1,638–1,527) Tg $CO_2$. This calculation method is applied to all years between 2006 and 2050. Thus, for international aviation, the corresponding RF calculations represent the *savings* in RF made from incremental mitigation strategies over the period 2006 to 2050 over the total aviation baseline scenario of S2, not the absolute RF for international emissions only, since this would require quantification of the domestic vs. international split in global emissions back to 1940.

In this study, we focus on the central aviation growth scenario, for simplicity, but nevertheless, all computations have been made for high and low growth scenarios. In addition, all the aviation growth scenarios have been calculated against the four background RCP scenarios, to represent a range of possible outcomes. This gives 12 basic RF scenarios, for which 23 mitigation options have been calculated (over S2), resulting in 288 RF calculations for international aviation, and 288 for total aviation. Each set of RF results was used against 20 sets of climate model parameters (as described in the Appendix A1.3) where 5,760 temperature responses were calculated

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[4] Terragrams, i.e. $1 \times 10^{12}$ grams; 1 Tg = 1 megatonne (Mt, millions tonnes)

for international aviation and another 5,760 for total aviation. Thus, every possible option has been calculated in order to obtain robust conclusions.

# 3 Results

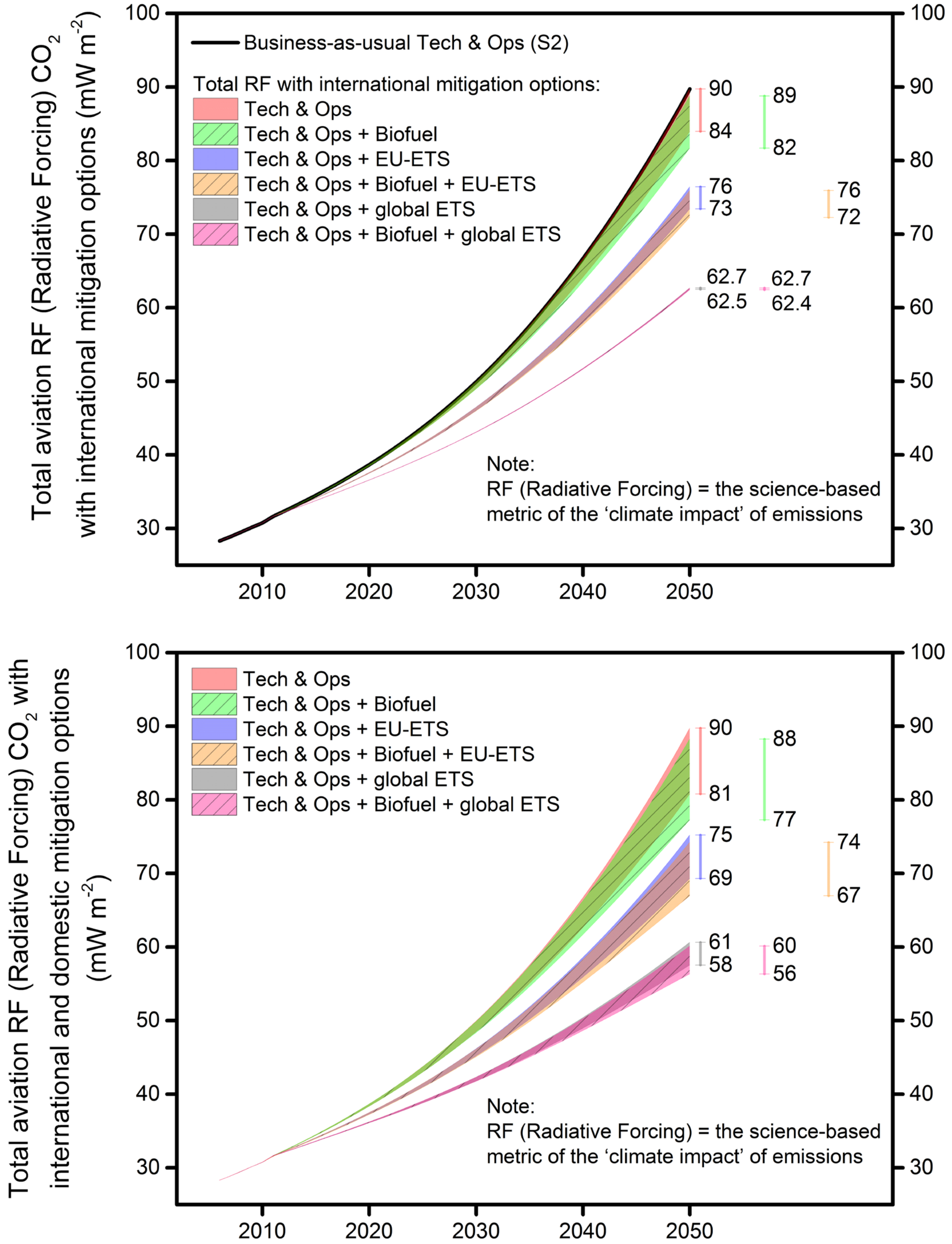



*Figure 4. Effect of mitigation options on $CO_2$ RF to 2050 attributable to international aviation (top panel), and total aviation (lower panel). The central aviation scenario has been used, and the RCP3-PD background scenario, for the purposes of illustration.*

The results of the study are tabulated in Tables 3.1 to 3.4. Tables 3.1 and 3.2 give end point emissions reductions (over BAU S2) of aviation $CO_2$ emissions in 2050, cumulative emissions savings by 2050, and RF savings by 2050 over S2 BAU for high, central, low aviation growth scenarios against each of the RCP background scenarios, for international aviation (Table 3.1) and total aviation (Table 3.2) by each of the mitigation combinations (23). Similarly, temperature responses are given in Tables 3.3 and 3.4 for international, and total aviation, respectively, except that these data are the median responses of 20 climate model simulations. All data in Tables 3.1 to 3.4 are ranked in order of RF or $\Delta T$ results (the rank order is the same).

The responses over time are shown in Appendix 2 (Figures A2.1 and A2.2) for RF and temperature respectively, for each of the RCP background scenarios, showing only the central growth scenario. Examples of these figures are shown in Figure 4, which depicts the effect of the various mitigation options on RF for international and total aviation (illustrated for the central growth aviation scenario, RCP3-PD background scenario). Each 'span' of results (shown as coloured fans) depicts the range of results on each mitigation option varied by technology/operational improvement scenario. So, for example (upper panel, Figure 4), the upper red fan shows a variation in RF response at 2050 between S2 and S5 of 90 mW $m^{-2}$ to 84 mW $m^{-2}$. Inevitably, the 'fans' of results overlap in places, which is reflected by the translucent shading scheme used.

These results were condensed and are presented in the following discussion section in order to determine rank orders of effectiveness in terms of RF and $\Delta T$ reductions, and whether and how results vary systematically (or otherwise) by aviation growth scenario and background RCP scenario, and whether temperature results follow a similar pattern to RF results or not.

*Table 3.1 Emissions (in 2050, and cumulative savings to 2050 from 2006) and radiative forcing savings (in milli Watts per square metre) by 2050 over a business-as-usual technology and operational scenario S2 for international aviation. Values for low, central, high aviation traffic growth, and by background RCP scenario (note line 1 – 'Tech & Ops S2' – gives absolute RF values for total aviation in 2050). Cumulative emissions and radiative forcing (RF) are ranked, so the effectiveness of each mitigation measure/combination can be seen (Note that 2050 emissions **do not** follow this rank order because of the long lifetime(s) of $CO_2$ and as explained in Section 1.1, is **not cumulative**, unlike cumulative emissions and RF. The emissions are provided for information only.)*

| International savings over S2 | Rank, 1=best | Emiss. 2050 Tg $CO_2$ | | | Cum emiss. Tg $CO_2$ | | | RCP3-PD RF mW $m^{-2}$ | | | RCP4.5 RF mW $m^{-2}$ | | | RCP6 RF mW $m^{-2}$ | | | RCP8.5 RF mW $m^{-2}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mitigation scenario | | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi |
| Tech & Ops S2 | | | | | | | | 75.5 | 89.7 | 99.7 | 68.7 | 81.6 | 90.6 | 69.9 | 83.1 | 92.3 | 61.8 | 73.4 | 81.5 |
| Tech & Ops S5 + Biofuel + Global ETS | 1 | 807 | 1,231 | 1,615 | 15,023 | 22,145 | 27,024 | 18.4 | 27.3 | 33.6 | 16.8 | 24.8 | 30.5 | 17.1 | 25.3 | 31.1 | 15.1 | 22.3 | 27.4 |
| Tech & Ops S5 + Global ETS | 2 | 802 | 1,225 | 1,608 | 14,989 | 22,090 | 26,968 | 18.4 | 27.2 | 33.5 | 16.7 | 24.7 | 30.5 | 17.0 | 25.2 | 31.0 | 15.0 | 22.2 | 27.4 |
| Tech & Ops S4 + Biofuel + Global ETS | 3 | 803 | 1,225 | 1,608 | 14,955 | 22,068 | 26,928 | 18.4 | 27.2 | 33.5 | 16.7 | 24.7 | 30.4 | 17.0 | 25.2 | 31.0 | 15.0 | 22.2 | 27.4 |
| Tech & Ops S4 + Global ETS | 4 | 799 | 1,221 | 1,603 | 14,934 | 22,031 | 26,891 | 18.3 | 27.2 | 33.4 | 16.7 | 24.7 | 30.4 | 17.0 | 25.1 | 31.0 | 15.0 | 22.2 | 27.3 |
| Tech & Ops S3 + Biofuel + Global ETS | 5 | 801 | 1,223 | 1,605 | 14,916 | 22,017 | 26,871 | 18.3 | 27.1 | 33.4 | 16.6 | 24.7 | 30.4 | 17.0 | 25.1 | 30.9 | 15.0 | 22.2 | 27.3 |
| Tech & Ops S3 + Global ETS | 6 | 797 | 1,218 | 1,599 | 14,894 | 21,977 | 26,831 | 18.3 | 27.1 | 33.4 | 16.6 | 24.6 | 30.3 | 16.9 | 25.1 | 30.9 | 14.9 | 22.1 | 27.2 |
| Tech & Ops S2 + Biofuel + Global ETS | 7 | 796 | 1,217 | 1,598 | 14,863 | 21,957 | 26,796 | 18.2 | 27.1 | 33.3 | 16.6 | 24.6 | 30.3 | 16.9 | 25.1 | 30.8 | 14.9 | 22.1 | 27.2 |
| Tech & Ops S2 + Global ETS | 8 | 794 | 1,214 | 1,594 | 14,853 | 21,934 | 26,777 | 18.2 | 27.0 | 33.3 | 16.6 | 24.6 | 30.3 | 16.9 | 25.0 | 30.8 | 14.9 | 22.1 | 27.2 |
| Tech & Ops S5 + Biofuel + EUETS | 9 | 584 | 863 | 1,117 | 9,829 | 14,041 | 17,064 | 12.2 | 17.5 | 21.4 | 11.1 | 15.9 | 19.4 | 11.3 | 16.2 | 19.8 | 9.9 | 14.3 | 17.5 |
| Tech & Ops S5 + EUETS | 10 | 508 | 761 | 989 | 9,154 | 13,157 | 16,011 | 11.3 | 16.3 | 20.0 | 10.2 | 14.8 | 18.2 | 10.4 | 15.1 | 18.5 | 9.2 | 13.3 | 16.3 |
| Tech & Ops S4 + Biofuel + EUETS | 11 | 516 | 772 | 1,003 | 8,879 | 12,870 | 15,658 | 11.0 | 16.0 | 19.6 | 10.0 | 14.5 | 17.8 | 10.2 | 14.8 | 18.1 | 9.0 | 13.1 | 16.0 |
| Tech & Ops S4 + EUETS | 12 | 461 | 697 | 910 | 8,411 | 12,256 | 14,926 | 10.4 | 15.2 | 18.6 | 9.4 | 13.8 | 16.9 | 9.6 | 14.0 | 17.2 | 8.5 | 12.4 | 15.2 |
| Tech & Ops S3 + Biofuel + EUETS | 13 | 482 | 724 | 944 | 8,339 | 12,166 | 14,842 | 10.3 | 15.1 | 18.6 | 9.4 | 13.7 | 16.9 | 9.5 | 14.0 | 17.2 | 8.4 | 12.3 | 15.2 |
| Tech & Ops S3 + EUETS | 14 | 423 | 644 | 845 | 7,845 | 11,517 | 14,068 | 9.6 | 14.2 | 17.5 | 8.8 | 12.9 | 15.9 | 8.9 | 13.2 | 16.2 | 7.9 | 11.6 | 14.3 |
| Tech & Ops S2 + Biofuel + EUETS | 15 | 412 | 629 | 827 | 7,544 | 11,181 | 13,663 | 9.3 | 13.8 | 17.0 | 8.4 | 12.5 | 15.5 | 8.6 | 12.8 | 15.8 | 7.6 | 11.3 | 13.9 |
| Tech & Ops S2 + EUETS | 16 | 380 | 586 | 773 | 7,258 | 10,806 | 13,216 | 8.9 | 13.3 | 16.4 | 8.1 | 12.1 | 14.9 | 8.2 | 12.3 | 15.2 | 7.3 | 10.9 | 13.4 |
| Tech & Ops S5 + Biofuel | 17 | 388 | 528 | 655 | 4,944 | 6,229 | 7,404 | 6.3 | 8.0 | 9.6 | 5.7 | 7.3 | 8.7 | 5.8 | 7.5 | 8.9 | 5.2 | 6.6 | 7.8 |
| Tech & Ops S5 | 18 | 244 | 332 | 412 | 3,645 | 4,528 | 5,380 | 4.6 | 5.8 | 6.9 | 4.2 | 5.2 | 6.3 | 4.2 | 5.3 | 6.4 | 3.7 | 4.7 | 5.6 |
| Tech & Ops S4 + Biofuel | 19 | 260 | 353 | 438 | 3,116 | 3,969 | 4,696 | 4.0 | 5.2 | 6.1 | 3.6 | 4.7 | 5.6 | 3.7 | 4.8 | 5.7 | 3.3 | 4.2 | 5.0 |
| Tech & Ops S4 | 20 | 155 | 211 | 261 | 2,216 | 2,789 | 3,289 | 2.8 | 3.6 | 4.2 | 2.5 | 3.2 | 3.8 | 2.6 | 3.3 | 3.9 | 2.3 | 2.9 | 3.5 |
| Tech & Ops S3 + Biofuel | 21 | 193 | 263 | 326 | 2,075 | 2,613 | 3,124 | 2.7 | 3.4 | 4.1 | 2.4 | 3.1 | 3.8 | 2.5 | 3.2 | 3.8 | 2.2 | 2.8 | 3.4 |
| Tech & Ops S3 | 22 | 81 | 110 | 137 | 1,123 | 1,365 | 1,637 | 1.4 | 1.8 | 2.1 | 1.3 | 1.6 | 1.9 | 1.3 | 1.6 | 2.0 | 1.2 | 1.4 | 1.7 |
| Tech & Ops S2 + Biofuel | 23 | 60 | 82 | 102 | 552 | 723 | 859 | 0.7 | 1.0 | 1.2 | 0.7 | 0.9 | 1.0 | 0.7 | 0.9 | 1.1 | 0.6 | 0.8 | 0.9 |

*Table 3.2 Emissions (in 2050, and cumulative savings to 2050 from 2006) and radiative forcing savings (in milli Watts per square metre) by 2050 over a business-as-usual technology and operational scenario S2 for <u>total</u> aviation. Values for low, central, high aviation traffic growth, and by background RCP scenario (note line 1 – 'Tech & Ops S2' – gives absolute RF values for total aviation in 2050). Cumulative emissions and radiative forcing (RF) are ranked, so the effectiveness of each mitigation measure/combination can be seen (Note that 2050 emissions **do not** follow this rank order because of the long lifetime(s) of $CO_2$ and as explained in Section 1.1, is **not cumulative**, unlike cumulative emissions and RF. The emissions are provided for information only.)*

| Total savings over S2 | Rank, 1=best | Emiss. 2050 Tg $CO_2$ | | | Cum emiss. Tg $CO_2$ | | | RCP3-PD RF mW $m^{-2}$ | | | RCP4.5 RF mW $m^{-2}$ | | | RCP6 RF mW $m^{-2}$ | | | RCP8.5 RF mW $m^{-2}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mitigation scenario | | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi |
| Tech & Ops S2 | | | | | | | | 75.5 | 89.7 | 99.7 | 68.7 | 81.6 | 90.6 | 69.9 | 83.1 | 92.3 | 61.8 | 73.4 | 81.5 |
| Tech & Ops S5 + Biofuel + Global ETS | 1 | 1,049 | 1,560 | 2,024 | 18,936 | 27,032 | 32,732 | 23.3 | 33.4 | 40.8 | 21.1 | 30.4 | 37.0 | 21.5 | 30.9 | 37.7 | 19.0 | 27.3 | 33.3 |
| Tech & Ops S5 + Global ETS | 2 | 975 | 1,459 | 1,898 | 18,246 | 26,129 | 31,658 | 22.4 | 32.2 | 39.3 | 20.3 | 29.3 | 35.7 | 20.7 | 29.8 | 36.4 | 18.3 | 26.3 | 32.1 |
| Tech & Ops S4 + Biofuel + Global ETS | 3 | 983 | 1,470 | 1,912 | 17,937 | 25,812 | 31,265 | 22.0 | 31.8 | 38.9 | 20.0 | 28.9 | 35.4 | 20.4 | 29.5 | 36.0 | 18.0 | 26.0 | 31.8 |
| Tech & Ops S4 + Global ETS | 4 | 928 | 1,397 | 1,821 | 17,459 | 25,186 | 30,519 | 21.4 | 31.0 | 37.9 | 19.4 | 28.2 | 34.4 | 19.8 | 28.7 | 35.1 | 17.5 | 25.3 | 31.0 |
| Tech & Ops S3 + Biofuel + Global ETS | 5 | 948 | 1,424 | 1,854 | 17,368 | 25,071 | 30,409 | 21.3 | 30.9 | 37.8 | 19.4 | 28.1 | 34.4 | 19.7 | 28.6 | 35.0 | 17.4 | 25.3 | 30.9 |
| Tech & Ops S3 + Global ETS | 6 | 890 | 1,345 | 1,757 | 16,863 | 24,409 | 29,620 | 20.6 | 30.0 | 36.8 | 18.8 | 27.3 | 33.4 | 19.1 | 27.8 | 34.0 | 16.9 | 24.5 | 30.0 |
| Tech & Ops S2 + Biofuel + Global ETS | 7 | 880 | 1,330 | 1,738 | 16,545 | 24,060 | 29,196 | 20.3 | 29.6 | 36.3 | 18.4 | 26.9 | 32.9 | 18.8 | 27.4 | 33.6 | 16.6 | 24.2 | 29.6 |
| Tech & Ops S2 + Global ETS | 8 | 849 | 1,288 | 1,686 | 16,251 | 23,676 | 28,740 | 19.9 | 29.1 | 35.6 | 18.1 | 26.4 | 32.4 | 18.4 | 26.9 | 33.0 | 16.2 | 23.8 | 29.1 |
| Tech & Ops S5 + Biofuel + EUETS | 9 | 807 | 1,173 | 1,505 | 13,033 | 18,225 | 22,119 | 16.2 | 22.8 | 27.8 | 14.7 | 20.7 | 25.3 | 15.0 | 21.1 | 25.8 | 13.2 | 18.6 | 22.7 |
| Tech & Ops S5 + EUETS | 10 | 662 | 976 | 1,260 | 11,683 | 16,451 | 19,960 | 14.4 | 20.4 | 25.0 | 13.1 | 18.6 | 22.7 | 13.3 | 18.9 | 23.1 | 11.8 | 16.7 | 20.4 |
| Tech & Ops S4 + Biofuel + EUETS | 11 | 677 | 997 | 1,287 | 11,153 | 15,908 | 19,342 | 13.8 | 19.8 | 24.3 | 12.6 | 18.0 | 22.1 | 12.8 | 18.4 | 22.5 | 11.3 | 16.2 | 19.8 |
| Tech & Ops S4 + EUETS | 12 | 571 | 853 | 1,108 | 10,207 | 14,664 | 17,808 | 12.6 | 18.2 | 22.3 | 11.4 | 16.5 | 20.2 | 11.6 | 16.8 | 20.6 | 10.3 | 14.8 | 18.2 |
| Tech & Ops S3 + Biofuel + EUETS | 13 | 610 | 906 | 1,174 | 10,081 | 14,513 | 17,728 | 12.5 | 18.1 | 22.2 | 11.4 | 16.4 | 20.2 | 11.6 | 16.7 | 20.6 | 10.2 | 14.8 | 18.2 |
| Tech & Ops S3 + EUETS | 14 | 497 | 752 | 982 | 9,083 | 13,199 | 16,109 | 11.2 | 16.3 | 20.1 | 10.2 | 14.8 | 18.3 | 10.3 | 15.1 | 18.6 | 9.1 | 13.3 | 16.4 |
| Tech & Ops S2 + Biofuel + EUETS | 15 | 476 | 723 | 947 | 8,487 | 12,534 | 15,304 | 10.5 | 15.5 | 19.1 | 9.5 | 14.1 | 17.4 | 9.7 | 14.4 | 17.7 | 8.5 | 12.7 | 15.6 |
| Tech & Ops S2 + EUETS | 16 | 415 | 640 | 844 | 7,923 | 11,797 | 14,428 | 9.7 | 14.5 | 17.9 | 8.8 | 13.2 | 16.3 | 9.0 | 13.4 | 16.6 | 7.9 | 11.9 | 14.6 |
| Tech & Ops S5 + Biofuel | 17 | 593 | 807 | 1,001 | 7,676 | 9,658 | 11,479 | 9.8 | 12.5 | 14.9 | 8.9 | 11.3 | 13.5 | 9.0 | 11.5 | 13.8 | 8.0 | 10.2 | 12.1 |
| Tech & Ops S5 | 18 | 373 | 508 | 630 | 5,669 | 7,031 | 8,354 | 7.1 | 8.9 | 10.7 | 6.5 | 8.1 | 9.7 | 6.6 | 8.3 | 9.9 | 5.8 | 7.3 | 8.7 |
| Tech & Ops S4 + Biofuel | 19 | 397 | 540 | 670 | 4,834 | 6,152 | 7,275 | 6.2 | 8.0 | 9.5 | 5.6 | 7.2 | 8.6 | 5.7 | 7.4 | 8.8 | 5.1 | 6.5 | 7.7 |
| Tech & Ops S4 | 20 | 237 | 322 | 399 | 3,444 | 4,329 | 5,103 | 4.3 | 5.5 | 6.5 | 3.9 | 5.0 | 5.9 | 4.0 | 5.1 | 6.1 | 3.5 | 4.5 | 5.3 |
| Tech & Ops S3 + Biofuel | 21 | 296 | 402 | 499 | 3,215 | 4,043 | 4,833 | 4.2 | 5.3 | 6.4 | 3.8 | 4.8 | 5.8 | 3.9 | 4.9 | 5.9 | 3.4 | 4.3 | 5.2 |
| Tech & Ops S3 | 22 | 124 | 169 | 209 | 1,746 | 2,116 | 2,537 | 2.2 | 2.7 | 3.3 | 2.0 | 2.5 | 3.0 | 2.0 | 2.5 | 3.0 | 1.8 | 2.2 | 2.7 |
| Tech & Ops S2 + Biofuel | 23 | 92 | 125 | 155 | 853 | 1,116 | 1,327 | 1.1 | 1.5 | 1.8 | 1.0 | 1.4 | 1.6 | 1.0 | 1.4 | 1.7 | 0.9 | 1.2 | 1.5 |

*Table 3.3 Medians of 20 model results of temperature savings (in milli Kelvin) by 2050 over a business-as-usual technology and operational improvements scenario S2 for international aviation. Values for low, central, high aviation traffic growth, and by background RCP scenario (note line 1 – 'Tech & Ops S2' – gives absolute temperature values for total aviation in 2050). Temperature savings (ΔT) are ranked, so the effectiveness of each mitigation measure/combination can be seen*

| International savings over S2 | Rank, 1=best | RCP3-PD $\Delta T$ mK | | | RCP4.5 $\Delta T$ mK | | | RCP6 $\Delta T$ mK | | | RCP8.5 $\Delta T$ mK | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mitigation scenario | | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi |
| Tech & Ops S2 | | 31.9 | 36.6 | 39.5 | 30.1 | 34.4 | 37.1 | 30.7 | 35.1 | 37.8 | 27.9 | 31.9 | 34.4 |
| Tech & Ops S5 + Biofuel + Global ETS | 1 | 6.1 | 8.9 | 10.7 | 6.1 | 8.5 | 10.0 | 6.2 | 8.8 | 10.3 | 5.6 | 8.1 | 9.5 |
| Tech & Ops S5 + Global ETS | 2 | 6.1 | 8.9 | 10.7 | 6.1 | 8.5 | 10.0 | 6.2 | 8.7 | 10.2 | 5.6 | 8.0 | 9.5 |
| Tech & Ops S4 + Biofuel + Global ETS | 3 | 6.1 | 8.9 | 10.7 | 6.0 | 8.5 | 10.0 | 6.2 | 8.7 | 10.2 | 5.6 | 8.0 | 9.5 |
| Tech & Ops S4 + Global ETS | 4 | 6.1 | 8.9 | 10.7 | 6.0 | 8.5 | 10.0 | 6.2 | 8.6 | 10.2 | 5.6 | 8.0 | 9.5 |
| Tech & Ops S3 + Biofuel + Global ETS | 5 | 6.1 | 8.9 | 10.6 | 6.0 | 8.5 | 9.9 | 6.1 | 8.6 | 10.2 | 5.6 | 8.0 | 9.4 |
| Tech & Ops S3 + Global ETS | 6 | 6.1 | 8.8 | 10.6 | 6.0 | 8.4 | 9.9 | 6.1 | 8.6 | 10.2 | 5.6 | 8.0 | 9.4 |
| Tech & Ops S2 + Biofuel + Global ETS | 7 | 6.1 | 8.8 | 10.6 | 6.0 | 8.4 | 9.9 | 6.1 | 8.6 | 10.1 | 5.6 | 8.0 | 9.4 |
| Tech & Ops S2 + Global ETS | 8 | 6.1 | 8.8 | 10.6 | 6.0 | 8.4 | 9.9 | 6.1 | 8.6 | 10.1 | 5.6 | 8.0 | 9.4 |
| Tech & Ops S5 + Biofuel + EUETS | 9 | 3.9 | 5.6 | 6.6 | 3.9 | 5.1 | 6.2 | 3.9 | 5.2 | 6.4 | 3.7 | 4.9 | 5.7 |
| Tech & Ops S5 + EUETS | 10 | 3.6 | 5.3 | 6.3 | 3.6 | 4.9 | 6.0 | 3.7 | 5.0 | 6.1 | 3.5 | 4.6 | 5.4 |
| Tech & Ops S4 + Biofuel + EUETS | 11 | 3.5 | 5.2 | 6.1 | 3.5 | 4.7 | 5.8 | 3.5 | 4.8 | 6.0 | 3.4 | 4.5 | 5.2 |
| Tech & Ops S4 + EUETS | 12 | 3.3 | 5.0 | 5.9 | 3.3 | 4.6 | 5.6 | 3.4 | 4.6 | 5.8 | 3.2 | 4.3 | 5.0 |
| Tech & Ops S3 + Biofuel + EUETS | 13 | 3.3 | 4.9 | 5.8 | 3.2 | 4.5 | 5.5 | 3.3 | 4.6 | 5.7 | 3.2 | 4.2 | 5.0 |
| Tech & Ops S3 + EUETS | 14 | 3.1 | 4.7 | 5.6 | 3.1 | 4.3 | 5.3 | 3.1 | 4.4 | 5.4 | 3.0 | 4.0 | 4.8 |
| Tech & Ops S2 + Biofuel + EUETS | 15 | 3.0 | 4.5 | 5.4 | 2.9 | 4.2 | 5.1 | 3.0 | 4.3 | 5.3 | 2.9 | 3.9 | 4.6 |
| Tech & Ops S2 + EUETS | 16 | 2.9 | 4.4 | 5.3 | 2.8 | 4.1 | 5.0 | 2.9 | 4.2 | 5.1 | 2.8 | 3.7 | 4.5 |
| Tech & Ops S5 + Biofuel | 17 | 1.8 | 2.2 | 2.6 | 1.8 | 2.2 | 2.5 | 1.8 | 2.2 | 2.5 | 1.8 | 1.9 | 2.3 |
| Tech & Ops S5 | 18 | 1.4 | 1.7 | 2.0 | 1.3 | 1.7 | 1.9 | 1.3 | 1.8 | 1.9 | 1.4 | 1.3 | 1.9 |
| Tech & Ops S4 + Biofuel | 19 | 1.2 | 1.4 | 1.6 | 1.0 | 1.5 | 1.5 | 1.0 | 1.5 | 1.6 | 1.1 | 1.1 | 1.6 |
| Tech & Ops S4 | 20 | 0.9 | 1.0 | 1.2 | 0.8 | 1.1 | 1.1 | 0.8 | 1.1 | 1.1 | 0.8 | 0.8 | 1.2 |
| Tech & Ops S3 + Biofuel | 21 | 0.8 | 0.9 | 1.0 | 0.7 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 0.8 | 0.7 | 1.0 |
| Tech & Ops S3 | 22 | 0.5 | 0.5 | 0.6 | 0.4 | 0.5 | 0.5 | 0.4 | 0.5 | 0.6 | 0.4 | 0.4 | 0.6 |
| Tech & Ops S2 + Biofuel | 23 | 0.2 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 | 0.1 | 0.3 | 0.3 | 0.2 | 0.2 | 0.3 |

*Table 3.4 Medians of 20 model results of temperature savings (in milli Kelvin) by 2050 over a business-as-usual technology and operational improvements scenario S2 for total aviation. Values for low, central, high aviation traffic growth, and by background RCP scenario (note line 1 – 'Tech & Ops S2' – gives absolute temperature values for total aviation in 2050). Temperature savings (ΔT) are ranked, so the effectiveness of each mitigation measure/combination can be seen*

| Total savings over S2 | Rank, 1=best | RCP3-PD $\Delta T$ mK | | | RCP4.5 $\Delta T$ mK | | | RCP6 $\Delta T$ mK | | | RCP8.5 $\Delta T$ mK | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mitigation scenario | | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi | Low | Cen | Hi |
| Tech & Ops S2 | | 31.9 | 36.6 | 39.5 | 30.1 | 34.4 | 37.1 | 30.7 | 35.1 | 37.8 | 27.9 | 31.9 | 34.4 |
| Tech & Ops S5 + Biofuel + Global ETS | 1 | 7.9 | 11.0 | 12.9 | 7.6 | 10.5 | 12.3 | 7.8 | 11.2 | 12.9 | 6.9 | 9.7 | 11.6 |
| Tech & Ops S5 + Global ETS | 2 | 7.6 | 10.6 | 12.5 | 7.4 | 10.2 | 11.9 | 7.6 | 10.4 | 12.2 | 6.7 | 9.5 | 11.3 |
| Tech & Ops S4 + Biofuel + Global ETS | 3 | 7.4 | 10.4 | 12.3 | 7.3 | 10.0 | 11.8 | 7.4 | 10.2 | 12.0 | 6.6 | 9.3 | 11.1 |
| Tech & Ops S4 + Global ETS | 4 | 7.2 | 10.2 | 12.1 | 7.1 | 9.8 | 11.5 | 7.2 | 10.0 | 11.7 | 6.5 | 9.1 | 10.8 |
| Tech & Ops S3 + Biofuel + Global ETS | 5 | 7.2 | 10.1 | 12.0 | 7.1 | 9.7 | 11.4 | 7.2 | 9.9 | 11.7 | 6.4 | 9.1 | 10.8 |
| Tech & Ops S3 + Global ETS | 6 | 7.0 | 9.8 | 11.8 | 6.9 | 9.5 | 11.1 | 7.0 | 9.7 | 11.3 | 6.3 | 8.9 | 10.5 |
| Tech & Ops S2 + Biofuel + Global ETS | 7 | 6.8 | 9.7 | 11.6 | 6.7 | 9.3 | 10.9 | 6.8 | 9.5 | 11.2 | 6.2 | 8.8 | 10.3 |
| Tech & Ops S2 + Global ETS | 8 | 6.7 | 9.6 | 11.4 | 6.6 | 9.2 | 10.7 | 6.7 | 9.4 | 11.0 | 6.1 | 8.7 | 10.2 |
| Tech & Ops S5 + Biofuel + EUETS | 9 | 5.2 | 7.1 | 8.6 | 5.2 | 6.8 | 7.9 | 5.3 | 6.9 | 8.1 | 4.9 | 6.5 | 7.5 |
| Tech & Ops S5 + EUETS | 10 | 4.6 | 6.5 | 7.8 | 4.7 | 6.1 | 7.3 | 4.7 | 6.2 | 7.4 | 4.5 | 5.8 | 6.8 |
| Tech & Ops S4 + Biofuel + EUETS | 11 | 4.4 | 6.3 | 7.5 | 4.4 | 5.8 | 7.0 | 4.5 | 6.0 | 7.1 | 4.2 | 5.6 | 6.5 |
| Tech & Ops S4 + EUETS | 12 | 4.0 | 5.9 | 7.0 | 4.0 | 5.4 | 6.6 | 4.1 | 5.5 | 6.7 | 3.9 | 5.2 | 6.0 |
| Tech & Ops S3 + Biofuel + EUETS | 13 | 3.9 | 5.8 | 6.9 | 4.0 | 5.3 | 6.4 | 4.0 | 5.4 | 6.6 | 3.8 | 5.1 | 5.9 |
| Tech & Ops S3 + EUETS | 14 | 3.6 | 5.4 | 6.4 | 3.6 | 4.9 | 6.0 | 3.6 | 5.0 | 6.2 | 3.5 | 4.6 | 5.4 |
| Tech & Ops S2 + Biofuel + EUETS | 15 | 3.4 | 5.1 | 6.0 | 3.3 | 4.7 | 5.7 | 3.4 | 4.7 | 5.9 | 3.2 | 4.4 | 5.1 |
| Tech & Ops S2 + EUETS | 16 | 3.2 | 4.8 | 5.7 | 3.1 | 4.4 | 5.4 | 3.2 | 4.5 | 5.6 | 3.0 | 4.1 | 4.9 |
| Tech & Ops S5 + Biofuel | 17 | 2.8 | 3.6 | 4.1 | 2.9 | 3.2 | 4.0 | 2.9 | 3.3 | 4.1 | 2.8 | 3.1 | 3.5 |
| Tech & Ops S5 | 18 | 2.2 | 2.6 | 3.1 | 2.1 | 2.5 | 2.9 | 2.1 | 2.6 | 3.0 | 2.1 | 2.2 | 2.7 |
| Tech & Ops S4 + Biofuel | 19 | 1.7 | 2.2 | 2.6 | 1.7 | 2.1 | 2.4 | 1.7 | 2.2 | 2.5 | 1.8 | 1.8 | 2.3 |
| Tech & Ops S4 | 20 | 1.4 | 1.6 | 1.9 | 1.2 | 1.7 | 1.7 | 1.2 | 1.7 | 1.8 | 1.3 | 1.3 | 1.8 |
| Tech & Ops S3 + Biofuel | 21 | 1.2 | 1.4 | 1.6 | 1.0 | 1.4 | 1.5 | 1.1 | 1.5 | 1.5 | 1.2 | 1.1 | 1.5 |
| Tech & Ops S3 | 22 | 0.7 | 0.8 | 0.9 | 0.6 | 0.8 | 0.9 | 0.6 | 0.8 | 0.9 | 0.7 | 0.6 | 0.9 |
| Tech & Ops S2 + Biofuel | 23 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.2 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 |

# 4 Discussion

## 4.1 Ranking and comparing mitigation by additional measures to business-as-usual technology and operational improvements

Taking the results presented in Tables 3.1 to 3.4, the effectiveness of various mitigation strategies, in terms of reductions in aviation $CO_2$ RF and temperature response, over a BAU situation can be examined in a number of ways. Here, biofuels, the EU-ETS and hypothetical global ETS are examined as incremental improvements on the BAU S2 technology scenario for both international and total aviation.

In Table 4.1, percentage reductions are given for mitigation strategies over the BAU S2 technology/operational improvements scenario in terms of improvements in RF and $\Delta T$, for international aviation. Similar data are given in Table 4.2 for total aviation. These calculations are made and tabulated for the high, central, and low aviation growth scenarios, and against each of the background RCP $CO_2$ scenarios.

Certain patterns emerge, enabling presentation in a simplified manner. The results (absolute RF/temperature values/differences) in Tables 3.1 to 3.4 largely show the same rank order in effectiveness regardless of aviation growth scenario, with the exception of one instance of a reversal of order between two mitigation options for the low growth scenario. However, that aside, rank order is invariant by background scenario, and invariant between RF and temperature results. Thus, a robust pattern emerges. From Tables 4.1 and 4.2, it can also be noted that the percentage reductions for either RF or temperature changes do not vary significantly by background scenario (although the absolute values change, as is expected – see Tables 3.1 to 3.4).

What the data in Tables 4.1 and 4.2 indicate is that there is a clear pattern of incremental improvements over the BAU S2 technology/operational improvement scenario; so, for international aviation:

- a small additional reduction of 1.1% (range 1.0 to 1.2%[5]) in RF is achieved by adding in "*likely*" (UK CCC, 2009) amounts of biofuels over S2 BAU;
- the EU-ETS alone over S2 BAU results in a 14.8% reduction in RF (range 11.8 to 16.5%);
- "*likely*" levels of biofuel and the EU-ETS, combined, reduce RF by 15.4% (range 12.3 to 17.1%) over S2 BAU;
- a hypothetical global ETS alone, reduces RF by 30.1% (range 24.1 to 33.4%) over S2 BAU;
- "*likely*" levels of biofuels and a hypothetical global ETS, combined, reduces RF by 30.1% (range 24.1 to 33.4%) over S2 BAU.

A similar pattern is shown for improvements in temperature over S2 BAU, broadly in line with the RF results (Table 4.1). Table 4.2 gives a similar analysis, but for total aviation, and despite the regional nature of the EU-ETS, a similarly large reduction in RF of 16.2% (range 12.8 to 18%) is found, since the coverage of the EU-ETS is quite extensive, in terms of global emissions.

[5] Note that the range comes from the different aviation growth scenarios modeled; the figure quoted is the central growth scenario and the range gives the low, high, growth scenario percentages.

These RF gains from international aviation, over time, and at the 2050 point are shown in Figure 4.1 (example of central aviation growth scenario, RCP8.5 background scenario).

*Table 4.1 Relative gains (in rank order) in radiative forcing (RF) and in global mean temperature ($\Delta$T) for selected mitigation strategies for <u>international aviation</u> over business-as-usual S2 technology and operational improvements scenario, for RCP background scenarios (3-PD, 4.5, 6, 8.5) and low, central, and high aviation growth scenarios*

| | *Rank* 1=best | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP3-PD background* | | | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP4.5 background* | | | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP6 background* | | | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP8.5 background* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi |
| | | | RF | | | RF | | | RF | | | RF | |
| S2 + biofuel | 5 | 1.0 | **1.1** | 1.2 | 1.0 | **1.1** | 1.2 | 1.0 | **1.1** | 1.2 | 1.0 | **1.1** | 1.2 |
| S2 + EUETS | 4 | 11.8 | **14.8** | 16.5 | 11.8 | **14.8** | 16.5 | 11.8 | **14.8** | 16.5 | 11.8 | **14.8** | 16.5 |
| S2 + biofuel + EUETS | 3 | 12.3 | **15.4** | 17.1 | 12.3 | **15.4** | 17.1 | 12.3 | **15.4** | 17.1 | 12.3 | **15.4** | 17.1 |
| S2 + global ETS | 2 | 24.1 | **30.1** | 33.4 | 24.1 | **30.1** | 33.4 | 24.1 | **30.1** | 33.4 | 24.1 | **30.1** | 33.4 |
| S2 + biofuel + global ETS | 1 | 24.2 | **30.2** | 33.4 | 24.2 | **30.2** | 33.4 | 24.2 | **30.2** | 33.4 | 24.1 | **30.1** | 33.4 |
| | | | $\Delta T$ | | | $\Delta T$ | | | $\Delta T$ | | | $\Delta T$ | |
| S2 + biofuel | 5 | 0.7 | **0.6** | 0.7 | 0.6 | **0.8** | 0.7 | 0.5 | **0.8** | 0.7 | 0.7 | **0.5** | 0.8 |
| S2 + EUETS | 4 | 9.1 | **12.0** | 13.3 | 9.4 | **11.8** | 13.4 | 9.4 | **11.9** | 13.5 | 10.0 | **11.7** | 13.1 |
| S2 + biofuel + EUETS | 3 | 9.4 | **12.4** | 13.7 | 9.7 | **12.1** | 13.9 | 9.7 | **12.2** | 13.9 | 10.4 | **12.1** | 13.4 |
| S2 + global ETS | 2 | 19.0 | **24.1** | 26.9 | 19.9 | **24.5** | 26.7 | 20.0 | **24.5** | 26.8 | 20.0 | **25.0** | 27.4 |
| S2 + biofuel + global ETS | 1 | 19.0 | **24.2** | 26.9 | 20.0 | **24.5** | 26.8 | 20.0 | **24.6** | 26.8 | 20.0 | **25.1** | 27.4 |

*Table 4.2 Relative gains (in rank order) in radiative forcing (RF) and in global mean temperature ($\Delta$T) for selected mitigation strategies for <u>total aviation</u> over business-as-usual S2 technology and operational improvements scenario, for RCP background scenarios (3-PD, 4.5, 6, 8.5) and low, central, and high aviation growth scenarios*

| | *Rank* 1=best | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP3-PD background* | | | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP4.5 background* | | | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP6 background* | | | Percentage (%) improvements in RF and $\Delta T$ over S2 BAU *RCP8.5 background* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi |
| | | | RF | | | RF | | | RF | | | RF | |
| S2 + biofuel | 5 | 1.5 | **1.7** | 1.8 | 1.5 | **1.7** | 1.8 | 1.5 | **1.7** | 1.8 | 1.5 | **1.7** | 1.8 |
| S2 + EUETS | 4 | 12.9 | **16.2** | 18.0 | 12.9 | **16.2** | 18.0 | 12.9 | **16.2** | 18.0 | 12.8 | **16.2** | 18.0 |
| S2 + biofuel + EUETS | 3 | 13.9 | **17.3** | 19.2 | 13.8 | **17.3** | 19.1 | 13.8 | **17.3** | 19.2 | 13.8 | **17.3** | 19.1 |
| S2 + global ETS | 2 | 26.3 | **32.4** | 35.8 | 26.3 | **32.4** | 35.7 | 26.3 | **32.4** | 35.7 | 26.3 | **32.4** | 35.7 |
| S2 + biofuel + global ETS | 1 | 26.8 | **33.0** | 36.4 | 26.8 | **33.0** | 36.3 | 26.8 | **33.0** | 36.3 | 26.8 | **33.0** | 36.3 |
| | | | $\Delta T$ | | | $\Delta T$ | | | $\Delta T$ | | | $\Delta T$ | |
| S2 + biofuel | 5 | 1.1 | **1.0** | 1.1 | 0.9 | **1.2** | 1.1 | 0.8 | **1.2** | 1.1 | 1.1 | **0.8** | 1.3 |
| S2 + EUETS | 4 | 10.0 | **13.1** | 14.6 | 10.3 | **12.9** | 14.7 | 10.3 | **12.9** | 14.8 | 10.9 | **12.9** | 14.3 |
| S2 + biofuel + EUETS | 3 | 10.5 | **13.9** | 15.3 | 11.0 | **13.5** | 15.5 | 11.0 | **13.5** | 15.6 | 11.6 | **13.7** | 15.0 |
| S2 + global ETS | 2 | 21.0 | **26.2** | 29.0 | 21.9 | **26.7** | 29.0 | 21.9 | **26.7** | 29.1 | 21.8 | **27.2** | 29.6 |
| S2 + biofuel + global ETS | 1 | 21.4 | **26.5** | 29.4 | 22.3 | **27.1** | 29.5 | 22.3 | **27.1** | 29.5 | 22.1 | **27.5** | 30.0 |

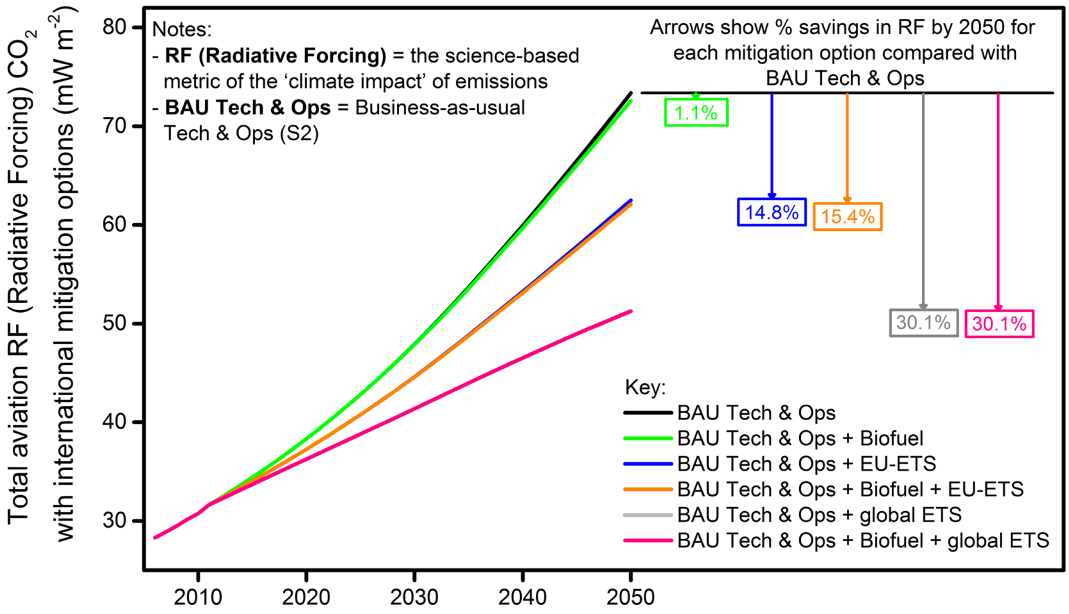



*Figure 5. The development over time of $CO_2$ radiative forcing savings from international aviation over the S2 business-as-usual (BAU) scenario, for: "likely" levels of biofuels; the EU-ETS; 'likely" levels of biofuels plus the EU-ETS; a hypothetical global ETS; "likely" levels of biofuels plus a hypothetical global ETS. Analyses are for the central aviation growth scenario with an RCP8.5 background emissions scenario.*

## 4.2 Ranking and comparing mitigation by additional measures to maximum feasible reductions (MFR) in emissions from technology and operational improvements

Table 4.3 give percentage reductions in RF and $\Delta T$ for international aviation over the S2 BAU case from MFR in emissions from technology and operational improvements, along with other measures, alone and combined, i.e. biofuels at "speculative" levels (UK CCC, 2009), the EU-ETS extended to 2050, and a hypothetical global ETS for international aviation. Table 4.4 gives similar data, but for total aviation.

A similar rank order of 'effectiveness' in RF and $\Delta T$ reductions emerges, as was the case for individual and combined measures over S2 BAU, except that in this comparison, MFR technology and operational improvements are compared with S2 BAU. So, for international aviation:

- MFR reductions in emissions from S5 technology and operational improvements result in a reduction of RF by 6.4% (range 6.1 to 6.9%) over S2 BAU;
- the addition of "*speculative*" levels of biofuels, combined with S5 MFR technology and operational improvements results in a reduction of RF by 9% (range 8.3 to 9.6%) over S2 BAU;
- the EU-ETS, combined with S5 MFR technology and operational improvements, results in a reduction of RF by 18.2% (range 14.9 to 20.1%) over S2 BAU;
- combining the EU-ETS with "speculative" levels of biofuels, and S5 MFR technology and operational improvements, results in a reduction of RF by 19.5% (range 16.1 to 21.5%) over S2 BAU;

- a hypothetical global ETS, combined with S5 MFR technology and operational improvements, results in a reduction of RF by 30.3% (range 24.3 to 33.6%) over S2 BAU;
- combining a hypothetical global ETS with "speculative" levels of biofuels, and S5 MFR technology and operational improvements, results in a reduction of RF by 30.4% (range 24.4 to 33.7%) over S2 BAU.

Changes in temperature response for international aviation were in the same rank order as changes in RF (Table 4.3), with broadly similar changes in incremental effectiveness of the various measures. For total aviation (Table 4.4), the rank order of incremental changes in terms of decreased RF/$\Delta T$ over an S2 BAU scenario for various measures, and their combinations, was the same as for international aviation.

The reductions in RF for various measures, individual and combined, over S2 for S5 maximum feasible reductions in emissions from technological and operational improvements, are shown in Figure 6.

*Table 4.3 Relative gains (in rank order) in radiative forcing (RF) and in global mean temperature (ΔT) for Maximum Feasible Reduction mitigation strategies for <u>international aviation</u> over business-as-usual S2 technology and operational improvements scenario, for RCP background scenarios (3-PD, 4.5, 6, 8.5) and low, central, and high aviation growth scenarios*

| | *Rank* 1=best | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP3-PD background* | | | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP4.5 background* | | | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP6 background* | | | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP8.5 background* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi |
| | | | RF | | | RF | | | RF | | | RF | |
| S5 | 6 | 6.1 | **6.4** | 6.9 | 6.1 | **6.4** | 6.9 | 6.1 | **6.4** | 6.9 | 6.1 | **6.4** | 6.9 |
| S5 + bio | 5 | 8.3 | **9.0** | 9.6 | 8.3 | **9.0** | 9.6 | 8.3 | **9.0** | 9.6 | 8.3 | **9.0** | 9.6 |
| S5 + EUETS | 4 | 14.9 | **18.2** | 20.1 | 14.9 | **18.2** | 20.0 | 14.9 | **18.2** | 20.0 | 14.9 | **18.1** | 20.0 |
| S5 + biofuel + EUETS | 3 | 16.1 | **19.5** | 21.5 | 16.1 | **19.5** | 21.5 | 16.1 | **19.5** | 21.5 | 16.1 | **19.5** | 21.4 |
| S5 + global ETS | 2 | 24.4 | **30.3** | 33.6 | 24.3 | **30.3** | 33.6 | 24.4 | **30.3** | 33.6 | 24.3 | **30.3** | 33.6 |
| S5 + biofuel + global ETS | 1 | 24.4 | **30.4** | 33.7 | 24.4 | **30.4** | 33.7 | 24.4 | **30.4** | 33.7 | 24.4 | **30.4** | 33.7 |
| | | | Δ*T* | | | Δ*T* | | | Δ*T* | | | Δ*T* | |
| S5 | 6 | 4.5 | **4.6** | 5.1 | 4.3 | **5.0** | 5.0 | 4.3 | **5.1** | 5.0 | 4.9 | **4.2** | 5.4 |
| S5 + bio | 5 | 5.6 | **6.1** | 6.7 | 5.9 | **6.3** | 6.7 | 5.9 | **6.4** | 6.7 | 6.5 | **5.9** | 6.8 |
| S5 + EUETS | 4 | 11.4 | **14.6** | 16.0 | 12.0 | **14.2** | 16.1 | 12.0 | **14.2** | 16.2 | 12.5 | **14.4** | 15.6 |
| S5 + biofuel + EUETS | 3 | 12.1 | **15.4** | 16.8 | 12.8 | **14.9** | 16.8 | 12.8 | **14.9** | 16.9 | 13.4 | **15.4** | 16.5 |
| S5 + global ETS | 2 | 19.1 | **24.3** | 27.1 | 20.1 | **24.7** | 27.0 | 20.1 | **24.7** | 27.0 | 20.2 | **25.2** | 27.6 |
| S5 + biofuel + global ETS | 1 | 19.2 | **24.3** | 27.1 | 20.2 | **24.8** | 27.0 | 20.2 | **25.2** | 27.2 | 20.2 | **25.3** | 27.6 |

*Table 4.4 Relative gains (in rank order) in radiative forcing (RF) and in global mean temperature (ΔT) for Maximum Feasible Reduction strategies for <u>total aviation</u> over business-as-usual S2 technology and operational improvements scenario, for RCP background scenarios (3-PD, 4.5, 6, 8.5) and low, central, and high aviation growth scenarios*

| | *Rank* 1=best | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP3-PD background* | | | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP4.5 background* | | | Percentage (%) improvements in RF and Δ*T* over S2 BAU *RCP6 background* | | | Percentage (%) improvements in RF, and Δ*T* over S2 BAU *RCP8.5 background* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi | Lo | Central | Hi |
| | | | RF | | | RF | | | RF | | | RF | |
| S5 | 6 | 9.4 | **10.0** | 10.7 | 9.4 | **10.0** | 10.7 | 9.4 | **10.0** | 10.7 | 9.4 | **10.0** | 10.7 |
| S5 + bio | 5 | 12.9 | **13.9** | 14.9 | 12.9 | **13.9** | 14.9 | 12.9 | **13.9** | 14.9 | 12.9 | **13.9** | 14.9 |
| S5 + EUETS | 4 | 19.1 | **22.8** | 25.0 | 19.1 | **22.8** | 25.0 | 19.1 | **22.8** | 25.0 | 19.1 | **22.7** | 25.0 |
| S5 + biofuel + EUETS | 3 | 21.4 | **25.4** | 27.9 | 21.4 | **25.4** | 27.9 | 21.4 | **25.4** | 27.9 | 21.4 | **25.4** | 27.9 |
| S5 + global ETS | 2 | 29.6 | **35.9** | 39.5 | 29.6 | **35.9** | 39.4 | 29.6 | **35.9** | 39.4 | 29.6 | **35.8** | 39.4 |
| S5 + biofuel + global ETS | 1 | 30.8 | **37.2** | 40.9 | 30.8 | **37.2** | 40.9 | 30.8 | **37.2** | 40.9 | 30.8 | **37.2** | 40.8 |
| | | | Δ*T* | | | Δ*T* | | | Δ*T* | | | Δ*T* | |
| S5 | 6 | 6.7 | **7.2** | 7.9 | 7.0 | **7.3** | 7.9 | 7.0 | **7.4** | 7.9 | 7.6 | **6.9** | 7.9 |
| S5 + bio | 5 | 8.7 | **10.0** | 10.4 | 9.6 | **9.3** | 10.8 | 9.6 | **9.4** | 10.9 | 10.2 | **9.8** | 10.1 |
| S5 + EUETS | 4 | 14.5 | **17.9** | 19.9 | 15.4 | **17.7** | 19.6 | 15.4 | **17.7** | 19.6 | 16.0 | **18.3** | 19.7 |
| S5 + biofuel + EUETS | 3 | 16.2 | **19.4** | 21.8 | 17.2 | **19.7** | 21.4 | 17.2 | **19.7** | 21.4 | 17.4 | **20.3** | 21.9 |
| S5 + global ETS | 2 | 23.8 | **28.9** | 31.8 | 24.6 | **29.6** | 32.2 | 24.6 | **29.6** | 32.3 | 24.2 | **29.7** | 32.7 |
| S5 + biofuel + global ETS | 1 | 24.7 | **30.0** | 32.7 | 25.3 | **30.6** | 33.3 | 25.4 | **31.9** | 34.2 | 24.9 | **30.5** | 33.6 |

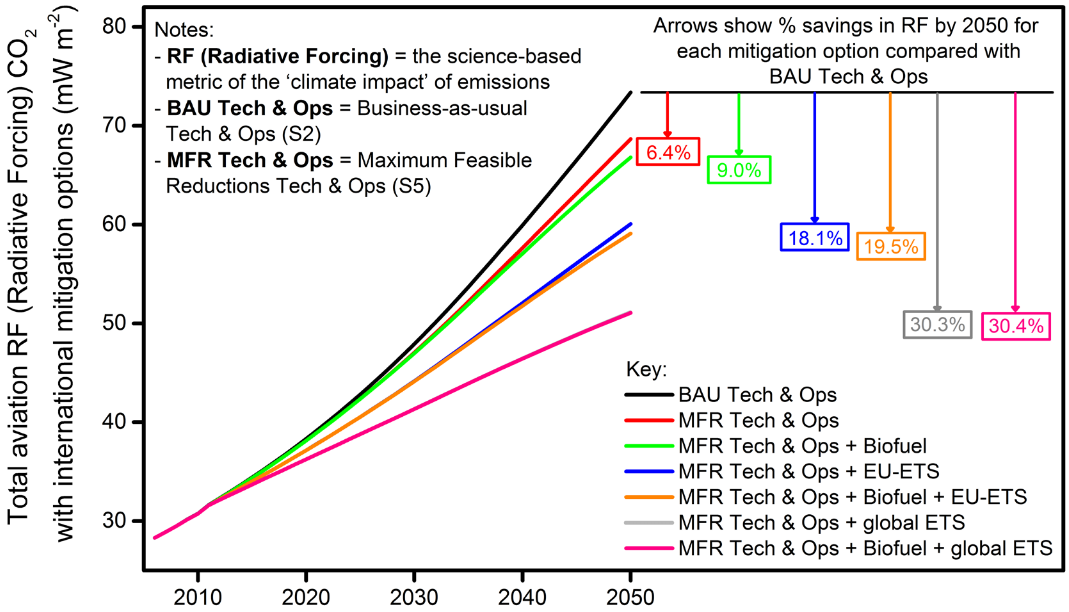
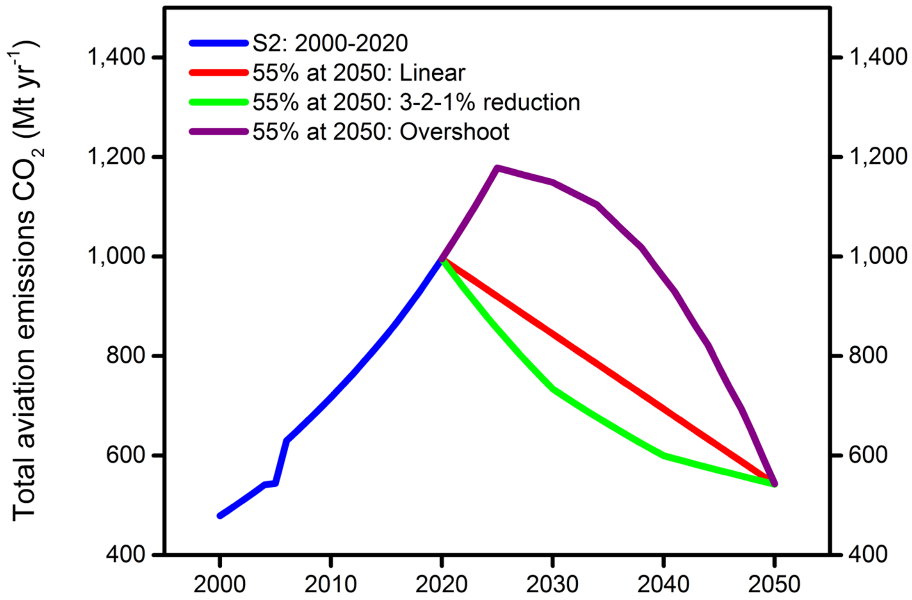



*Figure 6. The development over time of $CO_2$ radiative forcing savings from international aviation over the S2 business-as-usual (BAU) scenario, for: maximum feasible reductions (MFR) in technology and operations; MFR plus "speculative" levels of biofuels; MFR plus the EU-ETS; MFR plus "speculative" levels of biofuels plus the EU-ETS; MFR plus a hypothetical global ETS; and MFR plus "speculative" levels of biofuels, plus a hypothetical global ETS. Analyses are for the central aviation growth scenario with an RCP8.5 background emissions scenario.*

## 4.4 Sensitivity analysis and illustration; "timing is everything"

The critical point of the analyses presented here – as per part of the title "*…timing is everything*" – is that the end point emissions (say, in 2050) matter far less than the 'pathway' or 'trajectory' of emissions over time in reaching an end point. This is a well-known and studied science phenomenon concerning $CO_2$ emissions and radiative forcing or temperature response. However, policy and climate targets – including those of ICAO and aviation stakeholders – tend not to either appreciate or incorporate this idea: however, this concept is absolutely critical if the most cost-effective, and climate effective mitigation options are to be pursued.

To illustrate this point, three hypothetical aviation emissions scenarios of reaching a 2050 emissions target are formulated. In Figure 7, we explicitly model a hypothetical example of three different $CO_2$ emission pathways that lead to the same emission rate in 2050 (an arbitrary 'goal' of 55% of 2020 emissions by 2050). In this example, aviation emissions in two scenarios (red and green lines) are reduced from 2020 onwards, either linearly (red line) or at declining rates of reduction (green line). In the third scenario, emissions continue unabated until 2025 as an 'overshoot' scenario, and then decline, but all three scenarios reach the same hypothetical goal of an emission rate by 2050 of 55% of 2020 emissions. However, in the RF response, a clear rank order of the environmental effectiveness can be seen of 'green' being better than 'red', which is better than 'purple'. This clearly illustrates that it is not the achievement of the 'goal' in 2050 that is important, but the pathway taken there in terms of emissions as the three scenarios result in significantly different environmental responses.



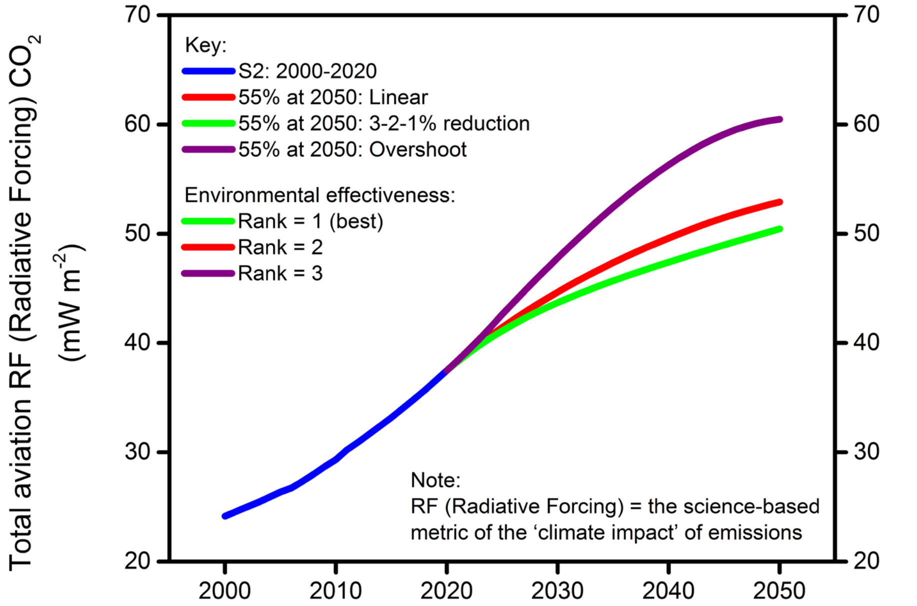




*Figure 7. Illustrative mitigation scenarios with the same 'end-point' hypothetical 'goal' emisions of 55% of 2020 emissions by 2050 (upper panel), showing early mitigation emissions (red/green) and late 'overshoot' reduced emissions (purple) and their different $CO_2$ RF responses (lower panel).*

Thus, the 'message' from the hypothetical scenarios shown in Figure 7 is that *early* emissions reductions result in environmental benefit in terms of a real response, RF, whereas late reductions – yet achieving the same emissions goal by 2050 – have a demonstrably poorer environmental performance in terms of their real effect – radiative forcing. This analogy is reflected in the results of the mitigation analysis performed in this study in that the emissions trading reductions achieve early reductions in $CO_2$ emissions (assuming that the trading system is operating efficiently) achieving real carbon reductions elsewhere (other sectors), whereas those mitigation strategies that are reliant on technological development of either engines/airframe, system operational efficiencies, production of carbon-reducing biofuels, tend to take longer. Historically, this has been clearly seen in the engine/airframe example, where development of new

technologies and its uptake into the fleet takes a decade, or more. So, in terms of the projections analysed here, the reduction in $CO_2$ emissions from international aviation moving from an S2 BAU technology and operational improvements scenario to an S5 MFR scenario on its own resulted in reduction in RF of 6.4% (range 6.1 to 6.9%). Such reductions would have significant costs, and S5 is a highly ambitious technology scenario. By contrast, introducing a MBM such as the EU-ETS with no extra technology developments other than BAU, offers a reduction in RF of 14.8% (range 11.8 to 16.5%). The advantage of market-based mechanisms such as emissions trading is the swift reductions in $CO_2$ that can be achieved. Furthermore, there are cost aspects that should also be considered in optimally mitigating aviation $CO_2$ emissions.

Whilst emissions trading is demonstrated here under the various stated scenario assumptions to offer the most efficient $CO_2$ reductions in terms of environmental response, this should not be taken as an argument to not pursue improved technological development, or the development of $CO_2$-efficent biofuels; these can only *add* to the ultimate mitigation response, as clearly demonstrated here (see Tables 4.1 to 4.4). Emissions trading offers an early 'win' – hence, "timing is everything".

# 5 Conclusions

The environmental response of international and total aviation $CO_2$ emissions in terms of radiative forcing and global mean surface temperature response at 2050 has been analysed in terms of a range of mitigation options that includes: technological and operational improvements, uptake of biofuels at different rates, the European ETS for aviation extended out to 2050. In addition a hypothetical global ETS for international departing flights has been considered in order to examine $CO_2$ emission reduction potentials.

For international aviation, of the currently existing mitigation options formulated, the EU-ETS offers the largest single potential reduction in aviation $CO_2$ RF by 2050, at 14.8% (range 11.8 to 16.5%) over the BAU (S2) scenario. The second largest single reduction potential came from Maximum Feasible Reductions (MFR) (S5) from technological and operational improvements, at 6.4% (range 6.1 to 6.9%); the smallest single reduction potential of a measure came from biofuels, at 1.1% (range 1.0 to 1.2%). If all the potential mitigation options are combined (MFR technology and operations, biofuels, EU-ETS), then the reduction in aviation $CO_2$ RF by 2050 over the S2 BAU scenario could be 19.5% (range 16.1 to 21.5%).

The hypothetical case of a global ETS for international departing flights starting in 2012 showed that this could have the largest reduction potential for RF by 2050, for international aviation $CO_2$ emissions, achieving a reduction of 30.1% (range 24.1 to 33.4%) over the BAU (S2) scenario (with no additional mitigation options).

Identical rankings were found for reductions in global mean temperature over those arising from a BAU (S2) scenario, by 2050, attributable to $CO_2$ emissions from aviation. The percentage reductions were not greatly dissimilar to those of RF but obviously varied because of the more complex nature of the temperature calculation. Nonetheless, the fact that the rank order was the same, confirms the conclusions from the RF results.

The conclusions regarding percentage reductions in RF or $\Delta T$ are largely invariant with aviation growth rate assumed in terms of rank order. The absolute RF reductions vary by background RCP emission scenario, as was expected; however, the *relative* reductions do not significantly vary by background RCP scenario. The systematic results

of this study combined with the exhaustive number of calculations to explore parameter space (demand scenarios, background scenarios, climate model parameters), under the assumptions made over emissions, give a large degree of confidence to the conclusions of rank order and relative benefits of the mitigation options studied.

The advantage of the EU-ETS and the hypothetical global ETS systems is the achievement of early $CO_2$ emissions reductions. This is further exemplified by a hypothetical example that reaches the same emissions goal by 2050, but by different emission pathways: early reductions in $CO_2$ emissions produce the best environmental response. The advantage of efficiently operating ETSs is that they produce early reductions in $CO_2$ emissions.

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# Appendix 1 – Detailed calculation methodology

## A1.1 Calculation of $CO_2$ concentrations from emissions

The response of $CO_2$ concentrations, *C(t)*, to a $CO_2$ aviation emissions rate, *E(t)* is modelled using the method described in Hasselmann et al., (1997) and is expressed as:

$$\Delta C(t) = \int_{t_0}^{t} G_C(t-t')E(t')dt'$$

where $G_C(t) = \sum_{j=0}^{5} \alpha_j e^{-t/\tau_j}$ , $\tau_j$ is the e-folding time of mode *j* and the equilibrium response of mode *j* to a unit emissions of $\alpha_j \tau_j$.

The mode parameters used in this study are presented in Sausen and Schumann (2000) and approximate the carbon-cycle model in Meier-Reimer and Hasselmann (1987). The applicability of these parameters in the context of aviation response was tested in a model inter-comparison exercise (Khodayari et al., 2013). For the time horizon of 50-60 years into the future, these were found to compare well with other more sophisticated carbon-cycle model such as MAGICC 6.0, which is widely used in the IPCC Fourth Assessment Report. Beyond this, aviation $CO_2$ concentrations will begin to have an impact on the ocean and biosphere uptake of $CO_2$ and the non-linearities of the system would have to be accounted for.

## A1.2 Calculation of $CO_2$ radiative forcing from concentrations

The radiative forcing, *RF(t)* of a $CO_2$ concentration at time, *t*, was calculated using the simplified expression first published in the IPCC Third Assessment Report (Boucher et al., 2001) and found to be still valid by the IPCC Fourth Assessment Report (Forster et al., 2007).

$$RF_{CO2}(t) = 5.35 \ln\left(\frac{C(t)}{C(0)}\right)$$

where *C(0)* is the pre-industrial $CO_2$ concentration.

Since the $RF_{CO2}$ increase is dependent upon the background concentration, historical background $CO_2$ concentrations were used from 1765 to 2010, and thereafter, until 2050, from the four RCP scenarios as described in Section 2.2. The contribution of aviation $CO_2$ concentrations was calculated explicitly as outlined in section A1.2, with the concentration being assumed to be the difference between background and aviation concentrations. Therefore, the $RF_{CO2}$ due to aviation was calculated as follows:

$$RF_{CO2}(t) = RF\left(C(t)_{Background}\right) - RF\left(C(t)_{Background} - C(t)_{Aviation}\right)$$

## A1.3 Calculation of global mean surface temperature response from radiative forcing

The temperature response approach was devised by Hasselmann et al., (1993) and has been used in various aviation impact assessments e.g. Sausen and Schumann (2000) and Khodayari et al. (2013). The climate response function approach can be represented by a convolution integral, the use which assumes that small aviation perturbations can be represented in a linearly additive manner. Thus, the temperature response, $\Delta T$ from a climate agent, *i*, to a radiative forcing *RF(t)* is:

$$\Delta T_i(t) = r_i \lambda_{CO2} \int_{t_0}^{t} \hat{G}_T(t-t') RF_i(t') dt'$$

$$\hat{G}_T(t) = \frac{1}{\tau} e^{-t/\tau}$$

where, $r$ is the efficacy and $r_{CO2} = 1$, $\lambda_{CO2}$ is the $CO_2$ climate sensitivity parameter and $\tau$ is the lifetime of the temperature perturbation. The $\lambda_{CO2}$ and $\tau$ parameters were derived from an Atmosphere-Ocean General Circulation Models (AOGCMs) experiment. In this study, 20 sets of parameters derived from various full-scale AOGCM experiments were used to capture the full range of likely temperature responses. Figure A1.1 illustrates the range of temperature responses for the central-S2 scenarios against the 4 RCP backgrounds, with the solid line indicating the median for the range.

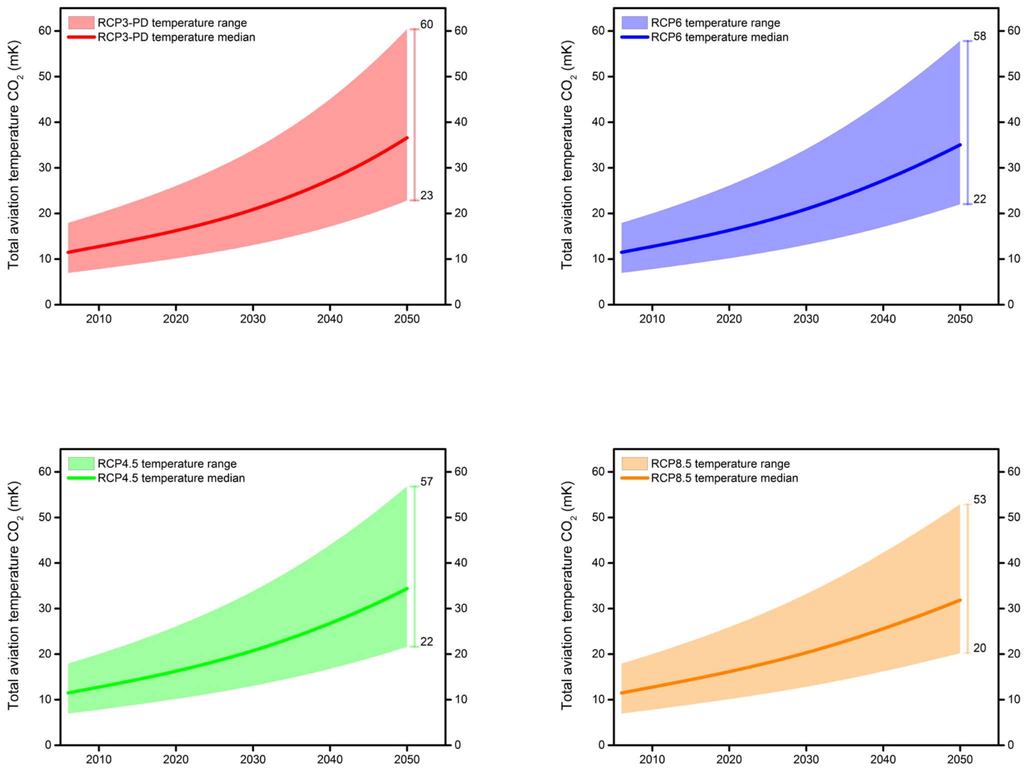


*Figure A1.1 Temperature response for the central demand, S2 aviation scenario against the RCP backgrounds; RCP3-PD (top left), RCP6 (top right), RCP4.5 (bottom left) and RCP8.5 (bottom right). The temperature range was derived from 20 set of AOGCM climate parameters, with the solid line denoting the median.*

## A1.4 Sensitivity analysis

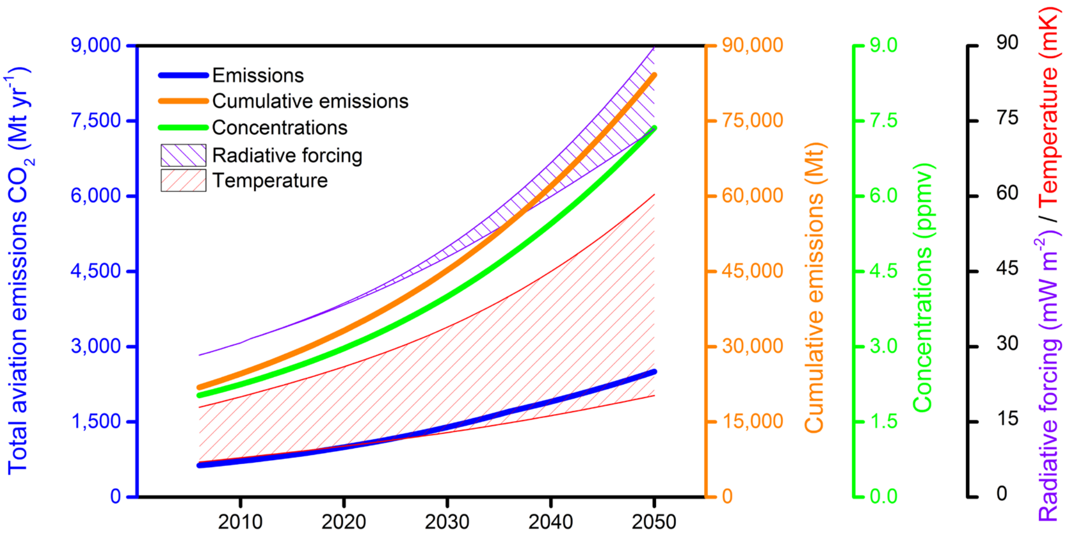


*Figure A1.2. Changes in annual emissions, cumulative emissions, and concentrations of $CO_2$ for the central growth scenario to 2050, and resultant ranges of potential aviation $CO_2$ RF response (for same emissions) according to background emission scenario used and aviation temperature response according to background emission scenario and range of parent AOGCMs.*

Figure A1.2 shows a time-series of annual emissions, cumulative emissions, the resultant marginal $CO_2$ concentrations attributable to aviation, and the range of potential RF results and temperature responses. The purpose of this graph is to illustrate that depending on the background emissions used, a range of RF responses can result *for the same aviation emissions*, and that our analytical approach of using multiple background scenarios and climate model temperature responses is comprehensive.

The background emissions come from the four RCP scenarios, as described in Section 2. Thus, the same aviation emissions may result in an aviation RF signal ranging between approximately 75 and 90 mW $m^{-2}$. The resultant range of temperature responses is even larger (red-lines between red curves). The uncertainty here is the result of our comprehensive analytical approach: the absolute magnitude of projected temperature response is well known to be dependent upon the climate model used. In our analysis, we parameterize the temperature response of our simplified climate model upon the responses of 20 coupled Atmosphere-Ocean General Circulation Models (AOGCMs), as described in Appendix 1.3. In our analysis, the median response is used to illustrate temperature trends.

It is important to note that a period of 46 years, as shown in Figure A1.2, is rather short in terms of climate response, and that the signal of 'response' to emissions (concentrations, RF, change in global mean surface temperature) appears to vary approximately linearly with emissions is entirely fortuitous because of the short period illustrated. For example, in Figure A1.2, it can be observed that in scenario RCP3-PD, the emissions decrease markedly over a period of 50 years, but nonetheless the concentrations of $CO_2$ continue to increase. This is because of the long lifetime(s) of $CO_2$ in the atmosphere; and there is even more 'lag' in the temperature signal because of the long response times of the oceans coming to an equilibrium temperature response.

# Appendix 2 – RFs and Δ*T* response by background RCP scenario

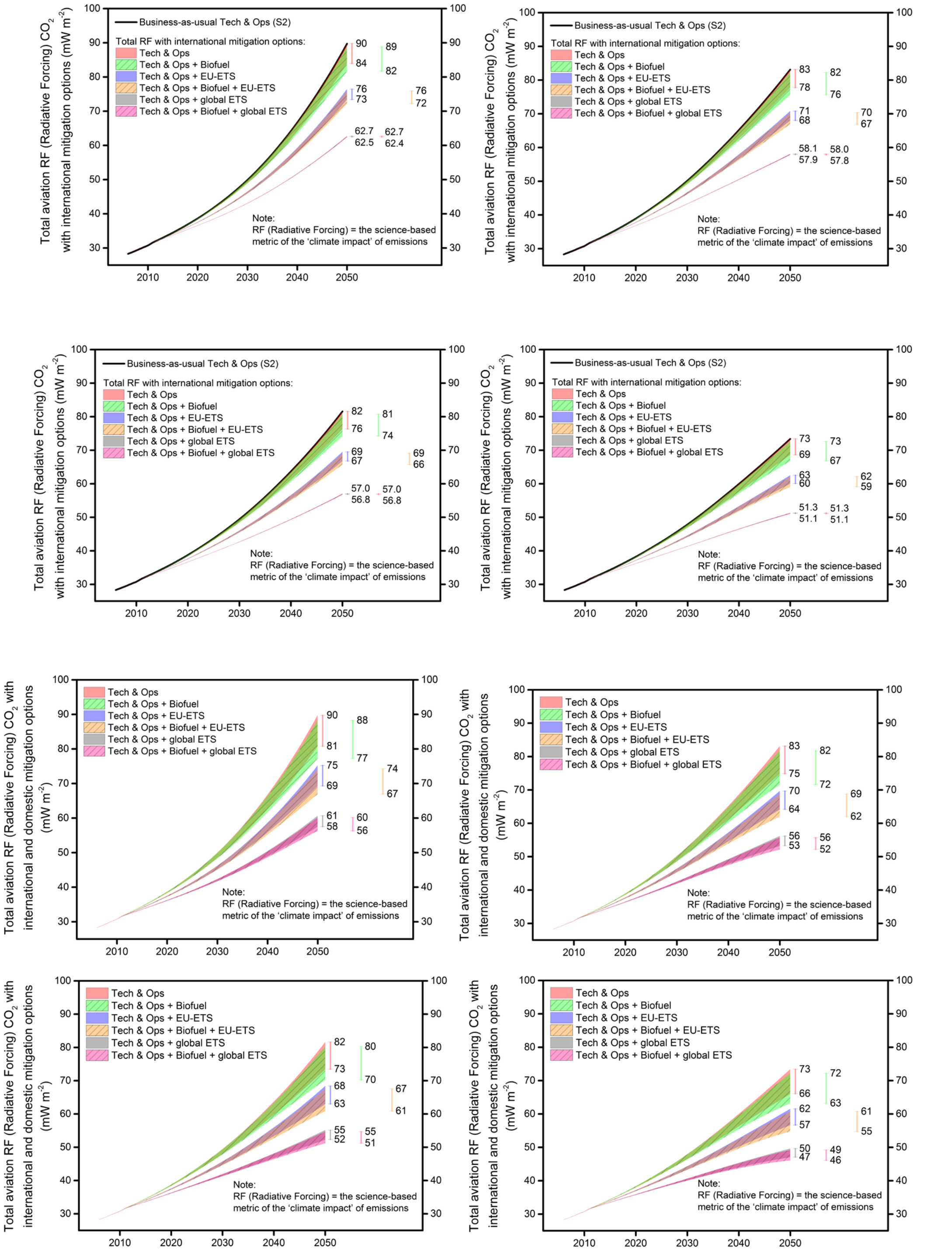


*Figure A2.1. Effect of mitigation options on $CO_2$ RF by 2050 attributable to international aviation (top four panels, by background scenario), and total aviation (lower four panels), by background scenario (all central aviation growth scenario). Scenarios (left to right, then upper to lower): RCP3-PD, RCP6, RCP4.5, RCP8.5.*

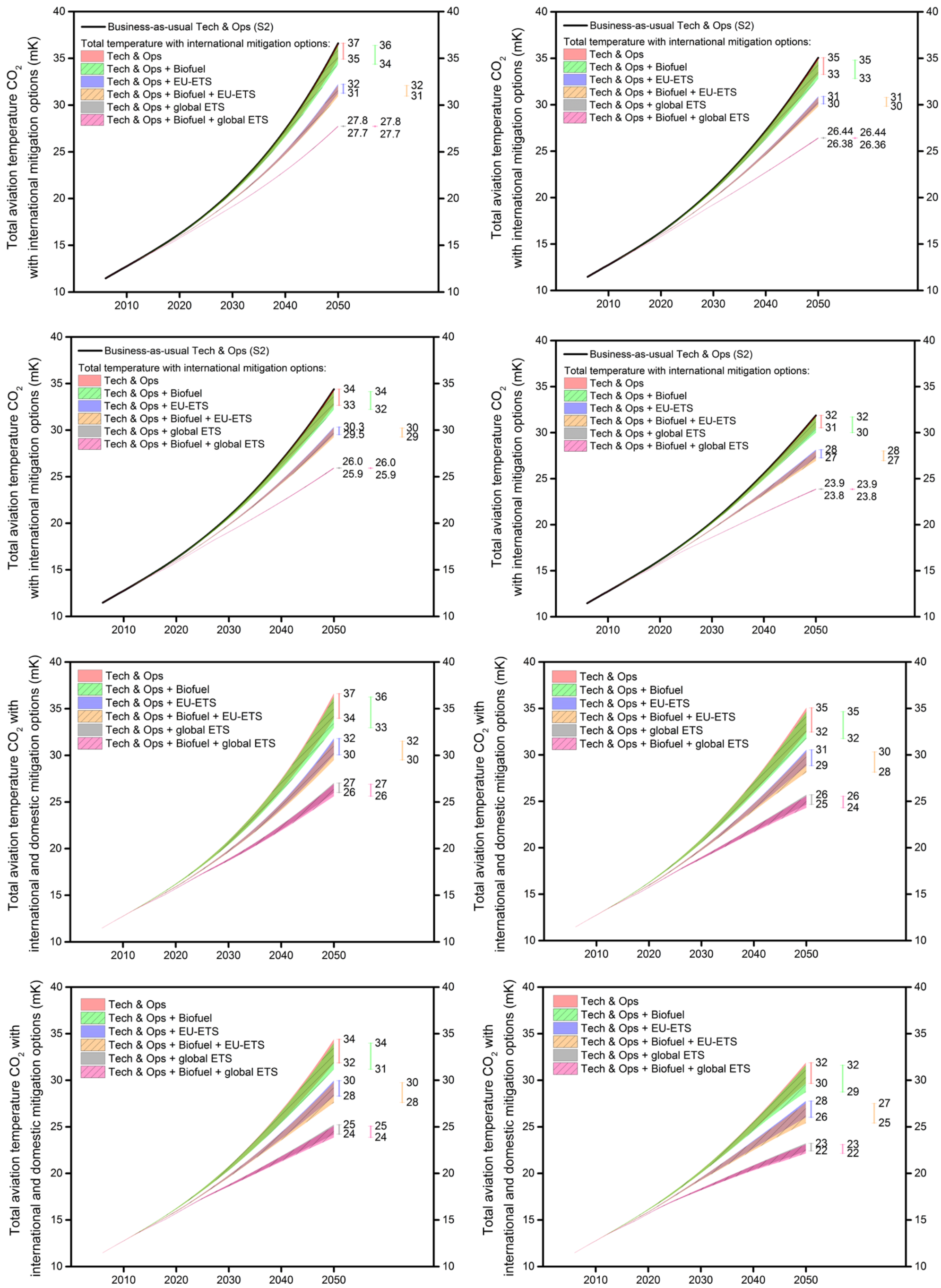


*Figure A2.2. Effect of mitigation options on $CO_2$ temperature response by 2050 attributable to international aviation (top four panels, by background scenario), and total aviation (lower four panels), by background scenario (all central aviation growth scenario). Scenarios (left to right, then upper to lower): RCP3-PD, RCP6, RCP4.5, RCP8.5.*