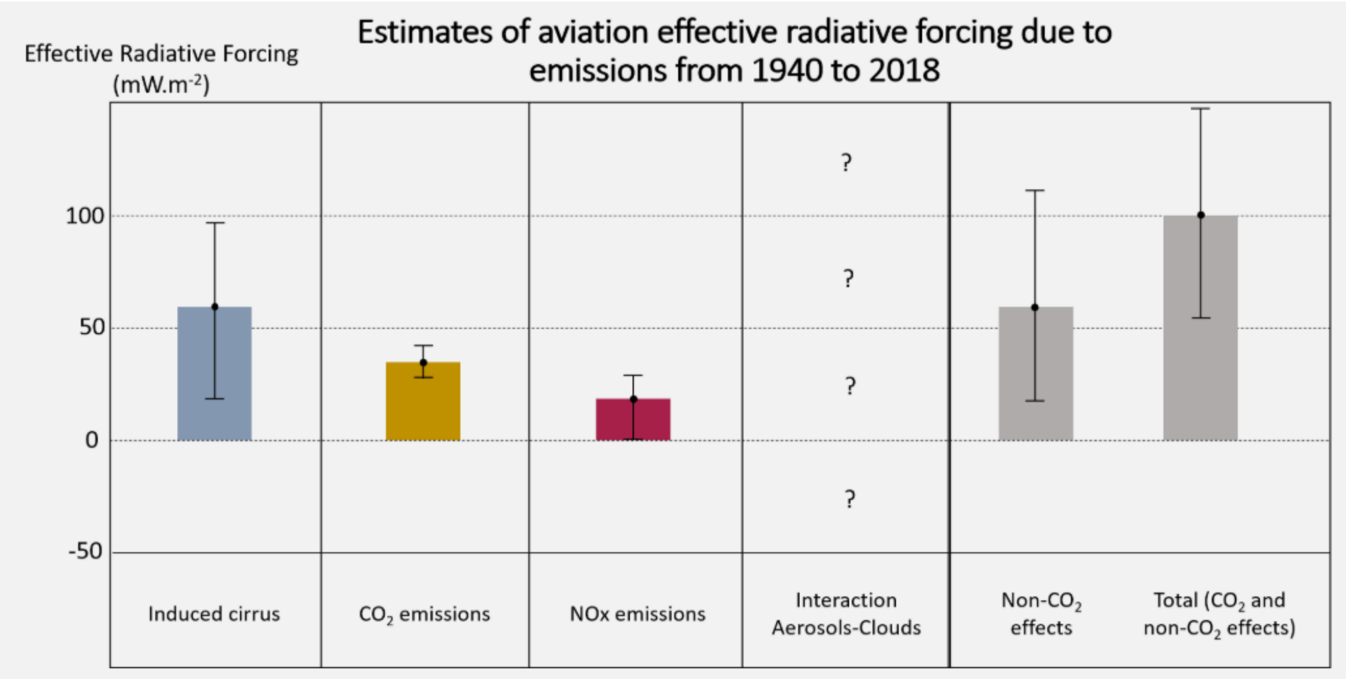
# Non-CO2 Emissions and Effects

Emissions from burning jet fuel consist of carbon dioxide (CO2), water vapor (H2O), nitrogen oxides (NOx), sulphur oxides (SOx), carbon monoxide (CO), soot (PM 2.5), unburned hydrocarbons (UHC), aerosols, and traces of hydroxyl compounds (-OH), most of which are released in the atmosphere at cruise altitudes of 8– 13 km above mean sea level. These emissions, or climate forcing terms, have both direct and indirect effects on the climate which can be both positive and negative.

Climate metrics, such as Effective Radiative Forcing (ERF), are often used to intercompare the quantitative importance and contribution of different climate forcing terms to climate change. The Effective Radiative Forcing (ERF) is a measure of how much a climate forcing term alters the Earth's radiation balance (i.e., incoming radiation from the sun minus outgoing radiation emitted from the Earth's surface) while accounting for some of the atmospheric adjustments and feedback. The ERF is expressed in Watts (W) or milliWatts (mW) per square meter ($m^2$).

The primary aviation non-CO2 effects which have been quantified result from the emissions of particulate matter (PM) and water vapor which can result in contrail formation, as well as from nitrogen oxides ($NO_x$). According to the latest assessment presented in Lee et al. (2021), contrails and $NO_x$ combined have a larger ERF than aviation $CO_2$ emissions, albeit with a much larger range of uncertainty of eight times as much. Non-CO2 effects are associated with more uncertainty largely because they involve more complex atmospheric processes (e.g., chemical transformations, microphysics, radiation, and transport, etc.) occurring on wide range of spatiotemporal scales. Modelling these processes and estimating their radiative and climate impacts with Earth System Models is challenging, although significant improvements have been made since non-CO2 effects were first highlight by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on *Aviation and the Global Atmosphere* in 1999. (insert footnote)




Source: [Climaviation – Research action on aviation and climate]

According to Lee et al. (2021), the ERF from CO2 in 2018 resulting from emissions since 1940 is approximately 34 mW $m^{-2}$ with an uncertainty range of 28-40 mW $m^{-2}$. Contrail cirrus is estimated to have the largest ERF, 57.4 mW $m^{-2}$, with an uncertainty range 17 – 98 mW $m^{-2}$. The net effect of NOx emissions is about half that of $CO_2$, 17.5 mW $m^{-2}$, with an uncertain range of 0.6 – 29 mW $m^{-2}$.

## Contrails

Contrails are line shaped clouds made up of ice crystals (like natural cirrus clouds) that sometimes form behind aircraft. They form when water vapor is released from jet engines at altitude under certain conditions (cold and humid) and condenses onto exhaust particles or ambient aerosols. If the air is sufficiently cold, these water droplets freeze into ice crystals and a cloud can form. Such clouds, formed from the condensation of exhaust aircraft water vapor, are called condensation trails or contrails.

Contrails both reflect incoming solar radiation (cooling albedo effect) and absorb and re-emit longwave radiation (warming greenhouse effect). Globally, the net climate effect of contrails is warming, although the net effect of an individual contrail can be warming or cooling. Only persistent contrails which form in ice supersaturated regions have a radiative or climatic effect. The net energy forcing of a contrail varies considerably and is dependent on several factors such as aircraft-engine, fuel composition, the geographical location and time of the day at which they are formed, the weather conditions, surface albedo, etc.

## $NO_x$ effects

The amount of NOx emitted by an aircraft depends primarily on engine design, technology, and operating conditions (idle, take-off, descent, etc.), as well as on the atmospheric conditions (temperature, pressure, and humidity) at which this engine operates. Once emitted into the atmosphere, NOx leads to a series of photochemical reactions which enhance the production of O3 (warming) and the decrease the lifetime and abundance of CH4 (cooling). As a secondary effect in response to decreased CH4, there is a longer-term reduction in background O3 as well as a reduction in stratospheric water vapor. Currently, the net NOx effect is warming, although this could change because it is dependent on the background chemical composition of the atmosphere which is projected to change in the future as surface emissions from other sectors are reduced.

## Aerosol direct and indirect effects

Aircraft engines emit non-volatile (black and organic carbon) and volatile (precursors of sulfate and nitrate) aerosol which directly interact with solar radiation and can therefore have an impact on the climate. Black and organic carbon, also known as soot, absorbs the Sun's short-wave radiation and have a warming effect (ERF = ~ 0.1 to 4.0 mW $m_{-2}$). Sulfate aerosol, which are produced from the oxidation of sulfur in the fuel, scatter short-wave radiation and therefore have a cooling effect (ERF = ~ -19 to -3 mW $m_{-2}$).. Both effects are estimated with large uncertainties.

In addition to direct effects, aerosol also have an indirect effect on climate through cloud interactions. Aerosol are essential in cloud formation as they provide surfaces (or nuclei) for water vapor in the atmosphere to condense on and form liquid cloud droplets or ice crystals. Through this process, emitted soot and sulfate particles can modify natural clouds. The current level of scientific understanding of the interaction between aviation emitted particles and clouds is very low, therefore no estimate can be confidently given at this time.

## Predicting the radiative and climate impact of an individual flight

Unlike CO2, non-CO2 effects are dependent on the time and geographical location in which they are emitted. The radiative impact of a contrail is highly sensitive to the surrounding meteorological conditions and can vary by several hundred W $m^{-2}$. While the effect of these emissions has been estimated in the literature at an aggregate level (e.g., global, annual), the capacity to accurately measure their climate impact at an airline or individual-flight level is very limited. This is mainly due to the large uncertainties associated with estimating meteorological parameters at cruise altitudes, as well as aircraft emissions.