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NONCO2 RESEARCH PROJECT

Climate Effect of Aviation Contrails

ANCEN Background Note

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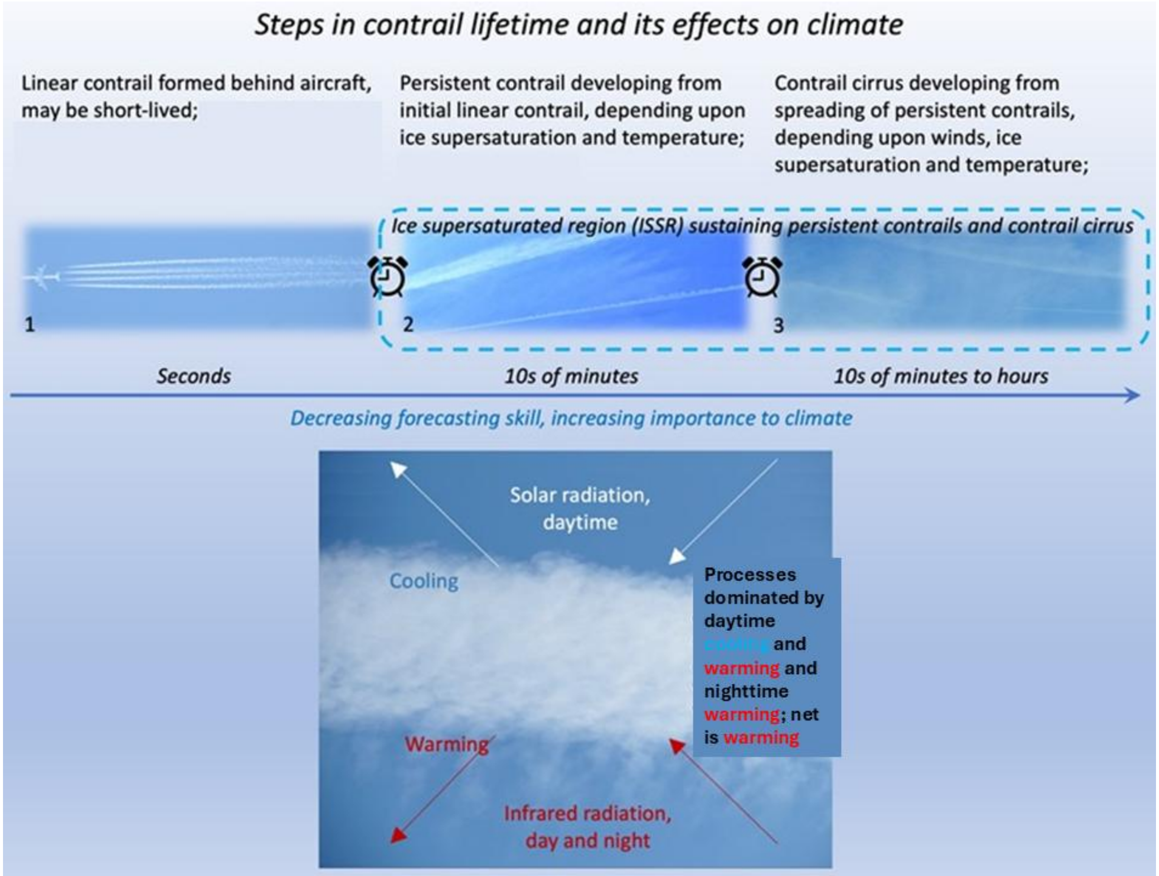
Climate effect of aviation contrails

Condensation trails (contrails) are the ice clouds that form in the engine exhaust plume behind aircraft when certain atmospheric conditions are met. On a global, annual average basis, contrail-cirrus clouds contribute to global warming [1]**, but the size of this contribution is uncertain and is a topic of fundamental research.**

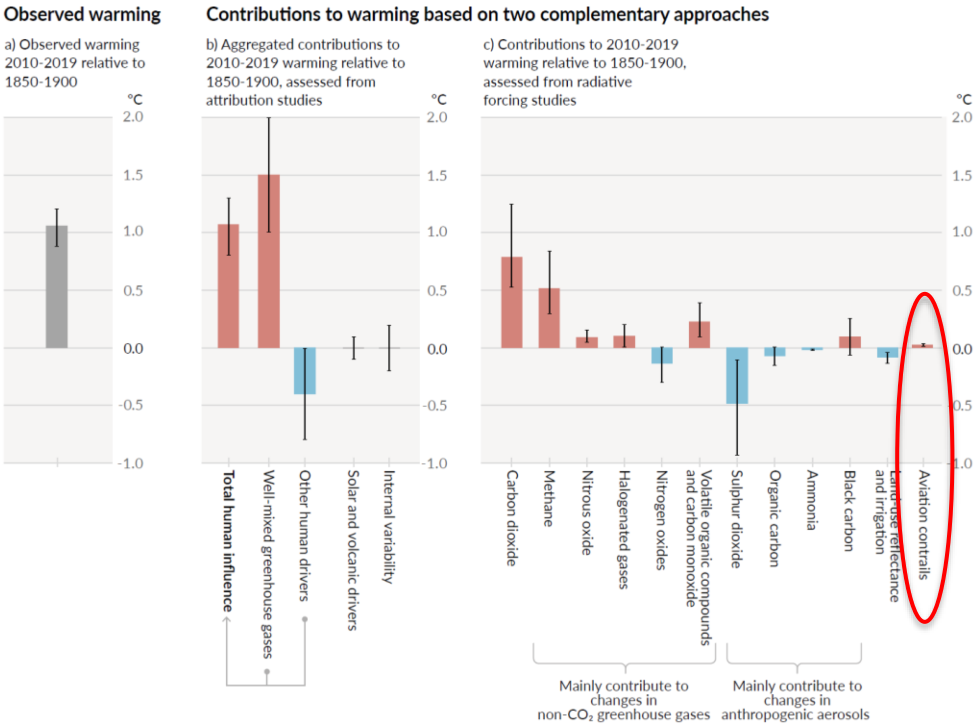
Contrail ice crystals form when conditions in the exhaust plume allow water vapour to condense onto particles emitted by the aircraft engine, which are formed by the combustion of fuel inside the engine, by chemical reactions in the exhaust plume, or are already present in the atmosphere. This process forms liquid water droplets that quickly freeze. When the ambient atmosphere is moist and cold enough to be ice-supersaturated, contrails persist and can spread and form contrail-cirrus clouds (Figure 1). These clouds reflect a fraction of incoming sunlight, which has a cooling effect on climate. But cirrus clouds also exert a greenhouse effect by emitting less radiation to space than the Earth's surface would have done in the absence of cirrus, leading to a warming. Contrails are warming during the night, since there is no sunlight to reflect. During the day, contrails cool or warm depending on the balance of their radiative effects.

Figure 1 – Illustration of the formation and evolution of contrails, and their modification of radiative fluxes. (Adapted from Figure 1 of Shine, K. And Lee, D.S. (2021), Green Air News commentary.)



The latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [2] **estimates that the contrail cirrus contribution to warming of global average surface temperature has a 90% chance of being between 0.01 to 0.05°C, with a best estimate of 0.02°C (Figure 2). This number represents 1.6% of the best estimate of total warming by human activities of 1.29°C in 2019, resulting from human emissions since 1750. Adding together aviation CO_2, contrails and other aviation non-CO_2 effects gives a contribution of aviation to total warming of about 4%** [3]**.**

Figure 2 – Observed warming is driven by emissions from human activities, including aviation contrails, with greenhouse gas warming partly masked by aerosol cooling (Source: Figure SPM.2 of the Summary for Policymakers of the 6th Assessment Report of the Intergovernmental Panel on Climate Change)



The large uncertainty in the estimates of contrail-induced warming is caused by uncertainties in quantifying contrail effective radiative forcing[1] (ERF) [2] [4] which triggers the contrail contribution to warming, and uncertainties in estimating the efficacy[2] with which contrail ERF affects global surface temperature. Research published after the IPCC Assessment Report suggests that contrail ERF may be slightly lower than assessed by

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[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. Effective radiative forcing (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.

[2] 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.

the IPCC [5] [6] [7]. However, a new assessment would be needed to determine how recent research affects the best estimates and uncertainty ranges.

The contribution of contrails to warming increases with air traffic, and contrail cirrus ERF may triple by 2050 in high growth scenarios [8] [9]. The contribution of contrails to aviation-induced warming is thought to increase proportionally for current aviation growth forecasts. Research suggests that assumption remains reasonable for the foreseeable future, as contrail coverage has only been shown to saturate in climate model simulations using air traffic levels that are greater than 8 times higher than the nominal forecast for the year 2050 [10]. Further, a substantial portion of the recent increase in air traffic has occurred in regions, especially Asia, where cruise altitudes are associated with relatively warm and dry conditions that have lower potential for persistent contrail formation [6] and the growth in these regions may continue to be higher than in other regions.

A large fraction of total contrail radiative forcing is caused by a minority of flights.

As a first approximation, the radiative forcing of an individual contrail is proportional to its optical depth and coverage, itself depending on contrail lifetime. Satellite observations of persistent linear contrails find that thin, short-lived contrails are produced in the largest numbers, with long-lived contrails and contrails with large optical depth being rarer [11] [12]. These characteristics of the contrail population are broadly reproduced by both climate models and reduced-complexity models [13] [14] [15], despite the simplifications in the representation of engine emissions and contrail predictions made in those models.

The sign and strength of contrail radiative forcing depend additionally on time of day and is modulated by the potential presence of other clouds. Despite this added complexity, different categories of models find that a large part of the contrail cirrus radiative forcing is connected to few flights or a relatively low number of meteorological situations [13] [14] [15] [16] [17]. However, different studies have different views of the attribution of total contrail radiative forcing. The view that arises from considering flights individually leads to the suggestion by a simplified model that globally about 2% of flights contribute 80% of total contrail radiative forcing [6]. In contrast, the view that arises from considering specific meteorological situations leads to the suggestion by a climate model that 70% of the contrail radiative forcing is exerted by contrail outbreaks happening on 25% of days, where many contrails form in a large-scale ice supersaturated region [15]. Whether those two different views identify the same subsets of flights as causing most of contrail radiative forcing has not yet been specifically studied.

In any case, the precise contrail climate effect depends on the region [16] [17], meteorology, time of day, and on the distributions of flight altitudes, engine emissions, fuel composition, and distances. The degree of concentration of flight paths that are traversing the same region of the atmosphere is also likely to matter.

It remains difficult to predict which flight belongs to the minority that exerts the strongest climate effect. This is due to the difficulty in forecasting the atmospheric conditions favourable to contrail formation and persistence; to limitations in our understanding of contrail radiative forcing and in the tools used to quantify that forcing; and to possible interactions between the evolution of adjacent contrails and existing clouds.

Estimating the contrail radiative forcing of individual flights involves weather forecasting to predict contrail evolution and lifetime as well as the presence of other clouds, but also involves knowledge of operating conditions, aircraft and engine specifications, fuel used, and the circumstances surrounding the flight (time of day, radiative properties of the surface or clouds underlying the contrail, etc.). Work to improve predicted locations of ice supersaturated regions is ongoing at weather forecasting centres. A recent study suggests that ice supersaturated regions can be forecast 6 to 18 hours in advance with 80% of observed ISSRs being correctly forecast for a selection of North Atlantic and European flights [18]. However, reaching this level of forecasting requires accepting errors of up to 150 km in the predicted location of the ice supersaturated regions. In addition, forecast skill varies in different regions around weather systems [19].

If a large fraction of contrail radiative forcing occurs during ‘outbreaks’, where many flights contribute contrails to the formation of large contrail cirrus, then linkages between the contrail formation potential of different flights becomes important. This is because a contrail-forming flight consumes atmospheric humidity at cruise level by turning water vapour into ice crystals that sediment to lower levels, leaving less humidity for other contrails to grow. These linkages imply the need to consider flights together rather than individually.

Finally, there are, for the moment, no tools to quantify contrail radiative forcing efficacy of individual flights, so it is not yet known whether flights that exert strong radiative forcing are also those that are most effective at warming surface temperatures. Contrail formation may also affect the dynamics of the atmosphere, affecting more than just surface temperatures, but those aspects are poorly studied at this point in time.

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