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How ambiguous are climate metrics? And are we prepared to assess and compare the climate impact of new air traffic technologies?

HIGHLIGHTS

- Posing the adequate climate question reduces a large amount of a perceived ambiguity of climate metrics.
- Five steps are proposed to adequately assess the climate impact of new technologies.
- Adequate reference, emission scenario, climate indicator, and time horizon can only be deduced from a well-posed question.

Politics, industry, science and the public are discussing many technical and political measures and strategies to mitigate climate change in general and for air traffic in particular. These measures include a reduction of climate relevant emissions and range from technical innovation to economic incentives. They include fossil fuel replacements, like fuel production from algae or hydrogen production from wind energy parks, more fuel efficient aircraft, less climate sensitive air traffic routings, and emission trading schemes. But how is the effectiveness of such a measure evaluated? At this place, climate metrics come into play for quantifying and comparing the impact of a specific activity and therefore of emissions on climate change. They are calculation rules, used to translate emissions in terms of kg per year to an impact parameter on a common scale which is relevant to climate change, such as the change in global mean surface temperatures. The climate metric[1] can then be used for a conversion of emissions into equivalent CO_2 emissions.

Now the question arises, what exactly is 'climate change'? There is a widely accepted indicator which is the global mean near-surface temperature change, though of course not unique (e.g. Sterner et al., 2014). The basic causal relationship of a climate relevant emission can be shortly summarized as follows: An emission changes the atmospheric composition (which might include cloudiness and cloud properties) which in turn changes the way solar radiation propagates through the atmosphere, warming the Earth's surface and how the Earth radiates back to space. The changed radiation budget leads to changes in climate, e.g. changes in temperatures. This chain of physical processes is represented in Earth system models (climate models). Climate metrics give a short-cut of this extremely complicated process and directly relate emissions to climate change. In many discussions, e.g. on conferences, we have learnt that these climate metrics are perceived as ambiguous or at will, because choices have to be made and impacts are evaluated differently when looking at different time horizons. Here, we are focussing on assessing and comparing aircraft technology options with respect to climate, e.g. new aircraft concepts. This is different from assessing the climate impact of a today's emission, which is used in emission trading systems. However the development of approaches dealing with technology assessments might be helpful for other objectives.

What climate metrics are currently used?[2] The simplest metric is the emitted mass of an individual species. It might serve as a first order indicator for comparing the relative importance of various sources or countries, but not for comparing different species, because it does not include any information on impacts on climate, though widely used. Instead, the radiative forcing (*RF*) is basically the radiation change caused by a concentration change. There is no standard approach to calculate this RF, but often past emissions are used to calculate the concentration change which is then imposed on a pre-industrial atmosphere to obtain the radiation changes. Note that with the use of RF a couple of assumptions are already made, such as the emission scenario to derive the concentration change or the reference time. The (absolute or relative to CO_2) global warming potential (AGWP, GWP) is summing up future impacts of radiation changes from today's concentration change to a chosen time horizon. The choice of the time horizon is not based on physical considerations and has been subjectively chosen between 20, 50 and 100 years in literature. Both the RF and GWP allow a comparison on the same scale. However, they are not yet considering an effect on climate, e.g., on temperature. Instead, the global temperature change potential (again absolute or relative to that of CO_2, GTP and AGTP) translates the radiation changes caused by a concentration change to a temperature change at a certain time horizon. GTP results in a physical quantity, which is directly associated with climate change. Like the GWP and even more, the GTP

[1] "Climate metrics" are also called "emission metrics" (IPCC, 2013). Here, a climate metric is regarded as the combination of emission scenario, time horizon and climate indicator (such as GWP, ATR, see below) to better discriminate between these terms.

[2] For a detailed overview the reader is referred to Fuglestvedt et al. (2010).

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depends critically on the chosen time horizon. The dependency on the time horizon is largely reduced by using the average temperature response (ATR), which is the mean future temperature development over a period up to the chosen time horizon. So far, we have discussed a pulse emission at a certain time leading to a concentration change and temperature change. Another option is to evaluate emission scenarios and the effect of changes in an emission scenario or contributions from different sectors. This gives a continuous development in e.g. temperature changes and a frequently used metric is then the temperature change at a certain time e.g. in the year 2000, 2050 or 2100.

This overview on climate metrics shows an important and often underestimated aspect in the evaluation of mitigation options and in the evaluation of the impact of emissions on climate: All these metrics target somehow 'climate change', but they provide different physical quantities measuring climate change and hence they provide answers to different questions. In the following, we explore these questions in more detail and show *why it seems that climate metrics are so ambiguous.*

Consider the question: "*What is the contribution of traffic to anthropogenic climate change?*". There is a wide range of possible answers, based on various climate metrics, considered emission scenarios and chosen time horizons (e.g. Berntsen and Fuglestvedt, 2008; Skeie et al., 2009). For example, the sign of the shipping contribution varies from cooling to warming, e.g., depending on the chosen time horizon. However, this wide range of results is an indication for an ill-posed underlying question, rather than an ambiguity of climate metrics. The question "*How large is the contribution of traffic in general to current climate warming?*", concentrates on the traffic emissions from the past to today and their impact on nowadays climate, e.g., temperature change. Here, the temperature response in the year 2014 from the past emissions is the appropriate climate metric. Clearly all metrics have their specific applications, since they can be used to answer meaningful questions about climate change. However the wording "climate change" has not a unique inherent meaning, which causes confusion, if not expressed clearly. This manifold in meanings of the wording "climate change" leads to the application of different climate metrics with qualitative and quantitative varying information and results. This reflects the ambiguity of the wording rather than the ambiguity of climate metrics.

So how can the ambiguity in the wording "climate change" in future be avoided? The answer is simple, whenever mitigation options, measures and strategies are assessed, the first and overall question to be answered is: "What exactly is the question?". What is actually meant by a climate assessment of a new technology? When the question is clearly formulated, only a very limited number of climate metrics, will be suitable to answer this question, largely reducing such ambiguity.

How to avoid misinterpretations? The false impression of ambiguity of climate metrics can be avoided by taking into account five steps:

1. Precisely posing the respective question,
2. Deducing from the question an adequate reference,
3. Deducing from the question an adequate emission scenario,
4. Deducing from the question an adequate climate change indicator/metric, and
5. Deducing from the question an adequate time horizon.

We do not think that climate metrics are ambiguous. Mixing results obtained from using different emission scenarios, such as pulse, sustained or scenario emissions, with various time horizons, or climate metrics, naturally produces a large variety of results, which in turn answers a large variety of very different questions.

To illustrate this approach we regard the EU-project AHEAD. There, a new combustion technology was analysed, as part of an engine and mounted on a blended wing body (Gangoli Rao et al., 2014). The question is now "Does it have a lower climate impact than conventional technology?". More precisely, "Is the AHEAD technology better in reducing the long-term climate impact, when introduced in 2050, than conventional technology?". Then conventional technology with some anticipated future enhancements is an appropriate reference and an emission scenario, which includes a fleet starting in 2050 and increasing up to an expected market share, would be an adequate emission scenario. A mean temperature change over 100 years (ATR100) after the entry into service fits then to the objective. Hence this procedure works for a technology assessment, because posing a detailed question already implicitly includes choices, such as the adequate emission scenario, time horizon and climate indicator. And hence a large part of possible choices, which might have been seen as ambiguous, is eliminated. However, further research is needed to adapt this approach to policy applications.

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