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# THE IMPACT OF CARBON DIOXIDE AVIATION EMISSIONS ON FUTURE CLIMATE CHANGE

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**KEYWORDS:** aviation, CO<sub>2</sub>, climate impact, future emission scenario, compact climate model, OSCAR

## ABSTRACT:

Aviation emissions are estimated to contribute to 5 % (2–14 %, 90 % likelihood range) of the anthropogenic radiative forcing of climate with an uncertainty dominated by non-CO<sub>2</sub> effects (Lee et al., 2010). Even if the level of scientific understanding is considered to be high by the IPCC for present-day aviation CO<sub>2</sub> impact compared to other non-CO<sub>2</sub> forcers (e.g. ozone, aerosols and contrails), the future (2050) aviation CO<sub>2</sub> climate impact remains highly uncertain. One major reason of these varying estimates is linked to the inherent assumptions made in the development of future global emission scenarios such as the one from international aviation (Boucher et al., 2016).

Hence, using the compact Earth System Model (ESM) OSCARv2.2 we quantify the climate impact of present and future (up to 2100) civil aviation carbon dioxide (CO<sub>2</sub>) emissions using eight aviation scenarios ranging from 386 Mt CO<sub>2</sub>/year (Factor 2 scenario) to 2338 Mt CO<sub>2</sub>/year (ICAO/CAEP scenario) in 2050. This approach will allow quantifying the uncertainty due to the difficulty to estimate the future mitigation effort. Another originality of the paper is that the influence of other emission sectors is evaluated using two background Representative Concentrations Pathways (RCP2.6 and RCP6.0).

Results show that 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<sub>2</sub> emissions ranges from 26 ± 2 mK (1.4 % of the total global warming associated with all fossil fuel emissions) for an ambitious mitigation strategy scenario (Factor 2) to 39 ± 4 mK (2.0 % of the total global warming) for the least ambitious mitigation scenario of the study (ICAO-CAEP).

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 100

mK in 2100 (ICAO/CAEP), which corresponds to 5.2 % of the total global temperature increase from total fossil fuel CO<sub>2</sub> emissions under RCP2.6.

## 1. INTRODUCTION

In 2017, worldwide flights carried nearly 4.1 billion passengers and produced 859 million tonnes of CO<sub>2</sub> (ATAG, 2019). In 2016, the International Civil Aviation Organization (ICAO) recalled that the aviation sector “accounts for under 2 % of the world’s annual CO<sub>2</sub> 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 %/year increase in the average annual global air traffic rate over the next 20 years (2015–2034) (Airbus, 2016), while Boeing forecasts a 4.9 %/year increase over the same period (Boeing, 2015). Between 1995 and 2010, the aviation sector recorded an average yearly growth rate of 4.6 %/year 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 %/year) over the 2015–2025 period (ICAO, 2019a), which could make the aviation sector a significant fossil fuel CO<sub>2</sub> emitting sector in the future (2050). It has previously been shown that aircraft emissions perturb the radiative budget of the Earth atmosphere (Intergovernmental Panel on Climate Change (IPCC), 1999; IPCC, 2007; Sausen et al., 2005; Lee et al., 2009; Brasseur et al., 1998; 2016). Aviation emissions are estimated to contribute to 5 % (2–14 %, 90 % likelihood range) of the anthropogenic radiative forcing of climate with an uncertainty dominated by non-CO<sub>2</sub> effects (Lee et al., 2010). The climate impact of CO<sub>2</sub> emissions from aviation has been previously assessed by different studies for the past, present and future (Lee et al., 2010; Gauss et al., 2006). Even if the level of scientific understanding is considered to be high by the IPCC for present-day aviation CO<sub>2</sub> impact (Lee et al., 2010) compared to other non-CO<sub>2</sub> forcers (e.g. ozone, aerosols and contrails), the future (2050) aviation CO<sub>2</sub> 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<sub>2</sub> 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 forcings representative of this goal of limiting global warming in 2100 to less than 2 °C above preindustrial levels (Collins et al., 2013; Van Vuuren., 2011). 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 (INDCs) 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<sub>2</sub> 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 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.

## 2. METHOD

In this study, we use the OSCAR compact Earth System Climate Change Model (ESCCM) to investigate the impact of CO<sub>2</sub> 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 to 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<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, halogenated compounds, tropospheric ozone and aerosols by balancing their historical anthropogenic emissions (production) against their removal from the atmosphere. 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 (CMIP) phase 5 exercise. In that sense, OSCAR is a meta-model whose modules are designed to emulate the behaviour of a more specialized model.

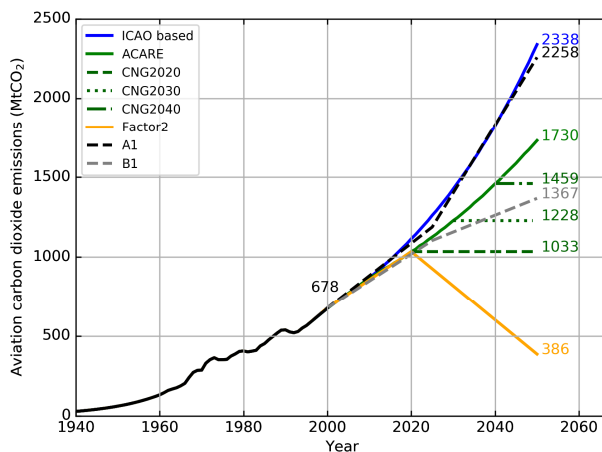
In most of the modules, different parameterizations are available (e.g. 12 for the oceanic carbon cycle, 13 for the land carbon cycle, 7 for land use and 28 for the climate model). It allows  $3 \times 10^4$  different possible setups that can be used to calculate the “physical uncertainty” linked to 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  $\pm 34$  % 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 (Gasser et al., 2018; Quilcaille et al., 2018; Gasser et al., 2017; Arneth et al., 2017).

A total of eight emission scenarios have been used to describe the future evolution

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

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., 2011). It is a “peak and decline” scenario, meaning that its radiative forcing (RF) level first reaches  $3 \text{ W/m}^2$  around 2020 before returning to  $2.6 \text{ W/m}^2$  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 radiative forcing ( $6 \text{ W/m}^2$ ) reaches more than twice that of RCP2.6 ( $2.6 \text{ W/m}^2$ ) in 2100. This implies that the global temperature in 2050 is  $1.5^\circ \text{C}$  warmer than under RCP2.6.



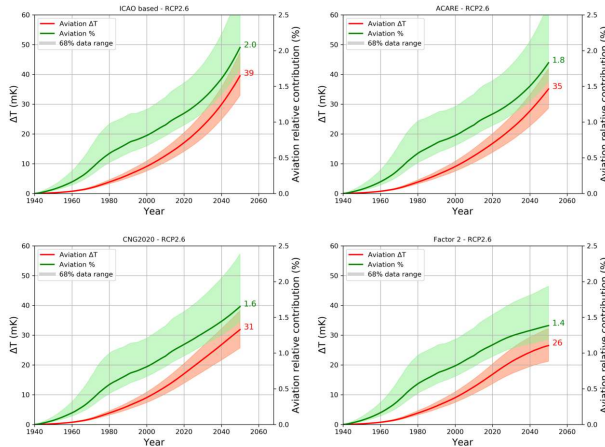
**Figure 1.** *CO<sub>2</sub> aviation emissions (Mt CO<sub>2</sub>/year) for the different aircraft emission scenarios over the 1940–2050 period. The black line refers to the historical data (Sausen and Schumann, 2001) and the coloured lines to the corresponding scenarios (see labels). Total emissions in 2000 (reference year) and in 2050 are also provided right to the corresponding curve*

### 3. RESULTS

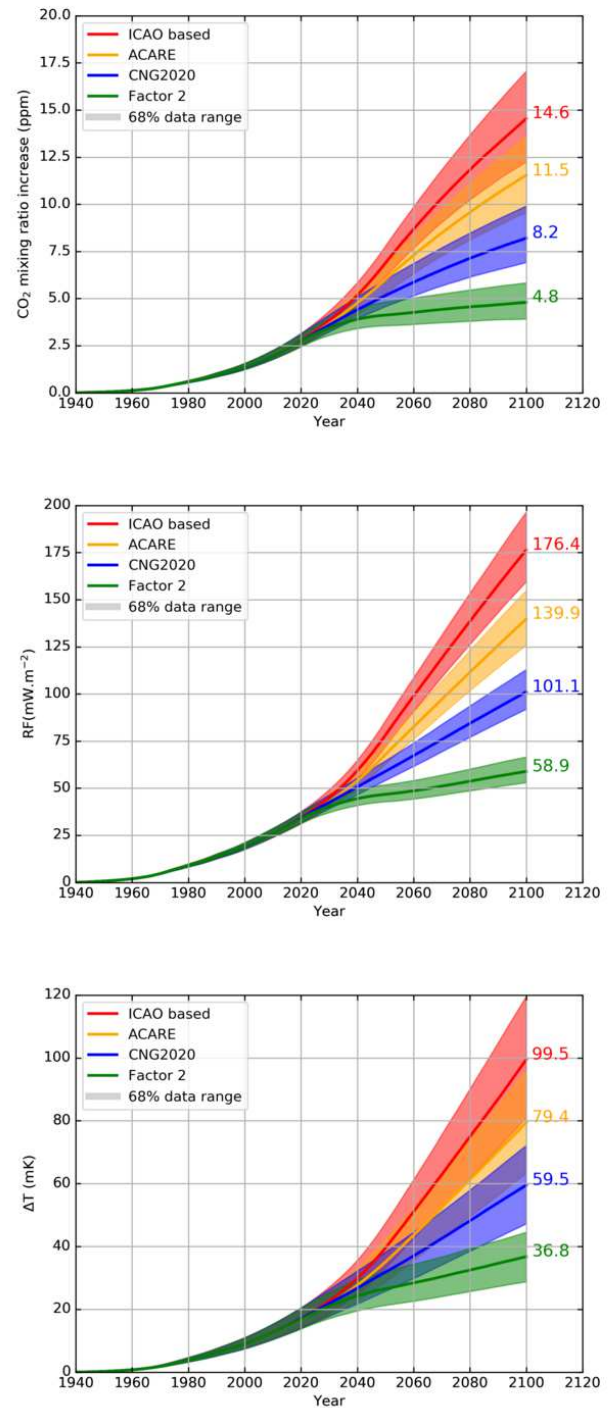
We first investigate the climate response associated with carbon dioxide emissions from the aviation sector over the 1940–2050 period. Figure 2 shows the temperature increase ( $\Delta T$  in mK) due to the CO<sub>2</sub> aviation emissions for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios. Note that for all variables ( $\Delta \text{CO}_2$ , RF and  $\Delta T$ ), the given value correspond to the increase due to CO<sub>2</sub> 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. On Figure 2, the red curves represent the median of the absolute differences of two distinct ensembles: one without aviation emissions and the other including aircraft CO<sub>2</sub> 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 ( $\pm$  one standard deviation of the ensemble). As illustrated in Figures 2, the same type of evolution is calculated for  $\Delta T$  over the 1940–2050 period. For the different aviation emission scenarios the highest  $\Delta T$  are calculated under the RCP2.6 storyline. In 2050, the modelled  $\Delta T$  range from 26 mK for the Factor 2 scenario to 39 mK for the ICAO based scenario. The aviation CO<sub>2</sub> contribution to the total anthropogenic radiative forcing ranges from 1.6 % to 2.5%. The 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 Figure 2 is higher for the  $\Delta T$  than for the two others variables ( $\Delta \text{CO}_2$  and RF) and is mainly related to the large range of climate sensitivity parameters that is used for the production of the ensemble. 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<sub>2</sub> emissions to the total anthropogenic RF and  $\Delta T$  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 Carbon Neutral Growth (CNG) scenario aims at stabilizing 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<sub>2</sub> greenhouse gas. The results show that the CNG 2020 under the RCP2.6 storyline produces the lowest  $\Delta T$  (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  $\Delta T$ . If CNG is delayed until 2040, the climate impact is higher than the 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<sub>2</sub> 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<sub>2</sub> 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.



**Figure 2.** 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.



**Figure 3.** Temporal evolution (1940–2100) of the aviation induced CO<sub>2</sub> mixing ratio increase (ppm), radiative forcing (mW/m<sup>2</sup>), and temperature increase (mK) for the ICAO based, ACARE, CNG2020 and Factor 2 scenarios (RCP2.6 storyline for non-aviation emissions).

Since CO<sub>2</sub> 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 21<sup>st</sup> 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 3 shows the long-term temporal evolution (1940-2100) of  $\Delta\text{CO}_2$  (top), RF (middle) and  $\Delta T$  (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  $\text{CO}_2$  emissions stay constant after 2050,  $\Delta T$  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  $\text{CO}_2$  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.

As shown in Figures 3, 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  $99.5 \text{ mK} \pm 20 \text{ mK}$ , 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 37mK, 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 Earth System Model (ESM) has been used to assess the climate impact of present and future civil aviation carbon dioxide ( $\text{CO}_2$ ) emissions. The impact of aviation  $\text{CO}_2$  emissions on future climate has been quantified over the 1940–2050 period, extending some simulations to 2100 and using different aviation  $\text{CO}_2$  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 Mt  $\text{CO}_2$ /year (Factor 2 scenario) to 2338 Mt  $\text{CO}_2$ /year (ICAO based scenario) in 2050.

In 2050, on a climate trajectory in line with the Paris Agreement limiting the global warming below  $2^\circ\text{C}$  (RCP2.6), we found that the impact of the aviation  $\text{CO}_2$  emissions ranges from  $26 \pm 2 \text{ mK}$  (1.4 % of the total anthropogenic warming) for an ambitious mitigation strategy scenario (Factor 2) to  $39 \pm 4 \text{ mK}$  (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  $99.5 \text{ mK} \pm 20 \text{ mK}$  in 2100 (ICAO based), which corresponds to 5.2% of the total anthropogenic warming under RCP2.6. The climate impact of aviation  $\text{CO}_2$  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  $\text{CO}_2$  concentration and on the future climate.

Please report on the Terrenoire et al. (2019) paper for full details about this work.

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