

## MEMORANDUM

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**SUBJECT:** **Non-CO<sub>2</sub> climate impacts of aviation emissions**

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The purpose of this memo is to provide a high-level summary of the state of knowledge on climate impacts of aviation emissions and emission metrics.

### **Key climate impacts of aviation**

There are a range of emissions from aviation that causes (directly or indirectly) impacts on the climate, including carbon dioxide (CO<sub>2</sub>), water vapor (H<sub>2</sub>O), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), Sulphur oxides (SO<sub>x</sub>) and soot. In addition, persistent linear contrails can be formed when the exhaust gas and the adjacent air meet certain humidity and temperature conditions (Schumann 1996). A fraction of these linear contrails are spread into contrail cirrus. These various non-CO<sub>2</sub> forcings may also have further impacts on the optical properties of contrails and contrail cirrus as well as cloud formation and properties (Burkhart & Kärcher, 2011; Gettelman & Chen, 2013; Kärcher, 2016; Tesche et al, 2016)

The different emissions have different impacts on the climate, where CO<sub>2</sub>, H<sub>2</sub>O, CO, BC has a warming effect, SO<sub>x</sub> has a cooling effect. NO<sub>x</sub> has both warming and cooling impacts, a positive warming effect as NO<sub>x</sub> causes tropospheric ozone (O<sub>3</sub>) formation, and a cooling effect as NO<sub>x</sub> induces nitrate aerosols and a reduction of the atmospheric lifetime of methane, which in turn leads to a reduction of tropospheric ozone.<sup>1</sup>

Overall, the radiative forcing (RF) impacts of aviation are operating over very different characteristic time scales. Persistent contrails have a life time in the order of hours, various aerosols in the order of days to weeks, NO<sub>x</sub> in the order of weeks to a decade (weeks for the short-term warming effect caused by O<sub>3</sub> formation and about a decade for the long-term cooling effect due to changes in the life time of CH<sub>4</sub>), CH<sub>4</sub> in the order of a decade, while the CO<sub>2</sub> dynamics cannot be described by a single time constant. About 40% of the initial CO<sub>2</sub> emission pulse remains in the atmosphere after 100 years and about 20% after 1000 years.<sup>2</sup> Hence, the different emissions from the aviation sector have climate

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<sup>1</sup> see Brasseur et al (2016) for more information

<sup>2</sup> see Joos et al (2013) for more information on the life time of CO<sub>2</sub>

impacts that occur over totally different time horizons and only that of CO<sub>2</sub> and the NO<sub>x</sub> impact on CH<sub>4</sub> are globally well-mixed. The other forcing impacts are local to regional and globally heterogeneous.

The uncertainty in the RF impact of aviation emissions are large, except for the warming contribution of CO<sub>2</sub>. Brasseur et al (2016) have performed a detailed analysis of the climate impacts of aviation and the corresponding uncertainties. For example, the models analyzed in Brasseur et al (2016) find that the RF contribution in 2006 from past global aviation are for sulphur aerosols (direct RF) between -7 to -3 mW/m<sup>2</sup>, soot direct RF between 0.6 and 1 mW/m<sup>2</sup>, linear contrails between 2.9 to 11.3 mW/m<sup>2</sup> and contrail induced cirrus 12.4 to 51.3 mW/m<sup>2</sup>. CO<sub>2</sub> is not assessed in Brasseur et al (2016). Lee et al (2009) found total aviation RF (excluding induced cirrus) in 2005 was ~55 mW/m<sup>2</sup> (23–87 mW/m<sup>2</sup>, 90% likelihood range), of which CO<sub>2</sub> contribute to 28 mW/m<sup>2</sup> and the rest of RF comes from tropospheric O<sub>3</sub> (26.3 mW/m<sup>2</sup>), CH<sub>4</sub> (-12.5 mW/m<sup>2</sup>), H<sub>2</sub>O (2.8 mW/m<sup>2</sup>), contrails (11.8 mW/m<sup>2</sup>), SO<sub>4</sub> (-4.8 mW/m<sup>2</sup>), and soot (3.5 mW/m<sup>2</sup>). When including estimates for aviation-induced cirrus RF a total aviation RF in 2005 is estimated to be 78 mW/m<sup>2</sup> (38–139 mW/m<sup>2</sup>, 90% likelihood range). The RF effects from ozone production and methane reduction come from the emission of NO<sub>x</sub> as we explained earlier in the text. In addition, these estimates, the various non-CO<sub>2</sub> forcers may have further cloud RF impacts (Burkhart & Kärcher, 2011; Gettelman & Chen, 2013; Kärcher, 2016; Tesche et al, 2016), although more research is needed to quantify the size of these effects.

Hence, the dominating climate impacts of aviation are likely CO<sub>2</sub> and linear contrails, contrail cirrus and potentially also indirect aerosols impacts affecting various clouds properties. As stated above the climate impacts of these forcers have distinctly different time characteristics. Ranging from hour to days for persistent contrails and others cloud impacts to centuries, millennia and beyond for CO<sub>2</sub>. This leads us to the next topic concerning comparison of forcers with distinctly different time characteristics using emission metrics.

### **Emission metrics and aviation**

In order to estimate CO<sub>2</sub>-equivalent emissions of aviation, i.e., make the climate impact comparable on an equal scale, emissions metrics are used. Within the United Nation Framework Convention on Climate Change (UNFCCC) Global Warming Potential (GWP) with a 100 year time horizon is used for a basket of globally well-mixed greenhouse gases. In the 5th IPCC assessment report the metric Global Temperature change Potential (GTP) is presented in addition to GWP (Myhre et al, 2013).

The GWP metric is a measure of the integrated radiative forcing from the emission of a forcer compared to the integrated radiative forcing of 1 kg emissions of CO<sub>2</sub> using a certain time horizon for the integration, while GTP is a measure of the temperature response at a certain time in the future from emission of a forcer divided by the corresponding temperature response of 1 kg of emission of CO<sub>2</sub> (Myhre et al, 2013). Hence, the total integrated warming effect over the next 100 years of a global average flight can be estimated, using GWP with a 100 year time horizon and the temperature impact in 100 years from now of an average global average flight can be estimated using GTP with a 100 year time horizon.

Using GWP-100 it can be estimated that a global average flight has a likely integrated warming effect that is 1.7 (Azar & Johansson, 2012) or 1.9 (Lee et al, 2010) higher than warming effect of aviation CO<sub>2</sub> alone. Both number are estimated using best estimates of the lifetime and the RF of the different forcers. The related uncertainty intervals are large.

Using GTP-100 it can be estimated that a global average flight has a likely temperature impact in 100 year from now are 1.1 (Lee et al, 2010; Azar & Johansson, 2012) higher than the impact of aviation CO<sub>2</sub> alone. As for the GWP-100 estimates both GTP-100 number are estimated using best estimates of the lifetime and the RF of the different forcers.

The large difference in the estimates of the strength of the non-CO<sub>2</sub> forcers in terms of CO<sub>2</sub>-equivalent emissions is a result of the short atmospheric life time of these forcers. They have a strong net warming contribution initially, which are taken into account in the GWP-100 metric, but the temperature signal of the non-CO<sub>2</sub> forcers after 100 will largely be gone, which explains why the GTP-100 metric becomes so low for non-CO<sub>2</sub> forcers. As a consequence of the short life time of the non-CO<sub>2</sub> forcers from aviation, a reduction of them now would translate into an immediate impact on the temperature on the short term and affecting near term rate of climate change, while the long-term temperature consequences (beyond 100 years) of a reduction of these emissions now is basically zero. It is important to note that there are other climate impacts other than temperature change, and the impacts on for example sea level rise are expected to be more long-lived than temperature (Stern et al, 2014), and ecological impacts such as species survival depends partly on the rate of climate change (O'Neill et al, 2016).

The widely different results regarding the valuation of the non-CO<sub>2</sub> impact of aviation in relation to aviation CO<sub>2</sub> points out the difficulty of how to value impacts that occurs over widely different time scales. For such estimations we cannot get a clear answer from science alone since it is partly a question of value judgements. Are the climate impacts now and during the coming years more important, or are the climate effects at the middle of this century and beyond more relevant? Science can contribute to knowledge about climate change impacts, but cannot make the assessment of what is most important and what time horizon we should adopt for our climate change policies. This should be guided by our values and our political decisions.

### **Issues to consider when determining whether to include non-CO<sub>2</sub> climate impacts in the LCFS**

Generally, the knowledge level on the non-CO<sub>2</sub> climate impacts of aviation is low compared to that of CO<sub>2</sub> (Boucher et al 2013; Lee et al 2009). There is a large uncertainty regarding the climate impacts of persistent contrails, contrail induced cirrus and the indirect effect of aerosols on persistent contrails, contrail cirrus and other clouds.

Recent research have shown that blending biofuel with fossil jet fuel can reduce aerosol emissions from aviation (Moore et al, 2017). This may have important consequences for the climate impact of aviation through its impact on contrails, contrail cirrus and other clouds (Burkhart & Kärcher, 2011; Gettelman & Chen, 2013; Brassuer et al, 2016; Kärcher, 2016; Tesche et al, 2016). However, the overall scientific understanding of the size of these climate impact is very low, and more studies are needed to provide more robust estimates of this finding of the potential climate benefit of using biofuels for aviation.

One additional fact that can be considered is that the contrail and contrail cirrus formation can be avoided through climate optimized air traffic routing (Grewe et al, 2017) though more research in terms of the potential benefits, economic costs, system efficiency, etc. will be needed to consider this as a viable option for climate mitigation.

### **Treatment of jet fuel emissions in other emission pricing policy schemes**

CO<sub>2</sub> emissions from aviation have been included in the EU emissions trading system (EU ETS) since 2012. The climate impacts of non-CO<sub>2</sub> gases from aviation are not included in the EU ETS since only well mixed greenhouse gases are included in the program (EC, 2003).<sup>3</sup>

An aviation tax was recently proposed in Sweden. The tax scheme is imposed to the airline industry on a per flight and passenger basis<sup>4</sup>. The underlying calculations regarding tax level did not take into account the climate impact of short-lived climate forcers, but only those of CO<sub>2</sub>.<sup>5</sup>

### **Treatment of short-lived climate forcers in other climate regulations in California**

California's cap-and-trade program covers seven GHGs: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF<sub>6</sub>), and nitrogen trifluoride (NF<sub>3</sub>). Within California's LCFS, emission factors, the basis for emission credits and debits generation, are calculated based on the CA-GREET model that only covers CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, which are then combined into a single CO<sub>2</sub>-equivalent emission factor (or carbon intensity, CI) using GWP-100. In March 2017, California finalized its Short-Lived Climate Pollutant (SLCP) Reduction Strategy plan covering anthropogenic black carbon, methane, and fluorinated gases (F-gases, including HFCs).<sup>6</sup> The document does not include non-CO<sub>2</sub> forcers from aviation emissions.

The strength of the non-CO<sub>2</sub> forcers from aviation in terms of CO<sub>2</sub> equivalent emissions depends strongly on the metric and the time horizon used for the metric calculation. Further, the RF caused by non-CO<sub>2</sub> forcers from aviation are uncertain and heterogenous; and the difference between biofuels and fossil jet fuel when it comes to RF from these non-CO<sub>2</sub> forcers are very (if not extremely) uncertain. These aspects taken together make it non-trivial to include aviation non-CO<sub>2</sub> forcers (for example sulphur aerosols, soot, linear contrails, NO<sub>x</sub>, and contrail induced cirrus) in the LCFS.

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<sup>3</sup> According to the EC report, " Under the EU ETS, all airlines operating in Europe, European and non-European alike, are required to monitor, report and verify their emissions, and to surrender allowances against those emissions. They receive tradeable allowances covering a certain level of emissions from their flights per year. The system has so far contributed to reducing the carbon footprint of the aviation sector by more than 17 million tonnes per year, with compliance covering over 99.5% of emissions."

<sup>4</sup> "Every [passenger on a] flight to a European destination would be taxed 80 Swedish krona (\$9), while [passenger on] flights outside Europe would be taxed 280 SEK (\$30). Longer intercontinental flights would be taxed a full 430 SEK (~\$50)."

<sup>5</sup> See <http://www.regeringen.se/4ae35b/contentassets/34d1f308247b4718b85ee4cb9ec49e4a/2016en-svensk-flygskatt-sou-201683> for more information (text in Swedish).

<sup>6</sup> [https://www.arb.ca.gov/cc/shortlived/meetings/03142017/final\\_slcp\\_report.pdf](https://www.arb.ca.gov/cc/shortlived/meetings/03142017/final_slcp_report.pdf)

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