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ISSUES AND UNCERTAINTIES AFFECTING METRICS FOR AVIATION IMPACTS ON CLIMATE

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Metrics are potentially important tools for evaluating and guiding decision making associated with tradeoffs between environmental impacts, aircraft design, and operations to minimize the impacts of aviation on climate, once their limitations are assessed and resolved.

While the Kyoto Protocol did not consider emissions from aviation, more recent climate policy considerations, like the European emission trading scheme introduced in December 2008, will include aviation emissions of carbon dioxide (CO_2), but not other climate effects from aviation. To inform mitigation policy considerations, analytical tools (i.e., metrics) are often used to quantify the ultimate climate impact of specific activities, such as aviation emissions (Penner et al. 1999; Wuebbles et al. 2007; Forster et al. 2006). A particular goal for these metrics is to relate different emissions to one another in order to maximize the application of mitigation policies and their benefits. Different metrics can provide differing perspectives; as a result, considering more than one metric can aid the decision-making process. Metrics can also be useful to guide decisions concerning future aircraft design and operations to minimize their climate impact, and to evaluate the tradeoffs and costs associated with potential responses to different environmental effects. The objective of this study, as part of the Aviation Climate Change Research Initiative (ACCRI), developed by the U.S. Federal Aviation Administration and other agencies, is to examine the capabilities and limitations of current climate metrics in the context of the aviation impact on climate change, to analyze key uncertainties associated with these metrics, and to the extent possible, make recommendations on future research and about how best to use the current metrics to gauge aviation-induced climate change. ACCRI overall is aimed at identifying and addressing key scientific gaps and uncertainties regarding climate impacts from aviation while providing timely scientific input to inform optimum mitigation actions and policies. [The work of Wuebbles et al. (2008) and Forster and Rogers (2008) inform the present study; see also www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/, for associated reports.]

For aviation as well as other sectors, it is desirable to have a metric that is closely related, to the degree possible, to the climate impact of concern. Yet as shown in Fig. 1, the uncertainties increase as we move from quantifying aviation emissions and radiative forcing to quantifying temperature and precipitation changes or trying to estimate the socioeconomic impacts. The current scientific understanding of the potential effects on climate from aviation emissions range from good, for the relatively long-lived carbon dioxide emissions, to fair, for the atmospheric chemistry and radiative effects from emissions of shorter-lived gases (especially nitrogen oxides and water vapor) and particles, and the radiative effects of contrails to poor for the emissions effects (from contrail formation and particle emissions) on cirrus clouds (Lee et al. 2009).

In order to be an effective tool for policymakers and their communication with scientists and industry, a metric should be easy to use and as scientifically well grounded as possible. Thus, the best metrics will be simple and will include uncertainties that reflect the state of knowledge in order to give users confidence in their scientific quality. A concern with developing new metrics is the need to weigh their applicability against the ease of understanding the results. When choosing a metric for climate impacts of emissions from aviation, some fundamental questions must first be answered (O'Neill 2000; Fuglestvedt et al. 2003), such as the following: What are the policy questions under consideration and what is the context for the application? What is the function or purpose of the metric? Can it be applied to various scenarios and forcings? What is its effectiveness for the user, whether for technology or policy considerations? Is it flexible enough to incorporate advances in scientific understanding? What is the time scale for the evaluation of potential climate impacts? In addition, the most useful metrics will be applicable to other transportation and/or energy sectors.

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METRICS: THE CURRENT OPTIONS. Many metrics are based on the concept of radiative forcing. Radiative forcing has been commonly used to compare different climate change effects (e.g., Houghton et al. 1990). The radiative forcing concept assumes that the globally averaged annual mean surface temperature at equilibrium is equal to the globally averaged forcing multiplied by a climate sensitivity factor. Intergovernmental Panel on Climate Change (IPCC) reports still use radiative forcing to compare different climate change mechanisms, but acknowledge its deficiencies (Forster et al. 2007). In particular, forcings can be compared effectively only in a global mean sense, and not all forcings necessarily have the same efficiency or "efficacy" in causing the climate to change. For example, although not substantiated, a radiative forcing from contrails may give a smaller global mean temperature change than an equivalent carbon dioxide radiative forcing due to differences in their spatial distributions.

The Kyoto Protocol has adopted the 100-yr global warming potential (GWP) to compare the climate impact from emissions for a basket of greenhouse gases. The GWP is the most widely used emission metric and the general standard being used in climate assessments (Houghton et al. 1990; Solomon et al. 2007); it represents the radiative forcing for either pulse or sustained emissions above the current background levels by integrating the forcing over a specific time interval and comparing that integral to the forcing from an equal mass emission of carbon dioxide (see Table 1). However, its adoption as a metric for short-lived emissions and aviation effects, in particular, has proved to be controversial (Penner et al. 1999). The GWP concept has limitations because aviation radiative forcings do not all rely on emissions alone (e.g., contrails); the lifetime of some effects are short (<<100 yr), and the distribution of forcings is inhomogeneous in the atmosphere. As a result, the IPCC Special Report on Aviation (Penner et al. 1999) made strong statements against its use for aviation. Instead, they proposed a radiative forcing index (RFI) to compare aviation effects. Despite the limitations of GWP, other authors and IPCC reports have presented GWPs for aviation effects (e.g., Solomon et al. 2007), largely to counter the misuse of the RFI as an *emission* metric by policy makers and carbon-offsetting sites (Forster et al. 2006). RFI is not a suitable emission metric because it does not take into account the different lifetimes of gases in the atmosphere.

Metrics beyond radiative forcing and GWP have been proposed but have not yet been used for policy decisions. The global temperature potential (GTP) is an alternative to the GWP that avoids some of its limitations (Shine et al. 2005, 2007; see also Table 1). The GTP is similar to the GWP, but it also takes into account the thermal inertia and response of the climate system. Thus, it provides a different perspective on the relative importance of emissions of different species and how this changes over time. GTP is also further down the cause-and-effect chain from emissions to impacts and may therefore have a higher relevance and be easier to understand than the somewhat abstract concept of integrated radiative forcing. However, the GTP remains largely untested at this time.

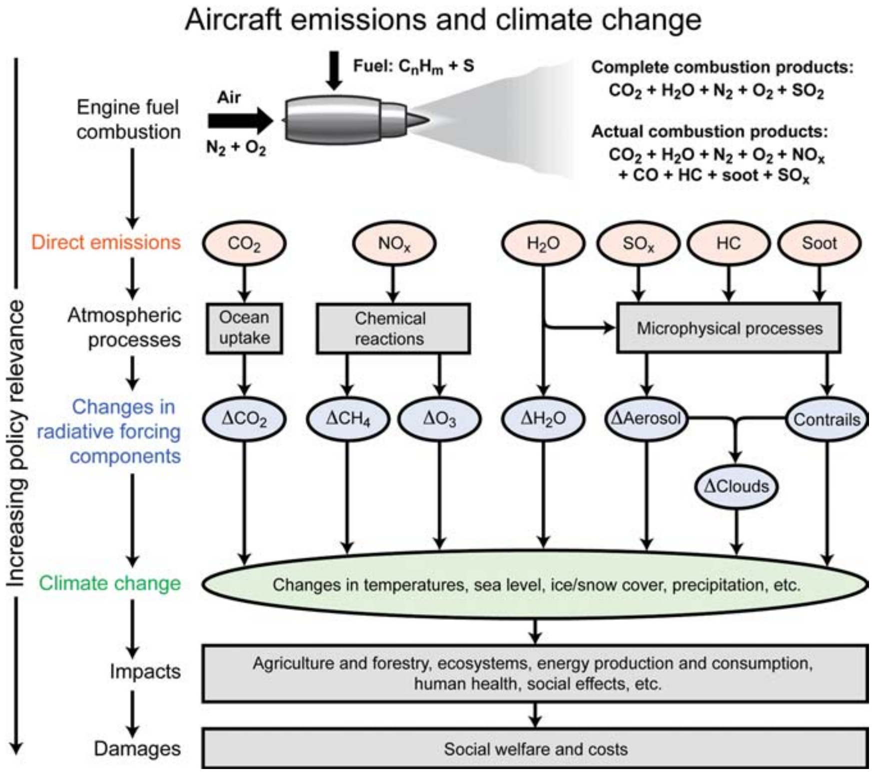

Fig. 1. Aircraft emissions and their resulting potential impacts on climate change and welfare (developed for a special report for the International Civil Aviation Organization, but adapted from Wuebbles et al. 2007; based on Penner et al. 1999; Fuglestvedt et al. 2003).

Sophisticated global climate models are rarely used for metric evaluation because the higher computational cost of increased complexity currently precludes multiple calculations to assess uncertainties; further, it is probably not worthwhile given the current poor understanding of processes such as cirrus cloud modification by aircraft (see Burkhardt et al. 2010). As an alternative to the comprehensive global climate models, linearized response and other simplified models can be used to estimate the response of the climate system to pulsed or sustained emissions (Marais et al. 2008; Lee and Wit 2006; Grewe and Stenke 2008). Simplified models are often tuned to reproduce key responses found in comprehensive global climate models and then are used to explore a range of emission scenarios while requiring fewer computational resources than the guiding global climate models. Importantly, they have the capability of including information about future scenarios both of aviation and other emissions. The more sophisticated of these models have the potential to include information on regional scales. However, uncertainties in many of the physical processes being represented in these models, particularly at the regional scale, raises questions about whether one can trust some aspects of the response of these models.

The evaluation of the climate impact of aviation emissions can be taken a step beyond quantifying radiative forcing or temperature changes to the evaluation of the socioeconomic damages and costs associated with climate changes, and with potential policy considerations and environmental tradeoffs. Economists and others argue that damages and abatement costs must be included in climate change metrics in order to make valid comparisons of abatement options and consequences across emissions types and geographic regions. Socioeconomic damage models are designed to provide such metrics, which potentially can be of direct policy relevance (e.g., Hammitt et al. 1996; Kandlikar 1996; Manne and Richels 2001; Marais et al. 2008). However, the current understanding of the links between climate change, aviation emissions effects, and damages are not defined well enough to adequately quantify such metrics.

Table 1. A comparison of the metrics and modeling tools that can be used for the evaluation of aviation's climate impact.			
Metric/approach	**Description**	**Advantages**	**Disadvantages**
Radiative forcing (RF)	Earth energy balance change, calculated from observations or models; dependent on integrated *past* emissions and the lifetime and radiative efficiency of their products in the atmosphere	Long-standing use in assessing climate impact of different effects	Without modification (efficacy factors) it does not account for differences in climate response between forcings (see Fuglestvedt et al. 2003; Berntsen et al. 2005); it is far removed from eventual climate impact; and it does not adequately account for regional variations of the climate effect
RFI	Total radiative forcing from the aviation sector relative to the radiative forcing from aviation CO_2 alone	Simple measure of importance on non-CO_2 effects of aviation	As for radiative forcing; it has been widely incorrectly applied to compare effects of future emissions; for radiative forcing, this is largely a backward-looking metric; it does not account for regional variation in impact
GWP	The integrated radiative forcing for either pulse or sustained emissions above the current background levels over a specific time interval compared to the forcing from an equal mass emission of carbon dioxide; time horizons are typically 50 and 100 yr	Simple analytical calculation; use is well established in emission regulation polices	Far removed from climate impact and without modification, it does not account for differences in climate response; changing background atmosphere is not taken into account; does not account for regional variation in impact
GTP	GTP combines the GWP with an analytical climate model to give the ratio of the surface temperature change for either pulse or sustained emissions that will occur at a chosen point in time to the temperature change for an equal mass emission CO_2	Analytical solution, yet gives an estimate of temperature change that is likely; more relevant for climate impact than GWP	Incorporates extra uncertainties from climate response; does not account for regional variation in impact; insufficiently tested at this time
Simple climate model based	Metrics usually compare scenarios of temperature response in a model with and without aviation effects.	Can allow for changing background changes and/or assess regional climate impact	Requires expertise in models, their analysis, and their interpretation, especially related with uncertainty
Complex global climate model based	Metrics could compare scenarios of many responses (temperature, rainfall, extreme weather, etc.) in a model with and without aviation effects	As above, but can include analysis of impacts beyond temperature	Models are slow and unwieldy to use; requires expertise in models, their analysis, and their interpretation, especially related with uncertainty; aviation signal likely smaller than natural climate variability, making interpretation difficult
Socioeconomic model based	Metrics would use an integrated model to assess social and/or economic impact of aviation emissions	Assess impacts of direct concern to policy makers	Many large uncertainties, approximations, and unknowns go into the formulation of such models

THE WAY FORWARD. The use of the radiative forcing has already been of substantial value in evaluating the climate impact of aviation emissions and operations and in placing the contributions of aviation in a quantitative framework with global emissions from other sectors. However, the limitations of radiative forcing as an emission metric have been widely acknowledged. Recommendations for the use and development of metrics appropriate for aviation are the following:

- *At present use only global metrics when evaluating the effect of global emissions on global response.*

Currently we have an insufficient quantifiable understanding of how regional emissions affect both the regional and global response or even how global emissions affect the local response. Furthermore, too few climate models have assessed aviation efficacies to justify their use in policy. We expect this situation to improve over the next 5–10 yr as our understanding and modeling capability improve.

- *Continue the use, evaluation, and development of the GWP and GTP metrics.* The GWP and GTP are the most usable metrics for aviation at present, even for short-lived emissions such as NO_x. Simplified models appear to be promising for policy studies, and development of new metrics should also be pursued. Existing metrics have limitations, so we suggest evaluating a range of metrics so as not to introduce bias.
- *Continue the development of global climate models.* All useful metrics ultimately depend on comprehensive climate models, either directly or indirectly. Improving the representativeness and accuracy of these models will directly improve the quality of metrics for aviation and other climate change perturbations. Regional forcing and responses can be addressed with improved models. Regional metrics will be less simple, but can be included in analyses with varied scenarios and mitigation options.
- *Attempt to adapt common metrics.* The value of metrics for aviation climate impact would be increased if they were applicable to emissions from other sectors, for example, surface transportation.
- *Continue development of socioeconomic metrics.* Socioeconomic metrics are not yet suitable to use in policy development for aviation impacts given the current uncertainties in their derivation. At this time, socioeconomic metrics are best viewed as a long-term research goal that eventually will be useful to assess the climate impact of both aviation emissions and the emissions of other sectors, and for analyses of policy options and possible environmental tradeoff considerations.

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