Bolin Centre
for Climate Research

Bolin Centre Climate Arena Policy Brief | October 2020

Aviation, climate, and the "high altitude" effect

The Bolin Centre Climate Arena aims to support cross-sector work aimed at "bending the curve" of climate change by:

- ✓ developing long lasting relations between academic, public, business and policy sectors,
- ✓ enhancing the impact and utilization of knowledge and research, and
- ✓ promoting climate education for the future.

Aviation's influence on climate

The public discussion of what effects aviation has on climate – and how to minimize these effects – has been confusing. Part of this confusion comes from an incomplete understanding of what the effects are and how they work. However, a substantial part of the confusion arises from a lack of clarity and consistency in what is being discussed. This policy brief aims at reducing the confusion by trying to be clearer about exactly what is being discussed and compared in regards to aviation's influence on climate.

Condensation trails. Photo: Kevin Noone, Stockholm University

Aircraft emissions

Like the bulk of our transport system, aircraft use internal combustion engines as their main means of propulsion. When flying (or even taxiing on the ground), aircraft emit carbon dioxide (CO_2), water vapor, oxides of nitrogen (NO_x), aerosol particles (such as soot or sulfates), and hydrocarbons – just like pretty much any other vehicle powered by an internal combustion engine. While values vary somewhat, commercial aviation is estimated to emit about **1 Gt** CO_2 globally (918 Mt CO_2 in 2018; [*Graver et al*., 2019]). For the same year, Le Quéré et al. (2018) estimated that the total anthropogenic emissions of CO_2 (from fossil fuels and land use change) were 39.9 Gt CO_2. Putting these numbers together we find that commercial aviation accounted for 2.3% of the total anthropogenic emissions of carbon dioxide.

The paradox with this number is that while commercial aviation accounts for a relatively small fraction of total human emissions, it often is a relatively large fraction of our personal CO_2 emissions. To put this into perspective, an average Swede emits about **6 metric tons** of CO2 to the atmosphere each year, which stands for territorial emissions[1].

Depending on what emissions calculator you use, a single return flight between Stockholm and New York in economy class is calculated to emit between 0.7 and 2.6 tons of CO_2. So, while the commercial aviation sector currently accounts for a relatively small fraction of the total global CO_2 emissions, a single intercontinental flight may account for between 10–50% of a typical Swede's yearly emissions.

1 gigaton (Gt) equals 1 billion metric tons, and 1 metric ton equals 1 000 kilograms (kg).

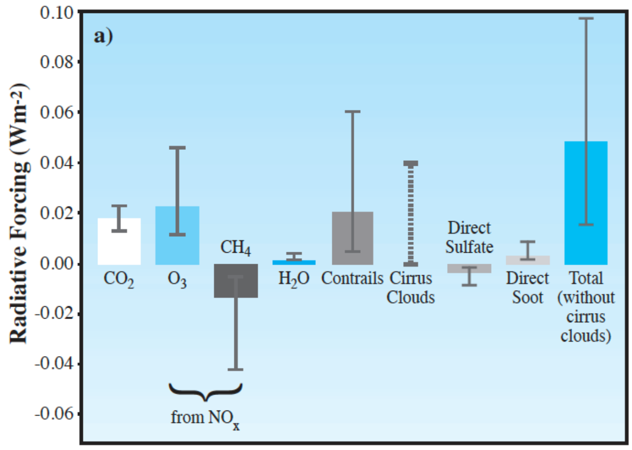
Why can't we be more precise about emissions from aviation?

You may think that the estimate of between 0.7 and 2.6 tons of CO_2 for a flight between Stockholm and New York is not very precise – and you are correct. The reason for the wide range in estimates is because different calculators use different methods to calculate the climatic effects of aircraft emissions. The International Civil Aviation Organization (ICAO) of the United Nations uses a **calculator** that accounts for aircraft type, passenger loading, how much freight is carried by the aircraft, the amount of fuel used, and then calculates how much CO_2 is produced by each passenger. This calculator gives the 0.7 ton estimate for the return flight between Stockholm and New York. **The Atmosfair calculator** uses a similar methodology, but multiplies carbon emissions by a factor of three to account for the effects of the other pollutants emitted by aircraft – the so-called "high altitude effect". Thus, this calculator gives the result of an estimated 2.6 tons of CO_2.

[1] EUROSTAT data show that the population of Sweden in 2018 was 10.1 million. The Swedish EPA estimates that Swedish territorial and consumption based (including international air travel) emission of CO_2 equivalents in 2018 was 63 and about 100 million metric tons, respectively.

The "high altitude" effect: A deeper dive

The "high altitude" effect is a bit of a misnomer. The idea with this effect is to try to account for the climatic effects of non-CO_2 emissions from aviation. These are shown in the figure on the right, taken from the Intergovernmental Panel on Climate Change (IPCC) Special Report "Aviation and the Global Atmosphere" from 1999. The nitrogen oxides (NO_x) emitted by aircraft can create ozone (O_3) (with a warming effect), but it also destroys methane (CH_4), a very potent greenhouse gas (producing a cooling effect). The water and particulate matter emitted by aircraft by themselves have little climatic effect.



This figure is modified from the IPCC Special Report "Aviation and the Global Atmosphere", (1999).

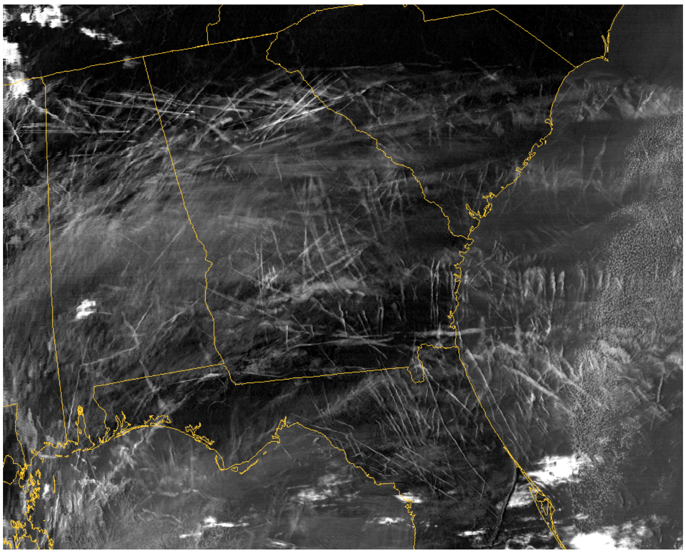
As anyone living close to an airport can attest, aircraft can produce thin, linear clouds as they fly at high altitudes. These are called condensation trails – or contrails. These optically thin clouds let most of the incoming sunlight pass through, but are good at absorbing the thermal radiation the Earth sends out to cool itself off. By doing so, they have a warming effect on the Earth's surface. This is essentially the source of the term "high altitude" effect, since these clouds only occur at high altitudes.

Referring back to the figure above, the bars show the central estimates of the change in the Earth's energy balance caused by these different effects, while the "whiskers" show estimated uncertainties. If you want to read more about the components of **aircraft-induced radiative forcing**, check the box on the next page.

The IPCC's estimate of the radiative effect of contrails has been decreasing as successive reports have come out, as illustrated in the table below, reflecting better understanding and more observations of these man-made clouds.

Hidden in the IPCC 1999 figure above (but discussed in more detail in the report itself) is the rationale behind multiplying CO_2 emissions from aviation with a number like three (as the Atmosfair calculator does) to estimate a total climate impact. The 1999 report introduced the concept of a Radiative Forcing Index (RFI), defined as the ratio of the total radiative forcing (measured in W/m^2) to that from CO_2 emissions alone. Digging into the details, we see that in the 1999 report the CO_2 forcing was estimated to be 0.018 W/m^2, while the total forcing was 0.049 W/m^2, giving an RFI of 2.7. Lee et al. (2010) summarized more

IPCC Report	contrail effect (W/m^2)	total anthropogenic effect (W/m^2)
AR3 (2001)	0.02	2.35
AR4 (2007)	0.01	1.6
AR5 (2013)	0.005	2.29



This image, taken on January 29th 2004 by the NASA Earth Observatory, illustrates cirrus clouds formed by contrails from aircraft engine exhausts.

recent estimates from the IPCC 4th Assessment Report (AR4) published in 2007 to show that the total radiative forcing from aviation from pre-industrial times to the year 2005 was estimated to be 0.055 W/m^2, while the CO_2 forcing alone was 0.028 W/m^2, resulting in an RFI of 1.96.

RFI limitations

While a scientifically valid concept, the RFI has serious limitations in terms of its utility. For instance, in Forster et al. (2007) Chapter 2 the IPCC AR4 writes: *One alternative, the RF index (RFI) introduced by IPCC (1999), should not be used as an emission metric since it does not account for the different residence times of different forcing agents.*

It also has serious limitations in terms of guiding policy decisions. This can be illustrated by the following hypothetical example. Coal-fired power plants – particularly dirty ones – emit CO_2, but also things like sulfur dioxide, oxides of nitrogen, and particulate matter – all close to the ground. Once in the atmosphere, the sulfur compounds react chemically and eventually turn into small particles. These particles can subsequently cool the surface either by reflecting incoming sunlight themselves, or by making low clouds more reflective or longer lived. If the cooling effect of the particulate matter was larger than the warming effect of the CO_2, the RFI would be less than one. In effect, the RFI in this very hypothetical case would tell us to build more dirty coal-fired power plants, since they might offset the warming caused by CO_2. This is, of course, not a good idea. The CO_2 we emit to the atmosphere can stay there for centuries, and we need to stop putting it there.

RFI is not the sole basis for the current estimates of the “high altitude” multiplication factor for aviation emissions. Other factors have influenced these estimates, even including economic metrics (Azar and Johansson, 2012). The fundamental problem remains that it is very difficult to assess the climatic effects of non-CO_2 emissions, and even more difficult to compare them across sectors.

The components of **aircraft-induced radiative forcing** estimated in this 1999 special report are: CO_2, +0.018 W/m^2; NO_x, +0.023 W/m^2 (via ozone changes) and −0.014 W/m^2 (via methane changes); contrails, +0.02 W/m^2; stratospheric water vapor, +0.002 W/m^2; sulfate aerosol, −0.003 W/m^2; and black carbon aerosol (soot), +0.003 W/m^2. For perspective, the total anthropogenic perturbation at the time of this report was estimated to be around 1.4 W/m^2 – so these effects sum to be 3.5% percent of the total anthropogenic perturbation of the Earth’s energy balance in 1992, the year of the latest data available for this special report.

Where do we go from here?

Sweden's goal is to become climate neutral by 2045, and the European Union as a whole by 2050. Achieving these goals will be aided by having a simple, consistent, clear, and transparent method by which emissions and their climate impacts can be captured.

For the commercial aviation industry, various climate compensation calculators have been developed to allow consumers to calculate the climate impact of their flights, and to engage in some sort of compensation for it. However, climate compensation also has its own problems, read more about this in our next policy brief which will cover this. As illustrated earlier in this policy brief, the results from these calculators can be very different. The average consumer may not have the time or inclination to delve into the details of the calculations and decide which to use, and the confusion may even result in climate compensation not being done at all.

Rather than having a plethora of emissions compensation calculators that use different methodologies (and thus are difficult to reconcile), another approach would be to have different levels of compensation – much like the different levels in the frequent flyer programs of many airlines. The base level would be to calculate only CO_2 emissions, and climate compensate for those. The highest level would be to use the largest evidence-based multiplication factor to account for the non-CO_2 emissions from flying. If combined with a clear description of the methodologies behind these calculations, the consumer would then be better informed and better able to make a choice about the level of compensation.

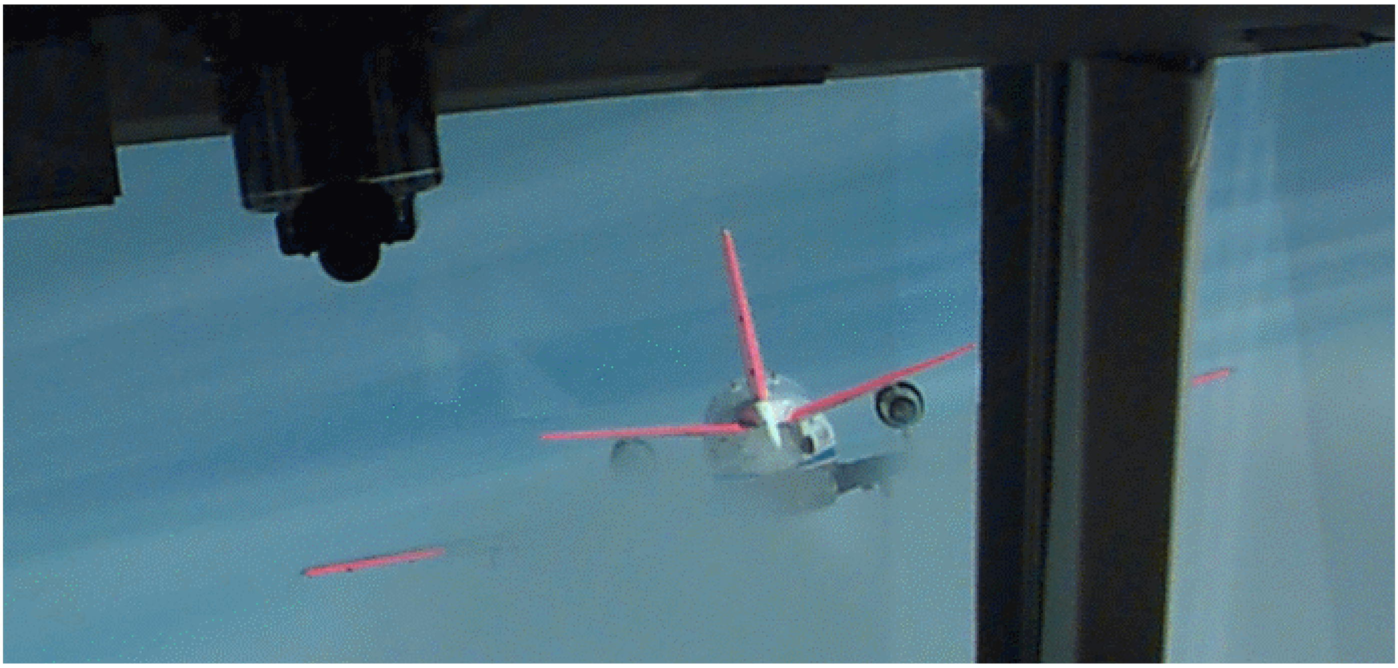


Photo: Johan Ström, Stockholm University

References

Azar, C., and D. J. A. Johansson (2012), Valuing the non-CO2 climate impacts of aviation, *Clim. Change*, 111(3), 559–579, doi:10.1007/s10584-011-0168-8.

Forster, P. V., et al. (2007), Changes in Atmospheric Constituents and in Radiative Forcing, in *IPCC 2007: Climate Change 2007: The Physical Science Basis. Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, pp. 129–234, Cambridge, United Kingdom and New York, NY, USA, Cambridge, United Kingdom and New York, NY, USA.

Graver, B., K. Zhang, and D. Rutherford (2019), CO_2 emissions from commercial aviation, 2018 *Rep. Working Paper 2019-16*, 13 pp, International Council on Clean Transportation.

Le Quéré, C., et al. (2018), Global Carbon Budget 2018, *Earth Syst. Sci. Data*, 10(4), 2141–2194, doi:10.5194/essd-10-2141–2018.

Lee, D. S., et al. (2010), Transport impacts on atmosphere and climate: Aviation, *Atmos. Envir.*, 44(37), 4678–4734, doi:https://doi.org/10.1016/j.atmosenv.2009.06.005

Photo: Kevin Noone, Stockholm University

This policy brief is an expert statement by Paul Glantz and Kevin Noone both of whom are scientists at the Bolin Centre for Climate Research.

Contact information

Kevin Noone, Department of Environmental Sciences (ACES)
+46 8 674 75 43, *kevin.noone@aces.su.se*

Paul Glantz, Department of Environmental Sciences (ACES)
+46 8 674 76 47, *paul.glantz@aces.su.se*

Bolin Centre for Climate Research