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Climate Metrics and Aviation:
Analysis of Current Understanding and Uncertainties

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Climate Metrics and Aviation: Analysis of Current Understanding and Uncertainties

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Executive Summary

The impact of climate-altering agents on the atmospheric system is a result of a complex system of interactions and feedbacks within the atmosphere, and with the oceans, the land surface, the biosphere and the cryosphere. Climate metrics are used as a proxy to simplify interpretation of the complex science and associated feedbacks to indicate the ultimate effect of constituent changes in the atmosphere. Aviation is just one contributor to these constituent changes in the atmosphere but the potential impact of aviation on climate is expected to grow over the coming decades as demand for air travel increases. It is necessary to quantify the impact of aviation so that appropriate policy actions may be defined. The objective of this report 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, to make recommendations on future research and about how best to use metrics currently to gauge aviation-induced climate change.

Climate change not only involves changes in temperature, but also changes in precipitations and changes in extreme events. Nonetheless, globally averaged surface temperature is generally used as a proxy for climate change because temperature changes are easier to predict and the effect of temperature changes are better understood than other atmospheric variables. When deciding which metric to use for aviation considerations, some general questions must first be answered, such as: What is the function or purpose of the metric? Can the metric be applied to various scenarios and forcings? What is the effectiveness of the metric for the user, whether it is for technology or policy considerations? Is the metric flexible enough to incorporate advances in scientific understanding? A useful metric should also be applicable to other transportation and / or energy sectors as well.

A useful metric must be easy to use and understand, as well as firmly supported by the science. When developing a metric or choosing between existing metrics one must balance the applicability of the metric to a wide range of climate altering scenarios with ease of use of the metric within the limits of scientific understanding. Aviation presents a very specific situation where emissions are deposited largely in the upper troposphere/lower stratosphere (UT/LS) region rather than at the Earth’s surface like other transportation or energy related emissions. Some emissions from aviation are both long-lived (e.g., a century or longer for carbon dioxide) while others are very short-lived (e.g., minutes to a few days for contrail and cirrus effects). Also, the total amount of emissions and corresponding changes in climate resulting from the existing aviation fleet is currently relatively small compared to the total human-induced emissions that are leading to climate change. Some specific questions that must be answered with regard to aviation-induced climate change are: What are the climate effects of aviation relative to other transportation sectors? What technology choices will minimize the impacts on climate? Which forcing agent in aviation should be the highest priority for policy considerations? What are the trade-offs between reductions of different forcing agents? What are the trade-offs between different policy considerations? How can the industry maximize the benefit while minimizing the cost of abatement? What metric or metrics would be most useful for analyses of the potential climate impacts from aviation emissions? Or from other transportation and energy sectors? The “best” metric probably depends on which question(s) are being addressed and no metric should be used blindly.

The most widely used metric for climate change has been radiative forcing (RF). It is also an integral part of many of the existing climate metrics. In fact, there is no single “radiative forcing” metric; there are several “flavors” of radiative forcing based metrics. Although the use of the stratospheric adjusted radiative forcing metric is often used for aviation studies (as well as many other climate analyses) and has been proposed by some policymakers for use in possible policy development relative to aircraft emissions, the classic evaluation of this metric has limited suitability for that purpose and it is clear that it only provides part of the story regarding aircraft effects on climate.

Of all the problems associated with RF (in all its flavors), the most serious limitation may come from the fact that not all forcing agents cause the same climate impact (for the discussion here, change in globally averaged surface temperature) for a given change in radiative flux. This means that RF from one cause cannot be compared to RF from another cause easily. One way to get around this problem is to define an “equivalent” RF where the forcing is weighted by its climate sensitivity. This additional multiplier term is called “efficacy”.

Existing metrics can be grouped into one of three categories: (1) concentration-based metrics which use constituent concentrations to gauge the change in radiative forcing; (2) emissions-based metrics that aim to control emissions and examine trade-offs; and (3) economics- and damage-based metrics which attempt to account for damages and abatement costs. The discussion in the report largely centers on the first two groups, the science-based metrics.

The most widely used metrics in climate assessments and policy considerations are stratospheric adjusted Radiative Forcing and Global Warming Potentials, but many other metrics have been proposed. At this point, the most promising metrics for future climate analyses including aviation are: Equivalent Radiative Forcing (Radiative Forcing with efficacies applied), Global Warming Potentials (GWPs), Global Temperature Potentials (GTPs) and Linearized Temperature Response (LTR) metrics. Efficacy factors should be applied to these metrics to account for the fact that not all constituents have the same impact on climate change. All of these metrics have strengths and some limitations towards addressing key policy questions related to the potential impacts of aviation on climate. However, all of these climate metrics should be further evaluated for their applicability to aviation-induced climate change because so far it is unclear which metric is most suitable to address the needs of policymakers.

In order to determine which metric is most applicable for which question, the applicability and robustness of individual metrics must be tested. These metrics must be tested both for global and regional applicability. A Metrics Working Group should be formed to evaluate the different metrics and their value for addressing policy questions using a variety of climate and chemistry-climate models. The Metrics Working Group will meet with policy makers to establish priorities because a metric preference particularly depends on the choice of questions to be addressed. One of the initial tasks of this working group will be to establish criteria for evaluating metrics, and then existing metrics will be compared in the context of the priorities established by policy makers. Efficacy factors will also need to be evaluated to determine if efficacies can adequately correct for differences in climate sensitivity to various aviation scenarios. The possible effects of changes in the background atmospheric conditions (effects of composition and climate changes) on derived aviation impacts need to be evaluated. Finally, metrics will be evaluated based on applicability to other transportation and energy sectors. These priorities will greatly enhance the understanding of climate metrics within the next five years using the current suite of tools, which include state-of-the-art chemical-transport and chemical-climate models, as well as the set of existing metrics.

The GWP concept cannot be ignored because it still is the most accepted metric in the international climate assessments and corresponding policy considerations. However, the GTP concept and the linearized temperature response (LTR) approach also have many advantages and may be the preferred approaches for technological and policy analyses relative to aviation. GTP has the advantage of being relatively simple, transparent, and flexible, but, like GWPs, they have not been adequately tested for application to aviation impacts on climate.

The latest LTR approaches, namely the APMT and AirClim assessment tools, appear to be quite promising for future studies of aviation. The AirClim approach may even provide a capability for analyzing regional impacts not considered otherwise. However, these tools are dependent on the validity of much more complex representations and understanding of the science, including the carbon cycle, chemistry interactions, aerosol direct and indirect effects, contrail formation and evolution, and the resulting impacts on climate. Current tools need much further development and evaluation before they will be applicable to policy considerations.

It will be important to take a systems point of view in any new study using existing metrics to evaluate the climate impacts from aviation. As such, it will be important to consider all of the uncertainties associated with current understanding of the effects of aviation emissions on climate, including the fact that with the exception of carbon dioxide, the effects of other emissions on climate are still not very well understood. In particular, it would be very difficult to provide a meaningful evaluation of the effects of contrails or the effects of contrails and aerosols on cirrus. However, metrics may be able to better consider the effects NOx emissions from aviation. To provide a perspective relative to prior assessments of aircraft effects, any new study done at this time should start with the use of stratospheric adjusted radiative forcing, but also include consideration of efficacies to the degree possible. The effects of uncertainties in the evaluation of the climate effects and in the metric itself will need to be clearly stated. The radiative forcing could be evaluated for the current time period but it can also be worthwhile to consider projections of effects on aviation based on reasonable scenarios for future emissions. Such scenarios, however, need to be carefully considered, and should be based on best available projections from ICAO and the FAA (or associated organizations like JPDO). Emissions-based metrics should also be considered, but interpretation is currently limited by the lack of a community-consensus on which metrics should be adopted and the by the limited application currently of the GWP and GTP approaches to evaluation of aviation impacts. The LTR approaches are promising as assessment tools but have not been evaluated by the science community and need further development to reduce existing uncertainties.

1. Introduction

Metrics have long been used in studies of climate change to simplify interpretation of the complex science and associated feedbacks and interactions that determine the ultimate effect of gaseous or particulate emissions on the atmosphere. Several different types of metrics have been developed, each with its advantages and disadvantages. Several of these metrics have been applied in various ways to study the effects of aviation on climate. However, there has been little attempt to assess what is known about climate metrics in order to evaluate the relevance and applicability of these metrics to aviation.

Climate is defined as the typical behavior of the atmosphere, the aggregation of the weather, and is generally expressed in terms of averages and variances of temperature, precipitation and other physical properties. A climate metric, in general, is a variable (or a set of variables) designed to parameterize a set of known or deduced influences on the climate system that may result in climate change. The climate metric variable is then used as a proxy to indicate the impact of forcing on the climate system resulting in a change in the energy balance of the earth-atmosphere system. This forcing results in a change in both the instantaneous and long-term equilibrium conditions of the Earth’s atmosphere, and a shift in the long-term average conditions of the Earth’s atmosphere. Climate change may be manifested by a variety of important parameters, including temperature, precipitation, humidity, cloudiness, soil moisture, sea surface temperature, and sea ice location and thickness.

Whereas comprehensive models of the climate system can be used to study the much larger climate effects of fossil fuel use and other human-related emissions at the Earth’s surface, the climate effects from current aircraft emissions are only a small fraction of the total impacts of human activities on climate (e.g., emissions of carbon dioxide from aviation are currently approximately two percent of the total emissions from fossil fuel burning and changes in land use). As a result, it is very difficult to use a climate model to directly evaluate the climate effects resulting from aviation. Metrics thus provide the primary means for evaluating the relative effects of different emissions, including policy or tradeoff options, from aviation on climate and for comparing the effects of aviation on climate relative to other human factors affecting climate.

However, the potential importance of aviation on climate is expected to grow over the coming decades, further increasing the need for well-defined metrics to study and understand the role of aviation on climate. For example, the U.S. projects demand for air transportation services to grow three fold by 2025 (e.g., Next Generation Air Transportation System, 2004). It is a daunting challenge for both the scientific and technological communities to satisfy this increasing demand, while still protecting our environment, including potential impacts on the Earth’s climate. With extensive growth demand expected in aviation over the next few decades, it is imperative that vigorous action be taken to understand the potential impacts of aviation emissions to help policymakers address climate and other potential environmental impacts associated with aviation. To meet the challenges presented by this growth, the President of the United States signed ‘Vision 100 – Century of Aviation Reauthorization Act” in 2003 and created a multi-agency integrated plan for the development of a Next Generation Air Transportation system (NGATS). The vision of the NGATS is “A transformed aviation system that allows all communities to participate in the global market-place, provides services tailored to individual customer needs, and accommodates seamless civil and military operations.” One of the challenges posed by the vision is achieving growth while reducing environmental impacts. At the same time, other countries (e.g., the European Union) and the United Nations' International Civil Aviation Organization (ICAO) face similar concerns and issues.

As stated in the 2006 Workshop on the Impacts of Aviation on Climate Change (Wuebbles et al., 2006; available from http://web.mit.edu/aeroastro/partner/reports/climatewrksp-rpt-0806.pdf), the integrated national plan for implementation of the NGATS initiative in the U.S. is carried out by a Joint Planning and Development Office (JPDO). The JPDO is comprised of a number of U.S. agencies: National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), Department of Transportation (DOT), Department of Homeland Security (DHS), Department of Commerce (DOC) and the Whitehouse Office of Science and Technology Policy (OSTP). The Environmental Integrated Product Team (EIPT) of JPDO has been tasked with incorporating environmental impact planning into the NGATS. To fulfill this strategy, it is necessary to quantify the climatic impacts of aviation emissions to enable appropriate policy considerations and actions. Understanding aviation's climate impact is also critical to informing the United States in the best considerations and trade-offs for setting standards in engine emissions, special flight operations, or other potential policy actions through the International Civil Aviation Organization. This cannot be adequately done until the policymakers can correctly capture the environmental effects of aviation emissions, including climate impacts. The extensive investment of new aircraft in the marketplace, with their long service lifetime (25-30 years or longer), emphasizes the urgent need for improving our current understanding of the effects of aviation on climate.

The vast majority of the emissions from aviation occur at cruise altitudes in the upper troposphere and lower stratosphere (UT/LS). The chemical species released during the fuel combustion process in aircraft engines include carbon dioxide (CO_2), water (H_2O), nitrogen oxides (NO and NO_2 or NOx collectively) and sulfur oxides (SO_x) along with small amounts of soot carbon (C_{soot}), hydrocarbons (HC) and carbon monoxide (CO). Once released at cruise altitudes within the UT/LS, these species interact with the background atmosphere and undergo complex processes, resulting in climate impacts and related damages. However, one also needs to bear in mind that the background atmosphere is also changing over time as a result of both natural and human drivers. As the background atmosphere changes, the response of atmospheric chemistry and the climate system to emissions from aviation may also change.

The schematic in Figure 1 illustrates how emissions from aviation can cause resulting climate impacts and subsequent damages. The impact of climate-altering agents leads to the following chain of events: Emissions lead to changes in atmospheric concentrations of gases and particles; these in turn lead to changes in the radiative transfer affecting the climate system, referred to as the radiative forcing on climate; changes in radiative forcing alters key climate parameters like temperature and precipitation (e.g., IPCC, 1999; IPCC, 2007a). These changes in the climate system can have resulting social and ecosystem impacts and can result in a variety of societal and economic impacts (IPCC, 2007b; O'Neill, 2000; Smith and Wigley, 2000; Fuglestvedt *et al.*, 2003). As one moves down the diagram, there is increasing policy relevance (in terms of observed changes that are likely to produce measurable economic or other types of social welfare damages) but there is also increasing uncertainty regarding the exact magnitude of the change as it depends not only on the forcing of the climate system by emissions but also on the vulnerability of individual natural and human systems.

Climate metrics are often used as an indicator of these climate impacts. Some climate metrics go further and indicate the influence of climate change on human-related factors, like economic damage or cost of abatement. This report is largely restricted to physical metrics, which do not consider costs or other economic factors. However, because there is a lot of potential interest in the use of metrics containing economic factors, we do provide a cursory discussion on the potential use of and the current issues associated with using economics in climate metrics.

The specific ways that aircraft emissions can alter the radiative budget of the Earth and contribute to human-induced climate change are:

- Aircraft engines emit CO_2 and water vapor, important greenhouse gases, that directly affect climate through their absorption and reemission of infrared radiation;
- Aircraft emitted NO_x (and hydrogen oxides (HOx) produced from water vapor emissions into the stratosphere) can modify atmospheric ozone concentrations through chemical interactions. Ozone affects the radiative balance of the climate system through both its shortwave and infrared (greenhouse effect) absorption;
- Through its resulting net production of upper tropospheric and lower stratospheric ozone, NO_x emissions from subsonic aircraft reduce the atmospheric abundance of CH_4, another important greenhouse gas, through enhancing the concentrations of tropospheric hydroxyl radicals (OH), the primary reactant for destruction of methane;
- Aircraft emit aerosols in the form of liquid particles containing sulfate and organics, and soot particles. Emissions of sulfur dioxide also increase the aerosol mass in aging plumes. These aerosols can be radiatively active themselves, either by scattering (sulfates) or absorbing (soot) solar radiation or can indirectly affect climate by triggering the formation of persistent condensation trails or altering natural cloudiness;
- Under the right meteorological conditions, aircraft emissions of water vapor (and aerosols) can lead to formation of contrails and possibly result in effects on upper tropospheric cirrus clouds – these effects may exert spatially inhomogeneous radiative impacts on climate.

As will be discussed further in subsequent sections of this report, the current scientific understanding of the potential effects on climate from aviation emissions range from good for the carbon dioxide emissions to fair for the NOx, water vapor, direct particle, and contrail effects to poor for the effects on cirrus clouds (also see the report from the 2006 Workshop on the Impacts of Aviation on Climate Change).

Although current fuel use from aviation is only a few percent of all combustion sources of CO_2, one of the dominant radiatively important gases currently affecting the climate system as a result of human activities, the expectation is that this percentage will increase in the future. On a multi-decadal time scale, aircraft emissions could become a more significant factor in climate change because of the projected increase in passenger demand and associated flights, and because of the likely decrease in other combustion sources as the world moves away from fossil fuels towards alternative and renewable energy sources. Although the long atmospheric lifetime of CO_2 implies little dependence on where emissions occur, the effects on climate from the other emissions from aviation are strongly affected by emissions primarily occurring at cruise altitudes in the upper troposphere and lower stratosphere. For example, aircraft nitrogen oxides released at these altitudes generally have a larger climate impact than those emitted at the surface, although a small fraction of the much larger surface emissions from energy and transportation sources also reach the upper troposphere.

There likely is no single perfect metric -- the specific metric needed likely depends on the question being asked. For example, for some analyses, policymakers and the aviation industry may both want to consider the total impacts that aviation is having on climate currently and into the future relative to other influences on climate, while for other studies, they may want to consider the integrated effects of a "pulse" of aviation emissions on climate relative to the emissions of other transportation sources. As another example, a metric based on integrated radiative forcing over a chosen time horizon is consistent with the current application of the 100-year integrated Global Warming Potentials in the Kyoto Protocol; however, a different target formulation – e.g. a defined ceiling for global mean temperature change – would require a different type of metric.

The objective of this report is to examine the capabilities and limitations of the metrics currently being used to study human-related and natural forcings on the climate system, to analyze key uncertainties associated with these metrics, and, to the degree possible, make recommendations about which metrics are likely to be most suitable for various applications associated with aircraft emissions. The aim is a focused in-depth review of the scientific principles, uncertainties and gaps, and the modeling capabilities, for determining suitable metrics for comparison of climate impacts from aviation, including those for well-mixed gases (e.g., CO_2, CH_4) and inhomogeneous forcing such as that resulting from changes occurring in the upper troposphere and lower stratosphere from perturbations to the distribution of ozone and particles, the formation of contrails and from perturbations to cirrus clouds. The next section discusses some of the general concerns about metrics for climate, followed by a discussion of the more specific considerations associated with analyzing the climate effects from aviation. Existing metrics being used are then discussed. Recommendations for aircraft studies are discussed and research needs to address specific issues related to aircraft-induced climate change are then defined.

2. A Review of Metrics for Climate Impacts

2a. General Comments About Climate Metrics

There are a number of general concerns that must be considered when trying to find a metric that is the most useful for analyses of aviation and other human-related impacts on climate.

First, it should be recognized that there is now overwhelming scientific consensus regarding the role of human activities in causing the changes in climate that have occurred over the last few decades. The science community has become increasingly convinced that the changes in climate being seen are primarily due to burning of fossil fuels and other human-related activities (IPCC, 2001, 2007a). Nonetheless, there are some significant uncertainties remaining in our understanding of the feedbacks on climate and the resulting impacts. Quantifying the role of aviation is further complicated by uncertainties in understanding the specific mechanisms whereby aviation can affect climate - for example, determining the effects of emissions of nitrogen oxides from aircraft on tropospheric and stratospheric ozone and the resulting effects on hydroxyl and methane concentrations. Since ozone and methane are radiatively important "greenhouse" gases that can affect climate, these effects need to be well understood. An even larger uncertainty is the extent of persistent contrails from aviation and the resulting effects on climate, the role of these contrails and the aerosol (particle) emissions from aviation on cirrus cloud production in the upper troposphere, and the role of cirrus in climate change.

Second, projections of regional changes in climate are, at this point, still less well understood than the global effects on climate. Regional impacts are driven by regional feedback mechanisms and the local distribution of forcing agents. Regional feedback mechanisms can be driven by such things as proximity to a large body of water, local climate and elevation. Local distribution of forcing agents is particularly important for short-lived species. These issues are particularly important for aircraft emissions because aircraft emissions contain both long- and short-lived constituents and span a wide range of geographic regions.

Also, the effects of temperature changes are also better understood than precipitation changes. It is for this reason that globally-averaged surface temperature is generally used as the primary model-derived output variable for climate change. As our ability to model other variables, such as precipitation, cloud cover, etc., improves, the climate change variable of choice may change as well.

Emissions-based metrics (e.g., Global warming Potentials) are often defined based on emissions put into the current atmosphere. However, the atmosphere is not at a steady state. The atmospheric composition, plus temperature and other physical variables, are changing, largely as a result of human-related activities. As a result of nonlinear relationships in atmospheric chemistry and in radiative and other physical processes, a metric calculated assuming the background corresponds to 2050 may result in very different values than if the metric is calculated relative to the background corresponding to the current atmosphere.

Some additional difficulties in developing metrics for climate change include the choice of an appropriate structure for the metric (which may depend on its intended use), the quantification of input values (due to underlying uncertainties) and the need for value judgements in the choice of parameters within these metrics (e.g., the evaluation of long term impacts versus short term impacts). Such value judgements go beyond natural sciences. In the choice of impact parameter there is also a trade-off between relevance and uncertainty.

The scientific limitations in our understanding of climate change and the impact of aircraft emissions will be discussed in more detail as we look at specific metrics and their usefulness. There are some general questions that must be answered in order to evaluate a metric. These questions include: What is the function or purpose of the metric? Can the metric be applied to various scenarios and forcings? What is the effectiveness of the metric for the user, whether it is for technology or policy considerations? Is the metric flexible enough to incorporate advances in scientific understanding?

2b. The Characteristics of a Climate Metric

Development of meaningful metrics for climate change requires a reasonably accurate capability for the evaluation of the effects of human-related and natural factors affecting climate. Such capabilities require complex state-of-the-art models that include representations of, and interactions among, the atmosphere, its chemical composition, the oceans, biosphere, cryosphere, etc. These models encapsulate our understanding of physical, chemical and biological processes. However, they are not useful in directly providing metrics for, for example, policymaking for several reasons. They require very large computer resources and considerable expertise to perform calculations and to diagnose results from the large amount of output that they produce. Hence, there is a limit on the number of different cases (e.g., emission scenarios) that can be considered. Alternatively, simplified models or metrics (that build on the results of the complex models) can be used.

Climate metrics have a number of potential uses, including:

- Providing flexible, rapidly-available input regarding the relative ability of various approaches to minimize the potential impact of human activities on the climate system;
- Assessing the relative contributions of emissions from different human activities to climate change;
- Comparing (and ranking) climate effects from competing technologies, energy uses – or the different emissions in a given sector like aviation;
- Ranking the emissions from various countries;
- Establishing a basis for comparing reductions in climate effects in various countries;
- Functioning as a signal for policy considerations to encourage some activities and discourage others;
- As an analysis tool for industries and countries to determine the best approaches for meeting commitments to reduce climate impacts

In general, a metric must be *scientifically well grounded*, but also *simple to use and easy to understand*. It must be an effective tool for communication between scientists, industry, and policymakers. Users, whether it is industry, policymakers, or others, should be able to make use of the metric without further input from the scientific community, so the metric should be *transparent* enough to convey a meaning all on its own. One main concern with developing new metrics is the need to weight *applicability of the metric* versus *ease in understanding the results*. So, the metric needs to be simple, yet users must be confident enough in the scientific quality of the metric to trust it and use it; therefore it should be *subject to a minimum of uncertainties* or have the effects of scientific uncertainties reduced (or at least represented) as much as possible. In the choice of impact parameter, there is also a trade-off between relevance and uncertainty. As stated before, the metric has to be *applicable to the questions or policy concerns of interest*.

Making the right choices is an important part of formulating a metric for climate change. The spatial and temporal scales of interest need to be considered. Are globally- and annually-averaged effects and impacts of climate change adequate or is it necessary to consider regional impacts. Generally metrics have been used at the global scale because of the uncertainties in representing regional impacts.

A choice also must be made as to what are the key parameters to use in representing climate change in the metric. While one could consider parameters like change in precipitation or change in sea level, the most commonly considered parameters are change in radiative forcing, change in temperature, or some sort of economic impact, such as change in damages and abatement costs. The first two (radiative forcing and temperature changes) have wide acceptance in the science community. While economists often argue that damages and abatement costs must be included and that this may be the only way to really compare climate change impacts across different emissions sources and at different geographic locations, there is no general consensus on what the best approaches are for doing so.

A choice must also be made as to how to consider temporal changes in the climate parameter and/or the emissions of interest, e.g., whether to consider the absolute change in the climate parameter over a given time period, the integrated change over a given time period, and/or to consider the effects of pulsed or sustained emissions. Such choices can affect decisions using the metric, e.g., whether it is best to reduce emissions of long-lived gases or short-lived gases or particles.

In considering a metric, it is important to recognize the current state of scientific understanding. It would be very difficult, for example, to define an accurate metric based on regional (or even global average) precipitation because current regional and global climate models have significant uncertainties in representing precipitation processes and their interaction with the global climate system well enough. Essentially all of the climate metrics being used in analyses of human-related emissions to date are based in some way on the change in globally-averaged (and annually-averaged) surface temperature as the measure of climate change since that is the projection in which we have the most confidence from a scientific perspective. As our scientific understanding improves, the metrics of choice might change.

Other considerations in metrics choice include also the choice of an appropriate structure (e.g., to be applicable to temperature targets) for the metric (this choice will likely depend on the design of any climate policy it is intended to serve), the quantification of input values (due to underlying uncertainties) and the need for value judgements in the choice of parameters within these metrics (e.g., the evaluation of long term impacts versus short term impacts). Such value judgements go beyond natural sciences.

2c. Special Considerations for Aviation Analyses

Emissions from aviation present some special problems for climate metrics. First, these emissions are deposited largely into the upper troposphere and lower stratosphere while other human-related emissions are mostly at the Earth’s surface. Second, the total emissions from aviation are relatively small when compared to the total emissions from other anthropogenic sources of radiatively active (either direct or indirect) constituents. Third, aircraft emissions contain both long- and short-lived constituents, meaning that both direct radiative effects and the indirect radiative effects via complex chemical and physical processes, such as impacts on ozone, methane and cloudiness, all need to be considered. Aircraft emissions also contain aerosols, which are difficult for climate metrics to accurately depict because of the non-linear effects of indirect forcings (Lohmann and Feichter, 2005).

Emission Region

A number of past studies have examined the relationship between radiative forcing and temperature change. Typically these have examined the effects resulting from long-lived gases or well distributed changes in forcing, such as changes in the solar flux. For example, Hansen et al. (2005) examined the climate sensitivity to CO_2 and solar irradiance changes. They found that the climate sensitivity does depend on the magnitude of the forcing, but for forcings close to the current state the sensitivity is nearly constant. As the forcing from CO_2 or solar irradiance in the model was changed, the climate sensitivity changed as well.

Aircraft emissions are deposited locally, both geographically and in altitude. Aircraft emissions are deposited predominately in the upper troposphere and lower stratosphere in the Northern

Hemisphere mid-latitudes. Part of the difficulty in understanding the chemical and physical impacts on climate from aviation emissions is because the upper troposphere / lower stratosphere (UT/LS) is a highly coupled region where dynamics, chemistry, microphysics and radiative processes are fundamentally interconnected. Water vapor and ozone, perhaps the two most important greenhouse gases in the UT/LS, are controlled by both transport processes, such as stratosphere-troposphere exchange, and chemical processes including multiphase chemistry, and cloud microphysics, which in turn are influenced by the temperature and aerosol distributions. The UT/LS is a region of much scientific scrutiny (e.g., Pan et al., 2007) because of the uncertainties surrounding these complex interactions.

Since aircraft emissions have such a unique region of influence, one might think that they would have an equally unique forcing signature. Unfortunately, Boer and Yu (2003b) and other studies suggest that this is not the case for different geographic distributions. Rather, they found that the geographic distribution of temperature change is predominately determined by the geographic distribution of the feedback mechanisms and only secondarily determined by the geographic distribution of the forcing agent.

Hansen et al. (2005) also determined that it was difficult to use the geographic pattern of the temperature response to determine the climate forcing agent responsible. They tested the climate response to different geographic patterns of CO_2, CH_4, O_3, BC (black carbon, soot) aerosols, N_2O and CFCs, as well as land use, volcanic emission and solar irradiance change, and found that the temperature response preferentially occurred in certain places, particularly high latitudes. In fact, Hansen et al. (2005) examined the geographic distribution of the temperature response normalized by the magnitude of the forcing (assuming constant sea surface temperature) so that the global average radiative forcing is the same for all runs and found that for well-mixed greenhouse gases “changes evoke nearly identical normalized response” patterns. This pattern also held for the all-forcings-at-once scenarios, but broke down somewhat for scattering aerosols and more so for absorbing aerosols.

On the other hand, Hansen et al. (2005) found that the vertical distribution of temperature change could be used to indicate a vertical distribution of forcing agent. Aircraft have a very distinct vertical influence, so it is possible that the vertical distribution of forcing can be linked to a change in environment lapse rate. Further studies are needed to determine if this is a reliable way to detect aircraft impacts. *This also raises the question of whether the normal surface temperature-based metric is capable of adequately capturing the climate impacts of aviation.*

Total Emission Size

Aircraft emissions are not large when compared to other anthropogenic sources of radiatively active constituents. It is not possible to evaluate emission signatures of the non-CO_2 short-lived emissions from aviation in climate models because the signal does not rise above the natural climate variability and model noise. In order to detect an aircraft signature in a climate model relative to natural climate variability, aircraft emissions have to be scaled to a larger size. Scaling presents its own set of problems because if the scaling factor is too large then the model is no longer in the linear regime of the emission-response function. As an example, scaling the NOx emissions from aviation to be able to detect effects on climate may be affected by nonlinearities in the chemistry and physical processes leading to the resulting changes in ozone and methane. For aircraft emissions, as with other anthropogenic emissions of short-lived it is unclear just how important such non-linear effects are in determining the climate response.

Short-lived Species

In addition to long-lived atmospheric constituents like CO_2, aircraft also emit short-lived pollutants that are either themselves radiatively active (e.g., aerosols) or can affect radiatively important gases, particles, or clouds. Short-lived emissions, which last from minutes to days, can affect the geographic region where they are emitted and the effect will likely be different for different geographic regions, even for the same emissions. In addition, the lifetime of gases like CH_4 depend on the chemical composition of the background atmosphere. In order for a climate metric to work effectively for aircraft emissions, the metric must take into consideration short-lived species.

Concentration-based metrics like radiative forcing are often being used to examine the change in climate forcing over a period of time and ignore the transient effects. Because it is unlikely that a transportation source like aviation is suddenly going to have no emissions tomorrow or even in a few years, it can be worthwhile to use a concentration-based metric like radiative forcing to consider what effects emissions are having on climate over a given time period. However, there is also significant value in considering the transient effects. The very different atmospheric lifetime of the emission effect associated with CO_2, NOx/O_3, CH_4, and contrails suggest that technology or policy changes could lead to vastly different short-term versus long-term effects on climate. Metrics that consider these transient effects thus can provide useful insights.

Contrails present a problem that is unique to aircraft emissions. Current models do not adequately simulate the ice-supersaturation environment necessary for persistent contrails, nor do they have the spatial resolution to represent individual contrails, so it is difficult to adequately model contrails. In addition, contrails typically have very short lifetimes as compared to other radiatively important aircraft effects. As a result, the climate effect from contrails is still poorly understood. Hansen et al. (2005) did climate simulations using “observed” contrail coverage multiplied by a factor of 10. Nonetheless, the climate effect may be large enough locally to be important to climate analyses. The problem is how to account for such uncertain effects in metrics being used for studying the climate effects associated with aviation.

Aerosols emitted by aircraft have a relatively small direct effect on climate but may be important as condensation nuclei for cirrus formation. The direct radiative effect of aerosols is reasonably well understood compared to the indirect effects on cloudiness. The indirect effects are harder to understand than the direct effect because of the poorly understood interactions between aerosols, cloud condensation nuclei and cloud properties. In addition to the indirect effects there is also a semi-direct effect caused by soot. Black carbon warms the air in the immediate vicinity and leads to cloud evaporation (Hansen et al., 1997). Chylek et al. (1996) also points out that the location of soot relative to the cloud is very important to radiative transfer. If soot is above the cloud layer, it behaves very differently than if it is below the cloud layer. Aerosols also change the optical properties of clouds and cause an increase in the ice nucleation efficiency of mixed-phase clouds (Lohmann, 2002). Smaller liquid droplets from aerosol-influenced clouds would decrease the freezing efficiency and allow supercooled droplets to penetrate higher into the cloud.

For subsonic aircraft, NOx emitted from aircraft are short-lived (lifetime of days) but the NOx emissions in the UTLS generally lead to O_3 formation and CH_4 destruction, depending on the background environment. Regional dependence of O_3 production depends on solar flux (varies by latitude), background NOx concentration, and local chemistry and emissions (IPCC, 2001;

Prather et al., 1999; Collins et al., 2006; Jacob et al., 2005). As a result, the impact of NOx emissions depends on where the emission occurs.

Current global-averaged analyses imply that cooling effects of CH_4 decreases and warming effects of O_3 increases from aviation are roughly of the same magnitude. CH_4 is well distributed globally because of its longer lifetime (~8 years, but recovery time after a CH_4 perturbation is closer to 12 years because of the resulting interactions with atmospheric hydroxyl), but aviation effects on O_3 not globally distributed because of the relatively short atmospheric lifetime of tropospheric (and lower stratospheric) ozone. As a result, the distribution of warming/cooling effects from ozone and methane perturbations from aviation will not be equally distributed across the globe. In addition, it has been shown than the regional climate response is not the same for all regions of the Earth. Equatorial latitudes show a stronger response to emissions than mid-latitudes (Bernsten et al., 2005; Fuglestvedt et al., 2003; Derwent et al., 2001).

Metric Considerations

There are a variety of potential questions that a user may want to address in terms of aviation applications using climate metrics. Depending on the question, more than one type of metric may be needed to fully address all aspects to be evaluated. Some examples of potential questions include:

- What are the climate effects of aviation relative to other transportation sectors?
- What technology choices will minimize the impacts on climate?
- Which forcing agent in aviation should be the highest priority for policy considerations?
- What are the trade-offs between reductions of different forcing agents?
- What are the trade-offs between different policy considerations?
- How can the industry maximize the benefit while minimizing the cost of abatement?

In order to answer such questions, a climate metric (or metrics) should be able to weight the different forcing agents and put them all on the same scale for comparison. While there has not been universal agreement, many studies of climate forcings compare the impact of various climate forcings with the forcing from changes in CO_2, the gas currently having the largest human-related impact on climate. Forcing agents are often considered in terms of their "CO_2 equivalent" forcing effect. Of course, then one has to decide what is meant by equivalence. Are forcings equivalent in terms of their radiative forcing, integrated radiative forcing, change in global average surface temperature, integrated change in global average surface temperature, etc.?

There may be metrics that would be particularly suitable for aviation emission, e.g., a metric that applies best to the climate effects associated with changes occurring in the upper troposphere and lower stratosphere. However, even if such a metric exists, another factor is just how useful the metric is for other climate policy considerations because metrics for aircraft emissions must also fit into the framework being used by policymakers and others for sectors analyzing human-related emissions effects on climate.

2d. Development of Radiative Forcing as a Metric

The most widely used metric for climate change has been radiative forcing. Since it is used in many of the concentration-based and emissions-based metrics, it is worthwhile to first look at the definition and historical development of radiation forcing. In fact, as seen in later sections, there is no single “radiative forcing” metric; there are several “flavors” of radiative forcing based metrics. Although the use of the stratospheric adjusted radiative forcing metric is often used for aviation studies (e.g., IPCC, 1999; Sausen et al., 2005) and has been proposed by some policymakers for use in possible policy development relative to aircraft emissions, the classic evaluation of this metric has limited suitability for that purpose and it is clear that it only provides part of the story regarding aircraft effects on climate. Other metrics will need to be considered – for example, emissions-based metrics provide important information not provided by the traditional use of radiative forcing as a concentration-based metric.

The term ‘radiative forcing’ as a metric applied to climate change has been used since the 1980s. It has been a central tool in all of the international assessments of climate change. The IPCC Assessment (2001) describes radiative forcing as “a useful concept, providing a convenient first-order measure of the relative climatic importance of different agents” without the need to actually conduct time consuming and computationally expensive climate model simulations. However, as discussed later, this concept has significant limitations for spatially inhomogeneous perturbations to the climate system and can be a poor predictor of the global mean climate response. As a result, alternative definitions have been developed.

Essentially, radiative forcing for a given greenhouse gas or other forcing agent requires two primary factors, its three-dimensional distribution and how this has changed over time, and its interactions with solar and thermal infrared radiation (Shine and Forster, 1999; Myhre et al., 2001).

Over time, the radiative forcing concept has been broadened to not only include changes in solar flux and changes in relatively long-lived greenhouse gases like CO_2, O_3, CH_4 and various halocarbons, but also to include the climate effects resulting from changing emissions and concentrations of short-lived gases and particles. Short-lived gases generally have little direct effect on climate but can have indirect climate effects through chemical interactions affecting radiatively important constituents like O_3 and CH_4. Emissions of and secondary production of atmospheric particles can have both direct effects on climate and indirect impacts on climate resulting from their effects on cloudiness.

The concept of radiative forcing arose directly from the assumption that the Earth-atmosphere system is always approximately in radiative convective equilibrium. Assuming radiative-convective equilibrium, the heating rate of the atmosphere can be derived as:

$$\frac{dH}{dt} = F - \frac{\Delta T}{\lambda},$$

where $H = \int_{z_b}^{\infty} \rho C_p T dz$ is the heat content of the atmosphere, F is the forcing on the system, ΔT is temperature change in the system, λ is the climate sensitivity parameter that accounts for the effects of climate feedbacks, ρ is the density of the atmosphere, C_p is the specific heat, and z_b is the depth that heat penetrates into the atmosphere. For analyses of changing solar flux and changes in the concentration of carbon dioxide, climate model calculations found an approximately linear relationship between global-mean radiative forcing at the tropopause and the change in equilibrium global mean surface air temperature. Because of the close linking of the troposphere to the surface through convection, climate models have typically found that the land surface, ocean mixed layer, and troposphere together respond to a radiative forcing for such perturbations with a relatively uniform increase in globally-averaged temperature.

As a result, the steady state form of the heat change equation is:

$$\Delta T = \lambda F.$$

This equation has traditionally been used to estimate surface temperature change given the radiative forcing, with an estimated value or uncertainty range in the climate sensitivity parameter (generally λ is taken to be the value corresponding to that expected for a doubling of the atmospheric concentration of CO_2 from pre-industrial levels, namely a 1.5 to 4.5 degree C change in surface temperature for a 4 Wm^{-2} increase in radiative forcing). The first applications of a radiative-convective model to predict radiative forcing effects of greenhouse gases and clouds in the Earth's atmosphere were done by Manabe and Strickler (1964) and Manabe and Wetherald (1967). These early studies demonstrated that the climate of the Earth can be affected by the influences (or forcings) of changes in solar irradiance and albedo and changes in the atmospheric distribution of certain radiatively active gases and aerosols.

A number of studies of examined the sensitivity factor λ, but without much success in reducing the uncertainty range (NRC, 2003; Meehl et al., 2004a; Schwartz, 2004; Andronova et al., 2007; Kiehl, 2007; Roe and Baker, 2007; plus discussion and references in the various IPCC assessments). The primary factors affecting the range of sensitivity factors founds in existing climate models appear to be uncertainties associated with the treatment of aerosols and cloud processes. However, Stuber et al. (2005) suggest that the two largest factors in the variability of λ are the varying strength of stratospheric water vapor feedback and the sea ice-albedo feedback.

Ramanathan et al. (1985) found that the climate sensitivity or climate feedback parameter, λ, was almost invariant to the type of forcing used in a one-dimensional radiative convective model. Many other climate modeling studies have shown an approximately linear relationship between the global mean change in radiative forcing at the top of the atmosphere resulting in a change in the equilibrium global mean temperature at the surface. Models have shown a large difference in λ between different climate models (thus the range of values mentioned above), but an approximately constant value for λ within a particular model for changes in solar flux and atmospheric concentrations of long-lived gases like CO_2, CH_4, and N_2O.

Ramanathan et al. (1987), as well as a number of later studies (e.g., Wang et al., 1986; Hansen et al., 1997; Jain et al., 2000; Naik et al., 2000; Forster et al., 2001; Gauss et al., 2003; Gohar et al., 2004; Huang and Ramaswamy, 2006; Meehl et al., 2004b; Tett et al., 2002), examined the effects of various trace gases on climate. Many trace gases absorb infrared radiation and can have a significant surface warming effect. Some gases can also affect climate indirectly by chemically altering the composition of the atmosphere. Wang et al. (1991) noted that global climate models had either neglected trace gases altogether in model simulations or did not study the differences in climate responses between trace gases and CO_2. Wang et al. (1991) recognized that the behavior of CO_2 is very different from that of other trace gases, because different gases absorb at different wavelengths and have different atmospheric lifetimes.

A number of studies have since examined the definition of radiative forcing. As stated in Chapter 15 (Ramanathan et al., 1985) of the WMO (1985) global atmospheric ozone assessment, "Radiative forcing due to trace gases can be considered either in terms of the changes in the fluxes of radiative energy into and out of the entire system (i.e., surface-troposphere system) or in terms of the change in the vertical distribution of the radiative heating rates. The choice between the two quantities depends on the region of interest. Within the troposphere, the vertical mixing of sensible and latent heat by convection and large scale motions is considered to be quite rapid compared to the time scales associated with radiative adjustment. As a result, the vertical distribution of the tropospheric temperature change is largely governed by the radiative forcing of the column. Hence, as a first approximation, we can ignore details of the vertical distribution of the tropospheric radiative forcing and focus, instead, on the radiative forcing of the entire surface-troposphere system."

Using this knowledge, column radiative transfer models were developed. Column models are much less computationally intensive than global climate models (GCMs). Column models can compute the globally averaged radiative forcing in a small fraction of the time it takes to run a full GCM and at a fraction of the cost. In addition to saving both time and money, the model noise level in column models is much lower than it is for global models so the impact of relatively small perturbations like those for the current aviation fleet is much easier to detect.

Later uses of radiative forcing built upon the fact that the climate responses differed for different substances in the atmosphere. The concept of radiative forcing was originally implemented for the global climate system, but during the 1990s, its use was extended to determine regional mean radiative forcing for various seasons in order to account for the effects of short-lived gases and aerosols that occur over certain regions (Wang et al., 1992; Haywood and Ramaswamy, 2006). Wang et al. found that the use of "effective CO_2" in climate models (as often used still) as a proxy for other gases such as methane and N_2O was generally fine for determining global average surface temperature (as long as the forcing was dominated by well-mixed gases), but it is not sufficient to assess future climate changes on a regional scale. Wang et al. (1992) emphasized the need for trace gases to be included in regional calculations. Cox et al. (1995) brought attention to the fact that the cooling effects of regional anthropogenic aerosols were "offsetting a substantial fraction of the global mean response to forcing due to greenhouse gases." Cox et al. (1995) found that the hemispheric temperature response was considerably less than expected, and the regional forcing also demonstrated substantial differences between forcing and temperature response. These differences are an indication that there is a need to represent the spatial and seasonal distribution of aerosol forcing when examining climate responses more detailed than the global and annual mean (Cox et al., 1995).

The generally accepted definition of radiative forcing, as adopted initially by IPCC (1990) is the change in net irradiance (in Wm^{-2}) at the tropopause after allowing stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures held fixed at the unperturbed values. Comparisons of radiative forcing from different forcing agents relied on the assumption that the climate sensitivity factor was constant, therefore a particular radiative forcing led to the same change in globally-averaged surface temperature. Recent studies have shown that the climate sensitivity parameter, λ, is not constant within a particular model for all climate forcings. For example, Hansen et al. (1997) found that there is sensitivity in the climate response to the altitude and latitude of the forcing. In particular, forcings that are inhomogeneously distributed, like aircraft-induced changes in ozone and the effects of contrails, can have very different (even negative) climate sensitivities (IPCC, 1999). Indirect effects due to unevenly distributed aerosols also may have different climate sensitivities.

Radiative forcing is a particularly attractive concept for well-mixed gases because it can be calculated either within a comprehensive climate or Earth system model, or it can be calculated, almost as accurately in a simple column radiative transfer model (RTM) (or more accurately since the column model can use a higher wavelength resolution form of solution). Though column models do not have grid-to-grid interactions, they are less noisy than full climate models so it is easier to pick the small aircraft signal out of the model noise. Column models are also much cheaper and much faster than larger, more comprehensive models.

2e. Existing Metrics

There are basically two families of science-based metrics that are currently being used in studies of and policy considerations relative to climate change. The first, referred to as concentration-based metrics do not directly account for emissions, but instead are based on the forcing or temperature change over a given time period. The other family of climate metrics are emissions-based, either assuming pulse, sustained or an emissions scenario over time. The following discussion is aimed at examining the advantages and limitations for each of the major metrics currently used. Other less used metrics are also discussed, along with the limitations that have kept them from being widely used and/or accepted. Some early climate metrics (e.g., Rogers and Stephens, 1988; Fisher et al., 1990) aimed at comparing chlorofluorocarbons and other halogenated gases are not discussed here.

Concentration-based Climate Change Metrics

The concentration-based metrics are largely different “flavors” of the radiative forcing concept and its application. Some new approaches (e.g., fixed surface temperature forcing; use of efficacies) may improve upon the traditional definition but have not yet gained wide acceptance and also appear at this point to have their own limitations.

Instantaneous radiative forcing

Instantaneous radiative forcing at the top of the atmosphere and/or at the tropopause is the most straightforward form of radiative forcing to derive because it involves the least amount of effort and does not account for feedbacks within the climate system. However, it was recognized early on that when forcings occur in the stratosphere, the temperature responds rapidly locally in order to restore the radiative balance in the stratosphere (IPCC, 1990; Hansen et al., 1997). This change in stratospheric climate in turn affects the tropospheric temperature. As a result, stratospheric adjustment has been adopted universally in the calculation of radiative forcing. IPCC has adopted the stratospheric-adjusted radiative forcing as the preferred climate metric. While instantaneous radiative forcing is often reported (e.g., in some cases in the IPCC, 1999, assessment of aviation), it is not generally used in assessing the potential impacts on climate.

Stratospheric adjusted radiative forcing

The most widely used metric as a proxy for climate change has been globally-averaged annual mean stratospheric adjusted radiative forcing (RF) at the tropopause (which is the same as the RF at the top of the atmosphere after stratospheric adjustment.) For this metric, as discussed in the previous section, globally-averaged annual mean surface temperature is assumed to be equal to the RF multiplied by a climate sensitivity factor. This method works well for well-mixed greenhouse gases, solar irradiance, surface albedo, and homogeneously distributed non-absorbing aerosols (IPCC, 2001). However, the linear relationship between RF at the tropopause and global mean surface temperature may not hold for forcing agents that have a strong response near the surface but very little response at the top of the atmosphere. This relationship also breaks down if the forcing agent is not homogeneously distributed. The classical definition of RF also applies best for global-mean climate response and does not account for regional climate change. In addition to the RF, we must also consider the efficiency of a particular forcing agent in causing climate change. This "efficacy" is not considered in current RF calculations using the traditional definition of RF. The effects of including efficacies in a revised definition of RF are provided later.

As a key example of the application of RF to aviation, an update of the IPCC (1999) globally averaged annual mean RF from aviation for the "current" time period (relative to no aircraft) has been presented by Sausen et al. (2005). Specifically, the forcing from CO_2 was calculated from the cumulative change in concentration of CO_2 from historical operation of the aircraft fleet. The other forcings were calculated from the steady state change in concentrations of O_3, CH_4, and H2O to the 1992 emissions. The forcing from sulphate, soot, contrails and contrail-cirrus also correspond to steady responses. Figure 2 summarizes their results as well as the findings from IPCC (1999). In view of the large error bars of IPCC (1999), the RF from CO_2, H_2O and direct effect of sulfate aerosols have not changed significantly, apart from the increase in air traffic from 1992 to 2000. The O_3 and CH_4 effects are changed due to more recent analyses from European chemical-transport models. The other major change is found for the direct global RF from (linear) contrails; the new value is roughly a factor of 3 smaller than IPCC (1999) based on results from Marquart et al. (2003) and Myhre and Stordal (2001), which were scaled (by fuel burn) to the year 2000 resulting in 6 mW/m^2 and 15 mW/m^2, respectively. As indicated in the bottom part of Figure 2, the overall conclusion from these analyses is that significant uncertainties still remain in quantifying the impacts of aviation emissions on climate. Except for carbon dioxide, the understanding of the climate effects from other aviation emissions range from fair to poor. Note that the RF for direct soot in Figure 2 are based on the atmospheric soot concentrations, and does not include the soot incorporated into clouds or long-term deposition to the ground.

Below is a list of strengths and weaknesses associated with the globally averaged annual mean RF calculations:

<u>Strengths:</u>

- Widely used in many climate assessments, including aviation studies (e.g., IPCC, 1999; Sausen et al., 2005).
- Forms the basis for evaluation of the emissions-based metric Global Warming Potentials, which is widely used in climate policy considerations, particular for emissions trading between different transportation and energy systems.
- Global mean surface temperature change is linearly related to the top of the atmosphere RF for many forcing agents, especially well-mixed greenhouse gases (Boer and Yu, 2003a; Hansen et al., 1997; IPCC, 1995; Joshi et al., 2003; Rotstayn and Penner, 2001).
- Easy to search parameter space.
- Fast and inexpensive to run using a radiative transfer model (RTM), so a number of detailed studies can be done and many factors can be considered.
- Much less concern about climate variability and model noise in RTMs than the complex global climate models, so smaller forcings can be considered.

- Easy to compare effects of different forcing agents, assuming the climate sensitivity is the same.
- Relatively easy to compare different models.
- Benchmarks relative to highly accurate line-by-line RF values exist for many gases.
- Observation-based estimates of radiative balance provide constraints to the RF values.

Limitations:

- Does not account for the lifetime expected for the forcing agent or the temporal response after the perturbation is initiated. Generally based on a “snapshot” atmospheric perturbation over a given time period.
- Difficult to determine RF from indirect changes using simple models.
- Difficult to interpret relative RFs for direct and indirect effects from gases and particles having short atmospheric lifetimes and inhomogeneous distributions.
- No hydrological response information is included.
- Light-absorbing aerosols are not fully treated (indirect aerosol effect and semi-direct effect).
- Does not characterize the regional responses.
- Non-linear response from large perturbations or perturbations that are not well mixed may not be accurate.
- RF comparisons depend on climate sensitivity, which is not well understood.
- Models show that climate sensitivity is not the same for aerosols and ozone as it is for CO_2 (Cook and Highwood, 2004; Hansen et al., 1997; Hansen et al., 2005).
- Models show that changes in ozone in the upper troposphere and lower stratosphere don’t have the same climate sensitivity and that they are also different from the climate sensitivity for CO2 (Joshi et al., 2003; Stuber et al., 2001).
- Does not consider dynamic feedback.
- Does not characterize non-RFs on climate (e.g., land use changes).
- Assumption of a constant, linear relationship between RF at the top of the atmosphere and global mean surface temperature.
- Requires a tropopause height.
- RF is sensitive to the choice of tropopause height (Forster et al., 1997; Myhre and Stordal, 1997; Freckleton et al., 1998).

Radiative Forcing Index (RFI)

The Radiative Forcing Index (RFI) was introduced in IPCC (1999) -- it is defined as the ratio of total RF to that from CO_2 emissions alone. In FRI, total RF induced by aircraft is the sum of all forcings, including direct emissions (e.g., CO_2, soot) and indirect atmospheric responses (e.g., CH_4, O_3, sulfate, contrails). RFI is intended to be a measure of the importance of aircraft-induced climate change other than that from the release of fossil carbon alone. However, it does not take into account the relative time scales of the climate effects or the atmospheric lifetimes of the direct and indirect effects on climate resulting from emissions of the gases and particles (Forster et al., 2006). Because of this, the simple sum of individual forcings used in deriving the total RF can lead to misinterpretation in policy considerations using the single value of the RFI as the basis for policy.

RFI as a climate metric has undergone much criticism since it was proposed. One major concern is that RFI is actually not an intrinsically fixed number (Wit et al., 2005). It is entirely dependent upon either the actual history of the emission or the assumed future scenario, or alternatively, background concentration of CO_2. Wit et al. (2005) and Lee and Wit (2006) show that the RFI will decrease over time even though the aviation emissions were held constant from year 2000 onwards. This is because CO_2 would assume a more and more important role as the time growing due to its long lifetime.

Global-mean radiative forcing at the surface

For forcing agents that change the vertical distribution of heat in the atmosphere, the RF at the tropopause may not be directly related to surface temperature change. One example of this is forcing due to absorbing aerosols, which have a large impact on RF near the surface but very little effect on the tropopause-level RF. Global-mean RF can also be calculated at the surface. Ramaswamy et al. (2001) and Menon et al. (2002a) suggest that this may be a more appropriate metric. If the RF at the tropopause and the surface are compared then we have an idea of how the lapse rate has changed and we may be able to account for some indirect changes like cloud response, precipitation and vertical mixing changes. This approach still does not account for regional climate change, nor does it consider the lifetime of forcing agents. This approach also does not account for dynamic and thermodynamic feedback, but by comparing the tropopause and surface RF values, we may get a sense of how strongly the dynamic and thermodynamic feedbacks could influence climate change. This may lead to an estimate of how much confidence we have in the resulting RF and whether we need to go to a more inclusive climate change, like a full GCM output. Sokolov (2006) suggests calculating a surface climate sensitivity and an atmospheric climate sensitivity, then using these values to modify the stratospheric adjusted RF.

Some of the strengths and limitations of the global mean RF at the surface are:

Strengths

- Gives surface energy budget information.
- By comparing surface RF with tropopause RF, we may get an idea of how strongly dynamic and thermodynamic feedback will influence climate change.
- Accounts for forcing agents that strongly influence the surface temperature, but minimally affect the RF at the tropopause.
- Easy and fast.

Limitations

- Has most of the same limitations as the traditional stratospheric adjusted RF definition.
- No dynamic or thermodynamic feedback

- Surface RF values have not been tested adequately in climate models to determine the climate sensitivity, or even if the surface RF can be directly related to surface temperature change

Fixed sea surface temperature forcing / Fixed surface temperature forcing

Hansen et al. (2002) developed the concept of fixed sea surface temperature (SST) forcing. This metric measures the RF at the top of the atmosphere as computed in a global climate model by holding the sea surface temperature (SST) constant and allowing tropospheric and stratospheric temperatures to reach a new equilibrium. This method has many of the same limitations as the stratospheric adjusted RF metric, but allows the inclusion of the direct and semi-direct aerosol effects within a GCM. This method still does not quantify the regional climate impacts, but it seems to have a more constant climate sensitivity parameter than stratospheric RF (Hansen et al., 2005). Because it depends on the use of a complete climate model, it is much more computationally intensive than the use of a RTM to calculate the traditional RF.

Shine et al. (2003) extended this idea by setting both the land and ocean temperatures constant and allowing the atmosphere to adjust. Their new forcing is called the "(global-mean) adjusted troposphere and stratosphere forcing". The Reading Intermediate GCM (IGCM) is used to illustrate the performance of this forcing. The calculations presented are based mainly on model integrations from a study of the semi-direct aerosol forcing by Cook and Highwood (2004) which used 2 m mixed layer ocean to speed the approach to equilibrium. Two additional calculations examining the impact of ozone changes are presented in Joshi et al. (2003), using a 25 m mixed layer ocean. The results presented were rescaled so the two sets of results have the same climate sensitivity parameter for increases in carbon dioxide concentration. RF is calculated using a 5-year integration of the model with spatially varying sea and land surface temperatures taken from a monthly mean, annually-repeating observed climatology. The global-mean equilibrium surface temperature response is calculated from the temperature change using the mixed-layer ocean after 30 years. Shine et al. (2003) shows an intercomparison of RF results and "fixed sea surface temperature forcing" (Hansen et al., 2002) for several forcing agents, as well as "stratospheric adjusted RF". The results show that the new forcing is a good predictor of the IGCM's surface temperature change for all of the forcing agents considered.

Hansen et al. (2005) further tested these metrics and determined that the fixed surface temperature metric yields a climate sensitivity factor that is closer to 1.0 than stratospheric adjusted RF for aircraft-related scenarios, such as: stratospheric water vapor, tropospheric and stratospheric ozone, and indirect aerosol effects. The “fixed sea surface temperature” and “fixed surface temperature” metrics require the use of a GCM. As discussed earlier, GCMs typically cannot differentiate the aircraft forcing signature from model noise (Hansen et al., 2005 tested 10 times present day contrail coverage). The results from aircraft studies still need to be tested further. One way to do this is to scale the aircraft forcing effect so that it is larger than model noise, but then the question is whether such studies would distort the actual effect of aviation on climate. Studies need to be done to determine if these scaled forcings still lie within the linear forcing-response regime.

Some of the strengths and limitations of the Hansen et al (2002) and Shine et al. (2003) approaches are:

<u>Strengths</u>

- Although this metric does require the use of a GCM, relatively short integrations are needed because the sea surface temperature is not allowed to vary. Nonetheless, this metric is much more computationally intensive than RTM-based metric calculations.
- Existing studies suggest these metrics are more accurate than other RF approaches.
- Includes the direct and semi-direct aerosol effects.
- RF can be calculated at any altitude.
- Fast atmospheric feedback is used to simulate climate change.
- Allows some dynamic and thermodynamic feedback as the atmosphere "relaxes" to a new equilibrium.
- Does not require the tropopause height to be explicitly declared.

Limitations

- Computationally more intensive than RTM-based metric calculations.
- Requires the use of a GCM, and thus is subject to uncertainties inherent in climate models, e.g., treatment of clouds.
- Use of a GCM makes it difficult to determine the aviation signature on climate relative to the model noise.
- Still subject to most of the limitations of the stratospheric adjusted RF approach.
- Much more difficult to compare between models.
- Does not consider non-radiative forcings.
- Does not fully account for lifetime of forcing agents because the results are still steady-state.
- Climate sensitivity parameter is not constant, though it is less variable than the climate sensitivity parameter for stratospheric adjusted RF.
- Not simple or fast.

Time-varying radiative forcing

Time–varying radiative forcing or radiative forcing time series has been used for natural forcing like solar flux variations for some time. Time-varying radiative forcing could be either a concentration-based or an emissions-based metric. As a concentration-based metric, it could be derived for a given scenario of changing concentrations and other forcing agents over time. As an emissions-based metric, it could be based on a pulse of emissions, sustained emissions, or a scenario of emissions over a given time period.

Although it is much more difficult to determine time-varying RF for ozone and aerosols because of the necessity to account for the past emissions, transport, chemistry and other processes affecting the concentration of constituents, there have been several attempts at this. For example, IPCC (2001), Myhre et al. (2001), and Hansen et al. (2002) provide time histories for RF. Time-varying RF has also been applied to aviation, for example, in IPCC (1999) and more recently at a presentation by MIT's Ian Waitz at the AIAA/AAAF Aircraft Noise and Emissions Reduction Symposium.

As applied by Waitz, this metric would calculate RF due to aircraft emissions as the emissions are emitted. RF is calculated for a time period, X, based on the emissions during that time period. The RF is then calculated at time X+dX using the emissions in time dX plus the emissions remaining in the atmosphere that were emitted at time X. This process would continue to yield a time-varying RF based on the time-varying emissions and the removal rate of previously emitted constituents. This approach has not been applied to specific scenarios for aviation emissions at this point. Essentially, this approach involves derivation of a time-dependent snapshot of RF that depends on the given assumptions of emissions.

In order to do this correctly, the adjustment time of the ocean-atmosphere system needs to be taken into account. The RF that will determine temperature for any given time would be a weighted average of the RFs during the previous years. It is not clear that this time-varying RF metric would yield different results than the stratospheric adjusted RF calculations using steady-state species concentrations, but it does have the benefit of explicitly considering short-lived species.

Some of the strengths and limitations of the time-varying RF approach are:

<u>Strengths</u>

- Easy to understand concept, but not necessarily easy to calculate.
- RF can be calculated at any time.
- Lifetime of the species can be explicitly considered in the calculations. As such, it could be considered to be an emissions-based metric. However, applications to this point have basically used observed changes in the forcing agents. The Waitz approach, if applied, would be an emissions-based metric.

<u>Limitations</u>

- Depending on how derived (RTM vs. climate model), it still subject to many of the limitations of the previously discussed RF approaches.
- As applied using observed changes in forcing agents, this metric really has not caught on and remains little used.
- Indirect effects require special consideration before can be considered.
- More computationally intensive than stratospheric adjusted RF calculation using a column model.
- No dynamic or thermodynamic feedback.
- Computationally more intensive than stratospheric adjusted RF.
- If column model RFs are used then this method still requires a declared tropopause height.
- Much more difficult to compare between models.
- Does not consider non-radiative forcings.
- Climate sensitivity parameter is unclear. Climate model studies would have to be done to determine how the RF calculated in this way are related to surface temperature change.

Equivalent (or efficacy-corrected) radiative forcing

Of all the problems associated with RF (in all its flavors), the most serious limitation may come from the fact that not all forcing agents cause the same climate impact (for the discussion here, change in globally averaged surface temperature) for a given change in radiative flux. This means that RF from one cause cannot be compared to RF from another cause easily. One way to get around this problem is to define an "equivalent" RF where the forcing is weighted by its climate sensitivity. This additional multiplier term is called "efficacy".

The equivalent RF metric appears to be becoming the new standard as a concentration-based metric for climate change. The equivalent RF is defined as the efficacy (climate sensitivity of the particular forcing agent divided by the climate sensitivity of CO_2) multiplied by the RF. The stratospheric adjusted RF is the most logical RF parameter to use because it does not require a GCM to calculate it.

Since aircraft forcing signals get lost in GCM noise, a metric that does not require the continual use of a GCM is highly desirable. As a result, for analyses of the effects of changes in aviation effects on the atmosphere over a given time, when a concentration-based approach is useful, the equivalent RF metric is likely the best choice.

However, while this approach is certainly a significant improvement over the standard RF definitions, it still has a major problem, namely the accurate determination of the efficacy factors. Determining the climate sensitivity to various forcing agents is the hard part and requires the use of a GCM. As the spatial distribution of emissions change over time or the background atmosphere changes, there is also the question of whether the efficacy has to calculated all over again. So far, the literature has not really addressed this question. For aviation, there remains the problem of signal to noise ratio, adding further to the potential uncertainties associated with using efficacies. All we can really say at this point is the use of efficacies are likely to be more meaningful than the traditional RF approaches.

Appendix A provides a discussion of currently available evaluations of efficacy factors. Existing efficacies, in general, have limited usefulness for application to aviation even though some scientists are adapting results from Hansen et al. (2005) for that purpose. The problem is that either the efficacies have been based on idealized changes in the distribution of a constituent or they have been based on only a single model that may or may not have wide spread applicability.

Some of the strengths and limitations of equivalent RF approach are:

<u>Strengths</u>

- Easy to understand concept.
- If efficacy factors can be accurately determined, then it is easy to calculate.
- Indirect effects can be considered through efficacy values, but not explicitly.
- Equivalence is determined in a way that is widely accepted.

<u>Limitations</u>

- Lifetime of forcing agents is not directly considered. Perhaps an efficiency factor could be used to scale a response depending on its lifetime, but at this point there has been no attempt to do so.
- Most of the limitations of stratospheric adjusted RF also apply to equivalent RF

- Requires a spatially-varying tropopause height location.

Emissions-Based Climate Change Metrics

These metrics all begin with emissions as their starting point. Many policy analyses are aimed at controlling emissions or examining tradeoffs relative to emissions – as a result, those types of analyses require emissions-based metrics.

Time-Dependent Radiative Forcing

When applied in terms of the emissions instead of just observed or modeled concentration changes, the time-dependent RF metric can be an emissions-based metric. The analysis can assume either a pulse, sustained, or a time-dependent scenario of emissions.

Time-dependent RF can account for the atmospheric lifetime of the emissions and can evaluate indirect effects as well as the direct effects of the emissions being considered. As with some of the other metrics, because of nonlinearities in atmospheric chemical and climate processes, RF can also depends on the initial conditions assumed and on the history of all emissions. Like other metrics, this metric is strongly dependent on the model of chemical and physical processes used for analyzing short-lived gases, particles, contrails and cirrus. It is also less simple and less transparent than other metrics. Efficacies can be used with metric (as they can with any metric using RF) towards creating an improved equivalence across different types of emissions.

Stevenson et al. (2004) uses pulse emissions and resulting RF to examine the effects of aviation NOx emissions on ozone and methane. With this approach, they are able to clearly show the effects of atmospheric lifetimes on the resulting RF with time. In general however, time-dependent RF is not commonly used. One of the difficulties with it as a metric is how to interpret time-dependent RF relative to the time-dependence of the resulting climate response. As pointed out by Shindell et al. (2005), the resulting climate effects of using emissions rather than concentration perturbations are quite different.

Global Warming Potentials (GWPs)

The concept of GWPs as generally used was developed for the first IPCC assessment (IPCC, 1990) by Wuebbles, Rodhe and Derwent (growing out of previous development of the Ozone Depletion Potential concept and alternative concepts for GWP-like metrics proposed by Lashof and Ahuja (1990), Rodhe (1990), Wuebbles (1989), and others). This concept has been extensively utilized, discussed, and criticized ever since (e.g., see discussions in other IPCC assessments). Despite all of the criticisms of its limitations (e.g., Wuebbles, 1995; Wuebbles et al., 1995; Smith and Wigley, 2000a, b; Fuglestvedt et al., 2000; Godal and Fuglestvedt, 2002), it remains the most popular emissions-based metric and it is likely that it will be used into the foreseeable future. GWPs have been adopted as an instrument for the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). Lashof and Ahuja (1990) developed a similar, but somewhat different concept that uses steady-state calculations (which unfortunately do not apply readily to CO_2 because of its complex decay function).

Global Warming Potentials (GWPs) provide a means of quantifying relative potential integrated forcing on climate from emissions of various greenhouse gases. In the international assessments, GWPs have been defined as the time-integrated RF from the instantaneous release of a unit mass of a gas expressed relative to that of the same mass of the reference gas, generally taken as carbon dioxide, the gas of most current concern to climate change. Thus, the concept of GWPs is an index to estimate the relative impact of emission of a fixed amount of one greenhouse gas compared to another for the globally averaged RF over a specified time scale. GWPs provide a better measure of the relative greenhouse impacts than RF alone as they help differentiate between gases that would reside in the atmosphere for vastly different amount of time, from days to, in some case, many centuries. The GWP concept is based on the science of greenhouse gas effects, but does not include climatic or biospheric feedbacks nor consider resulting impacts on the environment. GWPs have generally been applied to gases that are well mixed in the atmosphere, but they can be applied to short-lived gas emissions as well. Although it has not been done at this time, efficacies could be applied in the radiative forcing values used.

GWPs are calculated from the RF as follows:

$$GWP(H)_i = \frac{\int_0^H RF_i(t)c_i dt}{\int_0^H RF_{CO2}(t)c_{CO2} dt} = \frac{AGWP_i}{AGWP_{CO2}},$$

where H is the time horizon over which a forcing is integrated, RF is the RF for a particular forcing agent (i) or CO_2, and c is the remaining abundance of a particular forcing agent (i) or CO2 after a time-decaying pulse emission. AGWP (discussed as a separate metric below) is the Absolute Global Warming Potential for a particular forcing agent (i) or CO_2. The climate sensitivity is assumed to be equal for both the numerator and denominator and therefore cancels out. (This assumption can easily be modified to account for different climate sensitivities of different forcings, but the traditional GWP definition assumes the same sensitivity factor.) Uncertainties in GWPs depend on uncertainties in RF per unit molecule and the lifetime of a particular forcing agent. Efficacies can be also incorporated as a multiplier on the RF – this modified approach is likely better for emissions (e.g., aviation) that are short-lived enough so as to not result in well-mixed forcings on climate.

GWPs allow the direct comparison of integrated forcing for any forcing agent and the forcing due to CO_2. The basis for this is that CO_2 is the greenhouse gas of primary concern to climate change. While GWPs are relatively simple to derive for long-lived well-mixed gases, they are more difficult to derive for short-lived gases with indirect effects, e.g., like NOx emissions on ozone and methane. GWPs have a high degree of transparency in the methodology compared to other emissions-based metrics, which allows other scientists to easily verify calculations and policy makers to easily compare different forcing agents.

Unlike Ozone Depletion Potentials (ODPs), the metric used in the Montreal Protocol and other stratospheric ozone policy that can be calculated to steady-state it is not possible to integrate the AGWP for CO_2 to steady-state. Because of the complexity of the carbon cycle, the decay of atmospheric carbon dioxide is a complex function that generally is represented as the sum of a series of exponential removal terms. For this reason, GWPs are usually determined for select integration times. However, these integration times are arbitrary.

IPCC assessments have adopted multiple time horizons for the integration, generally 20, 100, and 500 years, reflecting that specific questions being addressed might need to consider different time horizons (e.g., what has the largest impact in the near term? in the long term?). Of these time horizons, the most discussed in policy considerations has been a time horizon of 100 years.

For example, the U.S. EPA has adopted the 100-year time horizon in its uses of GWPs for emissions trading. Policymakers tend to prefer having one value of a metric per forcing, not the range of values for different integration periods.

O'Neill (2000) uses a short time horizon and keeps track of the impact of current and future emissions on future RF and assigns responsibility for that forcing to a particular species. This method accounts for different lifetimes of different species, but it is computationally much more intensive. Smith and Wigley (2000a) found that GWPs used for short-time horizons were reasonably accurate, but accuracy declined as time horizon increased. Smith and Wigley (2000b) determined that the impulse-response function did not accurately capture the relationship between emissions and climate response due to RF (perhaps correctable by the use of efficacies).

Manne and Richels (2001) criticize the use of 100-year GWPs because it is not a time variant metric and therefore cannot account for fixed targets, like a given temperatures or amount of damages. However, time-dependent GWPs without a fixed time horizon would satisfy the objectives they present. The GTP concept would also satisfy their analyses (Shine et al., 2007).

Like the ODP concept for gases affecting ozone, the original GWP concept developed for IPCC was primarily aimed at comparing the relative potential effects of different gases. The GWP metric represents the accumulated RF over a certain period of time and was never intended to represent equivalent climate impacts and is not a very useful tool for evaluating future climate development.

For aviation, IPCC (1999) suggests that the flaws in the basic definition of GWPs may make it questionable to use them in addressing aviation emissions. For example, the formation of contrails is not only dependent on emissions of water vapor but also on atmospheric conditions being suitable for ice formation. IPCC (1999) also based their statement on the NOx effect on ozone not only depending on the amount of NOx emitted but also when and where it is emitted. It is possible that including efficacies into the RF analyses may be able to correct for this problem for a given fleet and assumed operations.

Although they are traditionally based on pulse emissions, GWPs can also be defined in terms of sustained emissions (e.g., Harvey, 1993; Shine et al., 2005b; Berntsen et al., 2005). Berntsen et al. (2005) also allow for the climate sensitivity factor to depend on the type of perturbation thus allowing for the use of efficacies. For surface NOx emissions, Shine et al. (2005b) find little difference in the resulting GWPs, but Berntsen et al. (2005) find a significant effect when efficacies are included.

Some of the important strengths and limitations of the GWP approach are:

Strengths

- Easy to understand concept and easy to calculate.
- Successful at transforming various gases to a common unit (CO_2 equivalent).
- Performs a time integration of the RF to project climate change to some future time.
- Can possibly be modified to include equivalent forcing using efficacies.
- Widely used in existing policy.

Limitations

- Only considers effects for which RFs are calculated.
- Does not evaluate the temperature change or the time evolution of temperature change.
- Not clear what time integration of radiative forcing means.
- Comparison of short-lived or inhomogeneous forcings is difficult (like all existing metrics).
- All of the limitations inherent in RF are also limitations for GWPs except that atmospheric lifetime is fully accounted for.
- Characterization of the impact of a gas is not robust with respect to the climate impact. For example, difficult to account for contrail formation using GWP approach.
- Primarily because of rapid improvements in the understanding of the carbon cycle, GWP values have changed essentially each IPCC assessment, leading to criticism from users who want stable metrics.
- Difficult to know what an appropriate time horizon should be, although the 100-year horizon has become the standard.
- Not applicable in traditional configuration (fixed integration period integration) for fixed target policy analyses.

Absolute Global Warming Potentials (AGWPs)

Absolute GWPs (AGWPs) as defined under the GWPs section (the numerator and denominator terms in GWPs) can have advantages for certain applications because they are not dependent on comparisons with CO_2. Comparison with CO_2 may not always be desired, e.g., comparisons of NOx emissions effects from aviation relative to NOx emissions from ground-based transportation systems.

AGWPs may have more associated uncertainties than GWPs because it is generally assumed that GWPs cancel out uncertainties about the climate sensitivity between the numerator and denominator. AGWPs have been determined for various greenhouse gases, but this metric is not commonly used.

Global Temperature Potentials (GTPs)

Global Temperature Potentials (GTPs) was proposed by Shine et al. (2005a) as an alternative to the GWP climate metric. Similar integrated temperature approaches had previously been proposed (e.g., Rotmans and Elzen, 1992) but did not gain wide acceptance.

GTP gives the global temperature change as a function of time rather than that integrated over a certain time. GTP starts out in much the same way as RF, but instead of assuming a steady-state solution, GTP looks at the time evolution of the solution. Following Shine et al., GTP can be defined either for pulse (GTP_p) or for sustained (GTP_s) emissions. GTPs may also be applicable to emission scenarios but have not been evaluated.

GTP assumes that the global mean surface temperature is given by:

$$C\frac{d\Delta T(t)}{dt} = \Delta F(t) - \frac{\Delta T(t)}{\lambda},$$

which has the general solution:

$$\Delta T(t) = \frac{1}{C}\int_0^t \Delta F(t')\exp\left(\frac{t'-t}{\lambda C}\right)dt',$$

where the exponential is an impulse response function to a forcing at some initial time t’, t is some time in the future, ΔT is the change in temperature as a function of time, ΔF is the change in RF, C is the heat capacity of the mixed-layer ocean and λ is the (assumed) climate sensitivity. Thermal inertia is represented by an ocean mixed-layer heat capacity, so the climate system has a single time constant, rather than a slow time constant (ocean) and a fast time constant (land). The concentration change over time, given a known time-independent increase (or decrease) in concentration (S) of forcing agent, is given by:

$$\Delta \mathrm{X}(t) = \alpha\Delta S\left[1 - \exp\left(-\frac{t}{\alpha}\right)\right].$$

Assuming the forcing (F) is given by AΔX(t), AGTP$_S$ (absolute GTP for a sustained emission change) at a particular time for a forcing x is given by:

$$AGTP_S^x(t) = \frac{\alpha_x A_x}{C}\left\{\tau\left[1 - \exp\left(-\frac{t}{\tau}\right)\right] - \frac{1}{\tau^{-1} - \alpha^{-1}}\left[\exp\left(-\frac{t}{\alpha_x}\right) - \exp\left(-\frac{t}{\tau}\right)\right]\right\} \text{ for } \tau \neq \alpha_x,$$

where α is the time constant for removal of the gas x, A is the RF for a 1 kg change in concentration of gas x, C is the heat capacity of the mixed-layer ocean, and τ is the time constant (λC) for the climate system. The AGTPs for CO_2 is more complicated because it has a more complex response function. Finally, time changing GTP for a forcing agent, x, is the ratio of AGTP for x divided by AGTP for CO_2 and given by:

$$GTP_S^x(t) = \frac{AGTP_S^x(t)}{AGTP_S^{CO2}(t)}.$$

Like GWPs, GTP is a relative change as compared to a known forcing due to CO_2. GTP moves one more step down the chain of events from forcing to temperature change caused by the forcing. AGWPs give the integral of a decaying pulse, while AGTPs give an exponential approach to an asymptotic temperature change due to either a decaying pulse or a sustained emission. GTP could be considered to be better than GWP because it calculates a temperature change over time, which is a clearer physical meaning. However, Shine at al. (2005a) found that the pulse emission effects compared poorly with an energy balance model and therefore may not be the metric of choice (more analysis needed however). The sustained emissions approach gives much better results, but then one has to assume sustained emissions. GTP still requires a climate sensitivity parameter, but this climate sensitivity is in the numerator and denominator so the effect of unknown sensitivity cancels out assuming the sensitivity is the same for the perturbation and reference forcing agent. (This assumption has come into question in recent studies, so GTP has the same problem in its traditional conception as GWP and RF.). One major benefit of GTP is that it can be used for short-lived gases because it better accounts for variations is forcing strength and lifetime of the gas.

Major strengths and limitations of the GTP approach include:

Strengths

- Relatively simple and transparent.
- Requires few input variables.
- Allows calculation of time-dependent change in temperature (not RF), which GWP does not.

Limitations

- May be limited to sustained emissions applications, but more studies of pulse emission effects are needed.
- Depends on the numerical value of climate sensitivity, which is not well known.
- No clear choice for how to define equivalence (could inclusion of efficacies help this?).
- Like GWPs and other emissions-based metrics, difficult to include non-emission related effects, like those occurring with the formation of contrails.

Global Temperature Index (GTI)

Akin to RFI but using pulse-based GTPs as the basis, this index was proposed by Lee and Wit (2006) as perhaps being a better approach for trading schemes. However, this index is totally untested and requires much more evaluation.

Linearized Temperature Response (LTR)

Using carbon cycle and climate models, linearized response functions have been developed in various research studies (e.g., Hasselmann et al., 1993, 1997; Hooss et al., 2001; Joos et al., 2001) as a way of deriving CO_2 from emissions and temperature changes without using a full climate model in further studies, mostly for examining effects of projections of future CO_2 emissions. Studies to determine these response functions have typically included a year of emissions of CO_2 treated as a pulse emission. In the past, such studies typically have not included emissions of short-lived emissions.

Sausen and Schumann (2000) use a combination of linearized response models in analyses of the effects of carbon dioxide and ozone (from NOx) emissions from current aircraft on surface temperature and on sea level. For the carbon cycle, they use linearized functions determined from the analyses of Hasselmann et al. (1997). RF is then derived using simple expressions from the literature (a logarithm function for CO_2). Finally, temperature change is derived using the response functions from Hasselmann et al. (1993, 1997) (with a climate sensitivity factor based on studies by Ponater and colleagues). The study by Sausen and Schumann (2000) found that, even though the RFs from CO_2 and from NOx were comparable, the aircraft-induced ozone increase causes a larger temperature change than the CO_2 forcing. Although regional climate effects are not considered, they note that regional effects may be larger than the global mean responses.

Lee and Sausen (2004) use the climate response model of Sausen and Schumann (2000) for a similar study except that they base the climate sensitivity factor on IPCC (2001). Like Sausen and Schumann (2000), they found a larger temperature response from ozone relative to CO_2 than would have been expected based on the RFs. However, they also recognize that this conclusion is highly dependent on the equilibrium response temperature function used and recommend that analyses from coupled climate (GCMs) and chemistry-transport models (CTMs) are needed to better understand the ozone temperature response.

Marais et al. (2007) and the companion report by Mahashabde et al. (2007) have adapted the concept of linearized temperature response (LTR) functions to the evaluation of the climate impacts from aviation. This APMT (Aviation environmental Portfolio Management Tool) modeling system has been developed for the U.S. Federal Aviation Administration. They likewise borrow from the approach of Sausen and Schumann (2000), but then build upon it.

Like earlier studies, the APMT model conceptualizes a year of aviation emissions as a pulse emission. They use published linearized response functions of the carbon cycle for CO_2 (Hasselmann et al., 1993, 1997; Hooss et al., 2001) and the response functions from the very simple Bern carbon cycle model (Joos et al., 2001). It should be noted that all of these response functions, including the Bern model, are all based on earlier versions of the ECHAM model, versions of this model that are generally recognized as being well out of date of the current state-of-the-art. For determining the CO_2 climate impact, they follow the approach of Hasselmann et al. (1997) and base the linearized temperature response functions on the earlier versions of the ECHAM model (Hasselmann et al., 1993, 1997; Hooss et al., 2001; Cubasch et al., 1992). They also use the simple energy balance model of Shine et al. (2005) with a fixed climate sensitivity value. Although they recognize this approach has “lower fidelity than the impulse response functions derived from the more complex (climate) models”, they also recognize that the other functions were based on papers from out-of-date climate models.

The RF (normalized to RF for the doubling of CO_2 relative to the preindustrial atmosphere, as generally used in deriving the linearized temperature response functions) times the resulting concentrations using these functions are then integrated with a given linearized temperature response function to determine the change in globally averaged temperature. Uncertainties in the climate sensitivity are accounted for via a scaling of the sensitivity of the model used for the linearized temperature response function derivation through the use of a simple energy balance model.

For short-lived emissions, they scale the normalized RF for different climate responses relative to CO_2 (much like Sausen and Schumann, 2000). Except for the methane and resulting ozone effect, all effects are assumed to only last for a period no more than the one year of the emissions. Efficacies are used in this scaling (based on either a value of one or values from Hansen et al., 2005). For ozone and methane effects, the emissions index is proportional to the NOx inventory. For all other impacts, the emissions index is proportional to the fuel burn.

Another new model, mentioned in Wit et al. (2005) uses a very similar approach developed by L.L. Lim, D. Lee, and R. Sausen (unpublished except for Wit et al. and one page on the Manchester Metropolitan University website under the Centre for Air Transport and the Environment). There are some other, more minor differences in the two approaches, but not enough is known to discuss this model in detail at this time.

All of the LTR metrics discussed so far represent the climate system through global-mean surface temperature, which may be misleading for the effects resulting from emissions of NOx (e.g., due to similar responses in each hemisphere for the methane effects but different hemispheric responses in ozone) and perhaps for the resulting effects from aerosols and contrails. However, other simple metrics generally have not addressed this issue either.

A related but somewhat different approach is proposed by Grewe and Stenke (2007). Although their temperature response is based exactly on that used by Sausen and Schumann (2000), the rest of their model is very different. Their assessment tool is called AirClim. For CO_2, they assume a constant 100-year lifetime, an overly simplified representation of the complex decay function for CO_2. On the other hand, their treatment of the RF for CO_2 and the other emissions from aircraft, as well as their residence times, includes representation of altitude and regional effects not considered as fully, if at all, in other metrics. Basically, they use a coupled climate-chemistry model (based on a recent version of ECHAM), to derive factors for 4 latitude regions and for 6 pressure (altitude) levels. This paper focuses on determining the effects from an assumed fleet of supersonic aircraft but the approach used should be expandable to subsonic aircraft. At this point, the modeling approach developed by Grewe and Stenke (2007) appears promising, but largely untested. More evaluation is required. In addition the treatment of the temperature response function needs to be upgraded (based on state-of-the-art climate model or models) and the carbon cycle complexity needs to be better accounted for.

While it could be argued that the simplified LTR models are not classic metrics in the way that radiative forcing or GWPs are metrics, the ability to greatly simplify the complexity of determining climate impacts from aviation or emissions from other transportation sectors could be a very useful tool to policy analysis and, as such, are a metric. By developing parametric models based on the results from much more sophisticated climate, carbon and chemistry models, the LTR approaches discussed here represent a pathway towards a potentially powerful capability that allows for extensive analyses of aviation and other climate forcings and evaluation of uncertainties. This new approach to a metric has not been adequately tested at this time, but the approach is certainly promising. A key problem with the existing models though is that they are all largely dependent on out-of-date linearized response functions developed from older versions of carbon cycle and climate models. The one exception may be APMT, which also uses a simplified energy balance climate model (from Shine et al., 2005a). However, such simplified models are only as good as the science and more sophisticated models they are based on. Thus, the choice of such simple models needs further evaluation.

As discussed earlier, GTP, whether for pulse emissions, GTP_p, or for sustained emissions, GTP_s, is defined as the ratio of the Absolute GTP (AGTP) for X relative to the AGTP for CO_2; in this way, it follows the ration approach developed for GWPs. On the other hand, the LTR approach derives the change in temperature with time akin to the AGTP. As such, LTR and AGTP are similar except that the goal in LTR is to use the results from complex climate models as the basis for the carbon cycle and temperature derivations rather than the simpler treatments used in GTP. However, use of the simplified energy balance model in AMPT may produce results very similar to those derived for AGTP using the same energy balance model.

<u>Strengths</u>

- Allows determinations of time dependent changes in globally-averaged temperature. Thus, readily understood response compared to using RF.
- Has a methodology for accounting for short-lived emission.
- Allows some sense of uncertainties to be included, by using different derived response functions for CO_2, temperature change and efficacies.

- Could be a very useful approach for addressing some technological and policy question, but may not be so useful for other questions (e.g., changing the flight altitude or a change in routing).

Limitations

- Methods have not been adequately tested and evaluated at this time.
- Limited by uncertainties in determined linearized temperature response functions.
- Requires knowledge that requires a GCM to calculate.
- Could potentially be applied to other sectors but this has not been done at this time.
- Requires more input parameters and is more difficult to determine than GWPs. Requires more complex input from scientists than other metrics.
- Not clear yet whether this approach really has much advantage over GWPs or GTPs.

Global Temperature Index

Wit et al. (2005) present another metric (developed by David Lee) in their report that combines the GTP concept with the use of linearized impulse response functions. This metric is called Global Temperature Index (GTI) and is supposedly analogous to using RFI. Like GTP, GTI assumes sustained emissions integrated over a certain time period (100 years). Efficacies are included. However, the overall methodology is not fully developed or tested (or even explained very well at this point). It is difficult to tell at this time just how useful this metric will be in future aviation and other sector studies.

Economics- and Damages-Based Metrics

Following Figure 1, it has long been recognized that development of climate policy would benefit from analyses of welfare and damages (Eckaus, 1992; Schmalensee, 1993; Kandlikar, 1995). A number of economists and policy experts have criticized existing physical-based metrics like GWPs because they do not account for damages and abatement costs (e.g., Manne and Richels, 2001).

A number of different studies have used economic approaches to assess impacts associated with future scenarios of climate change (e.g., Mendelsohn et al., 2000; Nordhaus and Bauer, 2000; Tol et al., 2002a, b; Manne and Richels, 2001; Bradford et al., 2001; Sygna et al., 2002; O’Neill, 2003; Hammond et al., 1990; Kandlikar, 1996). Especially designed for analyses of aviation impacts on climate, Marais et al., (2007) (and the corresponding report on the AMPT system for the FAA, Mahashabde et al., 2007) assume either a linear damage function or the damage function developed by Nordhaus and Boyer (2000), which assumes a quadratic relationship with the change in temperature. They also include discounting (e.g., see Nordhaus, 1997) to express future value in terms of present monetary terms. There have also been a number of attempts to develop alternative metrics that are welfare-based. For example, Hammitt et al. (1996) proposed the Economic-Damage Index (EDI).

While there is a large body of existing studies considering damages and their assessment through various indices, there is no widely accepted approach. There is no straightforward way to aggregate spatially and temporally diverse impacts into a single damages estimate. Such an index or metric would only be useful for policy considerations if it can successfully enumerate all of the relevant potential impacts on society and the environment resulting from climate change. This holds for studies of aviation-induced climate change as well. Part of the problem is that it is difficult to determine what “successfully” means in this regard. As a result, unlike the generally accepted metrics within the science community, RF and GWPs, even with recognition of their flaws, there are no community-wide accepted approaches for damages and abatement costs being used in policy considerations.

3. Uncertainties, Limitations, Gaps, and Needed Improvements

A variety of different metrics have been discussed in the previous sections. Some are physical science-based metrics like Radiative Forcing (Stratospheric Adjusted RF has been the standard, but Equivalent RF should likely be considered to be the new standard) and GWPs that have become the currently “accepted” approaches for evaluating climate policies and legislation related to reducing emissions of multiple greenhouse gases. Others, like LTR modeling, are relatively new and untested in climate assessments. Still others attempt to incorporate the human dimension of change through estimating the relative impact of emissions on economic or social damages.

Several different designations of climate metrics have been considered, and strengths and limitations of these metrics have been discussed in the previous section. This section is aimed at further understanding of the uncertainties, limitations, and gaps in knowledge and capability of these metrics (or at least those that seem most relevant to future use). In addition, this section examines issues that need improvement before these metrics can be used to fully address policy-related questions relating to the effects of aviation on climate. The first designation of metrics is based on concentration-based analyses using some form of radiative forcing. Table 1 provides further insight into some of the key uncertainties, gaps and issues needing improvement for these metrics. The second designation of metrics is emission-based analyses. The key uncertainties, gaps and issues needing improvement for emissions-based metrics are further discussed in Table 2. The third designation of metrics discussed earlier were those associated with economics or social damages, but there is no generally accepted treatment of these impacts at this time and there is no attempt here to further discuss these metrics.

The question is, what metric or metrics would be most useful for analyses of the potential climate impacts from aviation emissions? Or from other transportation and energy sectors? There is no simple answer to this question; in fact, there is no one answer. The best metric to use for a given situation depends on the question that is being asked. In order to make some generalized recommendations, it is instructive to first look at several other studies that address at least parts of this question. We can then make recommendations regarding additional research that is required to further address this question.

First, users of climate metrics need to bear in mind that simplified climate metrics should not be used in isolation without considering more fully the literature and assessments that take into account the many complexities affecting climate change. At the same time, it is not sufficient to only use emissions as the basis for policy – it is important to go further down the chain of Figure 1 towards evaluating the resulting climate impacts.

As mentioned in Forster et al. (2006), there have already been attempts to use simple multipliers (2-4, with a value of 2.5 used in some UK policy discussions) on the climate effect (radiative forcing) due to CO_2 effects from aviation by itself. The use of such a multiplier, e.g., based on

RFI, has been used extensively in climate model calculations, but primarily in accounting for the effects of other long-lived greenhouse gases. While, as mentioned earlier, the total RF does have value in considering the climate effect of aviation over a given period of time, it not only does not present the whole story needing to be considered in developing policy, and bears little relationship to the metric being applied in most current policy considerations from non-aviation emissions, namely GWPs. The GWP concept not only considers the lifetime of the emissions, but also provides a time-integrated RF from a pulse emission, a very different metric than RF.

If the total sum of RF were applied to other sectors, it would lead to a very misleading interpretation of the climate effects. For example, emissions from coal burning power plants without extensive scrubbing capabilities emit a significant amount of sulfur gases that rapidly transform to sulfate aerosols in addition to their emissions of CO_2 and NOx and some less important gases. The RF due to the cooling effect from the sulfate aerosols would counteract a large amount of the warming due to the CO_2 emissions and effects from the NOx emissions on tropospheric ozone, and the “total” RF would suggest that coal burning power plants are beneficial to climate. Similarly, using total RF as the only metric for aviation, one might conclude that reducing the cruise altitude to prevent contrails (e.g., Williams et al., 2003) would be beneficial to climate. However, the decreased energy efficiency would lead to more CO_2 emissions and in fact, the reduced flight altitude may be more harmful to climate. If the RF metric is to remain useful, then perhaps hemispheric or even regional “equivalent” RF could be derived using efficacy factors.

Forster et al. (2006) suggest that much more extensive evaluation of the impacts of short-lived aviation emissions be done before they are applied to any emission trading scheme. They conclude that RFI should not be used as an emissions index without giving due consideration to the timescales of the climate effects. RFI exaggerates the climate impact of aviation emissions, potentially putting too much weight on very short lived climate forcings. They also conclude that a number of other issues need to be considered in any emissions scheme used for emissions trading. First, any emissions-based weighting of non-CO2 climate effects should be applicable to all sectors – not just aviation. Secondly, it is important to choose an index that is emissions-based. Uncertainties need to be considered in the analyses. Third, a suitable time horizon needs to be chosen, e.g., say 100 years (but to what degree is this choice arbitrary?).

Other studies have compared several different climate metrics. Shine et al. (2005b) compares several different emissions-based metrics, both RF (e.g., GWPs) and temperature based (e.g., GTPs), for surface NOx emissions and finds little difference in the results. Shine et al. (2005b) also examines two more regionally-based metrics, based on the absolute value of the local change temperature relative to the same for a reference gas, called Linear Damage Potential (LDP) and the square of the local temperature change, called the Square Damage Potential (SDP). Such regional metrics may be useful, but their limited testing done for NOx emissions in Asia versus Europe is insufficient.

Wit et al. (2005) discuss different metrics for examining emissions trading relative to aviation impacts on climate. They conclude that RF and RFI are not useful for emissions trading because they do not account for effects occurring in the future. They also criticize GWPs as not being useful for emissions trading because (1) it is difficult to account for particles or their indirect effects; (2) the O_3 effects from NOx emissions is subject to large uncertainties; (3) the GWP concept is based on a per unit mass of emissions which does not apply readily to contrails; and (4) GWPs do not account for the climate sensitivity parameter. However, there is a response to all of these issues, the GWP concept can be appropriately modified to include these, e.g., GWP analyses are already being applied to NOx effects on O_3 from surface sources and one can include efficacies to account for the effects of the climate sensitivity parameter. Most of the remaining GWP issues raised would equally apply to any existing metric. The Wit et al. (2005) analysis does not account for current adaptations to the GWP concept. The one criticism of GWPs that cannot be readily addressed is that it lacks an equivalence to a climate response at some given point in time.

Wit et al. (2005) suggest that the GTP concept eliminates some of the key concerns about GWPs. The GTP concept does indeed have a number of key advantages. However, Shine et al. (2005a) suggests that GTPs don't work very well for pulse emissions, only for sustained emissions. This may not be a serious concern for most applications – long term integrations of 100 years or more tend to give similar results with GTPs and GWPs – but the particular use of a metric needs to carefully consider whether a pulse or sustained emission is desirable.

Despite the many criticisms, GWPs at this point are still the metric of choice for climate analyses by policymakers. This is largely because they are seen as simple (a table of values are published in the international climate assessments), transparent (easily reproduced), and flexible (new knowledge can be incorporated). While each of these points could be argued (and rightly so), the controversies in the science community about GWPs are not readily perceived by policymakers.

The GWP concept cannot be ignored because it still is the most accepted metric in climate analyses. However, the GTP concept and the linearized temperature response (LTR) approach also have many advantages and may be the preferred approaches for technological and policy analyses relative to aviation. GTP has the advantage of being relatively simple, transparent, and flexible, but, in the long run, it could be argued that a well tested and evaluated version of the LTR approach will better represent changes in the scientific understanding. However, LTR is largely untested at this point and it relies on more scientific input from complex numerical climate, carbon cycle, and chemistry models. Some of the same information is needed from such models for other metrics, so this may not be a real issue.

Table 1. Uncertainties, gaps and issues needing improvement for application of selected Concentration-based Climate Change Metrics to aviation.

Metric	Uncertainties	Gaps	Improvement issues
Stratospheric adjusted radiative forcing (RF)	Except for CO_2, RFs for other aviation climate impacts are not well known. Traditional definition does not account for nonlinear climate response due to location and timing of the forcing. Depends on model used in the derivation and time period evaluated.	RF has not been defined for regional emissions. Effect of atmospheric lifetime on resulting climate response is not accounted for. Unknown whether RF could be applied for regional analyses.	The basic science for determining the climate effects from non-CO_2 aviation emissions needs significant improvement. Effects of contrails and changes in cirrus are particularly uncertain.
Global-mean surface RF	The basic concept has not been tested adequately, but may provide useful info on dynamic and thermodynamic feedbacks relative to tropopause based RF. Large uncertainties about value of this approach until it is further evaluated.	Not clear at this point if it will really add to better understanding of climate effects relative to traditional tropopause based RF. Likely not applicable to regional analyses.	The value of this approach needs to be tested in climate models. This approach has not been applied to aviation.
Fixed land/ocean surface temperature RF			Need to determine how dependent values will be to different climate models.
Equivalent RF	Efficacies for aviation effects on climate are still poorly known.	This could be applied to any of the above approaches but this still needs to be done. Not clear if applicable to regional analyses.	Need systematic model intercomparison for efficacy evaluation. Test use of efficacies relative to the above RF approaches compared to climate models (for non-aviation forcing and then for aviation (bearing in mind possible scaling problems when multiplying aviation emissions to get sufficient climate signal).

Table 2. Uncertainties, gaps and issues needing improvement for application of selected Emissions-based Climate Change Metrics to aviation.

Metric	Uncertainties	Gaps	Improvement issues
Time-Dependent Radiative Forcing	Value not clearly known even though it has had some application to aviation.	Interpretation of this approach relative to resulting climate impacts is not understood.	Requires much further testing. Relative usefulness of pulse, sustained, and scenario emissions needs to be evaluated. Needs to be tested using efficacies.
GWPs -- Global Warming Potentials	Although commonly used in climate studies and policy considerations, it is not known how well this metric could be applied to aviation. Difficult to know what an appropriate time horizon should be, although the 100-year horizon has become the standard. Not clear if GWPs could be applied to regional analyses.	Not clear what time integration of radiative forcing means. Characterization of the impact of a gas is not robust with respect to the climate impact. Difficult to account for contrail formation and other non-emission related effects using GWPs. Not applicable in traditional configuration (fixed integration period integration) for fixed target policy analyses.	Applicability for aviation needs to be evaluated. Applicability for comparing aviation with other transportation / energy sectors needs to be tested. Testing needed using efficacies.
GTPs -- Global Temperature Potentials	The advantages and disadvantages of applying GTPs to pulse or sustained emissions are still poorly known. Similarly whether GTPs could be applicable to emissions scenarios. Not clear if GTPs could be applied to regional analyses	Like GWPs, difficult to include non-emission related effects, like those occurring with the formation of contrails. .	Overall method needs further testing. Also, need to include efficacies. Applicability for aviation needs to be evaluated. Applicability for comparing aviation with other transportation / energy sectors needs to be tested.
Linearized Temperature Response	A major advantage of LTR is the ability to couple to the capabilities of global climate models, but existing linear response functions are not based on state-of-the-art GCMs. Same concerns apply to the carbon cycle applications.	Like GWPs, difficult to include non-emission related effects, like those occurring with the formation of contrails.	LTR has not been adequately tested and evaluated at this time for either aviation or other sectors. One study suggests that LTR may be applicable to regional analyses, but this needs much further evaluation.

4. Prioritization for Tackling Outstanding Issues

Further evaluation of climate metrics is required before the right choices can be made for application to aviation policy studies. In particular, the individual questions of interest – e.g., whether requiring comparison of one species of aviation emissions with another or of aviation emissions with emissions from other sources - will determine the most appropriate metric to use. Input from policymakers as to what questions they see as priorities will be important to determining where efforts should go into further development of climate metrics for aviation.

At this time, it is not at all clear which metrics will be most suitable for addressing the questions related to aviation impacts on climate, or for possible considerations of tradeoffs relating to aviation emissions and climate. Even more difficult would be to consider tradeoffs of aviation climate concerns relative to air quality or noise issues associated with aviation (the difficulty in doing such tradeoffs is discussed in the 2006 workshop report, Wuebbles et al., 2006). As a result, at this time, the suite of metrics discussed in sections 2 and 3 should be tested, evaluated and prodded in every possible way in order to get to the point over the next few years where specific recommendations can be made regarding appropriate choices for the possible sets of questions related to aviation. Each of the uncertainties and issues discussed in section 3 will need to be considered. New metrics should also be considered. Input from policymakers regarding what they actually see as the key questions for metrics to address will be an important element of this evaluation. Also, the interest of policymakers in global (entire fleet) versus regional (as little as a single flight) evaluation of aviation impacts on climate needs to be known, so that priorities can be determined for global versus regional analyses. If the gaps listed in section 3 limit the metrics applicable to a given set of policy questions, effort may need to go into development of new metrics.

This section discusses priorities for research to greatly enhance the understanding of climate metrics for aviation studies so that within a five year time period policymakers will have a much enhanced set of tools for addressing key questions related to the impacts of aviation emissions on climate. Table 3 then summarizes the discussion in this section into a series of potential projects along with a rough estimate of the required effort (in full time equivalents) required and an associated estimate of cost. Within Table 3, there is also an attempt to provide a rough timeline for such studies.

In addition to assessing appropriate applications for individual metrics, the robustness of the existing metrics all need further evaluation. The most effort should likely go into testing and further developing the Equivalent Radiative Forcing, Global Warming Potentials, Global Temperature Potentials, and Linearized Temperature Response metrics. The usefulness of efficacies needs to be evaluated for all of these metrics. The Radiative Forcing and GWP metrics are already well-accepted approaches with well-known limitations, but the use of efficacies in these is relatively new and not fully tested. The GTP and LTR metrics and their various forms are not yet as accepted in the science and policy communities, but may be very useful. The capabilities of the various metrics should be further examined in comparison with each other and relative to their ability to address a range of policy questions. Such studies may also lead to the development of new metrics.

A combination of modeling tools will be needed for assessing the different metrics, including global and regional climate models, atmospheric chemistry-transport models (either coupled or decoupled from the climate models), and radiative transfer models. *Since different scientists have different experiences with different metrics, it may be worthwhile to develop a working group that together would evaluate the different metrics and their value for addressing different policy questions.* Detailed comparison with results from state-of-the-art climate models will be a necessary part of the evaluation of metrics (as well as in the development of better treatments of efficacies). As mentioned earlier, there is a possible issue with scaling of aviation effects within climate models to be able to fully detect the climate signal; this uncertainty will need to be considered within the evaluation of the different metrics. It is important to also recognize that the evaluation of climate metrics can only be as good as our understanding of the scientific understanding of the processes affecting climate impacts from the different aviation emissions.

Efficacies will likely become a norm for most of the future studies using metrics but they have not been adequately evaluated for aviation-based emissions. The sensitivity of efficacies to the background atmosphere and to a range of possible aviation emissions scenarios need to be evaluated for each of the separate climate concerns associated with aviation (including NOx effects on ozone and methane, aerosols, contrails, cirrus). These analyses will of course have to go hand in hand with improved understanding of the emissions effects themselves.

As stated in Fuglestvedt et al. (2003), there are no unambiguously agreed upon criteria for evaluating metrics. In examining potential uses of metrics for aviation, it would be useful to have a special meeting to establish these criteria, to set the stage for the studies to be done. Feedback from those involved in aviation policy will be a necessary part of this – the lack of clear goals currently for combating climate change from aviation affects the choice of metrics and the criteria to be evaluated. The scientists involved in evaluating and developing climate metrics also need to understand what tradeoffs are likely to be most important to the considerations of the aviation policy community.

Fuglestvedt et al. (2003) do suggest that different climate and/or coupled chemistry-climate models evaluate the robustness of radiative forcing for consistency across a variety of issues, e.g., to what degree are high latitude forcings more effective at affecting climate than low latitude forcings or shortwave forcings are more effective than infrared ones. Can efficacies adequately correct for such differences?

Climate modeling and coupled chemistry-climate modeling studies will play an important role in further evaluating metrics, but these modeling tools are computationally intensive, so the tests using these models need to be carefully considered.

Both of the latest LTR approaches, namely the APMT and AirClim assessment tools, appear to be quite promising for future studies of aviation. The AirClim approach may even provide a capability for analyzing regional impacts not considered otherwise. However, these tools are dependent on the validity of much more complex representations and understanding of the science, including the carbon cycle, chemistry interactions, aerosol direct and indirect effects, contrail formation and evolution, and the resulting impacts on climate. Current tools need much further development and evaluation before they will be applicable to policy considerations. In particular, both models need to have a much more carefully-considered representation of the carbon cycle and temperature response functions in order to better represent the state-of-the-art of the science.

Any metric being considered for aviation should also be applicable to other transportation sectors to enable comparisons between sectors. At this point, the GWP concept has been applied in a limited manner to such sectors, but there has been no attempt at applying the GTP or LTR concepts to such sectors. Further research is needed to test these capabilities.

One of the next step needs to be testing and comparison of the Equivalent RF, GWP, GTP and LTR metrics for NOx-O_3-CH_4 effects from aviation. These effects are known better than the effects from contrails and changes in cirrus and there is a real possibility that the effects, as well as remaining uncertainties, of NOx emissions can be better quantized within the next few years. Three-dimensional steady-state modeling studies could be done of these effects, but the applications of the concepts and interpretation of the results as used in metrics will require much analysis and thought. These analyses will be crucial in determining which metric or metrics) should be the primary focus for future aviation applications. One could also attempt to do rough analyses for contrails (using an approach akin to Hansen et al., 2005) although current science understanding of the contrail and cirrus effects may make it difficult to fully include these effects at this time.

Table 3. Research priorities over next 5 years towards enhanced capabilities of climate metrics for addressing the impacts of aviation on climate.

Project	**Effort required**
Near term (0-1 year)	
Establish Metrics Working Group (MWG) that will interact on evaluating and testing metrics for application to aviation impacts on climate. Develop criteria for evaluating aviation impacts in climate metrics.	Cost of meetings.
Meeting of Metrics Working Group with policymakers interested in aviation impacts to establish priorities for key questions to be addressed with climate metrics.	Cost of meeting.
Mid term (1-3 years)	
The Bakeoff: Evaluation, testing, and further development of existing metrics (different forms of RF; GWPs; GTPs; LTR metrics) first for aviation NOx emissions using chemistry-transport models and climate models (or coupled chemistry-climate models) first for ozone effect and then ozone and methane. Global models necessary for evaluating capabilities of metrics. Incorporate improved efficacies and improved understanding of science effects for various emissions as they become available. Determine capabilities for including contrails and cirrus effects in metrics. Determine needs for regional studies and test metrics relative to such needs as appropriate. Evaluate effects of background atmosphere.	MWG members: ~3-5 FTE*, roughly $500K per year for 2 to 3 years; quarterly meetings of MWG.
Development of improved efficacies for aviation emissions, starting with NOx emissions.	MWG members: 1-2 FTE, roughly $250 K per year for 2 years.
Development of scenarios for future growth of aviation and resulting emissions. Initial studies with metrics (after initial phases of Bakeoff).	Emissions scenario developers: 1-2 FTE, roughly $200K for 1 year; MWG: 1-2 FTE, roughly $250K for 1 year.
Studies with 2-3 existing state-of-the-art climate models (e.g., NCAR, GFDL; NASA Goddard) to develop new linearized functions for temperature and carbon cycle. These will be used in future LTR studies.	2-4 FTE, roughly $400K for 1 year.
Initial meetings (of MWG) with economics and others communities to determine best way forward for incorporating damages into metrics.	Cost of meetings.
Long term (3-5 years)	
After first stage of Bakeoff completed, test metrics for aviation sector relative to other transportation / energy sectors.	MWG: 2-4 FTE, roughly $400K per year for 2 years.
If determine that 2nd stage of Bakeoff is needed, then proceed with further evaluation and testing of metrics. At this point, we should know whether additional metrics are needed as well.	Not known; could be as much as 2-3 FTE, $400K per year for 2 years).
Initial studies using metrics in addressing climate tradeoffs. Update as science knowledge of climate impacts improves. Include damages if there is community agreed upon approach.	MWG: 2-3 FTE, $400K per year for 2 years.

* FTE = Full-time equivalent (assumes mixture of PhD scientists, post-docs, and graduate students)

5. Recommendations for Best Use of Current Tools

It will be important to take a systems point of view in any new study using existing metrics to evaluate the climate impacts from aviation. As such, it will be important to consider all of the uncertainties associated with current understanding of the effects of aviation emissions on climate, including the fact that with the exception of carbon dioxide, the effects of other emissions on climate are still not very well understood. In particular, it would be very difficult to provide a meaningful evaluation of the effects of contrails or the effects of contrails and aerosols on cirrus. However, metrics may be able to better consider the effects NOx emissions from aviation. Modeling capabilities for understanding the UT/LS region have improved greatly in the last few years (although there are definitely remaining uncertainties), such that determining the effects of NOx emissions from aviation on ozone and methane should be more possible than previously; it may be possible to get a stronger understanding of those effects and remaining uncertainties using analyses from current state-of-the-art chemistry-transport and chemistry-climate models.

To provide a perspective relative to prior assessments of aircraft effects, any new study done at this time should start with the use of stratospheric adjusted radiative forcing, but also include consideration of efficacies to the degree possible. The effects of uncertainties in the evaluation of the climate effects and in the metric itself will need to be clearly stated. The radiative forcing could be evaluated for the current time period but it can also be worthwhile to consider projections of effects on aviation based on reasonable scenarios for future emissions. Such scenarios, however, need to be carefully considered, and should be based on best available projections from ICAO and the FAA (or associated organizations like JPDO).

Emissions-based metrics should also be considered, but interpretation will be limited by the lack of a community-consensus on which metrics should be adopted and the lack of current application of the GWP and GTP approaches to evaluation of aviation. The LTR approaches are promising as assessment tools but have not been evaluated by the science community and need further development to reduce existing uncertainties.

It will be difficult to make useful policy decisions involving tradeoffs within the climate sector at this time.

6. Summary

A number of the existing metrics for climate have been considered. Advantages and limitations of the various metrics have been discussed. To some degree, we arrive at more questions than answers. Ultimately, the specific metric of choice in a given situation will always depend on the question being addressed. For aviation, there is no single metric currently in existence that does not have well-recognized shortcomings in either its application to this sector or in evaluation of its capabilities and limitations.

This said, there are still some metrics that demonstrate clear advantages over others, and may be appropriate for use in specific situations and/or after further research and testing, as recommended below.

Beginning with the well-accepted metrics of radiative forcing and GWPs, we find that they have major limitations that affect their interpretation when used to address many of the policy questions of interest to climate.

For example, the equivalent RF concept can be useful to address questions related to changes in climate for the atmospheric agents that have been emitted over a specific period of time. However, equivalent radiative forcing is not an emissions-based metric. Emissions-based metrics are likely the primary choice for addressing most questions of interest for technological or policy considerations and/or trade-offs.

GWPs (and AGWPs) are well established but may be difficult to apply to aviation emissions. We recommend that the existing concept be modified to include efficacies, and tests done to see if all effects can be conceptually included. While there have been many criticisms about this, no one has really attempted to see if the concept could be readily modified to include contrails and other cloud effects, e.g., by basing these effects in a more general sense on the emissions associated with fuel burn. Despite its limitations, the GWP concept is so well engrained in current international climate policy considerations that it might actually impede the progress of negotiations to promote use of an alternative metric. As a result, decision-makers are faced with weighing scientific precision relative to practical applicability (Fuglestvedt et al., 2000).

The answer may lie in using similar metrics that address some of the scientific concerns raised by GWPs. Specifically, the GTP and the LTR approaches have some major advantages, but neither has been adequately tested. GTPs assume either pulse or sustained emissions while LTR generally uses a pulse of one year of emissions. Both may also be applicable to emissions scenarios.

Additional research needs to be done to identify appropriate metrics for evaluating emissions from aviation and from other transportation and energy sectors. The application of existing metrics to aviation emissions needs to be evaluated individually and relative to each other. Some metrics such as the LTR approaches need further development to be scientifically robust. New metrics should also be considered.

Any new assessment of aviation impacts on climate done at this time, before the research outlined above has been done, will have to be limited in scope and subject to large uncertainties. A systems approach will be necessary so that the resulting metric studies are considered relative to remaining uncertainties in the scientific understanding of the processes affecting atmospheric composition and climate from aviation emissions.

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Appendix A: Discussion on Efficacy Factors

Efficacy is the factor relating surface temperature change from a particular forcing agent to that from equivalent CO_2 radiative forcing. It is defined as the ratio of the climate sensitivity parameter for a given forcing agent to the climate sensitivity parameter for CO_2 changes (Joshi et al., 2003). Joshi et al. (2003) tested the climate sensitivity to idealized forcing agents (mainly ozone) in three very different GCMs. They found that the climate sensitivity to any given forcing type was varied greatly between the models, but once the sensitivities were normalized by the climate sensitivity of CO_2 within the same model the efficacies were within 30% of one another. The effective radiative forcing for a given forcing agent would then be the radiative forcing (for this work, radiative forcing refers to the stratospheric adjusted radiative forcing discussed earlier) for a particular forcing type multiplied by the efficacy factor. The effective radiative forcing is then independent of forcing type and can be compared directly to CO_2 RF. Global mean surface temperature can then be calculated as:

$$\Delta T_s = \lambda_{CO2} E * \Delta F$$

where ΔT_s is the global mean surface temperature change, λ_{CO2} is the climate sensitivity for CO_2, E is the efficacy for a particular forcing type, and ΔF is the radiative forcing associated with a particular forcing type. Using an efficacy factor with RF is likely to give a much closer approximation to global surface temperature change than using RF alone (Sausen and Schumann, 2000; Hansen et al., 2005; Lohmann and Feichter, 2005). The difficult part is determining the efficacy for the many forcing types that are currently considered.

According to Boer and Yu (2003b), the efficacy associated with a particular forcing type depends on the spatial distribution of the forcing and how the forcing projects onto the climate feedback mechanisms. Numerous studies have shown that different patterns (both geographic and vertical) of forcings and any non-linearities associated with the forcing will affect the efficacy. It is generally found that higher latitude forcings (regardless of source) have a higher efficacy than tropical forcings (Boer and Yu, 2003b; Joshi et al., 2003; Hansen et al., 2005; Sokolov, 2006; Stuber et al., 2005; Sausen et al., 2002). Most of this effect is thought to be from the change in snow and ice albedo (Stuber et al., 2001; Joshi et al., 2003; Stuber et al., 2005).

Regional efficacies and efficacy for regionally distributed forcing agents have also been examined (Forster et al., 2000; Boer and Yu, 2003b; Joshi et al., 2003). Forster et al. (2000) examined efficacy for regional increases in CO2 and solar irradiance. Joshi et al. (2003) extended this study to include O_3 and ran experiments using three different GCMs. Each of the GCMs treats feedback mechanisms in different ways. In both Joshi et al. (2003) and Forster et al. (2000) it was found that while climate sensitivity for a particular forcing varied greatly from model to model, the climate sensitivity normalized by the climate sensitivity of CO2, were similar. This normalized climate sensitivity is the efficacy. Efficacies were generally within 30% of each other across models for a given forcing scenario. Efficacy was found to be lower for upper tropospheric O_3 changes and higher for lower stratospheric O_3 changes; lower for tropical changes and higher for extratropical changes. This systematic error in the stratospheric adjusted RF implies that an effective RF would be a better predictor of globally averaged surface temperature change. This work also seems to suggest that more regionally (upper troposphere, lower stratosphere, tropical, extratropical) appropriate efficacies be used in calculating the effective (globally averaged) RF.

Boer and Yu (2003b) looked in more detail at the spatial distribution of the forcing response. They determined that the geographic location of temperature change is strongly influenced by the feedback mechanisms that dominate that region. In fact they determined that the geographic location of the feedback mechanisms were more important than the geographic location of the forcing agent in determining the temperature distribution. Joshi et al. (2003), on the other hand, noticed that when a forcing maximum was located in the tropics/extratropics then the tropics/extratropics showed the greatest response. Boer and Yu (2003b) also noted that there was a tendency for certain areas (like the Northern Hemisphere high latitude region) to show a strong temperature response for all of the forcing scenarios tested, except those with sharp gradients. Some regions were preferentially changed even if the forcing was remote. Since GCMs treat climate feedback mechanisms in many different ways, it is not currently possible to determine efficacies for small geographic regions until we have a better understanding of climate feedback mechanisms.

Vertical distribution of the forcing and its effect on efficacy has also been examined in some detail (Hansen et al., 1997; Christiansen, 1999; Joshi et al., 2003; Cook and Highwood, 2004; Roberts and Jones, 2004; Forster and Joshi, 2005; Sokolov, 2006; Stuber et al., 2005). It is generally found that upper-troposphere forcings have smaller efficacy than forcings that affect the surface. However, climate feedback considerations, such as cloud cover and water vapor content, make it difficult to generalize this finding with confidence (Govindasamy et al., 2001b; Joshi et al., 2003; Sokolov, 2006).

Efficacies reported in the literature

We now examine the efficacies that are currently available in the literature (also see Table A). Efficacies that may be relevant for aircraft issues include: long-lived GHGs, stratospheric ozone, upper tropospheric ozone, scattering aerosols, absorbing aerosols, contrails and stratospheric water vapor. Efficacies are also given in the literature for total solar irradiance change (Gregory et al., 2004; Joshi et al., 2003; Cook and Highwood, 2004; Sokolov, 2006; Forster et al., 2000; Hansen et al., 2005) and for tropospheric ozone change near the surface (Hansen et al., 2005; Lohmann and Feichter, 2005; Mickley et al., 2004), but these are not directly relevant to aircraft studies and will not be discussed in this report.

Existing derived efficacies for gas and particle emissions or concentration perturbations to atmospheric concentrations have been adopted recently by various authors to aviation application – however, these efficacies were not specifically based on aviation emissions studies and may not be appropriate for the spatial and temporal emissions associated with aviation. At this point, there are no reliable efficacies for aviation impacts on climate.

For the forcing types relevant to aircraft issues, in looking at the existing analyses of efficacies, the exact experiment done to calculate the efficacy will determine whether the value may be of use for aircraft studies because aircraft forcings tend to have very specific characteristics (for example, geographic location and altitude.) Long-lived GHGs, contrails, stratospheric ozone, upper tropospheric ozone and stratospheric water vapor are directly relevant to aircraft issues regardless of the experiment, but we still examine the experiments used to determine efficacies for these forcing types. Scattering aerosols and absorbing aerosols efficacies reported in the literature may or may not be relevant to aircraft studies, depending on how they were determined. The efficacy value, as with RF, depends strongly on the definition of tropopause height (Ramaswamy et al., 2001; Chipperfield et al., 2003; Hansen et al., 2005). Efficacies for each aircraft-related forcing agent are given, along with an overview of efficacy values in the literature, a description of how the efficacy was calculated and a statement of how relevant this efficacy value is likely to be for aircraft studies.

Long-lived greenhouse gases:

IPCC (1995; and references therein) determined that the climate sensitivity for a wide range of forcing agents is invariant. Most of the climate forcings examined were long-lived greenhouse gases that are approximately spatially homogeneous. Hansen et al. (2005) suggests around 1.04 as an average efficacy for all well-mixed GHGs. Generally, long-lived GHG efficacies are thought to be around 1.0 (with an error of 10%). Long-lived GHGs include CO_2, N_2O and CFCs. CH4 is also a long-lived gas, but is considered in more detail because of its chemistry importance in the atmosphere

Very few studies have examined the efficacy for individual GHGs. Hansen et al. (2005) suggest slightly higher efficacies for individual GHGs with N_2O having an efficacy of 1.04 and CFC-11 and CFC-12 having a value of 1.32. On the other hand, some studies suggest that efficacies for CFCs should be slightly smaller than 1.0, such as Forster and Joshi (2005) who report 0.94. This suggests that the efficacies being derived are also dependent on the model used and the specific experiment.

Hansen et al. (2005) found that CH_4 had an average efficacy of 1.1.Two separate CH_4 experiments were done with concentrations of 2 and 6 times the current concentration. Efficacies were 1.10 and 1.13, respectively. This illustrates the potential nonlinearity associated with climate sensitivity. Indirect effects, such as the effect of CH_4 and CFCs on O3 and the effect of CH4 on water vapor are not included in these efficacies. Bernsten et al. (2005) determined that efficacies for methane were 1.08 and 0.95 for the ECHAM4 and UREAD models, respectively.

In summary, there is very little model consensus on the efficacies for individual long-lived greenhouse gases. The general consensus among journal articles that do not directly test the efficacy of long-lived GHGs remains that long-lived well-mixed GHGs have efficacies around 1.0 and most model experiments support this consensus for CH_4 and N_2O within about 10%. These efficacies should apply to aircraft studies without qualification because the species tend to be well mixed in the atmosphere.

UT/LS ozone:

Stratospheric ozone efficacies have been examined by Stuber et al. (2001), Joshi et al. (2003), Hansen et al. (2005) and Stuber et al. (2005) using idealized ozone changes. Hansen et al. (2005) used realistic stratospheric ozone changes. Ozone changes throughout the atmosphere and in the troposphere only were examined. It was found that both of these cases led to the same efficacy, implying that a stratospheric ozone change would have the same efficacy if the effects are linearly additive. This linearity was not tested but it would be a relatively easy experiment.

Stuber et al. (2005) examined the radiative forcing temperature response for ozone in the upper troposphere and lower stratosphere separately. They also examined homogeneous and inhomogeneous distributions for ozone for both UT and LS experiments. The inhomogeneously distributed O_3 had a maximum concentration at about 60 N. The Northern Hemisphere upper tropopause experiment matched the ozone distribution from aircraft emissions. The GCM used did not have a chemistry model, so the production of stratospheric water vapor from oxidation of CH4 is not included. Efficacies were found to be: 1.8 for a homogeneous distribution in the LS;

0.72 for homogeneous distribution in the UT; 2.26 for inhomogeneous distribution in the LS; and 1.07 for inhomogeneous distribution in the UT.

Joshi et al. (2003) applied O_3 changes in the UT in the tropics, UT in the Northern Hemisphere extratropics and globally in the LS. Three very different models were run for each study (UREAD, ECHAM4, and LDM), Efficacies were found to be: 0.71, 0.72 and 0.91 for the three models, respectively, in the UT tropics; 0.63, 1.17, and 0.55, respectively, in the Northern Hemisphere UT; and 1.39, 1.8, and 1.23, respectively, globally in the LS. The difference on stratospheric O_3 efficacies between the models is thought to be due to the different feedback mechanisms of stratospheric water vapor.

Forster and Shine (1999) found that lower stratospheric ozone had a 40% higher climate sensitivity than CO_2, while Joshi et al. (2003) found a 20-80% higher climate sensitivity using three different models. Stratospheric water vapor feedback was included in the stratospheric ozone efficacies for both of these studies and it was determined that this feedback accounts for the large efficacy values. The stratospheric water vapor reaction is already considered in steady-state CTM runs for aircraft emissions, so the efficacies used for radiative forcing should be lower than those found by Joshi et al. (2003).

At this time, it is premature to assign an efficacy with any confidence to stratospheric ozone changes, but the Joshi et al. (2003) and Stuber et al. (2005) results clearly suggest that the efficacy is not the same for UT and LS O_3. Bernsten et al. (2005) also found that ozone perturbations are not linearly additive when O_3 perturbations were tested over Europe and SE Asia separately and combined. The departure from linearity was approximately 8%.

Scattering aerosols (Direct effect):

As discussed earlier, aerosols have both a direct and indirect effects on the atmosphere. Cook and Highwood (2004) determined in idealized studies that the direct effect of scattering aerosols is very similar to the effect of changing total solar irradiance (near 1.0). Hansen et al. (2005) found an efficacy of 1.09 for tropospheric sulfates and determined that realistic changes in scattering aerosols had a larger effect at higher latitudes than at lower latitudes. This experiment doubled the current concentrations of sulfates, so it is not clear how relevant this efficacy value is for aircraft emissions near the tropopause. Rotstayn and Penner (2001) have also examined the direct effect of scattering sulfate aerosols. Sulfates in their experiment are distributed in the vertical so that there is an exponential decrease in concentration with height. Direct sulfate efficacy was calculated to be 0.68 for pure forcing (no feedback) and 0.73 for quasi-forcing that included longwave feedback effects. Generally, it is assumed that the direct effect of scattering aerosols has an efficacy between 0.7 and 1.1, with similar efficacies for both stratospheric and tropospheric aerosols. Again, none of these studies directly simulated a change in sulfate emissions by aircraft. In all likelihood, the sulfate effect due to aircraft at the tropopause would be much too small to rise above climate model noise unless the sulfate concentration was multiplied by a large factor.

Absorbing aerosols (Direct effect):

Absorbing aerosols are perhaps the most difficult forcing types to infer global mean temperature change from because the linear relationship between RF and temperature change breaks down, and efficacy is not constant for black carbon aerosols (Hansen et al., 1997; Cook and Highwood, 2004; Feichter et al., 2004; Roberts and Jones, 2004; Hansen et al., 2005). For simplicity, the effect of changes in boundary layer black carbon is not discussed here because they are not directly relevant to aircraft issues.

The relative locations of cloud and aerosol layers, along with surface albedo, affect the relationship between RF and temperature (Penner et al., 2003, Cook and Highwood, 2004; Feichter et al., 2004; Johnson et al., 2004; Roberts and Jones, 2004; Hansen et al., 2005). The source of the black carbon also appears to affect the efficacy. Hansen et al. (2005) find efficacies much larger than 1.0 for biomass burning and much smaller than 1.0 for fossil fuel carbon Hansen et al. (2005) found that black carbon had efficacies of 0.5 in the free troposphere to 0.3 in the upper troposphere.

So far, there appears to be no consensus on efficacy for absorbing aerosols. It appears that no simple relationship exists between radiative forcing due to all absorbing aerosols and global mean temperature change. Biomass burning efficacies would not be appropriate for aircraft studies, but the smaller values for fossil fuel carbon may be appropriate. More studies need to be done to gain confidence in these results.

Indirect aerosol effects:

The indirect effect of aerosols has been examined numerous times in the literature, with recent publications by Rotstayn and Penner (2001), Williams et al. (2001) and Lohmann and Feidhter (2005), but none of these studies relate to emissions in the upper troposphere and resulting effects on cirrus clouds. Rotstayn and Penner (2001) calculate the efficacy for the indirect effect of surface-emitted aerosols to be 0.83 for the first indirect effect (Twomey effect), 0.78 for the second indirect effect (cloud lifetime effect) and 0.86 for the total indirect effect due to sulfate aerosols. Lohmann and Feichter (2005) calculate the efficacy for first indirect effect to be 1.01. Williams et al. (2001) calculated the efficacy for the first indirect effect to be 0.82 and the second indirect effect to be 1.17. The radiative forcings for the first and second indirect aerosol effects do not add linearly.

Contrails:

Hansen et al. (2005) and Ponater et al. (2005) find that contrail efficacy is smaller than that for CO_2. Hansen et al. (2005) used 10 times the current contrail value in a GCM experiment to determine the contrail climate sensitivity. The contrail signal did not rise above the model noise level enough for a statistically significant climate sensitivity value to be determined. Ponater et al. (2005) used 20 times the FESG/Fa1 inventory for 2050 aviation contrails in a similar experiment. They calculated the climate sensitivity value for CO2 and contrails to determine the climate sensitivity in various regions of the world. As expected, there was a larger temperature response over the land than there was over the ocean. The globally averaged efficacy for contrails in this study is 0.6. This value has not been confirmed by any other studies.

Stratospheric water vapor:

Forster and Shine (1999) determined that the efficacy for stratospheric water vapor is approximately 1.1. Their experiment increased stratospheric water vapor assumed increases in water vapor of 40 ppbv/year in the lower stratosphere and 100 ppbv/year in the upper stratosphere. They noted that it was the change in the lower stratospheric water vapor that contributed most of the radiative forcing. Hansen et al. (2005) also examined stratospheric water vapor, but they only presented efficacy for radiative forcing calculated using a constant sea surface temperature (Fs) and did not present efficacy for stratospheric adjusted radiative forcing

(Fa). The efficacy for Fs is 0.96, but it is typically different from that for Fa. Since most of the forcing in the Forster and Shine (1999) scenario was due to lower stratospheric water vapor, this efficacy value is probably appropriate for aircraft studies. Unfortunately there are not enough studies to gain confidence in the value.

Table A. Summary of efficacies found in literature for various forcing agents.

Forcing Agent		**Efficacy**	**Source**
Long-lived GHGs	All	~1.0 +/- 10%	
	N2O	1.04	Hansen et al., 2005
	CFC (-11 & -12)	1.32	Hansen et al., 2005
	CFC (-11 & -12)	0.94	Forster & Joshi, 2005
	CH4	1.1	Hansen et al., 2005
	CH4	0.95 - 1.08	Bernsten et al., 2005
	CH4	1.18	Ponater et al., 2006
O3			
	UT (extratropics)	1.07	Stuber et al., 2005
	UT (extratropics)	0.55 – 1.17	Joshi et al., 2003
	UT (tropics)	0.71 – 0.91	Joshi et al., 2003
	LS (extratropics)	2.26	Stuber et al., 2005
	LS (global)	1.8	Stuber et al., 2005
	LS (global)	1.23 – 1.8	Joshi et al., 2003
	LS (global)	1.4	Forster & Shine, 1999
	aviation	1.37-1.55	Ponater et al., 2006
Sulfates (direct)			
	UT	1.09	Hansen et al., 2005
	UT	0.68	Rotstayn & Penner, 2001
	UT	0.73 (w/feedbacks)	Rotstayn & Penner, 2001
Soot (direct)			
	free troposphere	0.5	Hansen et al., 2005
	UT	0.3	Hansen et al., 2005
Sulfates (indirect)			
	1st	0.83	Rotstayn & Penner, 2001
	1st	1.01	Lohmann & Feichter, 2005

	1st	0.82	Williams et al., 2001
	2nd	0.78	Rotstayn & Penner, 2001
	2nd	1.17	Williams et al., 2001
Contrails		0.59	Ponater et al., 2005

References

Andronova, N., M. Schlesinger, S. Dessai, M. Hulme, and B. Li, 2007: The Concept of Climate Sensitivity: History and Development. In *Human-Induced Climate Change: An Interdisciplinary Assessment*. M. E. Schlesinger et al. (eds.), Cambridge University Press.

Berntsen, T. K., J. S. Fuglestvedt, M. M. Joshi, K. P. Shine, N. Stuber, M. Ponater, R. Sausen, D. A. Hauglustaine, and L. Li, 2005: Response of climate to regional emissions of ozone precursors: sensitivities and warming potentials. *Tellus, 57B,* 283-304.

Boer, G. J., and B. Yu, 2003a: Climate sensitivity and climate state. *Clim. Dyn*., 21, 167-176.

Boer, G. J., and B. Yu, 2003b: Climate sensitivity and response. *Clim. Dyn*., 20, 415-429.

Bradford, D. F., 2001: Global change: Time, money and tradeoffs. *Nature* 410, 649-650, doi: 10.1038/35070707

Boucher, O., and J. Haywood, 2001: On summing the components of radiative forcing of climate change. *Climate Dynamics, 18,* 297-302.

Chipperfield, M. P., W. J. Randel, G. E. Bodeker, and P. Johnston, 2003: Global ozone: past and future. In: *Scientific assessment of ozone depletion: 2002*: pursuant to Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer / World Meteorological Organization., C.A. Ennis (ed.). WMO, Geneva, pp. 4.1-4.90. Chapter 4.

Christiansen, B., 1999: Radiative forcing and climate sensitivity: The ozone experience. *Quart. J. Royal Met. Soc.,* 125, 3011-3035

Chylek, P., G. Lesins, G. Vindeen, J. Wong, R. Pinnick, D. Ngo, and J. Klett, 1996: Black carbon and absorption of solar radiation by clouds. *J. Geophys. Res*., 101, 23365-23371.

Collins, W. D., et al., 2006: Radiative forcing by well-mixed greenhouse gases: estimates from climate models in the IPCC AR4. *J. Geophys. Res*., 111, doi:10.1029/2005JD006713.

Cook, J., and E. J. Highwood, 2004: Climate response to tropospheric absorbing aerosols in an intermediate general-circulation model. *Q. J. Roy. Meteor.Soc.*, 130, 175-191.

Cox, S. J., W. C. Wang, and S. E. Schwartz, 1995: Climate response to radiative forcings by sulfate aerosols and greenhouse gases. *Geophys. Res. Lett.,* 22(18), 2509-2512.

Cubasch, U., K. Hasselmann, H. Höck, E. Maier-Reimer, U. Mikolakewicz, B.D. Santer, R. Sausen, 1992: Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Climate Dynamics*, 8, 55-69, DOI 10.1007/BF00209163. URL http://dx.doi.org/10.1007/BF00209163.

Derwent, R.G., et al, 2001: Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects. *Climatic Change*, 49, 463-487.

Echaus, R. S., 1992: Comparing the effects of greenhouse gas emissions on global warming. *Energy J.,* 13, 25-35.

Fisher, D. A., C. H. Hales, W.-C. Wang, M. K. W. Ko, N. D. Sze, 1990: Model calculations on the relative effects of CFCs and their replacements on global warming. *Nature*, 344, 513-516.

Forster, P. M. F., and M. J. Joshi, 2005: The role of halocarbons in the climate change of the troposphere and stratosphere. *Climate Change*, 71, 249-266.

Forster, P. M. de F., and K. P. Shine, 1999: Stratospheric water vapor changes as a possible contributor to observed stratospheric cooling, *Geophys. Res. Lett.*, 26, 3309-3312.

Forster, P. M. F. and K. E. Taylor, 2006: Climate forcings and climate sensitivities diagnosed from coupled climate model integrations. *J. Climate*, 19, 6181-6194.

Forster, P. M. F., M. Blackburn, R. Glover, and K.P. Shine, 2000: An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. *Clim. Dyn.*, 16, 833-849.

Forster, P. M. de F., R. S. Freckleton, and K. P. Shine, 1997: On aspects of the concept of radiative forcing. *Clim. Dyn*. 13, 547-560.

Forster, P. M. F., M. Ponater, and W. Y. Zhong, 2001: Testing broadband radiation schemes for their ability to calculate the radiative forcing and temperature response to stratospheric water vapour and ozone changes. *Meteorol. Z., 122*, 1-999.

Forster, P. M. F., K. P. Shine, and N. Stuber, 2006: It is premature to include non-CO_2 effects of aviation in emission trading schemes. *Atmos. Environ.*, 40, 1117-1121.

Freckleton, R. S., E. J. Highwood, K. P. Shine, O. Wild, K. S. Law, and M. G. Sanderson, 1998. Greenhouse gas radiative forcing: Effects of averaging and inhomogeneities in trace gas distribution. *Quart. J. Roy. Met. Soc.*124:2099-2127.

Fuglestvedt, J. S., T. K. Berntsen, O. Godal, R. Sausen, K. P. Shine, and T. Skodvin, 2003: Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change*, 58, 267-331.

Fuglestvedt, J. S., T. K. Bernsten, O. Godal, and T. Skodvin, 2000: Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophys. Res. Lett*., 27, 409-412.

Gauss, M. G. Hyhre, G. Pitari, M. J. Prather, I. S. A. Isaksen, T. K. Bernsten, G. P. Brasseur, F. J. Dentener, R. G. Derwent, D. A. Haughlustaine, L. W. Horowitz, D. J. Jacob, M. Johnson, K.S. Law, L. J. Mickley, J.-F. Muller, P.-H. Plantevin, J. A. Pyle, H. L. Rogers, D. S. Stevenson, J. K. Sundet, M. van Weele, and O. Wild, 2003: Radiative forcing in the 21st century due to ozone changes in the troposphere and lower stratosphere. *J. Geophys. Res.*, 108, NO. D9, 4292, doi:10.1029/2002JD002624.

Gauss, M., I. S. A. Isaksen, D. S. Lee, O. A. Sovde, 2005: Impact of aircraft NOx emissions on the atmosphere – Tradeoffs to reduce impact. *Atmos. Chem. Phys. Discuss*., 5, 12255-12311.

Godal O., 2003: The IPCC assessment of multidisciplinary issues: The choice of greenhouse gas indices. *Climatic Change*, 58, 243-249.

Godal, O., and J. Fuglestvedt, 2002: Testing 100-year Global Warming Potentials: impacts on compliance costs and abatement profile. *Climatic Change*, 52, 93-127.

Gohar, L. K., G. Myhre, and K. P. Shine, 2004: Updated radiative forcing estimates of four halocarbons. *J. Geophys. Res., 109,* D01107, doi: 10.1029/2003JD004320.

Govindasamy, B., K. E. Taylor, P. B. Duffy, B. D. Santer, A. S. Grossman, and K. E. Grant, 2001b: Limitations of the equivalent CO2 approximation in climate change simulations. *J. Geophys. Res.*, 106, 22593-22603.

Gregory, J. M., W. J. Ingram, M. A. Palmer, G. S. Jones, P. A. Stott, R. B. Thorpe, J. A. Lowe, T. C. Johns, and K. D. Williams, 2004: A new method for diagnosing radiative forcing and climate sensitivity. *Geophys. Res. Lett*., 31, L03205, DOI 10.1029/2003GL018747.

Grewe, V., and A. Stenke, 2007: A strategy for climate evaluation of aircraft technology: an efficient climate impact assessment tool – AirClim. *Atmos. Chem. Phys. Discuss*., 7, 12185-12229.

Hammitt, J. K., A. K. Jain, J. L. Adams, and D. J. Wuebbles, 1996: A welfare-based index for assessing environmental effects of greenhouse-gas emissions. *Nature*, 381, 301-303.

Hammond, A. L., E. Rodenburg, and W. Moomaw, 1990: Commentary in *Nature*, 347, 705-706.

Hansen, J., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res*., 102, 6831-6864.

Hansen, J., M. Sato, L. Nazarenko, R. Ruedy, A. Lacis, D. Koch, I. Tegen, T. Hall, D. Shindell, B. Santer, P. Stone, T. Novakov, L. Thomason, R. Wang, Y. Wang, D. Jacob, S. Hallandsworth, L. Bishop, J. Logan, A. Thompson, R. Stolarski, J. Lean, R. Willson, S. Levitus, J. Antonov, N. Rayner, D. Parker, and J. Christy, 2002: Climate forcings in Goddard Institute for Space Studies SI2000 simulations. *J. Geophys. Res*., 107, D18, 4347, doi:10.1029/2001JD001143.

Hansen, J., M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G.A. Schmidt, G. Russell, I. Aleinov, M. Bauer, S. Bauer, N. Bell, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, M. Kelley, N. Kiang, D. Koch, J. Lean, J. Lerner, K. Lo, S. Menon, R. Miller, P. Minnis, T. Novakov, V. Oinas, J. Perlwitz, J. Perlwitz, D. Rind, A. Romanou, D. Shindell, P. Stone, S. Sun, N. Tausnev, D. Thresher, B. Wielicki, T. Wong, M. Yao, and S. Zhang, 2005: Efficacy of climate forcings. *J. Geophys. Res*., 110, D18104, doi: 10.1029/2005JD005776.

Harvey, L. D. D., 1993: A guide to Global Warming Potenitals (GWPs). *Energy Pol*., 21, 24-34.

Hasselmann, K., R. Sausen, E. Maier-Reimer, and R. Voss, 1993: On the cold start problem in transient simulations with coupled atmosphere-ocean models. *Climate Dynamics*, 9, 53 - 61, doi: 10.1007/BF00210008.

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocana, and H. V. Storch, 1997: Sensitivity Study of Optimal CO_2 Emission Paths Using a Simplified Structural Integrated Assessment Model (SIAM). *Climatic Change*, 37, 345 - 386, doi: 10.1023/A:1005339625015.

Haywood, J.M., and V. Ramaswamy, 1998: Global sensitivity studies of the direct radiative forcing due to anthropogenic sulfate and black carbon aerosols. *J. Geophys. Res*. 103, 6043-6058.

Hooss, G., R. Voss, K. Hasselmann, E. Maier-Reimer, and F. Joos, 2001: A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS). *Climate Dynamics*, 18, 189 - 202, doi:10.1007/s003820100170.

Huang, Y., and V. Ramaswamy, 2006: Temperature dependence of gas absorptivity and its implication for climate change problem. *J. Geophys. Res*., submitted.

IPCC, 1990: *Climate Change 1990. The IPCC Scientific Assessment*. Working Group 1 report, Intergovernmental Panel on Climate Change, WMO and UNEP, Houghton, J.T., G.J. Jenkins and J.J. Ephraums (eds.), Cambridge University Press, Cambridge, U.K., pp 364.

IPCC, 1995*: Climate Change 1994. Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*. Cambridge, Cambridge University Press, Cambridge, U.K.

IPCC, 1999: *Aviation and the global atmosphere: a special report of the IPCC Working Group I and III*. J.E. Penner, D.H. Lister, D.J. Griggs, D.J. Dokken, and M. MacFarland (eds.). Cambridge University Press, pp. 373.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*, J. T. Houghton, et al., editors. Cambridge Univ. Press, Cambridge, UK.

IPCC, 2007a: *Climate Change 2007 – The Physical Science Basis*. Contribution of Working group I to the Fourth Assessment Report of the IPCC. S. Solomon, et al., editors. Cambridge Univ. Press, Cambridge, UK.

IPCC, 2007b: *Climate Change 2007 – Impacts, Adaptation and Vulnerability*. Contribution of Working group II to the Fourth Assessment Report of the IPCC. M. Parry, et al., editors. Cambridge Univ. Press, Cambridge, UK.

Jacob, D. J., R. Avissar, G. C. Bond, S. Gaffin, J. T. Kiehl, J. L. Lean, U. Lohmann, M. E. Mann, R. A. Pielke, V. Ramanathan, and L. M. Russell, 2005: Radiative forcing of climate change. The National Academy Press, Washington, D.C., 207 pp.

Jain, A. K., B. P. Briegleb, K. Minschwaner, and D. J. Wuebbles, 2000: Radiative forcings and Global Warming Potentials of thirty-nine greenhouse gases. *J. Geophys. Res*., 105, 20773-20790.

Joshi, M., M. Ponater, N. Stuber, R. Sausen, and L. Li, 2003: A comparison of climate response to different radiative forcings in three general circulation models: towards an improved metric of climate change. *Clim. Dyn., 20,* 843-854.

Joos, F., I. C. Prentice, S. Sitch, R. Meyer, G. Hooss, G.-K. Plattner, S. Gerber, and K. Hasselmann, 2001: Global warming feedbacks on terrestrial carbon uptake under the IPCC emission scenarios, Global Biogeochemical Cycles, 15, 891–907.

Kandlikar, M., 1995: The relative role of trace gas emissions in greenhouse abatement policies. *Energy Pol*., 23, 879-883.

Kandlikar, M., 1996: Indices for comparing greenhouse gas emissions: integrating science and economics. *Energy Economics*, 18, 265-282.

Kiehl, J. T., 2007: Twentieth century climate model response and climate sensitivity. *Geophys. Res. Lett*., 34, doi:10.1029/2007GL031383.

Lashof, D. A. and D. R. Ahuja, 1990: Relative contribution of greenhouse gas emissions to global warming. *Nature*, 344, 529-531.

Lee, D. S., and R. Sausen, 2004: Climate responses to aviation NOx and CO_2 emissions scenarios. Aviation, Atmosphere and Climate (AAC). Proceedings of a European Conference, Friedrichschafen, Germany, June 30 to July 3, 2003. R. Sausen, C. Fichter and G. Amanatidis, editors. European Commission, Air Pollution research report 83.

Lee, D. S., and R. C. N. Wit, 2006: Potential methods to include the full climate impact of aviation emissions into the European Trading Scheme and their scientific integrity. Proceedings of an International Conference on Transport, Atmosphere, and Climate (TAC), R. Sausen and A. Blum, editors, Oxford UK, June 26-29, 2006.

Lohmann, U., 2002: Possible aerosol effects on ice clouds via contact nucleation, *J. Atmos. Sci.,* 59, 647–656.

Lohmann, U., and J. Feichter, 2005: Global indirect aerosol effects: A review. *Atmospheric Chemistry and Physics*, 5, 715-737.

Manabe, S., and R.F. Strickler, 1964: Thermal equilibrium of the atmosphere with a convective adjustment. *J. Atmos. Sci*., 21(4), 361-385.

Manabe, S., and R. Wetherald, 1967: Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci*., 24, 241-259.

Manne, A. S., and R. G. Richels, 2001: An alternative approach to establishing trade-offs among greenhouse gases. *Nature*, 410, 675-677.

Marais, K., S. P. Lukachko, M. Jun, A. Mahashabde, and I. A. Waitz, 2007: Assessing the impact of aviation on climate. *Meteor. Z.*, in press.

Marquart, S., M. Ponater, F. Mager, and R. Sausen, 2003: Future Development of Contrail Cover, Optical Depth, and Radiative Forcing: Impacts of Increasing Air Traffic and Climate Change, *Journal of Climate, 16,* 2890-2904.

Mahashabde, A., K. Marais, M. Jun, and I. Waitz, 2007: *APMT Algorithm Description Document. Benefits Valuation Block – Climate Impact APMT System*. Federal Aviation Administration, document APMT-ADD-20-01.

Meehl, G. A., W. M. Washington, J.M. Arblaster, and A. Hu, 2004a: Factors affecting climate sensitivity in global coupled models. *J. Climate*, 17, 1584-1596.

Meehl, G. A., W. M. Washington, C. M. Ammann, J. M. Arblaster, T. M. L. Wigley, and C. Tebaldi, 2004b: Combinations of Natural and Anthropogenic Forcings in Twentieth-Century Climate. *J. Climate*, 17, 3721-3727.

Mendelsohn, R., W. Morrison, M. E. Schlesinger, and N. G. Andronova, 2000: Country-specific market impacts of climate change. *Climatic Change*, 45, 553-569.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo, 2002a: Climate effects of black carbon aerosols in China and India. *Science*, 297, 2250-2253.

Mickley, L. J., D. J. Jacob, B. D. Field, and D. Rind, 2004: Climate response to the increase in tropospheric ozone since preindustrial times: A comparison between ozone and equivalent CO2 forcings. *J. Geophys. Res*., 109, D05106, doi:10.1029/2003JD003653.

Myhre, G., and F. Stordal, 1997: Role of spatial and temporal variations in the computation of radiative forcing and GWP. *J. Geophys. Res*., 102, 11181-11200.

Myhre, G., and F. Stordal,, 2001: On the tradeoff of the solar and thermal infrared radiative impact of contrails. *Geophys. Res. Lett.*, 28, 3119-3122.

Myhre, G., A. Myhre, and F. Stordal, 2001: Historical evolution of radiative forcing of climate. *Atmos. Env.*, 35, 2361-2373.

Naik, V., A. Jain, K. O. Patten, and D. J. Wuebbles, 2000: Consistent sets of atmospheric lifetimes and radiative forcings on climate for CFC replacements: HCFCS and HFCs, *J. Geophys. Res.*, 105, 6903-6914.

National Research Council (NRC), 2003: *Estimating Climate Sensitivity: Report of a Workshop*. The National Academies Press, Washington, D. C.

Nordhaus, W. D., 1997: Discounting in economics and climate change. *Climatic Change*, 37, 315-328.

Nordhaus, W. D., and J. Boyer, 2000: *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA.

O`Neill, B. C., 2000: The Jury is Still Out on Global Warming Potentials. *Climatic Change*, 44, 427-443.

O`Neill, B. C., 2003: Economics, natural science, and the costs of Global Warming Potentials. *Climatic Change*, 58, 251-260.

Pan, L. L., J. C. Wei, D. E. Kinnison, R. Garcia, D. J. Wuebbles, and G. P. Brasseur, 2006: A set of diagnostics for evaluating chemistry-climate models in the extratropical tropopause region. *J. Geophys. Res.*, 112, D09316, doi:10.1029/2006JD007792.

Ponater, M., S. Marquart, R. Sausen, and U. Schumann, 2005: On contrail climate sensitivity. *Geophys. Res. Lett.*, 32, L10706, DOI 10.1029/2005GL022580

Ponater, M., V. Grewe, R. Sausen, U. Schumann, S. Pechtl, E. J. Highwood, and N. Stuber, 2006: Climate sensitivity of radiative impacts from transport systems. Proceedings of an International Conference on Transport, Atmosphere, and Climate (TAC), R. Sausen and A. Blum, editors, Oxford UK, June 26-29, 2006.

Prather, M., and R. Sausen, convening authors, 1999: Potential Climate Change from Aviation, Chapter 6 in Aviation and the Global Environment, Intergovernmental Panel on Climate Change, J. Penner, et al., editors, Cambridge University Press, Cambridge, UK, 189-215.

Ramanathan, V., R.J. Cicerone, H.B. Singh and J.T. Kiehl, 1985: Trace gas trends and their potential role in climate change. *J. Geophys. Res.*, 90, 5547-5566.

Ramanathan, V., P.J. Crutzen, J.T. Kiehl, and D. Rosenfeld, 2001: Atmosphere: Aerosols, climate, and the hydrological cycle. *Science*, 294, 2119-2124.

Ramanathan, V., L. Callis, R .D. Cess, J. Hansen, and I. Isaksen, 1987: Climate-Chemical Interactions and effects of changing atmospheric trace gases, *Rev. Geophys.*, 25(7), 1441-1482.

Ramaswamy, V., O. Boucher, J.D. Haigh, D.A. Hauglustaine, J.M. Haywood, G. Myhre, T. Nakajima, G.Y. Shi, and S. Solomon, 2001: Radiative forcing of climate change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). Cambridge University Press, Cambridge, UK, pp. 349-416

Roberts, D.L., and A. Jones, 2004: Climate sensitivity to black carbon aerosol from fossil fuel combustion. *J. Geophys. Res.*, 109, D16202 1-12.

Rodhe, H., 1990: A comparison of the contribution of various gases to the greenhouse effect. *Science*, 248, 1217-1219.

Roe, G. H., and M. B. Baker, 2007: Why Is climate sensitivity so unpredictable? *Science*, 318. 629 – 632, DOI: 10.1126/science.1144735.

Rogers, 1. D., and R. D. Stephens, 1988: Absolute infrared intensities for F-113 and F-114 and an assessment of their greenhouse warming potential relative to other chlorofluorocarbons. *J. Geophys. Res.*, 93, 2423-2428.

Rotmans, J., M. G. J. Den Elzen, 1992: A model-based approach to the calculation of Global Warming Potentials (GWP). *Int. J. Climatol.*, 12, 865-874.

Rotstayn, L. D., and J. E. Penner, 2001: Indirect aerosol forcing, quasi forcing, and climate response. *J. Climate, 14(13),* 2960-2975.

Sausen, R., M. Ponater, and N. Stuber, 2002: Climate response to inhomogeneously distributed forcing agents. Non-CO2 Greenhouse Gases, Van Ham, Baede, Guicherit and Williams-Jacobse (eds.). Millpress, Rotterdam, pp. 377-381.

Sausen, R., and U. Schumann, 2000: Estimates of the Climate Response to Aircraft CO_2 and NO_X Emissions Scenarios. *Climatic Change, 44,* 27-58.

Sausen, R., I. Isaksen, V. Grewe, D. Hauglustaine, D.S. Lee, G. Myhre, M. Kohler, G. Pitari, U. Schumann, F. Stordal, and C. Zerefos, 2005: Aviation radiative forcing in 2000: An update on IPCC (1999). *Meteor. Z., 14, No. 4,* 555-561.

Schmalensee, R., 1993: Comparing greenhouse gases for policy purposes. *Energy J.*, 14, 245-255.

Schwartz, S.E., 2004: Uncertainty requirements in radiative forcing of climate change. *J. Air and Waste Manage. Assoc.*, 54, 1351-1359.

Shindell, D. T., G. Faluvegi, N. Bell, and G. A. Schmidt, 2005: An emissions-based view of climate forcing by methane and tropospheric ozone. *Geophys. Res. Lett.*, 32, L04803, doi:10.1029/2004GL021900.

Shine, K. P., and P. M. de F. Forster, 1999: The effect of human activity on radiative forcing of climate change: a review of recent developments. *Global and Planetary Change, 20,* 205-225.

Shine, K. P., J. Cook, E. J. Highwood, and M. M. Joshi, 2003: An alternative to radiative forcing for estimating the relative importance of climate change mechanisms. *Geophys. Res. Lett. 30,* CLM 4, doi: 10.1029/2003GL018141.

Shine, K. P., J. S. Fuglestvedt, K. Hailemariam, and N. Stuber, 2005a: Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases, *Climatic Change, 68,* 281-302.

Shine, K. P., T. K. Berntsen, J. S. Fuglestvedt, and R. Sausen, 2005b: Scientific issues in the design of metrics for inclusion of oxides of nitrogen in global climate agreements, *Proceedings Nat. Acad. Sciences, 102, No. 44,* 15768-15773.

Shine, K. P., T. K. Berntsen, J. S. Fuglestvedt, R. B. Skeie, and N. Stuber, 2007: Comparing the climate effect of emissions of short- and long-lived climate agents. *Phil. Trans. R. Soc. A,* 365, 1903-1914.

Smith, S. J., and T. M. L. Wigley, 2000: Global Warming Potentials: 1. Climatic implications of emissions reductions. *Climatic Change*, 44, 445-457.

Smith, S. J., and T. M. L. Wigley, 2000: Global Warming Potentials: 2. Accuracy. *Climatic Change*, 44, 459-469.

Sokolov, A., 2006: Does model sensitivity to changes in CO_2 provide a measure of sensitivity to the forcing of different nature? *J. Climate*, 19, 3294-3306.

Stevenson, D. S., R. M. Doherty, M. G. Sanderson, W. J. Collins, C. E. Johnson, and R. G. Derwent, 2004: Radiative forcing from aircraft NO_X emissions: Mechanisms and seasonal dependence. *J. Geophys. Res., 109*, 13 pp.

Stuber, N., M. Ponater, and R. Sausen, 2001: Is the climate sensitivity to ozone perturbations enhanced by stratospheric water vapor feedback? Geophys. Res. Lett., 28, 2887-2890.

Stuber, N., M. Ponater, and R. Sausen, 2005: Why radiative forcing might fail as a predictor of climate change. *Clim. Dyn*., 24, 497-510.

Sygna, L., J.S. Fuglestvedt, and H.A. Aaheim, 2002: The adequacy of GWPs as indicators of damage costs incurred by global warming. *Mitigation Adaptation Strategies Global Change*, 7, 45-62.

Tett, S. F. B., G. S. Jones, P.A. Stott, D. C. Hill, J. F. B. Mitchell, M. R. Allen, W. J. Ingram, T. C. Johns, C. E. Johnson, A. Jones, D. L. Roberts, D. M. H. Sexton, and M. J. Woodage, 2002: Estimation of natural and anthropogenic contributions to twentieth century temperature change. *J. Geophys. Res.*, 107, 4306, doi:10.1029/2000JD000028.

Tol, R. S. J., 2002a: estimates of the damage costs of climate change. Part I: Benchmark estimates. *Environ. & Resource Econ*., 21, 47-73.

Tol, R. S. J., 2002b: estimates of the damage costs of climate change. Part I: Dynamic estimates. *Environ. & Resource Econ*., 21, 135-159.

Wang, W.; Wuebbles, D.J.; Washington, W.M.; Isaacs, R.G.; Molnar, G., 1986: Trace gases and other potential perturbations to global climate. *Reviews of Geophysics and Space Physics*, 24(1), 110-141.

Wang, W.-C., M. Dudek, and X.-Z. Liang, 1992: Inadequacy of effective CO_2 as a proxy in assessing the regional climate change due to other radiatively active gases. *Geophys. Res. Lett.*, 19(13), 1375-1378.

Wang, W.-C., M. Dudek, X.-Z. Liang, and J. T. Kiehl, 1991: Inadequacy of effective CO_2 as a proxy in simulating the greenhouse effect of other radiatively active gases. *Nature*, 350(6319), 573-577.

Williams, K. D., A. Jones, D. L. Roberts, C. A. Senior, and M. J. Woodage, 2001: The response of the climate system to the indirect effects of anthropogenic sulfate aerosols. *Clim. Dyn*., 17, 846-856.

Wit, R. C. N., B. H. Boon, A. van Velzen, M. Cames, O. Deuber, and D. S. Lee, 2005: Giving wings to emission trading, Design and impacts, Delft, CE, *05.7789.20*, 1-245.

WMO (World Meteorological Organization), 1985: Atmospheric Ozone: Assessment of Our Understanding of the Processes Controlling its Present Distribution and Change. 3 vol. WMO Report No. 16. Geneva.

Wuebbles, D. J., 1989: Beyond CO_2—the other greenhouse gases. Lawrence Livermore National Laboratory report UCRL-99883; Air and Waste Management Association paper 89-119.4.

Wuebbles, D. J., 1995: Weighing functions for ozone depletion and greenhouse gas effects on climate. *Annu. Rev. Energy Environ*., 20, 45-70.

Wuebbles, D. J., A. K. Jain, K. E. Grant, and K. O. Patten, 1995: Sensitivity of direct global warming potentials to key uncertainties. *Climate Change*, 29, 265-297.

Wuebbles, D. J., et al. (31 total authors), 2006: Workshop on the Impacts of Aviation on Climate Change: A Report of Findings and Recommendations. Partnership for Air Transportation Noise and Emissions Reduction, Report No. PARTNER-COE-2006-004 (available at http://web.mit.edu/aeroastro/partner/reports/climatewrksp-rpt-0806.pdf).

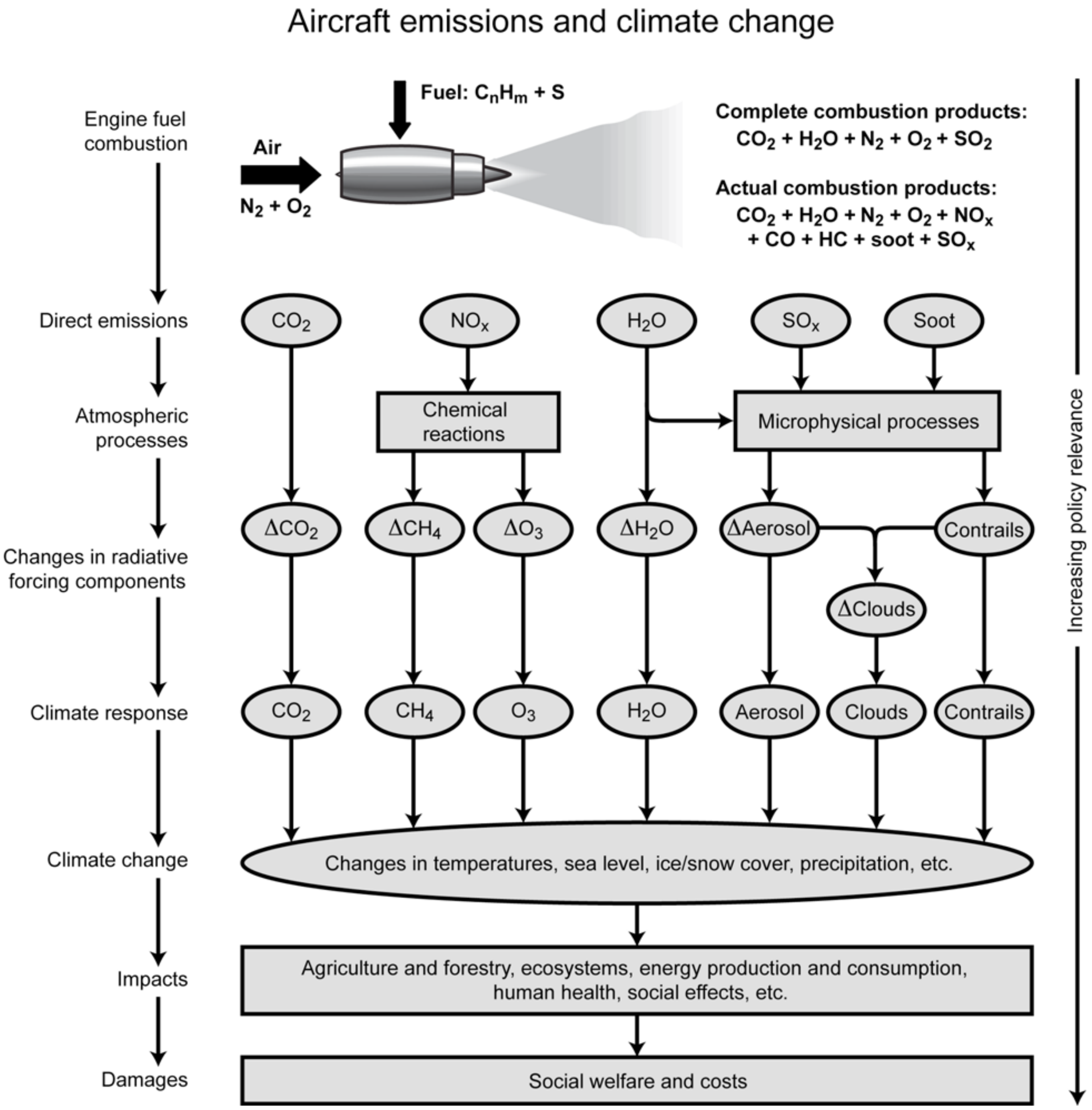

Figure 1. Aircraft emissions and their resulting potential impacts on climate change and welfare loss (developed for new report for CAEP, but adapted from Wuebbles et al., 2007, which in turn developed this figure based on IPCC, 1999 and Fuglestvedt et al., 2003).

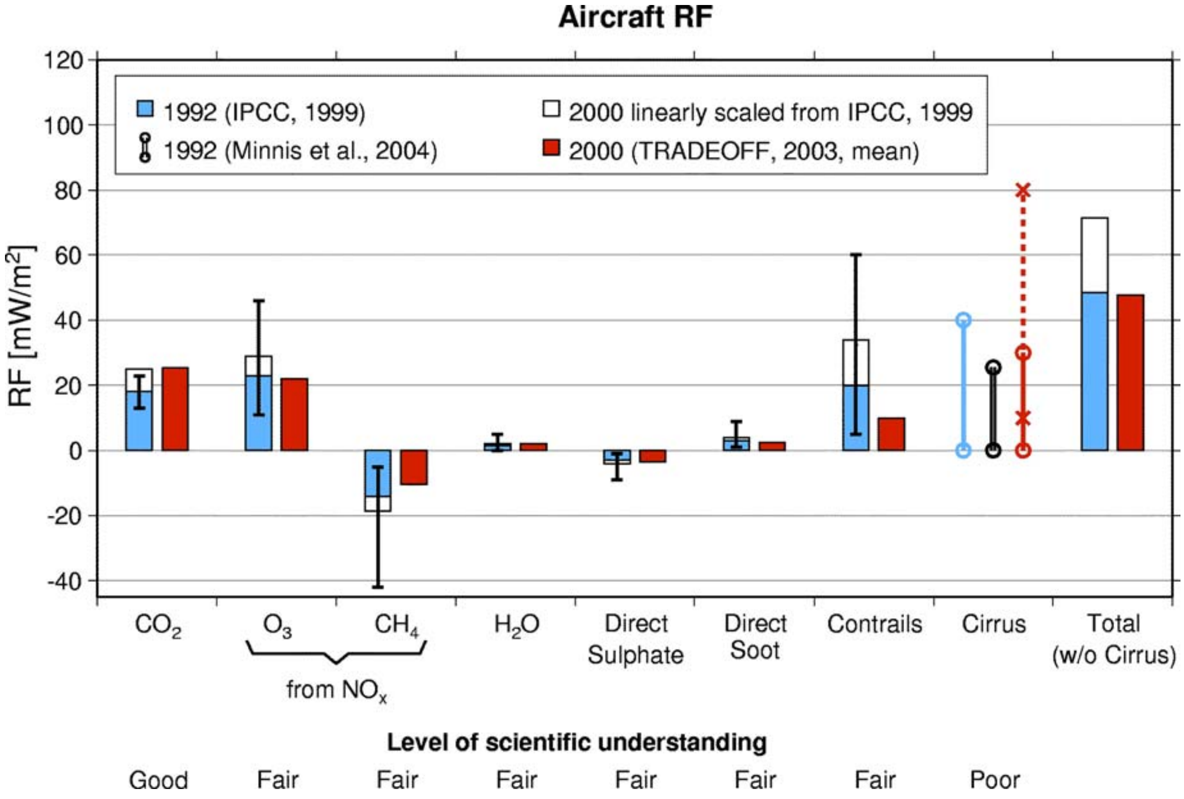

Figure 2. Global radiative forcing (RF) [mW/m^2] from aviation estimated for the years 1992 and 2000, based on IPCC (1999) and the European Union's TRADEOFF program results. The whiskers denote the 2/3 confidence intervals of the IPCC (1999) values. The lines with the circles at the end display different estimates for the possible range of RF from aviation induced cirrus clouds. In addition the dashed line with the crosses at the end denotes an estimate of the range for RF from aviation-induced cirrus. The total does not include the contribution from cirrus clouds (Sausen et al., 2005).