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NONCO2 RESEARCH PROJECT

Time scales of the climate effects of aviation CO_2 and non-CO_2 emissions

ANCEN Background Note

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Time scales of the climate effects of aviation CO_2 and non-CO_2 emissions

The different gases and particulate matter emitted by aircraft engines remain in the atmosphere for different lengths of time. Consequently, their radiative forcing[1] and the subsequent climate effects also occur on different time scales.

Carbon dioxide (CO_2) is removed slowly, so accumulates in the atmosphere for decades to millennia[2]. During that time, it exerts a positive radiative forcing on the climate system, which leads to a warming of surface temperatures. Therefore, a substantial fraction of past aviation CO_2 emissions continues to exert a positive radiative forcing today and will continue to do so in the future.

The lifetime of non-CO_2 emissions in the atmosphere is much shorter, so non-CO_2 radiative forcing is exerted by recent emissions. The main effects of aviation non-CO_2 emissions, starting with the shortest-lived, include:

- Aviation particulate matter can be involved in forming contrails, which last up to several hours. During that time, contrails exert a positive radiative forcing by their own greenhouse effect, leading to a warming of global surface temperature, and a negative radiative forcing by reflecting sunlight, leading to a cooling.
- Aviation particulate matter remains in the atmosphere for days to weeks. During that time, it interacts with sunlight and terrestrial radiation, exerting a positive or negative radiative forcing depending on the absorption properties of the particulate matter. In some cases, aviation particulate matter interacts with clouds, exerting a positive or negative radiative forcing depending on the type of cloud involved.
- Aviation Nitrogen Oxides (NO_X) remain in the atmosphere for several weeks. They trigger perturbations to ozone and methane concentrations that last months to decades, during which they exert positive and negative radiative forcings.

The radiative energy perturbation caused while the radiative forcing is exerted is transferred to the oceans. The resulting change in ocean heat content and, concurrently, in the surface temperature of the Earth, happens over several decades (Figure 1). This is true for both CO_2 and non-CO_2 emissions. Even individual contrails, which typically last only a few hours, can cause, if their radiative forcing is strong enough, a climate response that lasts several decades.

[1] Radiative forcing quantifies the energy imbalance between a perturbed climate system and a reference climate system that would have remained at preindustrial conditions. The perturbation is caused by an external change to the climate system, for example an increase in carbon dioxide concentrations caused by human activities. Energy travels in the form of radiation: solar radiation entering the atmosphere from the sun, and infrared radiation exiting as thermal radiation. If a perturbation causes more radiation to stay in the Earth system than leave (a positive radiative forcing), then the surface will warm up, causing further changes to the Earth's climate. See also the definition for "radiative forcing" in the Glossary of the 6th Assessment Report of the Intergovernmental Panel on Climate Change at https://apps.ipcc.ch/glossary/.

[2] At its simplest, carbon dioxide cycles between the atmosphere, oceans and land biosphere. Its removal from the atmosphere involves a range of processes with different time scales. About 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years (IPCC 4th Assessment Report, 2007). This is further elaborated in the 5th and 6th Assessment Reports.

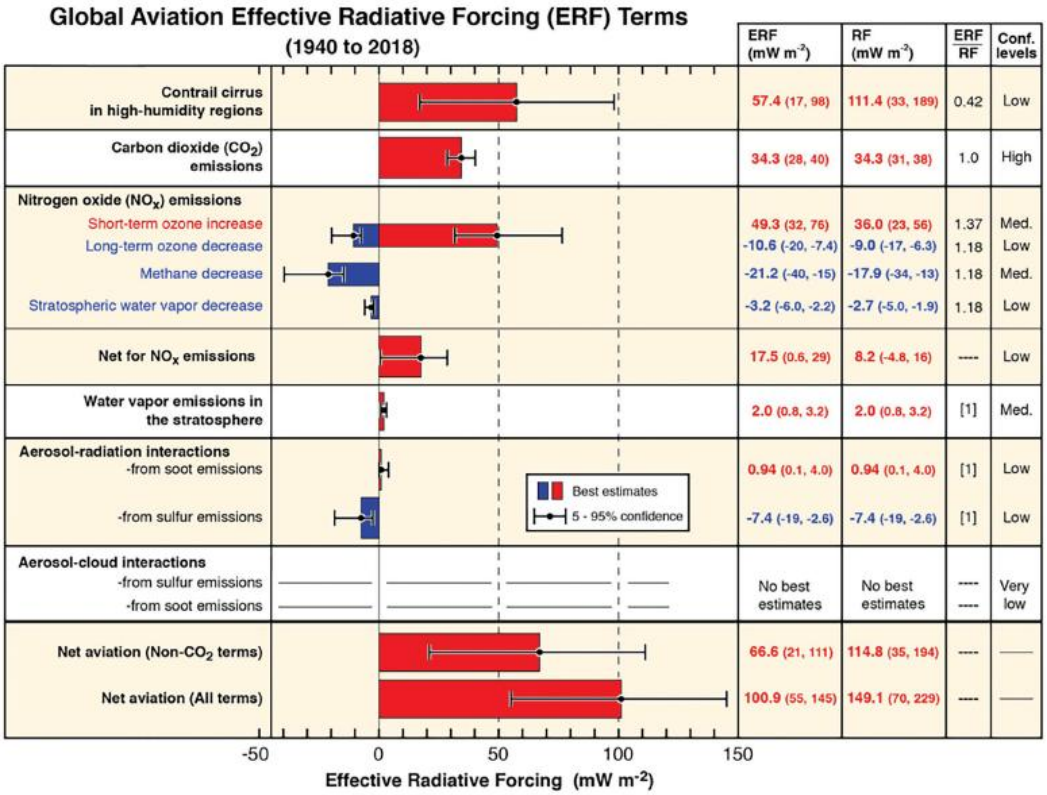
Backward-looking Perspective

The different time scales of CO_2 and non-CO_2 effects are particularly important to consider for aviation because a large fraction of its current radiative forcing may be caused by short-lived non-CO_2 effects.

The most recent assessment of the effective radiative forcing[3] (ERF) from historic global aviation emissions [1] (Figure 1) concluded that, based on best estimates, non-CO_2 effects contributed two thirds of total aviation ERF between 1940 and 2018, with CO_2 contributing the remaining third. This corresponds to a non-CO_2 to CO_2 ERF ratio of 2:1.

However, it is important to note that the best estimates are very uncertain, especially for the different non-CO_2 effects. Those uncertainties affect the non-CO_2 to CO_2 ERF ratio. Combining the different uncertainty ranges shown on Figure 1 gives non-CO_2 to CO_2 ERF ratios ranging from approximately 0.4:1 to 4:1. In addition, the assessment could not give a quantitative estimate and uncertainty range for one of the non-CO_2 effects, the effect of aviation particulate matter on clouds, which has the potential of exerting a large ERF. Accounting for that effect would further change the non-CO_2 to CO_2 ERF ratio.

Figure 1 – Most recent best estimates and uncertainty ranges for climate forcing terms of historic global aviation emissions from 1940 to 2018 (Figure 3 of Lee et al. 2021)

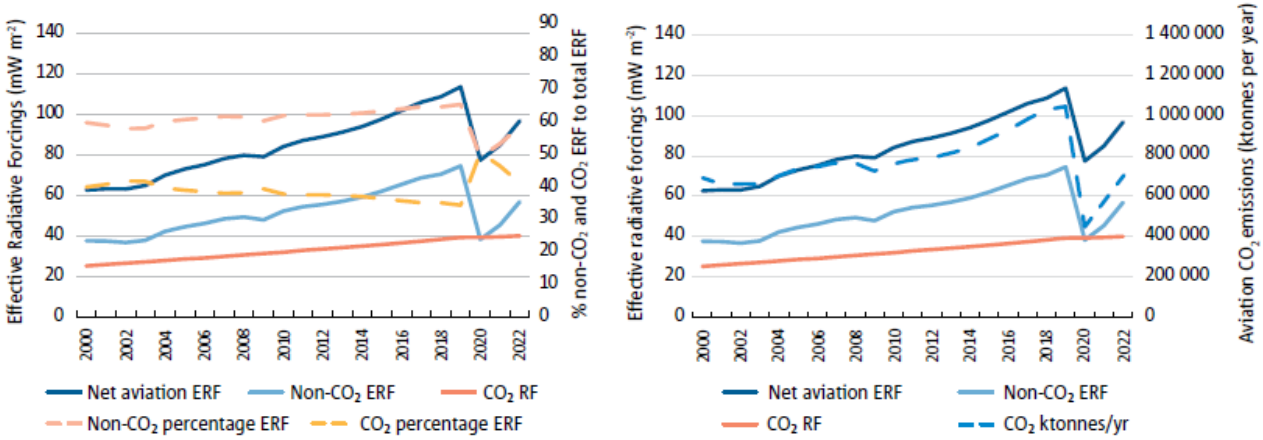


[3] ERF is a recent evolution of the radiative forcing concept. Like radiative forcing, it quantifies the energy gained or lost by the Earth system following an imposed perturbation, but ERF is computed once the atmosphere has adjusted to the perturbation but before surface temperature has changed. ERF is a better predictor of the surface temperature change than the initial radiative forcing. See Section 7.3 of the IPCC 6th Assessment Report.

The fraction of aviation radiative forcing caused by non-CO_2 effects depends on the growth rate of air traffic. It is larger when air traffic increases strongly.

Assessing the ERF of historic aviation emissions over a period when air traffic increased strongly emphasises the large but short-term contribution of non-CO_2 to total aviation radiative forcing. A good illustration of that behaviour came with the approximately 50% decrease in the number of flights caused by the response to the Covid-19 pandemic in the year 2020. As shown in Figure 2, non-CO_2 ERF for that year reduced significantly compared to previous years due to reduced non-CO_2 emissions. In contrast, CO_2 ERF only weakened slightly since the change in long-term cumulative CO_2 emissions since 1940 was small. So, despite the large non-CO_2 driven change in ERF, Covid-19 disruptions will have little influence on future aviation-induced warming, which is dominated by the effect of CO_2 emissions. Nonetheless, this behaviour shows that a similarly sized but more sustained decrease in non-CO_2 emissions could cause a relatively large and rapid reduction in aviation ERF.

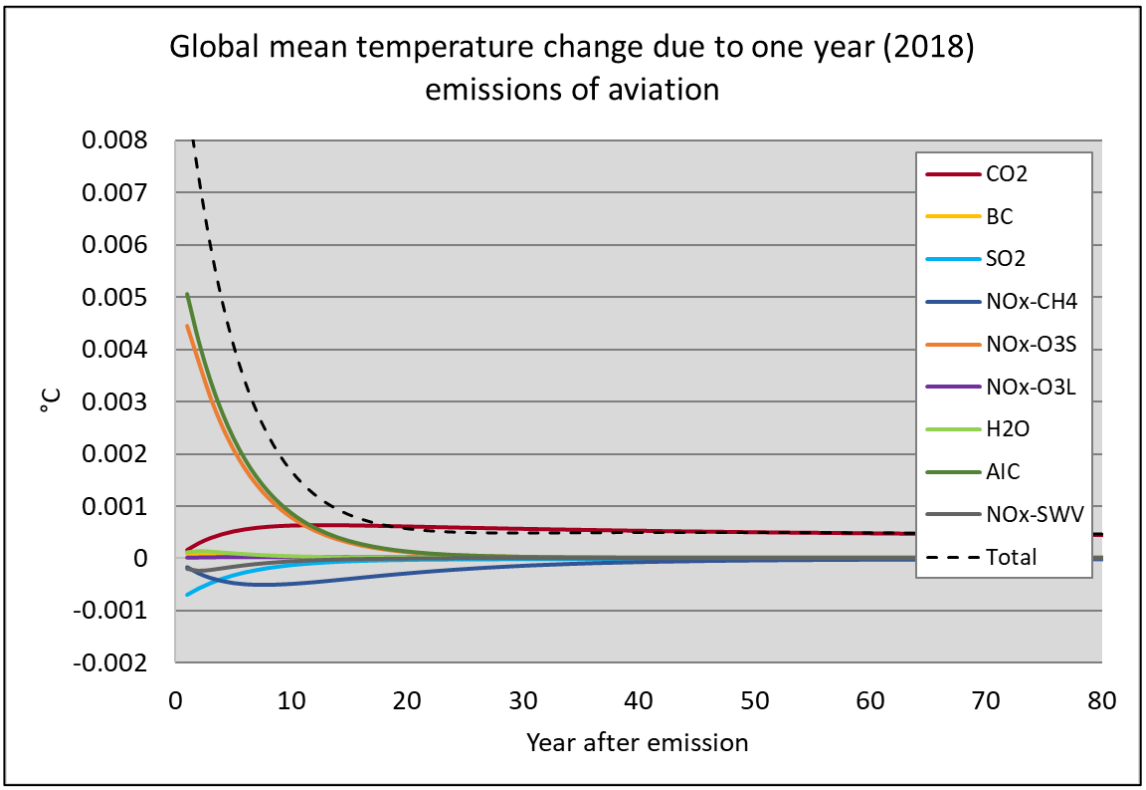
Figure 2 – Change in Effective Radiative Forcing (ERF) during the COVID pandemic. Total aviation ERF is in dark blue, aviation CO_2 ERF in orange, and non-CO_2 ERF in light blue (extended analysis based on Lee et al., 2021).



Forward-looking Perspective

The chart in Figure 3 shows the modelled time evolution of the global surface temperature response (°C) for a one year pulse of aviation CO_2 and non-CO_2 radiative forcings at their 2018 assessed values [1]. The short-lived nature of non-CO_2 effects means they dominate the temperature response for about 10 to 15 years after the aviation forcing has been imposed. The response to CO_2 forcing then takes over, but surface temperature responds to non-CO_2 forcings for decades.

Figure 3 – Modelled time evolution of global surface temperature response

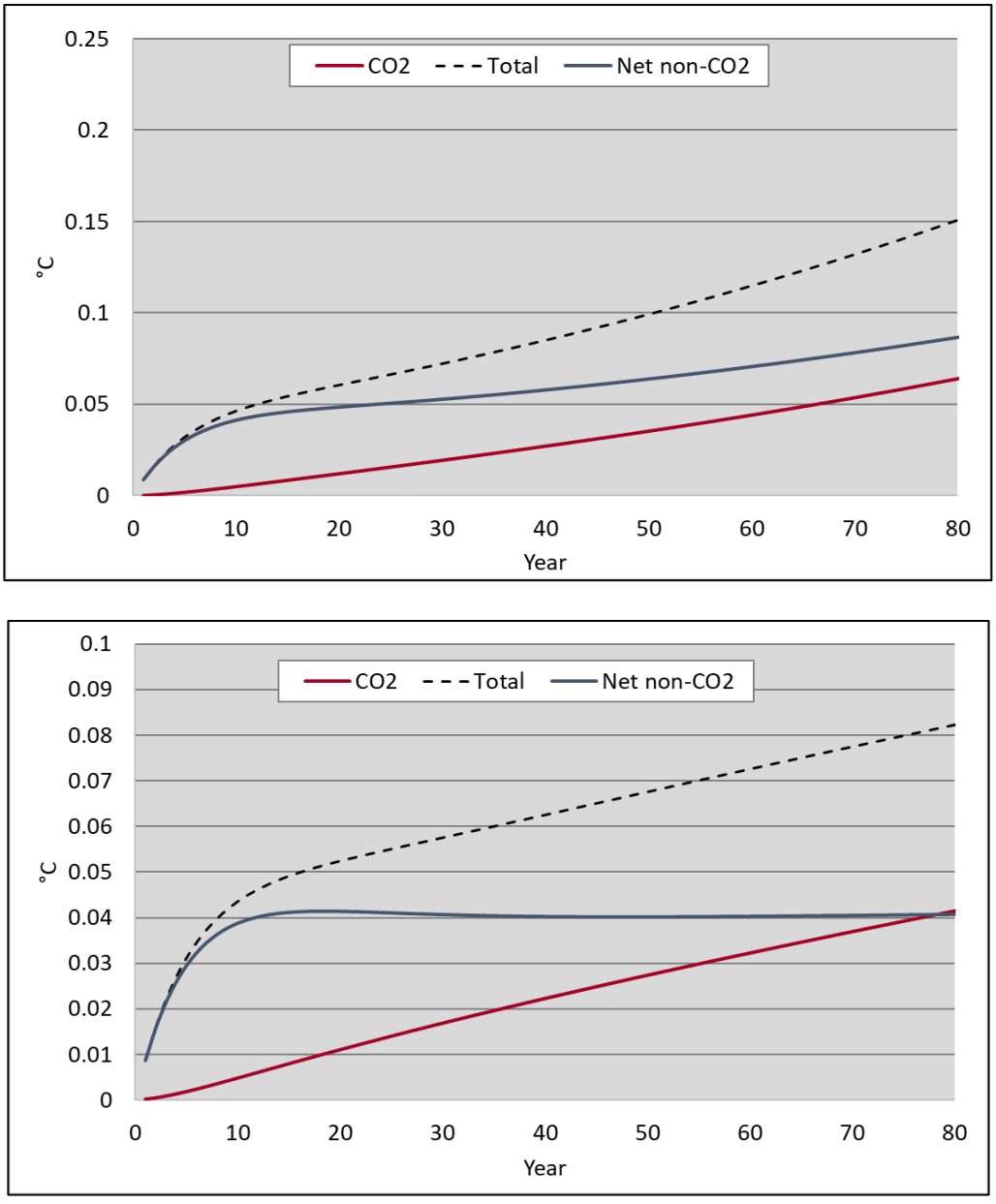


CO_2	*Carbon Dioxide*
BC	*Black Carbon (soot)*
SO_2	*Sulphur Dioxide*
NO_X-CH_4, NO_X-O_3S, NO_X-O_3L, NO_X-SWV	*Nitrogen Oxides effects on methane, short-term ozone, long-term ozone, stratospheric water vapour responses, respectively.*
H_2O	*Water Vapour*
AIC	*Aviation-Induced Cloudiness (contrail-cirrus)*

N.B.: Interactions between aviation particulate matter and clouds are not included in this quantification.

Pulse emissions are useful for understanding fundamental behaviour but in reality, emissions are continuous. Comparing the temperature response to increasing and sustained aviation emissions (Figure 4) illustrates further that, while aviation-induced warming is currently thought to be dominated by non-CO_2 effects, it is not a stable characteristic of aviation emissions but rather is a consequence of their recent history, which has seen strong year-on-year increases in flights. When aviation emissions increase, non-CO_2 contributions increase with time because warming from recent non-CO_2 emissions keeps getting larger. CO_2-induced warming also increases with time, at an accelerating rate. When emissions are sustained, non-CO_2 induced warming reaches a constant level, because warming from past non-CO_2 emissions gets weaker. In contrast, CO_2-induced warming increases at a constant rate in response to the accumulation of aviation CO_2 in the atmosphere. It follows from this behaviour that reducing the climate effect of aviation means reducing its CO_2 emissions while not increasing – but preferably also reducing – non-CO_2 emissions.

Figure 4 – Modelled time evolution of global surface temperature responses (°C) to CO_2 (red) and non-CO_2 (blue) aviation emissions that are increasing by 1% per year (upper chart) or sustained at their 2018 levels (lower chart). Interactions between aviation particulate matter and clouds are not included in the calculations.



The long-standing framework of CO_2-equivalence metrics has previously been used to quantify aviation climate effects of present and future aviation, although caution is needed when assessing CO_2 and non-CO_2 effects together.

Most economic sectors emit compounds with different climate effect time scales [2], so aviation is not unique in that respect. A common method to quantify how an economic sector affects global surface temperature in a single number is to calculate the amount of CO_2 that would exert the same warming as its total CO_2 and non-CO_2 emissions taken together over a given period. This number is called "*CO_2-equivalent emissions*".

This method of CO_2 equivalence can be applied using climate models that represent the different physical and chemical mechanisms by which a given sector modifies the climate, or by reduced-complexity models built to emulate the more complex climate models [3] [4]. Various simplified methods, called CO_2-equivalent metrics, have been proposed since the mid-1990s. The United Nations Framework Convention on Climate Change (UNFCCC) and the European Union Emissions Trading System (ETS) both use a radiative-forcing based quantity called the Global Warming Potential (GWP) with a time horizon of 100 years. Other temperature-based metrics such as the Global Temperature Change Potential (GTP) or Average Temperature Response (ATR), and other time horizons, have also been proposed. Different metrics serve different purposes, and a given metric may be best suited to specific mitigation options [5] or best fit the results of other methods to assess climate impacts [6]. For example, ATR calculated over the predicted lifetime of an aircraft was originally designed for assessing the climate effect of different aircraft engineering options [7].

Different definitions of CO_2-equivalence metrics imply different weightings given to CO_2 and non-CO_2 effects that can cause large differences between CO_2-equivalence values. For aviation, for example, the non-CO_2 climate effect of the current global aircraft fleet varies between approximately 0 to 3 times its CO_2 climate effect [1]. The smallest number is obtained using GTP with a time horizon of 50 years and the largest for GWP with a time horizon of 20 years. The differences between these numbers are due to differences in the designs of the metrics and do not reflect uncertainties in quantifying the climate effect of aviation.

All CO_2-equivalence metrics ultimately depend on the radiative forcing, but radiative forcing itself is not a direct measure of the climate effect. It is a measure of the changes in radiative effects that trigger changes in climate. The magnitude of surface temperature change per unit radiative forcing is not the same for all types of aviation CO_2 and non-CO_2 effects. There is a need to evaluate the efficacy[4] of each non-CO_2 effect by comparing the surface temperature change per unit radiative forcing caused by that effect compared to that of CO_2. The limited estimates of ERF efficacy for contrails are around 40% [8]. An efficacy-weighted definition of GWP has been proposed to account for the different weights placed on the different CO_2 and non-CO_2 contribution [6]. Although some non-CO_2 effects may be less efficient at warming surface temperatures than CO_2, they may still affect other aspects of the climate system, like atmospheric circulation and the hydrological cycle, including precipitation.

[4] The efficacy of a climate forcing is defined as the global mean surface temperature change per unit radiative forcing produced by a given climate forcing agent relative to the response to CO_2 forcing from the same initial climate state. The concept was introduced to account for the fact that different climate forcing agents will not necessarily induce similar changes in global mean surface temperature even for equal global radiative forcing. There is a high degree of overlap between efficacy-weighted radiative forcing and effective radiative forcing, but they are not equal. There is often a lack of clarity in scientific papers on the underlying methodology used to calculate quoted CO2 equivalence metrics, including whether they are based on radiative forcing or effective radiative forcing and whether they account for efficacy.

The challenges of combining cumulative and short-lived climate effects in a single quantity of CO_2-equivalent emissions can be avoided by giving the contribution of the different CO_2 and non-CO_2 effects separately [9].

The contribution of the global aviation fleet to surface temperature change can be assessed in principle by these methods, but not the contribution of individual flights.

Surface temperature change caused by the whole aviation global fleet, a group of flights, or an individual flight are driven by the same physical mechanisms. However, in practice the calculation of surface temperature change caused by a single flight, or a few flights, is not possible at present. Existing estimates for the global fleet based on climate models rely on significantly increased global air traffic to distinguish the response from the large natural variability of the atmosphere and climate system [8]. It is expected that the efficacies of non-CO_2 effects are spatially and temporally very variable, and consequently some flights will be better at warming surface temperatures than others per unit radiative forcing. Whether approximate estimates for an individual flight made with reduced-complexity models provide a reliable indication of the corresponding surface temperature change remains to be demonstrated.

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