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On the contribution of global aviation to the CO_2 radiative forcing of climate[☆]

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ABSTRACT

The aviation sector contributes to anthropogenic climate change through both CO_2 and non-CO_2 radiative effects. The CO_2 effect is considered to be much more certain than the non-CO_2 effects, yet there are relatively few studies that quantify it. Building on the scientific literature on burden sharing in the wake of the "Brazilian proposal", we discuss how to best attribute a fraction of the CO_2 radiative forcing to the aviation sector. For this we use the OSCAR compact Earth System model to estimate a contribution of aviation to the CO_2 concentration of 2.18 ppm in 2018. We further estimate the aviation contribution to the 2018 CO_2 radiative forcing to be 34.6, 32.6, 32.2 and 28.8 mW m^{-2} for the proportional, differential, time-sliced and marginal methods, respectively. The time-sliced method has our preference because it is invariant upon disaggregation or recombination and can differentiate the relative impacts of early and late emissions. It leads to a radiative forcing estimate that is 12% larger than the residual method that is commonly used despite not being additive. This work has implications on the total-to-CO_2 RF ratio and the assessment of potential mitigation measures involving a trade-off between the CO_2 and non-CO_2 radiative effects of aviation.

1. Introduction

Emissions from aircraft include carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and aerosols. It is customary to separate the contributions of these emissions to anthropogenic climate change into CO_2 and non-CO_2 radiative effects. The CO_2 emitted is long-lived in the atmosphere and its radiative effect is generally considered to be well quantified, while other emitted species are short-lived and their radiative effects (especially those associated with contrails, induced cirrus and aerosols) are much more uncertain. For past emissions, these effects are usually quantified by their radiative forcings (RF) and/or effective radiative forcings (ERF) that are key concepts in the traditional framework for understanding climate change (Sherwood et al., 2015). Radiative forcing integrates the effect of all past emissions onto the present-day radiation balance. While all past emissions matter for CO_2, given its long residence time in the atmosphere, only the most recent emissions matter when calculating the RF by short-lived species.

Quantifying the relative contributions of multiple causal factors to an observed or simulated change is referred to as the process of "attribution" and is a very classical topic in environmental sciences. The problem is made more complicated when the relationship between the cause and the consequence is non-linear as it is often the case in questions relating to air quality, atmospheric chemistry and climate change. In particular there are often non-linearities in the relationships between emissions and concentrations of atmospheric species (e.g., Grewe, 2013; Clappier et al., 2017) and between their concentrations and associated radiative forcings (e.g., for CO_2).

Attribution is an important step in framing responsibility in the climate change discourse. In particular the CO_2 forcing attribution has been an intense topic of discussion in climate research when it was envisaged in climate negotiations to set future mitigation efforts

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according to each country's past historical responsibility in RF or temperature increase. This burden-sharing scheme is known as the "Brazilian proposal" and it generated a number of scientific studies (e.g., Trudinger and Enting, 2005; Höhne and Blok, 2005) which are still very relevant. It has been shown that different attribution methods rely on different assumptions and approaches, yield different results and that each method has pros and cons especially in terms of i) fulfilling or not the desired properties for an attribution method, ii) being able or not to differentiate early versus late emissions in the industrial period, and iii) relying or not on simple and robust calculations.

In contrast attributing the CO_2 radiative forcing to different emission sectors has received much less attention. Yet there are many societal debates on the responsibility of particular economic sectors to the current climate change. In this study, we would like to revisit existing methods used to attribute the CO_2 radiative forcing taking the aviation sector as an illustration. For doing so we first review attribution methods for the CO_2 radiative forcing (section 2), describe our model and methodology (section 3) and then apply such methods for the specific case of the aviation sector (section 4). These sections are followed by a discussion and a conclusion (section 5).

2. RF attribution methods

A common attribution method is the "residual attribution method", whereby the RF attributable to CO_2 by a particular sector s at time t, $F_s(t)$, is expressed as:

$$F_s^R(t) = \Phi(Q(t)) - \Phi(Q(t) - Q_s(t)) \tag{1}$$

where $Q_s(t)$ and $Q(t)$ are the CO_2 concentration increases since preindustrial time due to the sector s and all anthropogenic activities, respectively, and Φ is the relationship between CO_2 concentration and radiative forcing. In this context the Φ function can be well approximated by a logarithmic function that depends only on the atmospheric CO_2 concentration (Ramaswamy et al., 2001):

$$\Phi(Q(t)) = 5.35\ \log\left(\frac{Q(t) + C_{\mathrm{preind}}}{C_{\mathrm{preind}}}\right) \tag{2}$$

where C_{preind} is the preindustrial CO_2 atmospheric concentration. In the case of a small perturbation, which is the case for the aviation sector $s =$ av, the residual method is equivalent to the "marginal attribution method" (Trudinger and Enting, 2005):

$$F_{\mathrm{av}}^R(t) = \Phi(Q(t)) - \Phi(Q(t) - Q_{\mathrm{av}}(t)) \approx F_{\mathrm{av}}^M(t) = \frac{\mathrm{d}\Phi}{\mathrm{d}Q}\Big|_{Q(t)} \times Q_{\mathrm{av}}(t) \tag{3}$$

The point at which the derivative in the last part of Eqn. (3) is computed matters because the Φ function is logarithmic and therefore non-linear. Computing the radiative forcing around the current CO_2 concentration minimizes the estimate. For instance the estimated CO_2 RF for aviation is 45% larger for the year 2018 if the derivative is computed around the pre-industrial concentration, $Q(0) = 0$, instead of the current concentration, $Q(t)$. It is hard to justify any of these two choices, and indeed none of the earlier investigators (Lim et al., 2007; Lee et al., 2009; Terrenoire et al., 2019; Lee et al., 2021, hereafter L21) have justified why they compute the aviation CO_2 RF around the current rather than the preindustrial concentration.

Furthermore, we would like any attribution method to be invariant upon disaggregation or recombination of different contributions. In particular, if $Q(t) = \sum_s Q_s(t)$, where s refers to different emission sectors, then one would expect the total forcing $F(t) = \Phi(Q(t))$ to be equal to $\sum_s F_s(t)$. This is the case for neither the residual method nor the marginal method, which represents a significant drawback for these two methods.

Trudinger and Enting (2005) have proposed several other methods to attribute a fraction of the CO_2 radiative forcing to a particular country or sector, which they judged against several criteria. We select and present three methods among those that satisfy the invariance to disaggregation or recombination discussed above, a criterion that Trudinger and Enting (2005) call "additivity". For convenience, we also continue to borrow their mathematical notations and consider specifically the aviation sector (i.e., $s =$ av in the following). The simplest method is probably the proportional attribution method whereby:

$$F_{\mathrm{av}}^P(t) = \frac{Q_{\mathrm{av}}(t)}{Q(t)} F(t) \tag{4}$$

This method ignores the time profile of the CO_2 emissions beyond the impact it has on Q_{av} and Q. It simply attributes the total CO_2 radiative forcing in proportion to the concentration perturbations which are assumed to be additive. The method can be easily modified if the concentration perturbations are not additive by changing the denominator with the sum of the concentration perturbations over all sectors. Other methods considered by Trudinger and Enting (2005) are the differential attribution method:

$$F_{\mathrm{av}}^D(t) = \int_0^t \frac{\mathrm{d}\Phi}{\mathrm{d}Q}\Big|_{Q(t')} \frac{dQ_{\mathrm{av}}(t')}{dt'} dt' \tag{5}$$

and the time-sliced attribution method:

$$F_{\mathrm{av}}^{TS}(t) = \int_0^t \frac{\mathrm{d}\Phi}{\mathrm{d}Q}\Big|_{Q(t,t')} \frac{\partial Q_{\mathrm{av}}(t,t')}{\partial t'} dt' \tag{6}$$

where $Q_{\mathrm{av}}(t, t')$ and $Q(t, t')$ are the CO_2 concentrations at time t due to emissions from aviation and all anthropogenic activities up to time t'. It should be noted that we made explicit the points at which the derivatives are evaluated, and in doing so, corrected a typo in Eqn. (5) of the original paper by Trudinger and Enting (2005). This shows more clearly that Eqns. (5) and (6) differ on the point at which $\mathrm{d}\Phi/\mathrm{d}Q$ are evaluated. The differential method is a direct integration over time of the aviation contribution to the CO_2 increased rate weighted by the marginal rate of the CO_2 forcing due to past total emissions at that time. In contrast, the time-sliced method integrates the contribution of past emissions to the current concentration change weighted by the marginal rate of the CO_2 forcing due to past total emissions.

We concur with Trudinger and Enting (2005) that "The residual (all-but-one) method […] is very easy to implement and understand, but has the major disadvantage that it is not additive." An important property of an attribution method in the context of the aviation sector relates to its capacity to differentiate the impact of early versus late emissions. Indeed aviation emissions started rather late in the historical period, hence at a time when the derivative of Φ has become smaller because of the log dependence on the current atmospheric concentration. We also concur with Trudinger and Enting (2005) that, among the different methods they propose, the time-sliced method turns out to be a better way of avoiding to attribute the consequences of early emitters to late emitters. However, the radiative forcing is more complex to evaluate through this method as it requires to compute both $Q_{\mathrm{av}}(t, t')$ and $Q(t, t')$ for all $t' \leq t$, as described in the next section.

3. Model description and methodology

Quantifying $F_{\mathrm{av}}(t)$ requires an estimate of $Q_{\mathrm{av}}(t)$ and, for some of the methods, estimates of $Q_{\mathrm{av}}(t, t')$ and $Q(t, t')$ for all t'. Unfortunately, neither $Q_{\mathrm{av}}(t)$ nor $Q_{\mathrm{av}}(t, t')$ and $Q(t, t')$ are observable, hence we have to rely solely on a model for these quantities. However $Q(t) = Q(t, t)$ is well observed, so it is important to check that the model can reproduce the observations as best as possible.

Using a single impulse response function is known to be imperfect and too simple to reproduce the evolution of the CO_2 concentration during the historical period. For instance Joos et al. (2013) have shown that CO_2 impulse response functions are significantly changed by the background conditions (both in terms of CO_2 concentration and climate). Their standard impulse response function is derived under a 2010 constant background and cannot therefore be applied throughout the 20th century as it would underestimate past carbon sinks. In order to avoid such problem, we use instead the OSCAR compact Earth system model (Gasser et al., 2017) to estimate $Q(t, t')$ and $Q_{av}(t, t')$.

Fossil-fuel (FF) emissions are from the Community Emissions Data System (CEDS) while land-use change (LUC) emissions are interactive in OSCAR using a bookkeeping approach (Gasser et al., 2020). Aviation emissions are taken from the Supplementary material of L21 for the period 1990–2018. Emissions used in L21 for 1971–1989 are proprietary and not publicly available so we cannot use them in this study. Instead we use historical emissions from the Community Emissions Data Systems (CEDS) as available in input4MIPs (Hoesly et al., 2017, 2018). They are multiplied by a normalization factor 1.074, so that the emission value for 1990 matches the value given in L21. The normalized input4MIPs emissions are very close to the estimate provided by Sausen and Schumann (2000) for the period until 1990 (figure not shown), which justifies this normalization factor. Emissions used in this study are shown in Fig. 1a. It can be seen that emissions from aviation started slowly and took off gradually during the 1950s and 1960s. They have reached 2.8% and 2.6% of total fossil-fuel and total fossil-fuel plus land-use emissions, respectively, in 2018. The growth rate of aviation CO_2 emissions has been larger than the growth rate of total emissions in the 1940s, 1950s, 1960s in the 1980s and in recent years (see Fig. 1b, a nine-year running mean of emissions is used to remove the noise). In contrast the growth rate was less than that of total emissions in the 2000s. Aviation emissions have collapsed in 2020 due to the COVID-19 pandemic (Liu et al., 2020a, 2020b; not shown here as the time series stops in 2018).

We prescribe the observed climate record to compute carbon sinks consistently and parameters were selected to obtain a good fit to the observed evolution of the CO_2 atmospheric concentration over the 1959–2018 period. This period was chosen because 1959 corresponds to the longest available record of CO_2 concentration with high accuracy. The atmospheric CO_2 concentration is underestimated by OSCAR until the late 1950s but then matches very well, within a few ppm, the observed values since then (Fig. 2). The underestimate in 2018 is only ~2 ppm compared to observations, which is very small compared to the increase in CO_2 concentration during the historical period.

In order to estimate $Q(t, t')$ and $Q_{av}(t, t')$, we perform additional experiments where anthropogenic fossil-fuel and land-use emissions are cut past a particular year. Specifically we perform three sets of experiments: in a first set all fossil fuel emissions are cut but land use change emissions are left unchanged; in a second set, both fossil-fuel and land use change emissions are cut; finally in a third set aviation emissions are cut at different years while other fossil-fuel and land use change emissions are left unchanged. In these experiments the atmospheric CO_2 concentration decreases as carbon sinks gets in equilibrium with respect to the atmospheric concentration while natural sources respond to the global warming (as can be seen in the curves for 1930, 1950 and 1970 stop in emissions, Fig. 2a). If only fossil-fuel emissions are cut past a particular year and land use emissions are calculated as before, the atmospheric CO_2 concentration increases much quicker, or decreases less for the later years when emissions are cut, because emissions associated with land-use changes partly or totally offset the effect of natural carbon sinks (Fig. 2b).

We can then estimate $Q_{ff}(t, t')$ and $Q_{ff+luc}(t, t')$ relative to C_{preind}, as well as $Q_{av}(t, t')$ by difference between two experiments (Fig. 3). The preindustrial CO_2 atmospheric concentration, C_{preind}, is set to 278 ppm. For both the differential and time-sliced methods, we discretize the integral with a 1 year timestep. We compute formally the derivative $d\Phi/dQ$ from Eqn. (2). It is evaluated at the mid-point between $Q(t'_i)$ and $Q(t'_{i+1})$ (resp. $Q(t, t'_i)$ and $Q(t, t'_{i+1})$) for the differential (resp. time-sliced) method.

4. Application to aviation

4.1. Results

OSCAR yields a contribution of aviation to the CO_2 concentration in 2018 of 2.18 ppm. Using $Q(t, t')$ computed with both fossil-fuel and land-use emissions cut, we can then estimate the aviation contribution to the 2018 CO_2 radiative forcing to be 34.6, 32.6, 32.2 and 28.8 mW m^{-2} for the proportional, differential, time-sliced and marginal methods, respectively (see also Fig. 4 for the time profiles). The three alternative methods to the marginal method thus lead to aviation CO_2 radiative forcings that are 20, 13 and 12% larger than the marginal method. In other words, the marginal method underestimates the aviation CO_2 radiative forcing by 11% against the preferred time-sliced method. The sign of the difference is expected because the marginal method majorizes the forcing estimate when computed with respect to the current concentration. These results are almost identical if $Q(t, t')$ is computed with fossil-fuel emissions (E_{ff}) being cut instead of both fossil-fuel and land use (E_{ff+luc}) emissions being cut. Hence we do not show or discuss further this case.

4.2. Comparison to previous studies

Our estimate of 2.18 ppm for the contribution of aviation to the CO_2 concentration in 2018 is less than the three estimates of 2.9, 2.4 and 2.4 ppm obtained by L21 with the LinClim, CICERO-SCM and FaIR models,

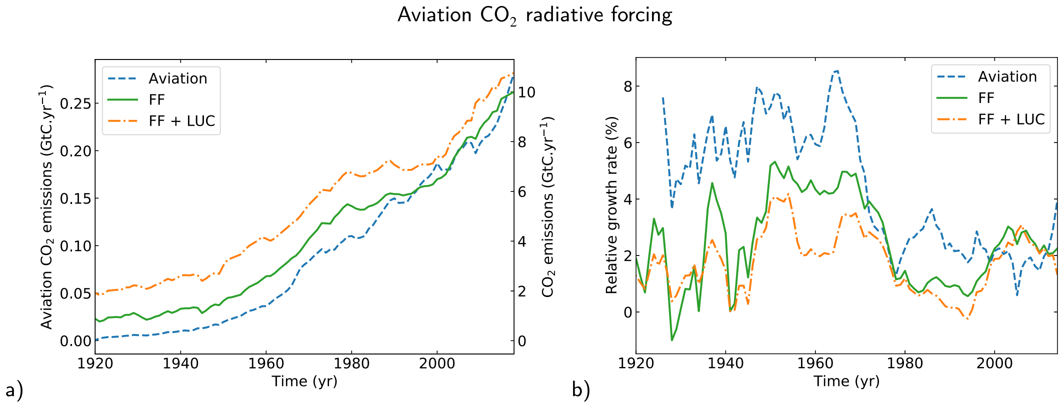

Fig. 1. (a) Historical CO_2 emissions due to aviation (blue dashed line, in GtC yr^{-1}, left-hand side *y*-scale) for the period 1920 to 2018. The solid green and dot-dashed orange lines show the total fossil fuel and fossil fuel plus land use change emissions, respectively (in GtC yr^{-1}, right-hand side *y*-scale) for the same period. See text for details. (b) Relative growth rate of the nine-year running average of the same emissions (%), for the period 1920 to 2014. The data begins only in 1926 for aviation emissions, because of the 9-year running average, and no growth rate prior to 1921 can be computed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

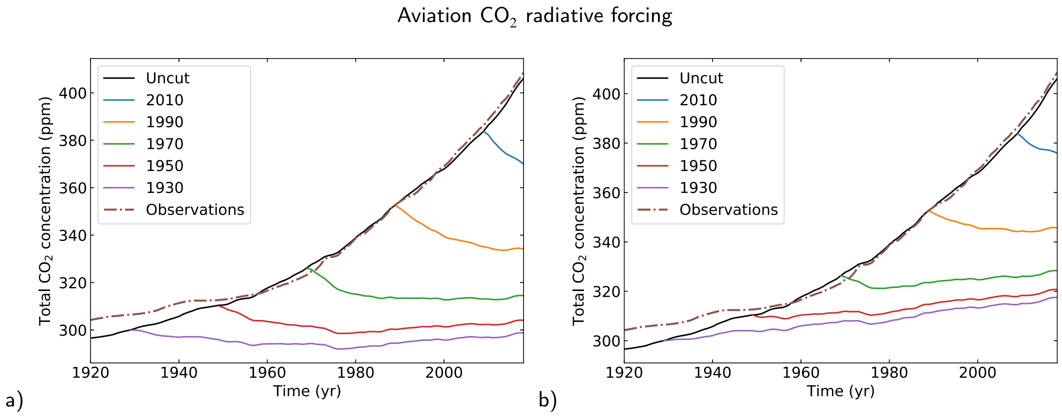

Fig. 2. Total CO_2 concentration estimated with the OSCAR model for the period 1920 to 2018 (solid black line). Solid coloured lines show the evolution of concentrations if (a) fossil-fuel plus land use change emissions or (b) fossil-fuel only emissions are cut in 1930, 1950, 1970, 1990 and 2010. The observed global CO_2 concentration is shown with the brown dot-dashed curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

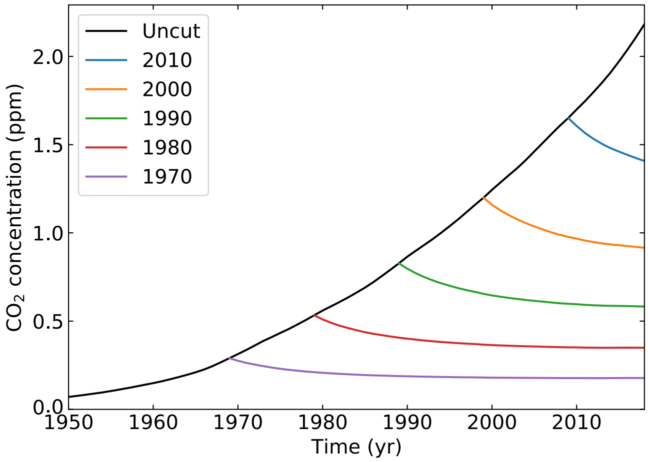

Fig. 3. Contribution of aviation to the CO_2 concentration increase for the period 1950 to 2018 (black line). Coloured lines show the evolution of concentrations if aviation emissions are cut in 1970, 1980, 1990, 2000 and 2010.

respectively. It is beyond the scope of this study to understand the differences between these four estimates. However it would be interesting to conduct an intercomparison study to attribute the differences to different choices in model structure, aviation emissions and/or methodology. We note that our value of 1.32 ppm for the year 2000 is consistent with the estimate of 1.3 ppm from Terrenoire et al. (2019) –who also used the OSCAR model but with a different dataset for past aviation emissions– and the estimate of 1.34 ppm from L21 using the FAIR model. It is not consistent with the LinClim estimate in L21 which is a bit of an outlier and relies on a fit to older models. A particularly relevant test for the simple models involved in such calculations is whether or not the observed time evolution of the atmospheric CO_2 concentration can be reproduced when the models are fed with our best knowledge of past emissions. We have shown this to be the case for our model after some parameter tuning. A Monte-Carlo methodology could also be used to quantify the uncertainty of $Q_{av}(t)$ under the constraint of $Q(t)$ matching the observations.

L21 translated their estimated aviation contributions to the atmospheric CO_2 concentration increase of 2.9, 2.4 and 2.4 ppm in 2018 into radiative forcing estimates of 38.6, 32.0 and 32.4 mW m^{-2} (average 34.3 mW m^{-2}). Our best guess estimate of 32.2 mW m^{-2} for the time-sliced method is only a little less than the value of 34.3 mW m^{-2} of L21. This is because the increase in forcing due to our preferred attribution method (the time-sliced method) is more than compensated by our lower estimate of the aviation contribution to the CO_2 concentration change.

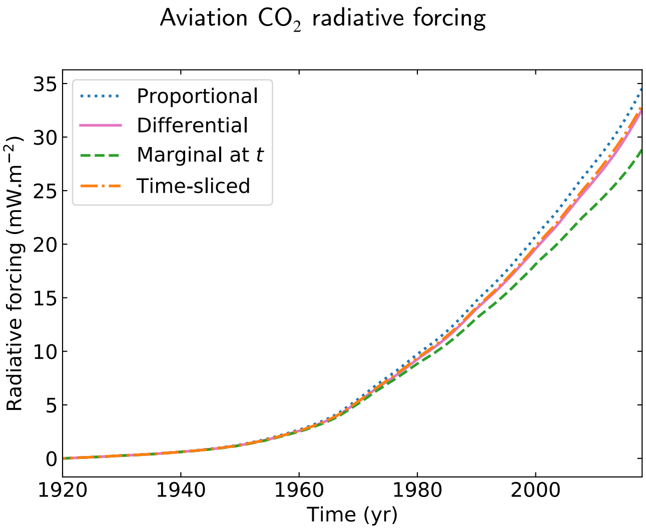

Fig. 4. Time evolution of the CO_2 radiative forcing (mW m^{-2}) due to aviation according to four attribution methods for the period 1920 to 2018. The proportional, differential, marginal and time-sliced methods are shown with the dotted blue, solid pink, dashed green and dot-dashed orange curves, respectively. The differential and time-sliced methods give very similar results and are difficult to distinguish on the plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Along with estimates of the impacts due to contrail cirrus, NO_x, stratospheric H_2O and aerosols, L21 conclude that "non-CO_2 impacts comprise about 2/3 of the net (effective) radiative forcing". Changing the attribution method for the CO_2 radiative forcing in L21 to our preferred method would lead to a change in the fraction of the net radiative forcing due to non-CO_2 effects and the radiative forcing index. Inflating the best estimate of L21 by 12% (the difference between our marginal and time-sliced methods) and ignoring aerosol-cloud interactions, the non-CO_2 impacts would comprise about 63% of the net effective radiative forcing instead of the 66% estimated by L21. This is a modest but non-negligible change.

5. Discussion and conclusions

In this article we estimate the contribution of aviation to the CO_2 radiative forcing using three robust attribution methods instead of the commonly-used residual method. We found that the three alternative methods lead to an aviation CO_2 radiative forcing that is 20, 13 and 12% larger than the residual method. Our preferred method is the time-sliced method because it allows to differentiate the impacts on concentrations of early and late emissions of CO_2 in the industrial period. More specifically, the residual method underestimates the aviation CO_2 radiative forcing by 11% against the time-sliced method. This method requires estimating the contribution of past CO_2 emissions to the current concentration change which we did using the OSCAR compact Earth System model. In doing so we found a smaller contribution of aviation to the anthropogenic perturbation to the CO_2 concentration than L21 did using three simple carbon-climate models. Although it is beyond the scope of this study to understand the differences between these four estimates, it would be interesting to conduct an intercomparison study to attribute the differences to different choices in model structure, aviation emissions or methodology. Finally it should be noted that although the OSCAR model accounts for non-linearities that exist in the emission to concentration relationship, the attribution method does not. Further development would be required to take such non-linearities into account.

It could be argued that estimating the CO_2 radiative forcing of an individual industrial sector is irrelevant because there has been a paradigm shift in international climate negotiations, with the recognition of the importance for each actor (whether it is a country or an industry) to achieve carbon neutrality as soon as possible. Accurately estimating and attributing contributions to RF by particular countries or industrial sectors has thus become less critical from a global policy viewpoint. However it remains important to quantify the net RF not only at the global scale in order to monitor and understand the ongoing climate change, but also at a much more granular level in order to make informed choices on industrial changes that imply a shift in the balance of emissions. In particular the debate on non-CO_2 effects is quite significant for aviation and the estimate of the CO_2 radiative forcing attributable to aviation is relevant to this debate.

RF and effective RF (ERF) are key concepts to understand climate change and the ratio of total-to-CO_2 forcing due to aviation has been widely used as a multiplier factor to account for the non-CO_2 radiative effects of aviation following its introduction by IPCC in a Special Report (IPCC, 1999). There is growing realization that aerosols emitted by aviation may be responsible for a radiative forcing due to aerosol-cloud interactions (L21). As the underlying mechanisms are still very uncertain, these effects are usually omitted from the multiplier factor, which is arguable. Furthermore, it should be remembered that RF and ERF are backward-looking metrics, they are not appropriate to quantify the effect of today's aviation into the future (Wuebbles et al., 2010; Lee, 2018). From a climate mitigation perspective it may thus be more relevant to assess the CO_2 and non-CO_2 effects using other metrics such as Absolute Global Warming Potential (AGWP) or Absolute Global Temperature change Potential (AGTP). However, such metrics also rely on an estimate of the additional CO_2 concentration due to a pulse emission and an attribution method to compute the subsequent RF. An additional complication for forward-looking calculations is that they also depend on the choice of a future emission scenario. Depending on the time horizon considered, it may be required to also consider long-term biogeochemical feedbacks, in particular those involving the carbon cycle. This topic is particularly relevant to mitigation measures involving a trade-off between the CO_2 and non-CO_2 radiative effects. Contrail avoidance measures through rerouting or adjusting the flight altitude have been widely discussed in the literature. Their implementation would require the choice of one or several climate metrics (e.g., Deuber et al., 2013). Implementing accurate CO_2 and contrail radiative forcing and temperature change calculations for no-regret rerouting decisions aiming at contrail avoidance will be the subject of further work.

CRediT authorship contribution statement

Olivier Boucher: Conceptualization, Writing. **Audran Borella:** Conceptualization, Investigation, Visualization, Writing. **Thomas Gasser:** Conceptualization, Investigation, Writing. **Didier Hauglustaine:** Writing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: OB and DH declare financial support from the Direction Générale de l'Aviation Civile (Ministère de la Transition Ecologique) through convention N°2021-39 relative to "Aviation & Climate".

References

Clappier, A., Belis, C.A., Pernigotti, D., Thunis, P., 2017. Source apportionment and sensitivity analysis: two methodologies with two different purposes. Geosci. Model Dev. 10, 4245–4256. https://doi.org/10.5194/gmd-10-4245-2017.

Deuber, O., Sigrun, M., Sausen, R., Ponater, M., Ling, L., 2013. A physical metric-based framework for evaluating the climate trade-off between CO_2 and contrails – the case of lowering aircraft flight trajectories. Environ. Sci. Pol. 25, 176–185. https://doi.org/10.1016/j.envsci.2012.10.004.

Gasser, T., Ciais, P., Boucher, O., Quilcaille, Y., Tortora, M., Bopp, L., Hauglustaine, D., 2017. The compact Earth system model OSCAR v2.2: description and first results. Geosci. Model Dev. 10, 271–319. https://doi.org/10.5194/gmd-10-271-2017.

Gasser, T., Crepin, L., Quilcaille, Y., Houghton, R.A., Ciais, P., Obersteiner, M., 2020. Historical CO_2 emissions from land use and land cover change and their uncertainty. Biogeosciences 17, 4075–4101. https://doi.org/10.5194/bg-17-4075-2020. URL:

Grewe, V., 2013. A generalized tagging method. Geosci. Model Dev. 6, 247–253. https://doi.org/10.5194/gmd-6-247-2013.

Hoesly, R., Smith, S., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J.J., Vu, L., Andres, R.J., Bolt, R.M., Bond, T.C., Dawidowski, L., Kholod, N., Kurokawa, J.i., Li, M., Liu, L., Lu, Z., Moura, M.C.P., O'Rourke, P.R., Zhang, Q., 2017. input4mips.pnnl-jgcri.emissions.cmip.ceds-2017-08-30. https://doi.org/10.22033/ESGF/input4MIPs.1604.

Hoesly, R.M., Smith, S.J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J.J., Vu, L., Andres, R.J., Bolt, R.M., Bond, T.C., Dawidowski, L., Kholod, N., Kurokawa, J.I., Li, M., Liu, L., Lu, Z., Moura, M.C.P., O'Rourke, P.R., Zhang, Q., 2018. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geosci. Model Dev. 11, 369–408. https://doi.org/10.5194/gmd-11-369-2018.

Höhne, N., Blok, K., 2005. Calculating historical contributions to climate change – discussing the 'Brazilian Proposal'. Climatic Change 71, 141–173. https://doi.org/10.1007/s10584-005-5929-9.

IPCC, 1999. In: Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.), IPCC Special Report on Aviation and the Global Atmosphere. Cambridge University Press, Cambridge, UK.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., Weaver, A.J., 2013. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos. Chem. Phys. 13, 2793–2825. https://doi.org/10.5194/acp-13-2793-2013.

Lee, D., 2018. International aviation and the Paris Agreement temperature goals, prepared for uk department for transport. URL: http://e-space.mmu.ac.uk/622562/.

Lee, D., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., Doherty, S., Freeman, S., Forster, P., Fuglestvedt, J., Gettelman, A., De León, R., Lim, L., Lund, M., Millar, R., Owen, B., Penner, J., Pitari, G., Prather, M., Sausen, R., Wilcox, L., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmos. Environ. 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834.

Lee, D.S., Fahey, D.W., Forster, P.M., Newton, P.J., Wit, R.C., Lim, L.L., Owen, B., Sausen, R., 2009. Aviation and global climate change in the 21st century. Atmos. Environ. 43, 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024.

Lim, L., Lee, D., Sausen, R., Ponater, M., 2007. Quantifying the effects of aviation on radiative forcing and temperature with a climate response model. In: Sausen, R., Blum, A., Lee, D., Brüning, C. (Eds.), International Conference on Transport, Atmosphere and Climate (TAC). Office for Official Publications of the European Communities, Luxembourg, pp. 202–207.

Liu, Z., Ciais, P., Deng, Z., Davis, S.J., Zheng, B., Wang, Y., Cui, D., Zhu, B., Dou, X., Ke, P., Sun, T., Guo, R., Zhong, H., Boucher, O., Bréon, F.M., Lu, C., Guo, R., Xue, J., Boucher, E., Tanaka, K., Chevallier, F., 2020a. Carbon Monitor, a near-real-time daily dataset of global CO_2 emission from fossil fuel and cement production. Scientific Data 7. https://doi.org/10.1038/s41597-020-00708-7.

Liu, Z., Ciais, P., Deng, Z., Lei, R., Davis, S.J., Feng, S., Zheng, B., Cui, D., Dou, X., Zhu, B., Guo, R., Ke, P., Sun, T., Lu, C., He, P., Wang, Y., Yue, X., Wang, Y., Lei, Y., Zhou, H., Cai, Z., Wu, Y., Guo, R., Han, T., Xue, J., Boucher, O., Boucher, E., Chevallier, F., Tanaka, K., Wei, Y., Zhong, H., Kang, C., Zhang, N., Chen, B., Xi, F., Liu, M., Bréon, F. M., Lu, Y., Zhang, Q., Guan, D., Gong, P., Kammen, D.M., He, K., Schellnhuber, H.J., 2020b. Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. Nat. Commun. 11 https://doi.org/10.1038/s41467-020-18922-7.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G., Solomon, S., 2001. Radiative forcing of climate change. In: IPCC Third Assessment Report. Cambridge University Press, pp. 349–416.

Sausen, R., Schumann, U., 2000. Estimates of the climate response to aircraft CO_2 and NOx emissions scenarios. Climatic Change 44, 27–58. https://doi.org/10.1023/A:1005579306109.

Sherwood, S.C., Bony, S., Boucher, O., Bretherton, C., Forster, P.M., Gregory, J.M., Stevens, B., 2015. Adjustments in the forcing-feedback framework for understanding climate change. Bull. Am. Meteorol. Soc. 96, 217–228. https://doi.org/10.1175/BAMS-D-13-00167.1.

Terrenoire, E., Hauglustaine, D.A., Gasser, T., Penanhoat, O., 2019. The contribution of carbon dioxide emissions from the aviation sector to future climate change. Environ. Res. Lett. 14, 084019 https://doi.org/10.1088/1748-9326/ab3086.

Trudinger, C., Enting, I., 2005. Comparison of formalisms for attributing responsibility for climate change: non-linearities in the Brazilian proposal approach. Climatic Change 68, 67–99. https://doi.org/10.1007/s10584-005-6012-2.

Wuebbles, D., Forster, P., Rogers, H., Herman, R., 2010. Issues and uncertainties affecting metrics for aviation impacts on climate. Bull. Am. Meteorol. Soc. 91, 491–496. https://doi.org/10.1175/2009BAMS2840.1.