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The contribution of carbon dioxide emissions from the aviation sector to future climate change

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Abstract

The compact Earth system model OSCARv2.2 is used to assess the climate impact of present and future civil aviation carbon dioxide (CO_2) emissions. The impact of aviation CO_2 on future climate is quantified over the 1940–2050 period, extending some simulations to 2100 and using different aviation CO_2 emission scenarios and two background Representative Concentrations Pathways (RCP2.6 and RCP6.0) for other emission sectors. Several aviation scenarios including weak to strong mitigation options are considered with emissions ranging from 386 $MtCO_2$/year (Factor 2 scenario) to 2338 $MtCO_2$/year (ICAO based scenario) in 2050. As a reference, in 2000, the calculated impact of aviation CO_2 emissions is 9.1 ± 2 mK (0.8% of the total anthropogenic warming associated to fossil fuel emissions). In 2050, on a climate trajectory in line with the Paris Agreement limiting the global warming below 2 °C (RCP2.6), the impact of the aviation CO_2 emissions ranges from 26 ± 2 mK (1.4% of the total anthropogenic warming associated to fossil fuel emissions) for an ambitious mitigation strategy scenario (Factor 2) to 39 ± 4 mK (2.0% of the total anthropogenic warming associated to fossil fuel emissions) for the least ambitious mitigation scenario of the study (ICAO based). On the longer term, if no significant emission mitigation is implemented for the aviation sector, the associated warming could further increase and reach a value of 99.5 mK ± 20 mK in 2100 (ICAO based), which corresponds to 5.2% of the total anthropogenic warming under RCP2.6. The contribution of CO_2 is estimated to represent 36%–51% of the total aviation radiative forcing of climate including short-term climate forcers. However, due to its long residence time in the atmosphere, aviation CO_2 will have a major contribution on decadal time scales. These additional short-terms forcers are subject to large uncertainties and will be analysed in forthcoming studies.

1. Introduction

In 2017, worldwide flights carried nearly 4.1 billion passengers and produced 859 million tonnes of CO_2 (ATAG 2019). In 2016, the International Civil Aviation Organisation (ICAO) recalled that the aviation sector 'accounts for under 2% of the world's annual CO_2 emissions' (ICAO 2016). The growing aviation sector is expected to experience a three-fold increase between 2000 and 2050 in terms of passengers (Berghof *et al* 2005, Horton 2006). Airbus plans a 4.6%/yr increase in the average annual global air traffic rate over the next 20 years (2015–2034) (Airbus 2016), while Boeing forecasts a 4.9%/yr increase over the same period (Boeing 2015). Between 1995 and 2010, the aviation sector recorded an average yearly growth rate of 4.6%/yr in terms of revenue-passenger-kilometres, despite the drop linked to the world economic recession in 2008. The mean annual growth rate is projected to remain constant (4.1%/yr) over the 2015–2025 period (ICAO 2019a), which could make the aviation sector a significant fossil fuel CO_2 emitting sector in the future (2050).

It has previously been shown that aircraft emissions perturb the radiative budget of the Earth atmosphere (Brasseur *et al* 1998, 2016 Intergovernmental Panel on Climate Change (IPCC) 1999, Sausen *et al* 2005, IPCC 2007, Lee *et al* 2009). Aviation emissions are estimated to contribute to 5% (2%–14%, 90% likelihood range) of the anthropogenic radiative forcing (RF) of climate with an uncertainty dominated by non-CO_2 effects (Lee *et al* 2010). The climate impact of CO_2 emissions from aviation has been previously assessed by different studies for the past, present and future (Gauss *et al* 2006, Lee *et al* 2010). Even if the level of scientific understanding is considered to be high by the IPCC for present-day aviation CO_2 impact (Lee *et al* 2010) compared to other non-CO_2 forcers (e.g. ozone, aerosols and contrails), the future (2050) aviation CO_2 climate impact remains highly uncertain. The main cause of these varying estimates is not linked to the understanding of the physical and biogeochemical properties of CO_2 but rather to the inherent assumptions made in the development of future global emission scenarios such as the one from international aviation (Boucher *et al* 2016).

In 2018, 158 Parties ratified the Paris agreement which aims to '[*hold*] *the increase in the global average temperature to well below* 2 °*C above pre-industrial levels and pursuing efforts to limit the temperature increase to* 1.5 °*C above pre-industrial levels.*' The framework of the present study is the 2 °C objective decided during the twenty-first session of the Conference of the Parties (COP 21) which was held in Paris in 2015. Hence, among the four Representative Concentration Pathways assessed in the fifth assessment report of the Intergovernmental Panel on Climate Change, the scenario RCP2.6 constitutes a good background scenario for global climate forcers representative of this goal of limiting global warming in 2100 to less than 2 °C above preindustrial levels (van Vuuren *et al* 2011, Collins *et al* 2013). Achieving this objective is very ambitious and requires a rapid and significant reduction in greenhouse gas emissions (Raftery *et al* 2017, IPCC 2018). Moreover, Boucher *et al* (2016) showed that the Intended Nationally Determined Contributions remain insufficient to bring global greenhouse gas emissions onto a path to limit global warming below 2 °C. The RCP6.0 scenario which implies, for example, that the global temperature in 2050 is warmer by 1.5 °C than under RCP2.6 is therefore seen as a plausible alternative scenario.

The impact of aircraft CO_2 emissions on climate has been assessed for instance by Sausen and Schumann (2000), Lee *et al* (2010) and Khodayari *et al* (2013). In this paper, a compact Earth system model (ESM) including a detailed carbon cycle representation is used to quantify the global climate impact of the aviation sector and its uncertainties in the framework of the Paris agreement using updated aviation emissions scenarios. Compact climate change models are fast and relatively easy to use in the sense that they do not require the manipulation of big input datasets and large computer resources (Harvey *et al* 1997, Meinshausen *et al* 2011b, Gasser *et al* 2015, Li *et al* 2017, Strassman and Joos 2018). These models include parametric equations describing global (or regional) air-sea interaction and air-biosphere exchange, and they can produce a close representation of the outputs from more expensive complex carbon cycle models. These models can be used for different applications: quantification of the impact of different economic sectors (past, present, future) on climate, regional attribution of climate change, quantification of the radiative impact of different chemical species and aerosols.

This paper aims to give an updated estimate of the global climate impact of CO_2 emissions from the aviation sector according to multiple future scenarios using a Monte Carlo methodology to quantify the 'physical' uncertainty of the model. The aviation climate impact is quantified over the 1940–2050 period with an extension to 2100, according to updated aviation emission scenarios and for the two aforementioned RCP (RCP2.6 and RCP6.0) storylines for background of CO_2 concentration and climate future evolution. The contribution of CO_2 is estimated to represent 36%–51% of the total aviation RF of climate including short-term climate forcers (Lee *et al* 2009, Grewe *et al* 2017, Karcher 2018). However, due to its long residence time in the atmosphere, aviation CO_2 will have a major contribution on decadal time scales. In section 2 we provide a description of the OSCAR model used in the study and of the emission scenarios considered to represent the future aviation CO_2 exhaust. In section 3 we present the results of the model simulations and provide the contribution of aircraft CO_2 emissions to the future climate change at the 2050 and 2100 time horizons. The conclusion of this study is provided in section 4.

2. Methods

2.1. The OSCARv2.2 compact climate change model

In this study we use the OSCAR compact Earth System Climate Change Model to investigate the impact of CO_2 emissions from the aviation sector on climate. Carbon dioxide is a long-lived greenhouse gas with an apparent atmospheric lifetime of several hundreds of years. Therefore, because its lifetime is much longer than the typical mixing time of the atmosphere (about 2–3 years), the location of emission matters very little when it comes to estimating its climate impact and the use of an integrated model such as OSCAR is well justified for this long-lived greenhouse gas. The OSCAR v2.2 model is a compact coupled biogeochemical cycles and climate change model that calculates the global concentration of CO_2, CH_4, N_2O, halogenated compounds, tropospheric ozone and aerosols by balancing their historical anthropogenic emissions (production) against their removal from the atmosphere.

Table 1. Characteristics of the aviation emission scenarios used in this study (1940–2050) and corresponding yearly CO_2 emissions from the aviation sector in 2050 ($MtCO_2$ and % of total fossil fuel emissions in parenthesis). The historical non-aviation CO_2 emissions for the 1940–2010 period are based on the Carbon Dioxide Information Analysis Centre (CDIAC) (Boden *et al* 2013) and based on the RCP2.6 for the 2011–2050 period (van Vuuren *et al* 2011).

Scenario	Assumptions for the 2000–2050 period	Emissions in 2050 $MtCO_2$ (%)
ICAO based	Traffic: 4.6%/yr. Efficiency gain: 2.0%/yr.	2338 (16%)
ACARE	Traffic: 4.6%/yr. Efficiency gain: 2.7% /yr.	1730 (12%)
CNG 2020	ACARE up 2020. Carbon neutral growth after 2020.	1033 (7%)
CNG 2030	ACARE up 2030. Carbon neutral growth after 2030.	1228 (8%)
CNG 2040	ACARE up 2040. Carbon neutral growth after 2040.	1459 (10%)
Factor 2	ACARE up to 2020; linear reduction after 2020 to achieve in 2050 50% of ACARE 2005 value.	386 (3%)
QUANTIFY A1	Traffic: 4.3%/yr up to 2020, GDP based afterwards (see Owen *et al* 2010). Efficiency gain: 1.0%/yr to 2050.	2258 (15%)
QUANTIFY B1	Traffic: 4.3%/yr up to 2020, GDP based afterwards (see Owen *et al* 2010). Efficiency gain: 1.0%/yr to 2020 and 1.3%/yr for 2020–2050.	1367 (9%)

The representation of these processes including the model climate sensitivity are all calibrated against more complex models, most of them corresponding to deterministic three-dimensional global circulation models such as those used and described in the Coupled Model Intercomparison Project phase 5 exercise. In that sense, OSCAR is a meta-model whose modules are designed to emulate the behaviour of a more specialised model.

In most of the modules, different parameterisations are available (e.g. 12 for the oceanic carbon cycle, 13 for the land carbon cycle, 7 for land use and 28 for the climate model). It allows 3×10^4 different possible setups that can be used to calculate the 'physical uncertainty' linked to the parametrization formulations using a Monte-Carlo approach. Based on some pre-tests performed with the model, an ensemble of 1000 members is considered appropriate to assess the uncertainty of a numerical experiment. The results presented in the next sections correspond to the median of the ensemble with the uncertainty (shaded area in the figures) corresponding to the 68% data uncertainty range based on the percentiles of the distribution, meaning that ±34% of the ensemble values around the median are included in this uncertainty range. The evaluation of the model is beyond the scope of this paper, which rather focuses on the quantification of future aviation climate impact. Please note that OSCAR has already been used as a carbon-cycle and climate emulator many times, and its performance has been demonstrated by comparison to observations (Gasser *et al* 2017a) or to comprehensive models (Arneth *et al* 2017, Gasser *et al* 2017b, Gasser *et al* 2018, Quilcaille *et al* 2018).

2.2. Carbon dioxide emissions from the aviation sector

A total of eight emission scenarios have been used to describe the future evolution of the CO_2 emissions from the aviation sector. Table 1 details the characteristics of the various scenarios used for the climate model simulations over the 1940–2050 period and the corresponding CO_2 emission from the aviation sector in 2050. From 1940 to 1995, the emission data are based on Sausen and Schumann (2000) with aviation emissions neglected prior to 1940.

The aircraft emission scenarios A1 and B1 discussed by Owen *et al* (2010) and developed in the framework of the European research project QUANTIFY (QUANTIFY 2018) are used as a reference and for comparison with the additional scenarios assessed in this study. The A1 and B1 QUANTIFY aircraft emission scenarios should be seen respectively as a Business As Usual (BAU) scenario and a moderate CO_2 mitigation scenario. As a yearly value between 1995 and 2050 is needed for the model, a linear interpolation is performed to calculate the value between 1995 and 2050 using two intermediate years (2000 and 2025) and the corresponding 2050 value, all from the QUANTIFY scenarios.

In addition to the pre-existing QUANTIFY scenarios, we have used 6 future emission scenarios. In 2008, the global stakeholder associations of the aviation industry (Airports Council International, Civil Air Navigation Services Organisation, International Air Transport Association and International Coordinating Council of Aerospace Industries Association) recognised the need to address the global challenge of climate change and adopted a set of ambitious targets to mitigate CO_2 emissions from air transport (EEA 2016). These targets are mostly based on an average improvement in fuel efficiency by aviation of 1.5% per year from 2009 to 2020; a cap on net aviation CO_2 emissions from 2020 onward (carbon-neutral growth); and a reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels.

In the spirit of those ambitious objectives, ICAO has proposed in its 39th assembly resolution (ICAO 2019b), a trajectory for CO_2 emissions with an efficiency gain of 2%/yr until 2020, followed by a Carbon Neutral Growth (CNG). In addition, ICAO resolutions mention the aspirational goal of pursuing an efficiency gain of 2%/yr until 2050. Based on this

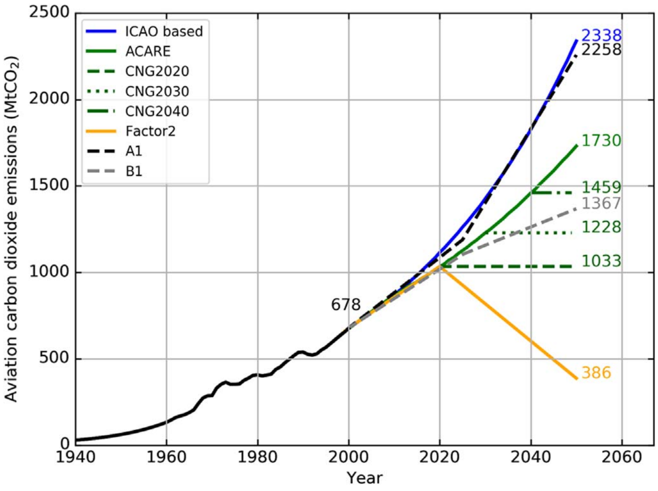

Figure 1. CO_2 aviation emissions ($MtCO_2/yr$) for the different aircraft emission scenarios over the 1940–2050 period. The black line refers to the historical data (Sausen and Schumann 2000) and the coloured lines to the corresponding scenarios (see labels). Total emissions in 2000 (reference year) and in 2050 are also provided right to the corresponding curve.

ICAO resolution, we propose in this study an 'ICAO based' scenario with a 2% efficiency gain every year from 2000 until 2050.

On the European side, ACARE has fixed a very challenging 2050 objective (ACARE, Advisory Council for Aeronautics Research in Europe 2011) which is to reach a 75% CO_2 reduction per passenger kilometre for new technology (aircraft/engines) with new operational practices (air traffic management, flight optimisation) in 2050 relative to aircraft, engines and operations representative of year 2000. As proposed by the FORUM-AE European project (FORUM-AE 2016), we consider an 'ACARE' derived scenario where it is assumed that ACARE CO_2 2050 objective would be achieved and also implemented in the whole fleet, which is very optimistic, leading to an average 2.7% efficiency gain per year till 2050. Hence, the ACARE derived scenario is more ambitious than the ICAO based scenario. For both ICAO based and ACARE scenarios, we retain a constant global traffic increase from 2000 to 2050 equal to (4.6% per year, which reflects well aircraft manufacturers views as well as ICAO long-term traffic forecast (ICAO 2019a). As mentioned above, for those two scenarios (ICAO based and ACARE), we use the QUANTIFY 2000 emission value as the reference level (678 $MtCO_2$) (Owen *et al* 2010).

For the CNG scenarios used in this work, we assume that the emissions follow the ACARE scenario before they remain constant using the 2020 ACARE value for CNG 2020, the 2030 ACARE value for CNG 2030 and the 2040 ACARE value for CNG 2040. By testing different CNG years, we aim to quantify the potential impact of CO_2 from aviation on global climate by delaying the original 2020 CNG objective. For the so-called Factor 2 scenario, we assume that the emissions follow the ACARE scenario until 2020 and then that they are reduced linearly until 2050 to achieve half of the 2005 level of ACARE scenario.

Figure 1 shows the various scenarios used in this study for future CO_2 emissions by the aviation sector. In 1940, the emissions are estimated to be equal to 28 $MtCO_2$ (Sausen and Schumann 2000) when aviation was emerging. Then, the emissions are projected to reach in 2050 as much as 2338 $MtCO_2/yr$ according to the ICAO based projection. The ACARE scenario (1730 $MtCO_2/yr$ in 2050) is less ambitious and fits between the A1 (2258 $MtCO_2/yr$ in 2050) and B1 (1367 $MtCO_2/yr$ in 2050) QUANTIFY scenarios. The CNG2020, CNG2030 and CNG2040, scenarios follow the ACARE scenario before their pathway stabilises at 1033, 1228, and 1459 $MtCO_2/yr$ from 2020, 2030 and 2040, respectively. The Factor 2 scenario drops down from 1033 $MtCO_2/yr$ in 2020 to 386 $MtCO_2$ in 2050.

In order to respect the carbon emission reduction objectives, in 2016, the ICAO's 191 Member States decided to implement the Carbon Offsetting and Reduction Scheme for International Aviation (ICAO 2019b) that uses carbon offsetting as the main tool to reduce aviation carbon emissions. Therefore, the CNG and Factor 2 scenarios consider carbon offsetting as an important driver to reduce carbon emissions. In this study focusing on CO_2, the assumption that offset emissions are used to compensate aviation emissions is valid. However, this would not be the case, if non-CO_2 effects were considered, due to the different location of emissions and residence time of climate perturbation. Indeed, emitted along with CO_2, the non-CO_2 emissions cannot be directly compensated on the assumption that offset emissions are equal to aviation emissions as for some agents (e.g. NO_x) the time and location of the emissions will affect theirs final global climate impact. Hence, the efficiency of carbon offsetting is subject to debate. Nevertheless, we consider that discussing the veracity of this market-based measure is out of scope in this paper.

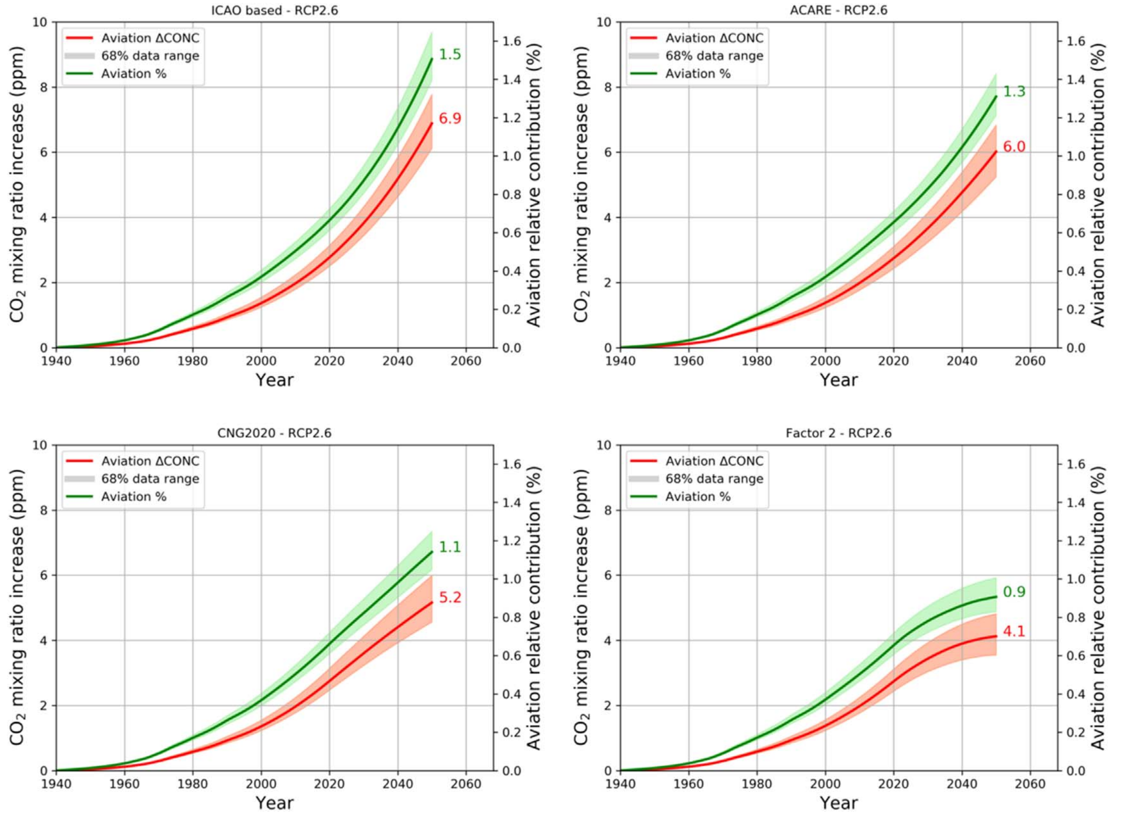

Figure 2. Temporal evolution (1940–2050) of carbon dioxide mixing ratio increase (ppm) due to aircraft emissions (in red, left axis) for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios (RCP2.6 scenario for the non-aviation emissions). In green (right axis), the corresponding relative aircraft contribution to the CO_2 increase due to total anthropogenic emissions (%). The 2050 values are reported next to each curve.

The emission range of the different scenarios used in this study is rather high, reflecting the high uncertainty on future emissions by the aviation sector. These scenarios lie within all the different scenarios proposed for instance by Owen *et al* (2010) or Wilkerson *et al* (2010). These scenarios should be considered as indicators of low (Factor 2) and high (ICAO based) possible futures aviation emission scenario. These scenarios encompass uncertainties that are difficult to precisely quantify such as traffic growth, aircraft engines efficiency with potential disruptive architectures, carbon offsetting efforts and penetration rate of alternative fuels. In other words, it is assumed that the climatic impact of future aviation CO_2 emissions will lie between the responses calculated by the two proposed 'extreme' scenarios (ICAO based and Factor 2). The results for QUANTIFY A1 and B1 scenarios will only be given as a reference to earlier estimates, as this study will concentrate on the other updated selected scenarios.

Two different scenarios are used for non-aviation emissions. The use of two different scenarios allows the evaluation of the influence of two different background carbon dioxide concentrations and climate change on the future aviation climate impact. The RCP2.6 was developed using the Integrated Model to Assess the Greenhouse Effect (IMAGE 2.4) integrated assessment modelling framework of the PBL Netherlands Environmental Assessment Agency (van Vuuren *et al* 2011). It is a 'peak and decline' scenario, meaning that its RF level first reaches 3 $W m^{-2}$ around 2020 before returning to 2.6 $W m^{-2}$ by 2100, and was used in the fifth assessment report of the Intergovernmental Panel on Climate Change (AR5 from IPCC) report published in 2013 (Meinshausen *et al* 2011a). The RCP6.0 scenario is also used and is less optimistic than RCP2.6 as the total anthropogenic RF (6 $W m^{-2}$) reaches more than twice that of RCP2.6 (2.6 $W m^{-2}$) in 2100. This implies that the global temperature in 2050 is 1.5 °C warmer than under RCP2.6.

In the next section, the aviation CO_2 emissions are introduced in the OSCAR compact climate change model in order to calculate the RF of climate and the temperature change over the 1940–2050 period. We compare these results to the total anthropogenic RF and climate change in order to determine the relative contribution of the aviation sector. Since CO_2 has an atmospheric residence time of more than 100 years, we will also extend the time horizon from 2050 to 2100 in order to illustrate the committed long-term climate impact of the adopted aviation emission scenario.

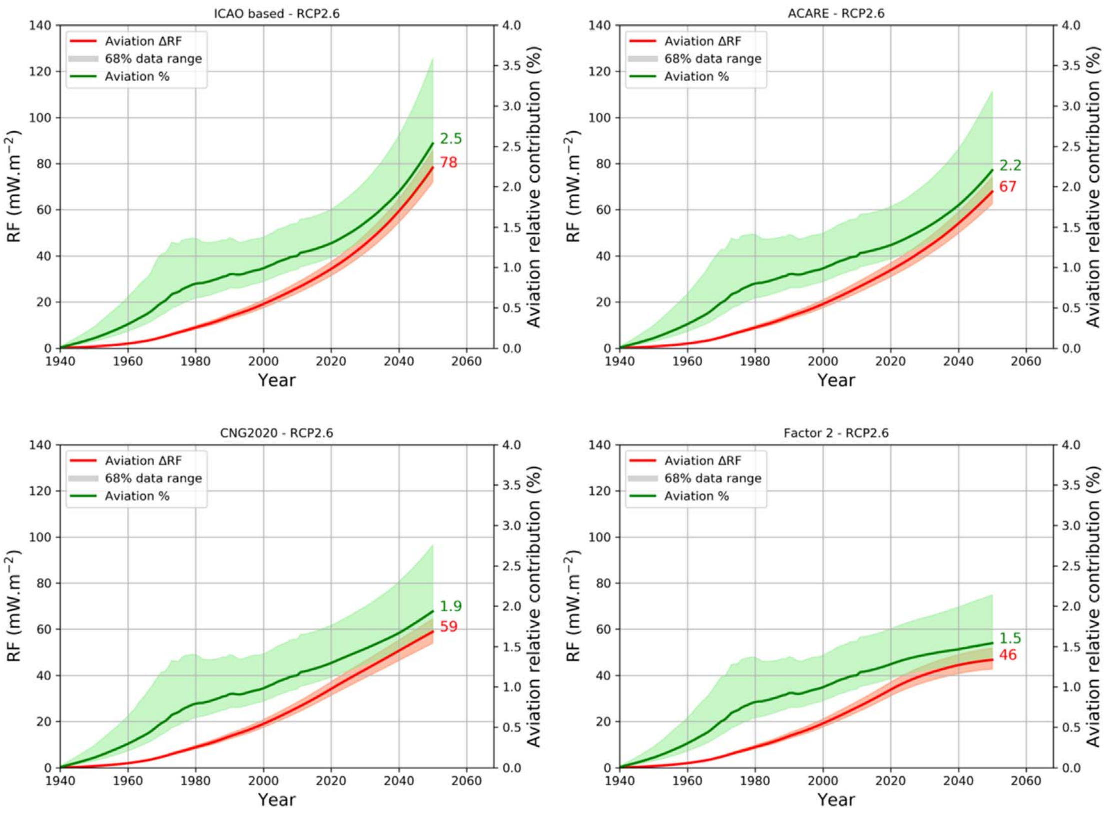

Figure 3. Temporal evolution (1940–2050) of CO_2 radiative forcing (mW/m^2) due to aircraft emissions (in red, left axis) for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios (RCP2.6 scenario for the non-aviation emissions). In green (right axis), the corresponding relative aircraft contribution to the CO_2 radiative forcing due to total anthropogenic emissions (%). The 2050 values are reported next to each curve.

3. Results

3.1. Impact of CO_2 aviation emissions at a 2050 time horizon

We first investigate the climate response associated with carbon dioxide emissions from the aviation sector over the 1940–2050 period. Figure 2 shows the temporal evolution (1940–2050) of CO_2 mixing ratio increase (ΔCO_2 in ppm) due to the CO_2 aviation emissions for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios. Figure 3 shows the associated RF of climate (RF in $mW\,m^{-2}$) and figure 4 shows the corresponding temperature increase (ΔT in mK). Note that for all variables ($\Delta CO_{2,}$ RF and ΔT), the given value correspond to the increase due to CO_2 aviation emissions only. Those scenarios are representative of the full range of the future carbon dioxide aviation emission scenarios considered in this study. Note that these figures illustrate the perturbations adopting the RCP2.6 storyline for other anthropogenic emissions. The aviation contribution to climate change under the RCP6.0 storyline has also been simulated. These results are summarised in table 2 for the various aviation emission scenarios and for the two RCP storylines for the 2050 time horizon. Results for the QUANTIFY A1 and B1 aviation emission reference scenarios are also given in table 2. On figures 2–4, the red curves represent the median of the absolute differences of two distinct ensembles: one without aviation emissions and the other including aircraft CO_2 emissions. The green curves show the relative contribution of the aviation emissions with respect to the total fossil fuel emissions. The shaded areas on the sides of the red and green curves correspond to the 68% data range uncertainty (± one standard deviation of the ensemble).

Figure 2 clearly shows an increase of the CO_2 mixing ratio due to aviation that reaches 7.0 ppm in 2050 using the ICAO based scenario. This increase reaches 6.0 ppm in 2050 for the ACARE scenario. Under the CNG2020 scenario, the increase reaches 5.2 ppm while under the mitigation Factor 2 scenario, a stabilisation of the CO_2 mixing ratio increase due to aviation at 4.1 ppm occurs in 2050. The relative contribution of the aviation emissions to the CO_2 atmospheric concentration ranges from 0.9% in the case of the Factor 2 scenario to 1.5% for the ICAO based scenario. As illustrated in figures 3 and 4, the same type of evolution is calculated for RF and ΔT over the 1940–2050 period. For the different aviation emission scenarios the highest RF and ΔT are calculated under the RCP2.6 storyline. In 2050, the modelled RF and ΔT range from 45 $mW\,m^{-2}$ and 26 mK for the Factor 2 scenario to 78 $mW\,m^{-2}$ and 39 mK for the ICAO based scenario. The aviation CO_2 contribution to the total anthropogenic RF ranges from 1.6% to 2.5%. The

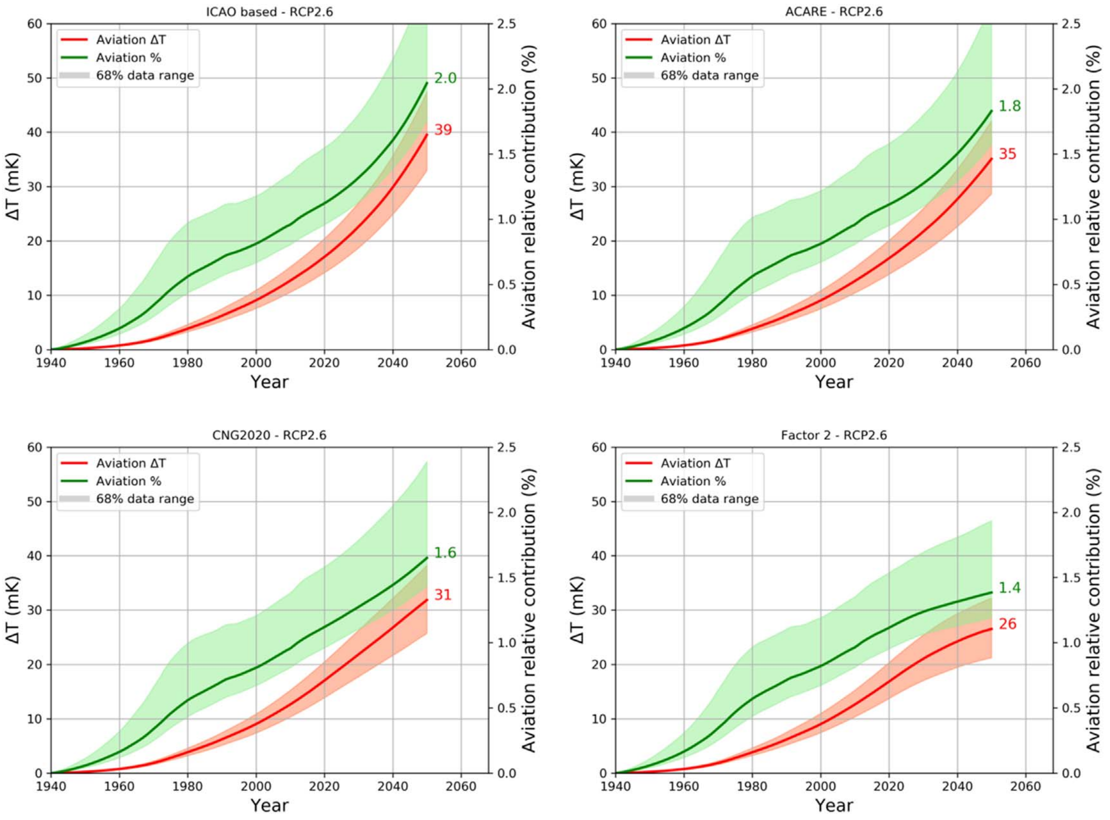

Figure 4. Temporal evolution (1940–2050) of the global temperature increase (mK) due to aircraft emissions (in red, left axis) for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios (RCP2.6 scenario for the non-aviation emissions). In green (right axis), the corresponding relative aircraft contribution to temperature increase due to total anthropogenic emissions (%). The 2050 values are reported next to each curve.

temperature increase due to aviation emissions from the ICAO based and Factor 2 scenarios correspond to 1.4% to 2.0% of the global warming, respectively. It should be noted that the uncertainty represented by the shades area on figures 2–4 is higher for the ΔT than for the two others variables (ΔCO_2 and RF) and is mainly related to the large range of climate sensitivity parameters that is used for the production of the ensemble.

Lee *et al* (2009) and Owen *et al* (2010) reported a RF associated with aviation CO_2 emissions for the reference year 2005 of 28.0 ± 12.0 mW m^{-2} higher than that the RF calculated by OSCARv2.2 (19.5 ± 1.8 mW m^{-2}). We note however that the aircraft CO_2 emissions used in our simulations with OSCAR for the reference year 2005 is slightly higher (780 Tg) than in this previous work (733 Tg) due to a somewhat different version of the QUANTIFY emissions. The main reason explaining the difference in the RF between the previous work and our study is therefore associated to the carbon cycle modelling. In OSCAR, an explicit and nonlinear carbon cycle model is used, rather than the linear parameterisation of Hasselmann *et al* (1997). The importance of the nonlinear model formulation followed by OSCAR has been extensively discussed elsewhere (Joos *et al* 2013, Gasser *et al* 2017b).

The relative contribution of aviation to the total anthropogenic forcing is of course very dependent on the scenario used for the emissions by other sectors (e.g. baseline). Under the RCP2.6 scenario, the relative contribution of aviation CO_2 emissions to the total anthropogenic RF and ΔT shows a strong increase for all scenarios throughout the whole period (1940–2050), especially towards the last 20 years of the period (2030–2050) when emissions from other sectors start to strongly decrease. For example, for the ICAO based scenario, aviation contributes to 2.5% to the total anthropogenic RF in 2050, while under RCP6.0 this contribution decreases to 1.8%. Using the mitigation ACARE scenario, the aviation contribution decreases from 2.2% for RCP2.6 and to 1.6% for RCP6.0.

Although the original CNG scenario aims at stabilising emissions starting in 2020, two other starting years (2030 and 2040) of neutral growth have been used to assess the influence of the starting year for the long-lived CO_2 greenhouse gas. The results show that the CNG 2020 under the RCP2.6 storyline produces the lowest RF (59 mW m^{-2}) and ΔT (32 mK) in 2050 of the three tested CNG scenarios. In fact, the 2050 climate impact of the CNG 2040 scenario lies between the mitigation QUANTIFY B1 scenario and the ACARE scenario in terms of ΔT. If CNG is delayed until 2040, the climate impact is higher than the

Table 2. Carbon dioxide concentration increase (ppm) in 2050, associated radiative forcing of climate (mW/m^2) and temperature increase (mK) due to global CO_2 aviation emissions for the various aircraft emission scenarios and in context of RCP2.6 and RCP6.0. The relative aviation contribution (%) to the total fossil fuel emissions, anthropogenic radiative forcing of climate and temperature change are also given in parenthesis. The reference value (2000) is also given.

Scenario	Concentration increase ppm (%)	Radiative forcing mW m^{-2} (%)	Temperature increase mK (%)
	Reference year (2000)		
QUANTIFY	1.3 (0.4)	19 (1.0)	9.1 (0.8)
	2050 *RCP* 2.6		
ICAO based	6.9 (1.5)	78 (2.5)	39 (2.0)
ACARE	6.0 (1.3)	68 (2.2)	35 (1.9)
CNG 2020	5.2 (1.1)	59 (1.9)	32 (1.6)
CNG2030	5.5 (1.2)	62 (2.1)	33 (1.7)
CNG2040	5.9 (1.3)	63 (2.2)	34 (2.0)
Factor 2	4.1 (0.9)	45 (1.6)	26 (1.4)
QUANTIFY A1	6.6 (1.5)	77 (2.5)	39 (2.0)
QUANTIFY B1	5.5 (1.2)	62 (2.1)	33 (1.7)
	2050 *RCP* 6.0		
ICAO based	6.9 (1.4)	71 (1.8)	37 (1.6)
ACARE	6.1 (1.2)	62 (1.6)	34 (1.5)
CNG 2020	5.2 (1.1)	54 (1.4)	29 (1.3)
CNG2030	5.6 (1.1)	57 (1.5)	31 (1.4)
CNG2040	6.1 (1.2)	60 (1.5)	33 (1.4)
Factor 2	4.2 (0.8)	43 (1.1)	24 (1.1)
QUANTIFY A1	6.9 (1.4)	70 (1.8)	37 (1.6)
QUANTIFY B1	6.0 (1.2)	59 (1.5)	32 (1.4)

QUANTIFY B1 scenario and is likely to reach the one of the less ambitious ACARE scenario by 2050, showing therefore the importance of starting the CNG as soon as possible in order to reduce the climate impact of aviation.

The Factor 2 scenario is the most ambitious mitigation case of the assessed aircraft CO_2 emission scenarios. The ultimate 2050 goal for this scenario is similar to a return to the 1978 aviation emissions, which seems very challenging under the traffic growth rate and calls for a strong offset of future CO_2 emissions. Different tools such as an improvement in fuel efficiency driven by the renewal of the aircraft fleet with new aircrafts, and improvements in operational practices as well as carbon compensation mechanisms explain why this objective is put forward. It is really this Factor 2 scenario, however, that can significantly reduce the climate impact of the aviation, reducing the aircraft RF relative contribution to 1.6% of the total anthropogenic forcing and 1.4% of the total anthropogenic warming in 2050, under RCP2.6.

Similarly, the associated absolute change for the three studied variables is higher when using the RCP2.6 rather than the RCP6.0. For example, in the case of the ICAO based scenario the aviation RF absolute contribution decreases from 78 mW m^{-2} for RCP2.6 to 71 mW m^{-2} for RCP6.0 and from 39 to 37 mK for the absolute temperature change. This decreasing tendency is seen for all scenario but rather insignificant. Hence, in 2050 there is no real influence of a stronger baseline on the absolute climate impact of aviation.

3.2. Longer term climate impact

Since CO_2 is a long-lived greenhouse gas remaining in the atmosphere for more than 100 years, the benefit of the aviation emission mitigation will be more visible during the second half of the 21st century. In order to illustrate this feature, OSCAR is used to extend the simulations to 2100. However, after 2050, the aviation emissions are highly uncertain and we simply assume that they remain constant at their 2050 value over the 2050–2100 period. Figure 5 shows the long-term temporal evolution (1940–2100) of ΔCO_2 (top), RF (middle) and ΔT (bottom) for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios combined with the RCP2.6 storyline for non-aviation emissions. Even if aircraft fossil fuel CO_2 emissions stay constant after 2050, ΔT continues to increase to 99.5 mK for the ICAO based scenario and to 79.4 mK for the ACARE scenario, which corresponds respectively to 5.2% and 4.1% of the total anthropogenic warming in 2100. Even in the case of the CNG2020 scenario, the temperature continues to increase to a value of 59.5 mK (3.1%) in 2100. This highlights the long lifetime of CO_2 in the atmosphere and the inertia of the coupled climate system (Friedlingstein *et al* 2011). It is only in the case of the Factor 2 scenario, that the temperature increase tends to flatten after 2060 reaching 36.8 mK (1.9%) in 2100.

The OSCAR model includes a representation of the carbon cycle and calculates the carbon fluxes between the various reservoirs: atmosphere, land and ocean. Like other fossil fuel CO_2 emissions into the atmosphere, the CO_2 emitted by aviation will be slowly be removed from the atmosphere through land and oceanic uptakes. Figure 6 shows the direct carbon emission from aviation into the atmosphere and the associated aviation-induced oceanic and land removal fluxes, for the two extreme scenarios analysed in this study (ICAO and Factor 2) and for the RCP2.6 and RCP6.0 storylines. For the ICAO based scenario, 2338 $MtCO_2$/yr are emitted by aviation into the atmosphere after 2050. For the RCP2.6 storyline, in 2100, 701 $MtCO_2$ and 413 $MtCO_2$ of this additional emitted carbon are removed yearly from the atmosphere to the oceanic and land carbon reservoirs, respectively, and 1223 $MtCO_2$ accumulate in the atmosphere causing the aviation-induced CO_2 concentration to increase. For this RCP2.6 storyline, the modelled fluxes show that the oceanic CO_2 uptake due to aviation emissions is larger than the land uptake. Using the same RCP2.6 background storyline, the oceanic and land uptakes are reduced to respectively 173 and 79 $MtCO_2$/yr when using the mitigation Factor 2 aircraft scenario

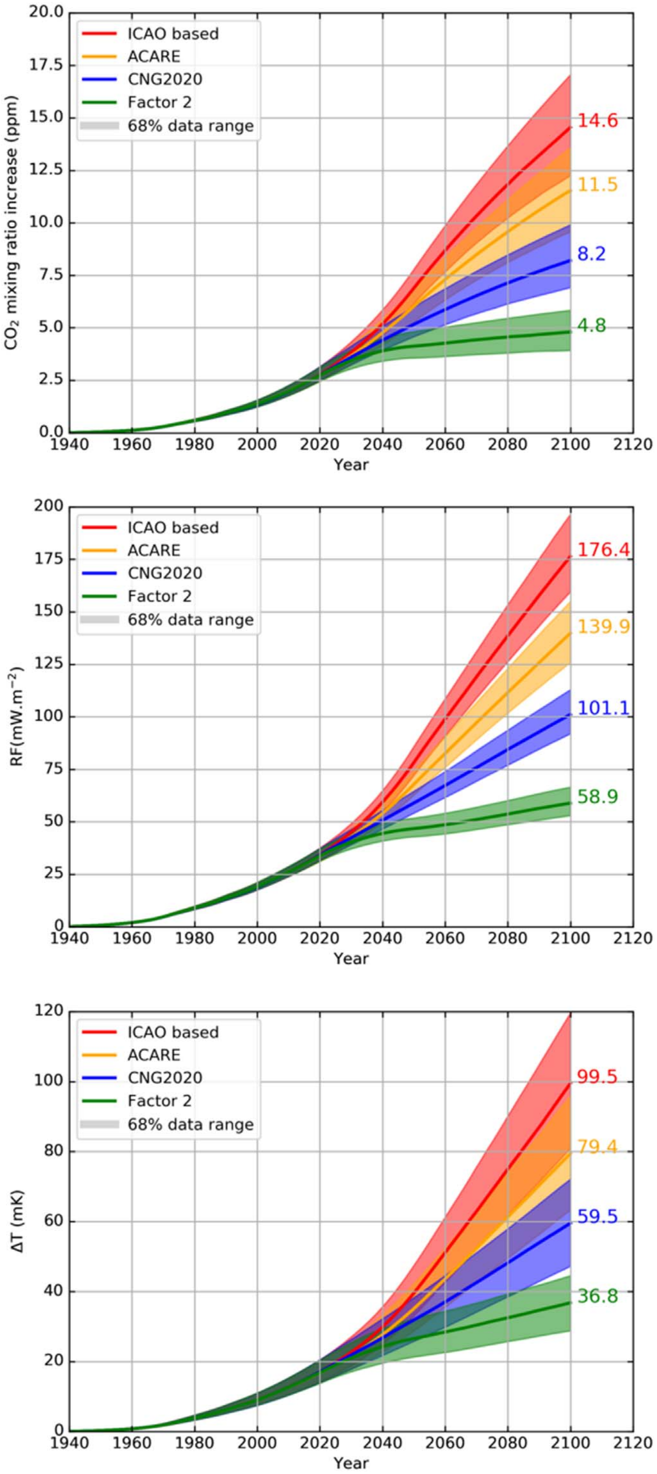

Figure 5. Temporal evolution (1940–2100) of the aviation induced CO_2 mixing ratio increase (ppm), radiative forcing (mW/m^2), and temperature increase (mK) for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios (RCP2.6 storyline for non-aviation emissions).

and 133 $MtCO_2$ accumulate in the atmosphere for a total of 386 $MtCO_2$ emitted by aviation yearly. These results indicate that the ocean and land uptakes depend on the history of CO_2 emissions and that the possible saturation effect of the carbon sinks needs to be accounted for in the simulations. As calculated above, 52% of the aviation emitted CO_2 remains in the atmosphere for the ICAO based scenario while 34% only remains in the atmosphere for the Factor 2 scenario amplifying the climate impact of the high emission scenario.

Figure 6 also shows that the carbon uptake to the land and oceanic reservoirs depends on the considered storyline for CO_2 emissions from other activity sectors and hence on the considered climate. In the case of the Factor 2 aviation scenario and RCP6.0 storyline, the

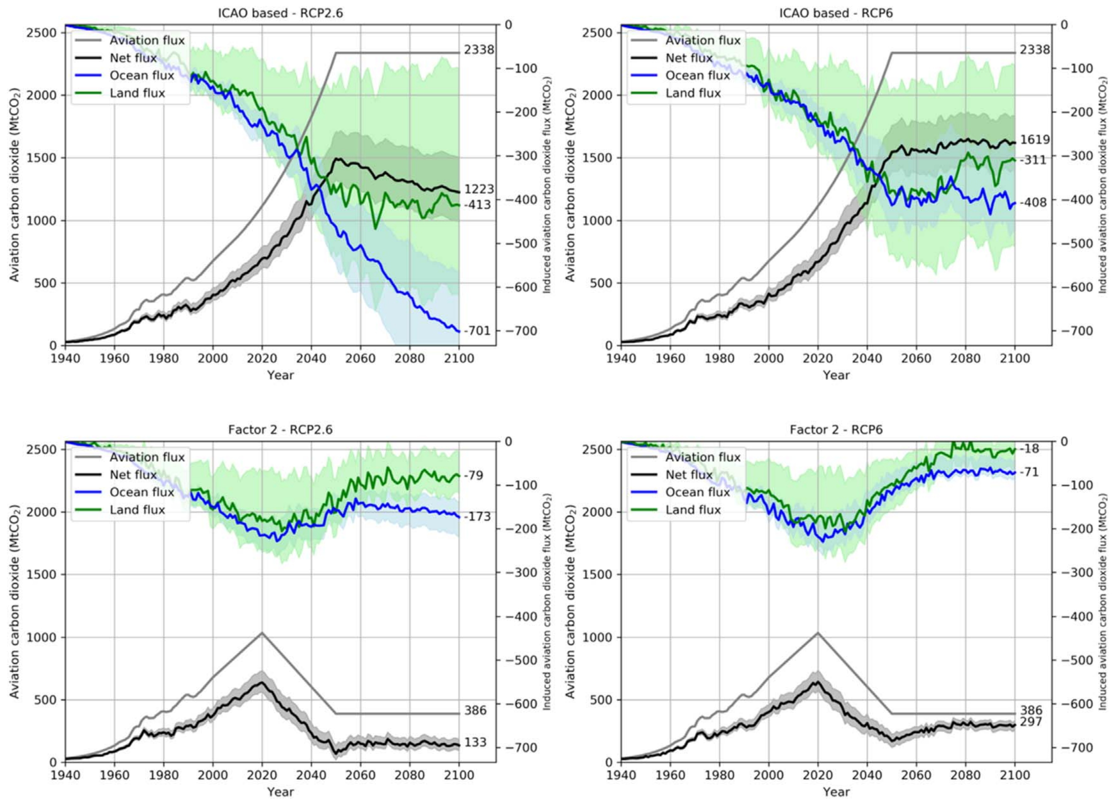

Figure 6. Temporal evolution (1940–2100) of the aviation carbon emission (black, left *y*-axis), the net oceanic flux (blue, right *y*-axis), the net land flux (green, right *y*-axis) and the total net flux (grey, left *y*-axis) (all in MtCO$_2$/year) for the ICAO based and Factor 2 scenarios. The shaded part represents the 68% confidence interval. (Left) RCP2.6 storyline and (right) RCP6.0 storyline for non-aviation CO$_2$ emissions. The values reached in 2100 are indicated right to the curves. The positive aviation emission and total flux refer to the left ordinate axis and the negative uptake fluxes to the land and ocean reservoirs refer to the right ordinate axis.

uptake by the ocean and land are significantly reduced compared to the RCP2.6 case to respectively 71 and 18 MtCO$_2$ in 2100. In this case, 77% of the aviation carbon emitted annually remains in the atmosphere compared to 34% for the RCP2.6 storyline. Therefore, despite the fact that in the Factor 2 scenario, but also in the ICAO based scenario, emissions are kept constant after 2050, in the RCP2.6 context the net aviation carbon flux decreases after 2050 while in a warmer climate (RCP6.0), the net flux is slightly increasing. These features are a consequence of the fact that in a higher CO$_2$ and warmer climate, both ocean and land carbon sinks are less efficient per unit emitted CO$_2$, as illustrated by Raupach *et al* (2014).

As shown in figures 5 and 6, the 68% uncertainty range (shaded areas) grows rapidly as the simulation goes forward in time. On top of this ‘physical uncertainty’ related to the selected parametrisation options and quantified using the Monte-Carlo methodology, numerous challenging predictable factors come into play making the extension towards 2100 very uncertain. Those highly uncertain factors refer to events that control the future emissions from the aviation sector such as the penetration rate of alternative fuels into the global current fuel market or the change in aviation technology. Those uncertainties are usually taken into account by the emissions scenarios such as the ones used in this study. In addition, the carbon uptake from the atmosphere by land and ocean are also very dependent on the future atmospheric composition and climate. Considering this uncertainty, the present work suggests that the temperature increase associated with aircraft emissions could reach, by the end of the century, as much as 99.5 mK ± 20 mK, which represents 5.2% of the global warming from anthropogenic origin. The temperature increase resulting from the alternative aviation scenarios (ACARE, CNG and Factor 2) are significantly mitigated and could decrease to 37 mK, which correspond to 1.9% of the global anthropogenic warming in 2100 in the case of the ambitious Factor 2 scenario. The CNG scenarios indicate that the sooner the start of the CNG will be, the lower the future impact of aviation on the global temperature will be. Hence, to be efficient in terms of climate change mitigation, the CNG needs to start as soon as possible, as the positive impact of this scenario on future climate decreases rapidly with time.

4. Discussion and conclusion

In this study, a compact ESM has been used to assess the climate impact of present and future civil aviation carbon dioxide (CO$_2$) emissions. The impact of aviation CO_2 emissions on future climate has been quantified over the 1940–2050 period, extending some simulations to 2100 and using different aviation CO_2 emission scenarios and two background Representative Concentrations Pathways (RCP2.6 and RCP6.0) for other emission sectors. Several aviation scenarios including weak to strong mitigation options have been considered, ranging from 386 $MtCO_2$/yr (Factor 2 scenario) to 2338 $MtCO_2$/yr (ICAO based scenario) in 2050.

In 2050, on a climate trajectory in line with the Paris Agreement limiting the global warming below 2 °C (RCP2.6), we found that the impact of the aviation CO_2 emissions ranges from 26 ± 2 mK (1.4% of the total anthropogenic warming) for an ambitious mitigation strategy scenario (Factor 2) to 39 ± 4 mK (2.0% of the total anthropogenic warming) for the least ambitious mitigation scenario of the study (ICAO based). On the longer term, if no significant emission mitigation is implemented for the aviation sector, the associated warming further increases to 99.5 mK ± 20 mK in 2100 (ICAO based), which corresponds to 5.2% of the total anthropogenic warming under RCP2.6. The climate impact of aviation CO_2 emissions depends on the greenhouse gas emission scenario adopted for other activity sectors as illustrated here in the context of two different RCP scenarios (i.e. RCP2.6 and RCP6.0 scenarios). This arises mostly because the aviation carbon uptake from the atmosphere by the land and ocean sinks depends on the future atmospheric background CO_2 concentration and on the future climate.

In this study, we focused on the aviation carbon dioxide emissions on climate. Due to its long residence time in the atmosphere, CO_2 is a major driver of the aviation impact on climate on decadal time scales. However, it should be emphasised that the impact of CO_2 emissions is only one aspect of the possible impact of aviation on climate. Other climate agents directly emitted or affected by aircraft also contribute to the aviation total RF of climate on shorter time scales. This is in particular the case for aircraft NO_x emissions affecting tropospheric ozone and the methane lifetime, emissions or formation of particles (black carbon, sulphates, nitrates) and, more importantly, formation of linear contrails and induced cloudiness (Karcher 2018). The aviation CO_2 RF of climate is estimated to represent 36%–51% of this total forcing including short-term climate forcers (Lee *et al* 2009, Grewe *et al* 2017, Karcher 2018). These additional terms are subject to large uncertainties and will be analysed in forthcoming studies with the OSCAR compact carbon cycle-climate change model in order to account for the different lifetimes of the various climate agents involved or with the more complex LMDz-INCA chemistry-climate model.

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