How to Integrate non-CO_2 Effects in Monitoring, Reporting and Verification Mechanisms – an Insight into Technical Options

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Introduction

Aviation contributes to global climate change, not only with its carbon dioxide (CO_2) emissions but also through non-CO_2 effects. These include emissions of nitrogen oxides (NO_x), water vapor, soot particles, and the formation of condensation trails (contrails), which significantly contribute to global warming. Recent scientific assessments estimate that non-CO_2 effects are responsible for around one-half to two-thirds of aviation's total climate impact. Unlike CO_2, which has a long atmospheric lifetime and a globally uniform effect, non-CO_2 effects are highly variable, depending on factors such as flight altitude, geographic location, weather conditions, and the chemical composition of emissions.

Effectively addressing these climate effects requires more than simply counting carbon. A sophisticated system is needed to quantify and monitor the total climate impact of aviation emissions in a comparable unit—CO_2 equivalents (CO_{2e}). This allows for integrating CO_2 and non-CO_2 effects into a single climate accountability framework. The process involves selecting suitable climate metrics, identifying required flight and emission data, managing data uncertainties, and recommending practical implementation pathways.

This article presents key scientific insights and results on how to calculate the climate impact of aviation emissions, especially non-CO_2 effects, with the purpose to integrate this understanding into monitoring, reporting and verification (MRV) systems.

Understanding Non-CO_2 Effects in Aviation

Aviation emissions impact the atmosphere through multiple mechanisms. While CO_2 emissions are directly linked to fuel consumption, other substances such as NO_x alter atmospheric chemistry, leading to the formation of ozone and reduction of methane—both greenhouse gases. Contrails, created when aircraft fly through ice-supersaturated air masses, can trap outgoing infrared radiation and form cirrus clouds that can have a warming effect, especially at night.

However, not all contrails are equal: studies show that only about 20% of flights form contrails, and among these, only a small fraction cause strong warming. In fact, around 5% of flights are responsible for the majority of contrail-related warming. This means that both the timing and location of emissions are critical in determining their climate impact. Meteorological conditions such as temperature, humidity, and solar angle further influence the net effect.

Importantly, recent research indicates that it is possible to significantly reduce non-CO_2 climate effects through operational measures. Examples include avoiding contrail-prone regions through appropriate flight planning or using sustainable aviation fuels. However, these measures must be evaluated in the context of their total climate impact, including possible trade-offs with CO_2 emissions.

Quantifying the Climate Impact: Climate Metrics

To integrate non-CO_2 effects into climate policy and emissions reporting, they must be expressed in the same unit as CO_2 emissions. This is done through climate metrics that convert the warming impact of different emission species into CO_2 equivalents.

This can be generally done in two different ways, either with a climatological approach, which evaluates the impact of a flight that is repeatedly offered over a longer period of time, or with a weather-based approach that considers the current weather situation at the time of an individual flight. Which approach to use depends on the suitability for a particular aircraft operator. The weather-based approach, however, has a larger climate mitigation potential and should therefore be the preferred one[1].

Based on an evaluation of different climate metrics regarding transparency, stability, scientific soundness, and policy compatibility the following two metrics turn out to be best suited for use in an MRV[1]:

- Global Warming Potential (GWP): The most widely used metric, particularly over a 100-year time horizon (GWP100), integrates the radiative forcing (a measure of atmospheric energy imbalance) over time. While GWP is stable and widely understood, it does not fully capture the short-term dynamics of aviation emissions.
- Average Temperature Response (ATR): This metric measures the average temperature increase caused by emissions over a specific period. ATR is closer to temperature-based climate goals and better accounts for the atmospheric response to short-lived pollutants. It is also relatively stable and suited for comparing new fuels and aircraft technologies.

Comparative studies suggest that ATR and GWP offer the best balance between scientific accuracy and policy usability, especially for long-term climate goals. For consistency with existing international frameworks and to take into account that short time horizons can lead to climate mitigation measures that might help in the short-term, but have less beneficial consequences in the long-term, a time horizon longer than 70 years is generally recommended. In case the GWP is chosen, it is recommended to adjust the metric such that it also accurately captures the climate effect of aviation non-CO_2 emissions by considering the efficacy of the different species[1].

Modeling Aviation Emissions and Climate Effects

To calculate the CO_{2e} in one of the above climate metrics, models are needed that can capture how different emissions affect the atmosphere. An MRV framework should generally be flexible enough to work with various different climate models and to incorporate new models as well.

For the climatological approach climate response models (e.g., AirClim) that combine emission inventories with precomputed atmospheric responses to estimate large-scale, long-term impacts are well suited. For the weather-based approach a combination of statistical models (e.g., algorithmic Climate Change Functions, aCCFs) and detailed physical models (e.g., CoCiP) can be used. While statistical models use precomputed correlations between meteorological conditions and climate effects, enable fast estimates and provide reasonable accuracy, the detailed physical models can simulate contrail formation and lifecycle in high resolution, using weather forecasts and aircraft-specific data. These models can inform precise contrail avoidance strategies[1].

Each model has its strengths. Simpler models are suitable for large-scale assessments and routine reporting, while detailed models are better for evaluating specific mitigation strategies, such as rerouting or fuel switching. All models require flight data, meteorological input, and assumptions about emission characteristics. They must also be periodically updated to reflect advancements in climate science.

1 See also: de Haes et al., 2024, "Support for establishing a monitoring, reporting and verification system for non-CO_2 effects in aviation, stemming from the revision of the ETS Directive", final report.

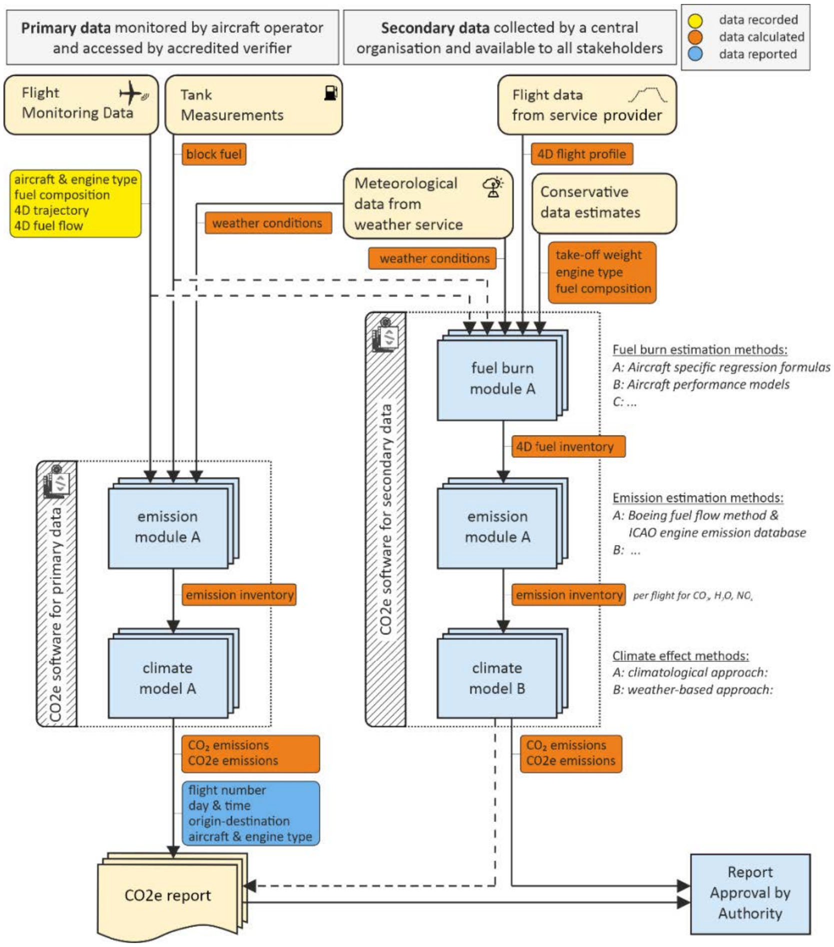

FIGURE 1: Flowchart of possible MRV framework for aviation non-CO_2 emissions (adapted from Niklass et al., 2024[2]).

Data Requirements for Effective Monitoring

To monitor, report, and verify aviation's non-CO_2 climate effects, flight data is required. The data collection should be limited to what's necessary for environmental benefit while minimizing MRV effort. Data needs vary by modeling approach, mitigation strategies, and MRV purpose.

It is useful to distinguish between three different data types[2]: primary (directly monitored by operators and verifiable), reporting (basic data to assign emissions), and secondary (used for conservative emissions estimates by services like EUROCONTROL). Secondary data also supports cross-checking by authorities. Operators can optionally provide more detailed data to improve accuracy.

Minimum data needed for basic assessments include at least:

- Aircraft and engine type,
- Flight profile: (departure, arrival, altitude),
- Fuel consumption,
- Flight times and distances.

Additional data that improve accuracy:

- Real-time 4D flight trajectory data (with timestamps),
- Fuel composition (especially hydrogen and aromatic content),

2 Niklass et al., 2024, "Implementing an EU Agreement on Monitoring, Reporting and Verification of Non-CO_2 Climate Effects in Aviation", German Aerospace Congress 2024, Hamburg.

- Meteorological data during the flight (e.g., temperature, humidity, wind),
- Engine performance parameters.

For simplified models, historical averages and assumptions may suffice. More advanced models, especially those enabling flight-specific assessments, require high-resolution, flight-by-flight data.

Managing Data Gaps and Uncertainties

In practice, full data availability cannot always be guaranteed. Therefore, strategies are needed to manage data gaps[1]:

- Default values and estimation methods: Where specific data are missing, conservative default values based on aircraft type or historical averages can be used.
- Substitution from trusted databases: Aircraft and engine registries, fuel specifications, and meteorological archives can provide reference data.
- Interpolation and extrapolation: Missing segments in flight paths or weather data can be estimated using nearby or similar flights.

Uncertainty is inherent in estimating non-CO_2 climate effects. Key sources include model assumptions, variability in meteorological conditions, and incomplete understanding of contrail dynamics. These uncertainties must be incorporated and examined through suitable validation, evaluation, and assessment processes to enhance understanding and enable the quantification of risks and impacts. Although these uncertainties exist, they can be managed through transparent methodologies, conservative assumptions, and continuous model refinement and should not prevent the implementation of MRV frameworks[1].

Enabling Implementation in Aviation Monitoring Systems

For practical use, these insights must be embedded in operational systems that allow airlines, authorities, and verification bodies to monitor and report non-CO_2 climate impacts. The proposed setup includes[1]:

- A central platform to process flight data and apply the chosen climate models and metrics.
- Interfaces for airlines to upload flight and fuel data.
- Verification mechanisms to ensure data quality and compliance.
- Modular design to allow gradual integration of advanced models and technologies.

Operators can choose between simplified approaches (using average values and basic models) and advanced methods (using weather-dependent models and full data sets), depending on their capabilities and ambitions. This flexibility supports broad adoption while encouraging continuous improvement.

Incentivizing the Reduction of Aviation's Climate Impact

The ultimate goal of quantifying non-CO_2 effects is to reduce aviation's total climate impact. By making these effects visible and measurable, airlines can be incentivized to:

- Avoid contrail-prone regions and altitudes,
- Adopt sustainable fuels,
- Optimize aircraft design and flight operations,
- Invest in innovative low-emission technologies.

While technical and economic challenges remain, integrating non-CO_2 effects into climate accountability frameworks is a critical step toward climate-responsible aviation.

Conclusion

By selecting appropriate climate metrics, modeling tools, and data strategies, aviation stakeholders can take meaningful steps toward measuring and mitigating their full climate impact. The path forward involves balancing complexity with feasibility, managing uncertainties transparently, and building systems that can evolve with new technologies and scientific insights. As the climate urgency intensifies, addressing all climate-relevant emissions from aviation becomes not just a scientific necessity but a policy imperative.