SEI Discussion Paper

Carbon Offsetting & Air Travel
Part 2: Non-CO_2 Emissions Calculations

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1. Introduction

Companies and individuals are increasingly interested in calculating and minimizing their climate footprint[1]. Although aviation emissions are small[2] when compared to other sectors of the economy, air travel can contribute a significant proportion of an individual's climate footprint. For example, the average European emits about 11 metric tons of carbon dioxide (CO_2) per year. If a European takes one transatlantic round-trip flight, say from Frankfurt to New York, they will add 0.8 – 2 metric tons[3] of CO_2 (excluding non-CO_2 effects) to their climate footprint. It is important to have an accurate metric to calculate the climate impacts of air travel. Yet calculating air travel's impact on climate change is a complex task, and the currently available air travel calculator estimates can vary by up to a factor of three (Kollmuss, 2007).

The following is the second of two papers that examine the key factors that have to be taken into account when calculating air travel emissions for the purpose of climate footprint and offset calculations. The first paper examined methods of calculating CO_2 emissions only, and provided a framework for how to allocate responsibility for these emissions among various aviation users (e.g. passengers, cargo customers) (Kollmuss and Lane, 2008). This paper has a broader scope in that it explains all the emission factors that affect climate change and discusses appropriate metrics that take into account all these factors. However, it does not directly address allocation of responsibility at the individual level.

In order to estimate the full effect of aviation on climate, it is necessary to account for CO_2 as well as for all other, non-CO_2 warming and cooling effects. This paper is written for a non-technical audience and explains how to account for non-CO_2 impacts of air travel emissions.

Much research has been conducted over the last few years on the non-CO_2 warming effects caused by aviation[4]. Nevertheless, controversy and confusion exist among policy makers and the general public about what these non-CO_2 effects are, how strong their impacts are, and how and if they should be integrated into global warming emissions calculations for aviation[5].

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[1] Usually an individual's or a company's contribution to climate change is called their 'carbon footprint.' This is slightly misleading because, as we discuss in this paper, carbon dioxide (CO_2) is just one of many greenhouse gases that have an impact on climate. To include the impact of all greenhouse gases, we use the term 'climate footprint.'

[2] Aviation currently accounts for approximately 2-5% of total carbon dioxide (CO_2) emissions and approximately 13% of all transportation related CO_2 emissions (IPCC, 1999). If non-CO_2 warming effects are included, the contribution of aviation to global climate change is even larger. Yet civil aviation is growing rapidly at 5.9% per year (IPCC 2007: Mitigation of Climate Change, p 334; ICAO, 2007). This is faster than any other mode of transportation (WBCSD, 2002), and the sector's contribution to climate change will therefore continue to increase.

[3] Estimated emissions depend on the type of airplane, occupancy rate and seat class, among other things. See our first paper (Kollmuss and Lane, 2008) for details.

[4] For an excellent but more technical update on the various scientific issues involving aviation and climate change, see the ACCRI papers available at:
http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/ or http://tinyurl.com/7oagzt

[5] As no scientific debate is completely sheltered from politics, it is also relevant to note that the aviation industry has thus far shown opposition to including non-CO_2 warming effects into greenhouse gas (GHG) calculations, whereas environmental groups (e.g. World Wildlife Fund–see references) have advocated for inclusion.

The non-CO_2 warming effects of aviation are most commonly accounted for in emissions calculators through a *Radiative Forcing Index (RFI)* or a *multiplier.* These terms refer to a dimensionless factor which is multiplied by the calculated CO_2 emissions in order to account for all warming effects. The multipliers used by different calculators lie between 1 (i.e. not accounting for non-CO_2 warming effects) and 3 (i.e. the total warming effect is calculated at three times that of the CO_2 emissions alone). These numbers are usually chosen in reference to the IPCC special report on aviation (IPCC, 1999). Unfortunately, these multipliers are often scientifically flawed. This paper seeks to explain why.

Many air-travel offset calculators avoid the issue of non-CO_2 warming effects and calculate only CO_2 emissions (multiplier of 1). We argue that this approach is not defensible: despite the difficulties of quantifying non-CO_2 warming effects from air travel emissions, most models and studies indicate that the magnitude of these effects is relevant. There is great urgency in addressing the climate crisis (Hansen et al., 2008). An argument can therefore be made that all climate changing agents[6] have to be included when setting reduction targets or calculating offsetting responsibilities[7].

Our discussion shows the limitations to developing a dimensionless multiplier for the integration of non-CO_2 effects into emissions calculators. These limitations are to some extent caused by scientific uncertainty, such as limited knowledge about the effects of cirrus clouds. Yet we also show that developing a multiplier is influenced to a great extent by value-based decisions that underlie the chosen approach and parameters (i.e. climate impact parameters, time frame, damage function, and discount rate[8]) and not just by the uncertainties that arise from a lack of scientific knowledge.

Though science-based reasoning discourages the use of a simple multiplier to account for non-CO_2 effects, such a multiplier is desirable from a policy and climate protection point of view. We elaborate on a number of scientific and value-related issues and conclude that **a multiplier of 2 or greater should be used for air travel emissions calculators to account for non-CO_2 warming effects**. The paper is structured the following way:

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[6] The gases that cause global warming are generally referred to as *greenhouse gases*, yet not all molecules that affect climate are gaseous (e.g. soot and other particulates). Usually these are referred to as *warming agents*. For the sake of simplicity, we use the term greenhouse gases (GHGs) to refer to all warming agents.

[7] We are very aware that offsetting, especially voluntary offsetting of emissions, can only be a small part of the climate solution (Kollmuss et al., 2007, Kollmuss et al., 2008). Yet carbon markets are growing rapidly (Capoor & Ambrosi, 2008) and consumers as well as carbon offset providers need a workable policy solution for addressing the need to accurately calculate emissions from air travel. Furthermore, such accurate calculators may help consumers choose between available modes of transport (e.g. train vs. air travel).

[8] The discount rate reflects the degree to which society prefers to receive benefits in the present rather than the future. In terms of the economics of climate change, there are those who argue that the future benefits provided by greenhouse gas emissions abatement should be discounted at a rate equal to the average return on a typical private-sector investment, or returns of 6% per year (Nordhaus, 1994). Yet critics argue that the use of high positive (c. 6%) discount rates can support policy outcomes that are unfair to future generations because unmitigated climate change would impose major, uncompensated costs on future generations. Similarly, some argue that equal weight should be attached to the welfare of both present and future generations. Economists have long recognized that the use of low (c. 1%) discount rates supports aggressive steps to stabilize global climate (Cline, 1992).

Chapter 2 explains how climate impacts are measured and modeled. It includes definitions of several important terms such as climate response, climate forcing, and climate impact.

Chapter 3 describes the climate changing effects from greenhouse gases (GHGs) and other non-CO_2 warming agents.

Chapter 4 examines some of the metrics that have been developed to account for non-CO_2 emissions, such as Radiative Forcing Index (RFI), Global Warming Potential (GWP), and Global Temperature Change Potential (GTP).

Chapter 5 summarizes the issues laid out in previous chapters and discusses the most pertinent issues that must be addressed when calculating climate impacts from air travel for climate footprint calculations, concluding with our recommendations.

2. How to Measure Climate Impacts

Models are used to estimate aviation's impacts on climate change. One type of model calculates how greenhouse gas emissions change the energy balance in the atmosphere. Another type of model goes one step further and calculates the temperature change that will be caused by the change in energy balance. The next types of models are even more complex and estimate how the predicted temperature change will cause changes in physical and biological systems (e.g. rainfall patterns or biodiversity) and how much these changes will cost human society (e.g. effects on GDP).

The results of the latter models have much higher uncertainty and depend to a much larger degree on assumptions and value-related decisions than the results of models that calculate physical changes, such as energy balance or temperature difference. Yet such impact models are often more policy-relevant than purely physical models. In other words, knowing the impacts on an ecosystem and its societal costs is more relevant and more important for risk assessment and policy actions than just understanding the radiative forcing of GHG emissions. But because we have to make many more assumptions when determining climate costs than when calculating radiative forcing, the results are more uncertain, and are shaped by underlying political or ethical decisions (e.g. discount rate or damage function). This trade-off between accuracy and relevance is also reflected in the many different approaches that have been used to account for climate impacts from aviation (see Chapter 4).

These different modeling approaches have all been used in calculating the contribution of aviation to climate change. In order to better understand the advantages and drawbacks of each of these approaches it is useful to break down the process of modeling climate change into the following consecutive steps (Figure 1):

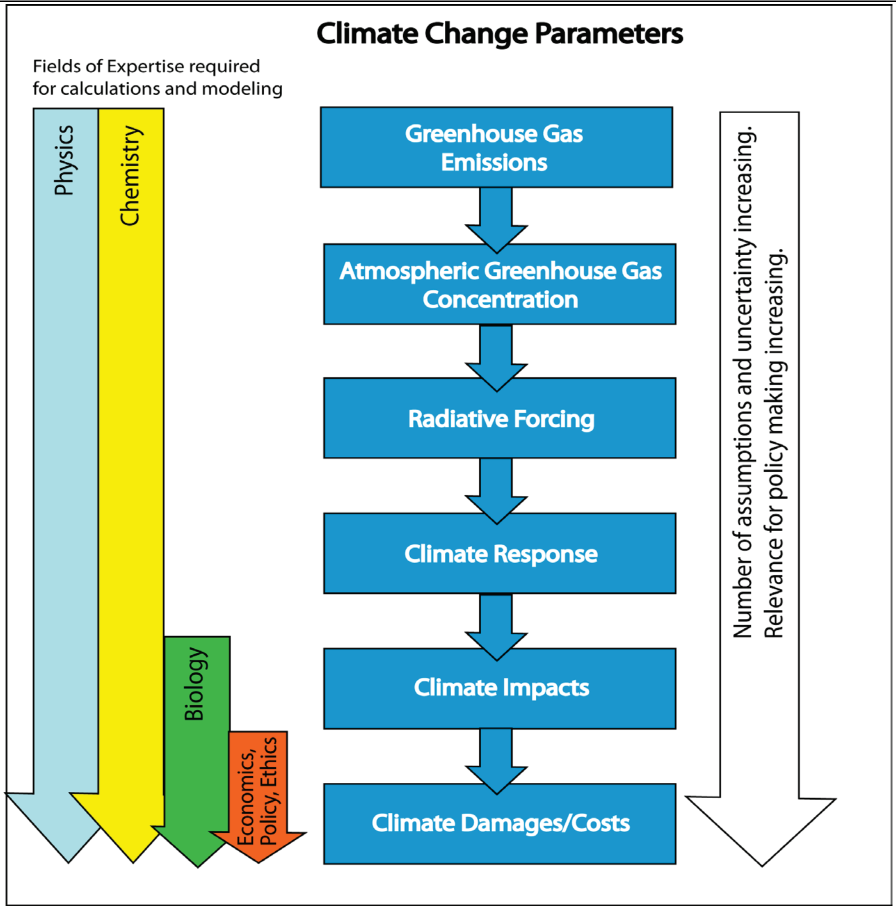

Figure 1: Measuring Climate Impacts
This figure is a simplified illustration of how climate impacts are modeled and estimated. The arrows on the left indicate the fields of expertise required to calculate the climate change parameters (blue boxes in the middle). The arrow to the right indicates theincrease in assumptions to calculate or model these parameters as we progress down the list. Results therefore become more uncertain. Yet relevance for policy making decisions increases as we move down the chain of climate change parameters. (A similar graph can be found in Fuglestvedt et al., 2003.)

Step 1: Calculating Greenhouse Gas Emissions from Human Activities
Humans emit greenhouse gases (GHGs) and other warming agents into the atmosphere through burning of fossil fuels, industrial and agricultural processes, and deforestation. These anthropogenic (human-induced) emissions raise the concentrations of these gases in the atmosphere, contributing to climate change. To calculate emissions from transportation, we need to know the type of fuel burned (e.g. gasoline), the greenhouse gas content of the fuel (e.g. 21 pounds of CO_2 per gallon of gasoline) and the amount of fuel burned (e.g. number of gallons).

Step 2: Calculating Atmospheric Greenhouse Gas Concentrations
To ascertain the atmospheric concentration of a particular GHG, we can either directly measure it by taking air samples, or calculate concentrations using models. In order to calculate the concentration of a greenhouse gas in the atmosphere, we need to know how much was emitted, how long the gas remains

in the atmosphere, how much of it is absorbed by water and land, and how strong a greenhouse gas it is. (These properties are explained in more detail in Chapters 3 and 4.) Atmospheric concentrations are usually expressed in parts per million (ppm) or parts per billion (ppb); for example, the global atmospheric CO_2 concentration has risen from approximately 280ppm to 385ppm in the last approximately 250 years.

Step 3: Determining Radiative Forcing (RF)

Once we know the atmospheric concentration of GHGs, we can calculate their impact on the global energy balance. Greenhouse gases trap solar energy (i.e. heat) in the atmosphere. The term 'Radiative Forcing' expresses the capacity of greenhouse gases to alter the temperature (energy balance) of the atmosphere (see section 4.1). To calculate radiative forcing, we need to know the physical properties of the gas (i.e. how much energy a molecule can absorb) and its atmospheric concentration. Radiative forcing is expressed in watts per square meter (W/m^2).

Step 4: Modeling Climate Response

Once we have calculated the radiative forcing of GHGs, we can model how the Earth will react to the additional energy the gases trap in the atmosphere. The term 'Climate Response' refers to Earth's physical and chemical responses to changes in the atmospheric energy balance, such as changes in average global temperature and the resultant changes in precipitation patterns.. To calculate climate responses, we need to know not only the radiative forcing of greenhouse gases but also how natural systems respond to these changes in the energy balance. This requires in-depth knowledge of highly complex systems. In order to model such systems, we also need to understand the following:

Climate Feedback

The term 'climate feedback' refers to an initial climate response that triggers a second process that in turn intensifies or reduces the initial response. A positive feedback intensifies the original process, and a negative feedback reduces it. An example of a positive feedback is the albedo effect in the Arctic: if Arctic ice melts due to warmer temperatures, the white snow surface is replaced by a much darker ocean surface. The dark ocean absorbs much more heat than white ice and snow surfaces. The newly-exposed dark surfaces will therefore lead to additional warming. Including climate feedbacks in climate calculations increases the accuracy of climate models because it better describes how much warming or cooling a GHG will cause. To express the potential of GHG emissions to cause climate feedbacks, the term 'climate efficacy' is used:

Climate Efficacy

Two greenhouse gases with the same radiative forcing do not necessarily lead to the same temperature increase. The term 'climate efficacy' is defined as "the global temperature response per unit forcing relative to the response to CO_2 forcing" (Hansen et al., 2005). Climate efficacy expresses the difference in effectiveness of different GHGs in causing warming or cooling.[9] In other words, climate efficacy expresses the initial climate response to a GHG emission as well as the secondary climate feedbacks that the GHG causes. As we will demonstrate, many of the current models used for aviation climate calculations do not take climate efficacy into account[10].

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[9] For example, human-caused methane has an efficacy of about 145% compared to CO_2, if indirect effects on stratospheric H_2O and tropospheric ozone are included (Hansen et al., 2005).

[10] For more information on efficacy ranges for aviation emissions, see Ponater, M., S. Pechtl, R. Sausen, U. Schumann, and G. Huttig (2006), "Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment," *Atmospheric Environment*, 40: 6928-6944..

Climate Sensitivity[11]

The term 'climate sensitivity' expresses how responsive the climate is to added forcing from GHG emissions. In other words, if there are strong positive climate feedbacks to GHG emissions, the climate sensitivity is higher than if there are no such feedbacks. Or, expressed in terms of climate efficacy: if GHG emissions have a high climate efficacy, they will lead to more warming, which in turn translates into higher climate sensitivity. More technically, it refers to the change in surface air temperature following a change in radiative forcing. The higher the climate sensitivity, the more the climate changes in response to GHG emissions. Climate sensitivity is expressed in degrees Celsius per watts per square meter (°C/Wm^2).

Step 5: Modeling Climate Impacts

The term 'climate impact' refers to ecosystem changes due to climate responses. Examples include: change in species composition and extinction, increase in vector-borne diseases, and impacts on agricultural crops. These effects can be quantified in many ways; for example, number of species threatened with extinction or number of people displaced by sea level rise.

Step 6: Modeling Climate Damages or Costs

The term 'climate damages or costs' refers to climate impacts expressed in economic terms. Climate damages are usually expressed in monetary units, such as property lost to sea-level rise or flooding, medical costs of heat waves and disease, etc. Many assumptions are required to calculate such costs, and to discount them to present economic values; many important climate damages, such as loss of human life, cannot easily be expressed in monetary terms[12]. Simple economic models frequently express all climate damages through a damage function, assuming a mathematically simple relationship between climate changes (measured by temperature increase) and the total value of associated damages. The choice of damage function relies on scientific and non-scientific assumptions and therefore leads to results that are to a large extent value-based. (For more, see Ackerman, 2009.)

[11] In the IPCC Reports, equilibrium climate sensitivity refers specifically to the equilibrium change in global mean surface temperature following a doubling of atmospheric CO_2 equivalent concentration.

[12] Prices for loss of human life are established regularly (e.g. life insurance industry) yet none of these estimates can resolve the issues between the economic realities and ethical considerations (e.g. Is the life of a rich person worth more than that of a poor person? Or is the life of a young person worth more than an old person?)

3. Aviation Emissions' Impacts on the Climate

There are four main ways that aviation emissions affect climate (Fuglestvedt et al., 2008), each of which is described in more detail below:

1) Direct emissions of Greenhouse Gases (GHGs): notably carbon dioxide (CO_2) and water vapor (H_2O)
2) Indirect impacts on GHGs: non-GHGs or weak GHGs such as nitrogen oxides (NO_x) catalyze changes in concentrations of other GHGs such as ozone (O_3) and methane (CH_4)
3) Emissions of aerosols[13]: emissions of particulates that have cooling or warming effects such as sulfates and soot
4) Formation of contrails and cirrus clouds

These emissions occur in the troposphere and lower stratosphere. The troposphere is the lowest part of Earth's atmosphere and its height extends to altitudes between 8 and 15km. The stratosphere lies between the troposphere and the mesosphere. It starts at an altitude of 8 to 15km and extends to 50 km.

3.1 Direct Emissions of Greenhouse Gases

Carbon Dioxide

Carbon dioxide (CO_2) is emitted during the combustion of aviation fuel (kerosene) in direct proportion to the kerosene consumed: 3.16 kilograms CO_2 are produced per kilogram of kerosene burned (IPCC, 1999). Given the current condition of the carbon cycle, natural CO_2 sinks (e.g. oceans and vegetation) absorb CO_2 from the atmosphere at approximately half the rate that anthropogenic atmospheric CO_2 emissions are produced[14], leading to a net accumulation. The resultant long-lived[15] CO_2 spreads globally and affects climate independent of where the emissions originated. CO_2 is the leading anthropogenic (human-induced) GHG and its warming effects are well understood; it is therefore often used as the basis for comparison of all other emission effects (see sections 4.2 and 4.4 on Radiative Forcing Index and Global Warming Potential). The climate response to CO_2 emissions is independent of where emissions occur; CO_2 from aircraft has the same effect as CO_2 from other ground level sources (IPCC, 1999).

Water Vapor

Water vapor (H_2O) is another GHG that is emitted during air travel. Most subsonic aircraft water vapor emissions are removed from the atmosphere through precipitation within one to two weeks and therefore cause short-lived, regional effects (IPCC, 1999). These effects are greater at high altitudes (i.e. a stronger climate response occurs when water vapor is emitted in the upper stratosphere than in

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[13] Fine solid or liquid particles that are suspended in a gas.

[14] Climate change can also affect the capacity for land and oceans to act as carbon sinks, another example of a positive feedback mechanism (Fung et al., 2005).

[15] CO_2 does not have a mean atmospheric lifetime. CO_2 emissions are absorbed by oceans and by the terrestrial biosphere. About half of CO_2 emitted into the atmosphere is removed in the first 30 years, a further 30% is removed within a few centuries and the remaining 20% will typically stay in the atmosphere for many thousands of years (IPCC, 2007).

the lower stratosphere[16]) where water vapor stays longer and can accumulate (Holton et al., 1995). This would have climate implications if air travel was expanded into these higher altitudes, but this is currently not common with commercial aircraft. Current science indicates that the warming effect of water vapor from air travel emissions is small (Sausen et al., 2005). (For information on the effects of condensed and frozen water, see Section 3.4 on contrails and cirrus clouds.)

3.2 Indirect Impacts on Greenhouse Gases

Certain chemicals emitted by airplanes, though not direct GHGs themselves, can act to modify, produce, or destroy GHGs. Nitrogen oxides[17] (NO_x) and their impacts on methane and ozone concentration are of primary concern.

Nitrogen Oxides and Impact on Ozone and Methane

Nitrogen oxides are produced in aircraft engines under high temperature and high pressure conditions by the reaction between oxygen and atmospheric nitrogen. Nitrogen oxides catalyze the following chemical reactions which lead to both warming and cooling effects:

1. NO_x (and hydroxides (-OH) produced from water vapor and volatile organic emissions) catalyze production of the short-lived greenhouse gas ozone (O_3). NO_x released during air travel increases ozone in the upper troposphere but destroys ozone in the lower stratosphere (IPCC, 1999). The process of O_3 formation is similar to ground level smog formation from transportation and industrial emissions. As with ground level smog, ozone formation depends on the concentration of NO_x because NO_x catalyzes not only the formation of ozone but also its destruction. This means, paradoxically, that lower ambient NO_x concentrations can lead to a greater production of O_3 than higher NO_x concentrations[18]. The O_3 effects of a particular flight therefore depend on the existing atmospheric conditions (Forster and Rogers, 2008).

   Because of increased UV radiation at high altitude (above approximately 9 km[19]) ozone is formed more effectively there than at ground level and leads to a larger radiative forcing (Berntsen et al., 2005). Ozone formation in the upper troposphere and the lower stratosphere is particularly sensitive to NO_x (Forster and Rogers, 2008). Furthermore, ozone occurring in the subtropics and tropics has greater radiative forcing than ozone emitted at higher latitudes (Berntsen et al., 1997). *Thus the O_3 effects of a particular flight depend on where changes occur geographically.*

   To summarize, the climate response of ozone formation is a function of UV radiation, water vapor concentration, temperature, and input of NO_x, as well as input of volatile organic compounds (VOCs), all of which have ambient concentrations and effects that differ with 1) the

[16] The stratosphere lies between about 10 km (6 miles) and 50 km (31 miles) altitude above the Earth's surface at moderate latitudes. At the poles, the stratosphere starts at about 8 km (5 miles) altitude.

[17] Strictly speaking, NO_2 is also a (weak) GHG. Yet because NO_2 tends to oxidize rapidly, it has a more important role in its impacts on ozone and methane than as a GHG.

[18] Lower NO_x concentrations do not always lead to a greater production of O_3 than higher NO_x concentrations. It depends on the proportion of NO_x and volatile hydrocarbons and also on temperature, humidity, and UV light.

[19] Aircraft usually travel at or above 9km (29,500 feet) for distances of more than 500 km (IPCC, 1999).

physical and chemical background levels, 2) altitude and latitude, and 3) climate sensitivity (Berntsen et al., 1997 and 2005).

2. NO_x emissions also lead to indirect destruction of methane (CH_4) through the creation of ozone. Methane is a strong GHG with an average lifetime of approximately 12 years. Creation of ozone results in hydroxyl radicals (-OH) that break down CH_4 into CO_2 and water, which are weaker GHGs than methane.[20] NO_x-induced ozone production that reduces atmospheric methane therefore results in a small net cooling. The effects of NO_x on methane last a little more than a decade (Stevenson et al., 2004).

3. Lastly, NO_x emissions and the resulting reduction in methane in turn lead to a longer-term decrease in O_3, and therefore a small cooling effect over the same lifetime as the methane reaction (Stevenson et al., 2004.) Ozone itself has an average lifetime on the order of weeks.

To summarize, NO_x emissions lead to an initial increase in ozone (net warming) followed by a longer-term decrease in methane (net cooling) and later a decrease of ozone (net cooling). However, the small decrease in ozone does not outweigh the larger initial increase in ozone. Therefore, overall changes in ozone concentration incur a warming effect whereas decreased methane has a cooling effect (Berntsen et al., 1997 and 2005; Marais et al., 2008). But it would be incorrect to assume that the two effects cancel each other out, since they occur on different time scales and have different geographical distributions.

While the scientific understanding and modeling of NO_x effects have substantially improved over the last few years, there is still uncertainty regarding the exact extent to which NO_x emissions from air travel affect climate change (Workshop on the Impacts of Aviation, 2006). In general, uncertainties for emissions that have indirect impacts on GHGs are higher than for direct GHG emissions, as the climate response may be dependent on geographic location and time of emission (IPCC, 2007, p 214).

3.3 Particulate Emissions

Sulfates & Soot Aerosols

Aircraft emissions of sulfates and soot particles also affect climate. Direct sulfate emissions cause cooling because sulfates reflect sunlight, while direct soot emissions have a warming effect, since the dark soot particles (black carbon) absorb solar radiation and decrease albedo when deposited over snow[21]. These anthropogenic (human-caused) aerosols are short-lived. The warming and cooling impact of aerosols from aircraft emissions is currently poorly understood[22] (Penner et al., 2009; Workshop on the Impacts of Aviation, 2006).

[20] If NO_x is added to a NO_x-limited environment, there will be higher production of ozone and hydroxyl (-OH). More -OH leads to the faster breakdown of methane into CO_2. Though flight levels are usually NO_x-limited, if NO_x is added to a VOC-limited regime, less ozone production will lead to less –OH production and a longer methane lifetime.

[21] This is an oversimplification. The key is the relative change in albedo as compared to the absence of aerosols which can affect temperature and humidity structure and thus alter the formation of clouds (Fuglestvedt et al., 2009).

[22] The direct effect of particles from aircraft is fairly well understood and is estimated to be a small effect. Indirect effects, however, are poorly understood.

The warming effects of soot are reduced at high altitude (Pueschel, 1996). Light-scattering particles, on the other hand, are less altitude-dependent in their effects (Hansen et al., 1997). Also, climate responses can vary with location of emission. For example, soot emissions have a stronger warming effect when emitted over white surfaces, e.g. aircraft flying over the snow- and ice-covered Arctic.

Aircraft sulfate particles can also impact climate change by influencing cloud formation. Water vapor in saturated air can condense on certain particles (ice nucleation), resulting in contrails and cirrus clouds (see Section 3.4). The exact impact of soot from air travel emissions is not well understood because of the many factors that influence its efficacy in causing cloud formations. These factors include, but are not limited to, natural particle concentrations, temperature fluctuations, and humidity levels (Penner et al., 2009). The warming impact of enhanced cloud formation due to aerosols acts on a shorter time scale than the effects of most GHGs and is currently poorly understood (IPCC, 2007, section TS2.2 of AR4 WG I Technical Summary).

3.4 Contrails & Cirrus Clouds

Clouds can have either a cooling or a warming effect: they can cause warming by trapping long-wave (infrared) radiation from the Earth, but also cool it by reflecting short-wave (visible and ultraviolet) solar radiation back into space. Overall, however, clouds caused by air-travel emissions are considered to have a net warming effect.

Contrails are linear ice clouds formed in the wake of aircraft, which, when persistent, can result in the formation of cirrus cloud cover (Williams, et al., 2002). Aircraft emissions trigger condensation of ambient water vapor into ice crystals in the atmosphere (Lee et al., 2009). Contrail formation and persistence depends on flight altitude and the temperature and humidity of the air through which a plane flies; thus contrail and cirrus formation is seasonally dependent. Approximately 10-20% of all jet flights occur in air masses with a humidity level sufficient to cause contrails. In 1992, contrails were estimated to cover about 0.1% of the Earth’s surface on an annually averaged basis, with larger regional values. According to the IPCC’s most likely scenario, coverage is expected to grow to 0.5% by 2050 (IPCC, 1999). Contrails are short-lived and have an overall warming effect that is similar to thin, high clouds.[23] Warming effects of contrails are different during the day than at night. During the day, contrails trap infrared radiation (a warming effect) and reflect solar radiation (a cooling effect). At night, only infrared radiation is trapped and re-emitted downward. The warming effect of contrails is therefore stronger at night (Stuber et al., 2006). It is important to note that because contrails are short-lived, formed in areas of high air traffic density, and can affect existing cirrus clouds, they may cause local or regional climate responses[24] (Burkhardt et al., 2008).

[23] For an interesting example of how contrails affect surface temperatures, see the study on the effect of the lack of contrails on surface temperatures during the no-fly period following Sept 11th, 2001: "Regional variations in U.S. Diurnal temperature range for the 11-14 September 2001 aircraft groundings: Evidence of jet contrail influence on climate," *Journal of Climate*, 17: 1123-1134.

[24] Line-shaped contrails cause a global radiative forcing of approximately 10 mW/m^2 (see section on radiative forcing). For the most updated research on contrails and contrail cirrus clouds, see the recent ACCRI report (Burkhardt et al., 2008).

Cirrus clouds are composed entirely of ice crystals and occur above ~6 km, covering approximately 30% of the Earth's surface (Penner et al., 2009) . Extensive cirrus cloud development has been observed after the formation of persistent contrails. The science on this relationship is still developing, and while cirrus clouds are acknowledged to have a net warming effect, the significance of this effect is still uncertain. The scientific understanding of cloud formation and modification due to air travel is still limited (Burkhardt et al., 2008). As the most recent IPCC assessment report notes, "Because spreading contrails lose their characteristic linear shape, a component of [aviation-induced cloudiness] is indistinguishable from background cirrus" (IPCC, 2007, WG I, section 2.6.3, p 187). The warming impact from cirrus clouds was therefore excluded from the Radiative Forcing (RF) and Radiative Forcing Index (RFI) figures of the research discussed later in this paper (Chapter 4).

Yet to get an accurate estimate of total warming impacts from aviation, cirrus effects should be included. Although uncertainty remains about the precise nature of aviation-induced cirrus-caused warming, we do know how cirrus clouds form, and that they have a warming impact. According to some researchers, this warming impact could be very significant (David Fahey, personal communication, May 2008); Workshop on the Impacts of Aviation, 2006). For more information, see the ACCRI papers on contrails and aviation, available at http://tinyurl.com/7oagzt.

Table 1 summarizes the climatic response to aircraft emissions of the different GHGs and forcing agents.

Table 1: Summary of Climatic Response to Aircraft Emissions[25]:

	CO_2	NO_x → Ozone increase	NO_x → Methane decrease	NO_x → Ozone decrease	Aerosols (particulates)	Contrails and Cirrus Clouds
Mean temperature response	warming	warming	cooling	cooling	warming (soot) and cooling (sulfates)	Net warming
Duration on the order of:	centuries	weeks to months	decade	decade	days to weeks	contrails: hours aviation-induced cirrus: hours - days
Spatial distribution	global	continental to global	continental to global	continental to global	soot: local to global sulfates: continental to global	local to continental
Scientific understanding (Scale: good - fair - poor)	good	fair	fair	fair	fair	poor

[25] Sources : Sausen et al., 2005; Forster and Rogers, 2008

4. Metrics for Expressing Total Climate Impacts of Aviation

A metric is needed to calculate total contribution to climate change of current air travel so that an individual's or a company's climate footprint can be accurately calculated. Such a metric must capture the future effects of current emissions. Such a metric must:

a) Exclude warming responses from past air travel.
b) Include the future impacts of current air travel.
c) Exclude warming responses from future air travel.

This chapter explains some of the currently available metrics that try to quantify non-CO_2 climate effects: Radiative Forcing (RF), Radiative Forcing Index (RFI), Global Warming Potential (GWP), Global Temperature Change Potential (GTP) and Economic Cost Calculations. All these metrics have been used to determine aviation's total impact on climate change. This chapter examines the strengths and weaknesses of each approach and explains which of these metrics are most appropriate for calculating the climate footprint of air travel.

4.1 Radiative Forcing

The Earth's surface temperature is determined by the balance between incoming solar radiation and outgoing infrared radiation. Radiative Forcing (RF) is the measurement of the capacity of a gas or other forcing[26] agents to affect that energy balance, thereby contributing to climate change. Put more simply, ***RF expresses the change in energy in the atmosphere due to GHG emissions***. The RF of a gas is defined as the difference between incoming solar radiation and outgoing infrared radiation caused by the increased concentration of that gas[27]. Radiative forcing is expressed in Watts per square meter (W/m^2) or the "rate of energy change per unit area of the globe as measured at the top of the atmosphere" (IPCC, 2007, WG I, p. 136)[28].

Positive radiative forcing results in an increase in Earth's energy budget and ultimately leads to warming. Because GHGs absorb infrared radiation and re-emit it back to the Earth's surface, thus increasing the Earth's energy balance, they have positive RF values[29].

Negative radiative forcing results in a decrease in the energy budget and ultimately leads to cooling. Aerosol particles reflect solar radiation, leading to a net cooling, and therefore have negative RF values.

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[26] The use of the word "forcing" refers to the capacity to drive Earth's radiative energy balance away from its current state.

[27] More exactly, radiative forcing of a given forcing agent is defined as the difference between incoming and outgoing radiation, allowing the stratospheric temperatures to adjust to the forcing agent, but keeping tropospheric and surface temperatures fixed at unperturbed values.

[28] Currently, total radiative forcing of human-caused greenhouse gas emissions is approximately 1.5 W/m^2.

[29] The absorption of infrared radiation by many greenhouse gases grows linearly with their abundance. Yet a few important exceptions display non-linear behavior (e.g., CO_2, CH_4, and N_2O). For those gases, the relative radiative forcing will depend upon abundance and hence upon the future emission scenario assumed. The relationship between carbon dioxide and radiative forcing, for example, is logarithmic, so that the warming effect of rising concentrations increases, but at a diminishing rate.

The radiative forcing of a GHG is determined by its atmospheric concentration, warming capacity, residence time, and spatial distribution:

> **Amount/Atmospheric Concentration** is determined by the emitted quantity of a GHG and by how much of it stays in the atmosphere. The greater the concentration of a GHG in the atmosphere, the larger its impact will be.
>
> **Warming or Cooling Capacity** refers to the "strength" or potency of an emitted gas to act as a GHG. Not all GHGs have the same warming/cooling capacity; some gases are more effective than others at trapping heat[30]. For example, over a 100-year time frame (see section 4.4 on Global Warming Potential), a molecule of methane is approximately 25 times more potent (effective at trapping radiation and inducing warming) than a molecule of CO_2 (IPCC, 2007, WG 1, Table 2.14, p 212).
>
> **Duration/Residence Time in the Atmosphere** refers to the time a GHG stays in the atmosphere. Some GHGs are short-lived[31] while others remain in the atmosphere for hundreds or thousands of years. To properly asses the climate impacts of a combination of gases, the lifetime of each gas has to be taken into account. For example, the warming impacts of CO_2 persist for hundreds of years, whereas the warming impacts of ozone or contrails last only days or months.
>
> **Spatial Distribution** refers to how far GHGs spread geographically. Long-lived greenhouse gases spread across the entire global atmosphere (e.g. CO_2 and methane); their warming impact is therefore global in scale. Other gases are short-lived and their warming effects are local or regional. Residence time of GHGs is therefore related to spatial distribution. Globally-averaged radiative forcing calculations (see, for example, Figure 2) do not take into account these differences in spatial distributions.

Radiative forcing has been used as a proxy to express the climate response of different GHGs. Figure 2 illustrates the RFs from aircraft emissions in 1992 and 2000 as reported by Sausen et al. (2005)[32]. These RF calculations are based on atmospheric concentrations of GHGs in 2000 due to aviation emissions starting in the 1940s[33].

[30] GHGs do not just absorb heat, they also re-radiate it. More precisely: GHGs absorb heat arriving from one direction (the direction of the heat source, i.e, the sun, or the surface of the Earth) and re-radiate it in all directions. GHGs may also have indirect effects on energy budgets due to chemical reactions with other gases in the atmosphere, which can lead to warming or cooling effects.

[31] We use the terms "lifetime" or "short- vs. long-lived" in reference to average atmospheric residence time of an emitted gas.

[32] Sausen et al. (2005) updates the figures reported in the 1999 IPCC aviation report and uses other sources, such as Minnis et al, 2004 and TRADEOFF, 2003. Sausen et al. (2005) and IPCC (1999) use aircraft emissions data based on jet fuel production reporting from IEA (the data includes commercial and military aviation, yet military aviation accounts for only about 10-15% of the emissions).

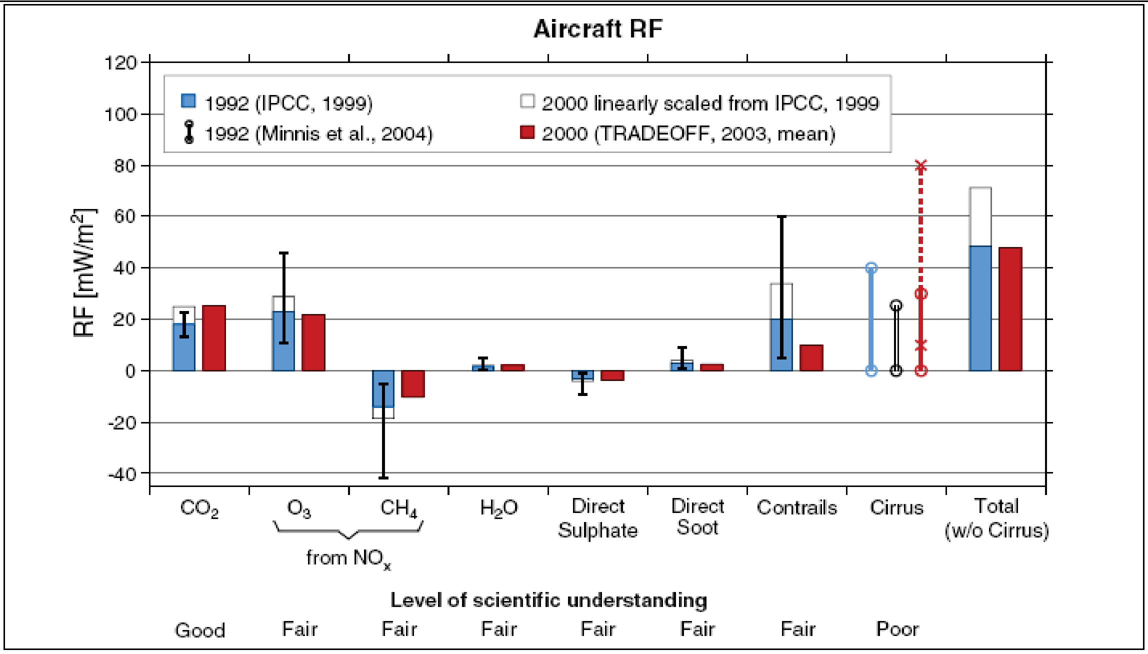

Figure 2: Radiative Forcing of Aircraft Emissions in 1992 and 2000 (emissions from 1940 to 2000) (Source: Sausen et al., 2005)

Scientific Uncertainty: Figure 2 reflects scientific uncertainties of specific emissions both with error bars and terminology along the x-axis. For example, little is known about the warming impacts of aircraft-induced cirrus clouds, as indicated by the rating of "poor" at the bottom and by the different graphical representation (lines instead of bars for the cirrus RF). Because of these uncertainties, total RF on the right does not include effects of cirrus clouds.

Future Impacts Not Counted: Figure 2 does not represent future warming impacts from any of the emissions. This underestimates the total impacts of long-lived gases such as CO_2 when compared to short-lived gases like ozone.

Past Cumulative Impacts: Figure 2 shows the RF of long-lived GHGs from air travel which have accumulated over approximately 60 years. The RF for short-lived gases, on the other hand, does not include past emissions, but only current emission levels, because short-lived gases decay quickly and past emissions are therefore no longer present in the atmosphere.

In order to evaluate if RF can be used as a metric for determining the climate footprint of an air travel passenger, it is important to understand the following characteristics of RF:

RF is an ***instantaneous measure***: it expresses the climate forcing of a greenhouse gas at a particular point in time. Yet it also has a temporal component: it is a ***backward-looking*** metric because it measures the RF of a GHG that has accumulated in the atmosphere over a certain period of time (e.g. aviation emissions over approximately 60 years in Figure 2).

Short-lived GHGs, such as ozone, do not accumulate over time because they decay rapidly. The RF given in Figure 2 therefore shows only the RF of *current* concentrations of short-lived gases, whereas it shows the RF of *accumulated* concentrations for long-lived GHGs. In other words: if emissions stay constant, the RFs for short-lived GHGs stay constant over time. Long-lived gases such as methane and

CO_2, on the other hand, accumulate over time, even if emissions stay constant, and thus their RF will increase over time.

4.1.1 What Radiative Forcing Does Not Show

Because RF is an instantaneous, backward-looking metric, it does not account for future impacts of GHGs. Long-lived GHGs will continue to warm the atmosphere for the duration of their residence time. Consequently, RF values do not express the total climate response of long-lived gases.

Globally-averaged RF values, such as the ones in Figure 2, do not account for regional variability in forcings and their climate responses. This is pertinent, since the potential damage of local warming due to locally-occurring GHGs (and their potential positive feedbacks) might be more intense than if the warming impact of those GHGs is spread out globally (RF values in Figure 2 apply only to total global annual emissions). If RFs are globally averaged, it might seem that cooling effects and warming effects can neutralize each other, yet this is not necessarily the case:

> *Importantly, global cancellations between the responses of different forcings do not necessarily represent regional cancellation between their responses. […]The net effect, given the regional pattern of airline flights, is therefore a Northern Hemisphere warming and Southern Hemisphere cooling (Forster and Rogers 2008).*
>
> *It is, for example, plausible that a small global-mean temperature response could occur from large temperature changes of opposing signs in the two hemispheres; it is unlikely that the global-mean response would adequately reflect the impact (e.g. the damage) associated with such a response. However, we are unaware of any simple models that have, as yet, adequately addressed this generic weakness (Sausen et al., 2006).*

To summarize, RF calculations as used in the IPCC aviation report (IPCC, 1999) and in Sausen et al. (2005) are based on instantaneous measures of atmospheric concentration, warming capacity, residence time, and spatial distribution of GHGs due to aviation emissions from the 1940s to 2000. Yet, to calculate total forcing from current air travel, future impacts also have to be included. RF values reported in the IPCC aviation report and in Sausen et al. (2005) are therefore not the correct metric for determining current air travel's total contribution to climatic change, or as the IPCC states:

RF provides a limited measure of climate change as it does not attempt to represent the overall climate response. (IPCC, 2007, WG I, p. 133)

4.2 Radiative Forcing Index

The Radiative Forcing Index (RFI) has been used to quantify non-CO_2 warming effects of air travel. RFI is the ratio of total radiative forcing (RF) of all GHGs to RF from CO_2 emissions alone for aircraft emissions (IPCC, 1999).

$$RFI = RF_{total} / RF_{CO2}$$

Many air travel calculators use a dimensionless multiplier between 2 and 3 to account for non-CO_2 warming effects. Usually these multipliers are based on the RFI calculated in the 1999 IPCC report on aviation. The RFI for aviation emissions was estimated by the IPCC to be 2.7 with an uncertainty of ±1.5 (IPCC, 1999). In other words, the IPCC estimated that total RF of aviation was 2.7 times that of just CO_2 emissions from aviation. When the IPCC estimates were updated, RFI was calculated to be approximately 2 (Sausen et al., 2005).

Yet RFI is an inappropriate metric to use for personal air travel emissions calculators because RFI calculations are based on RF values for aviation emissions from the last approximately 50 years. RFI therefore includes warming responses from past air travel emissions. Furthermore, future warming due to long-lived greenhouse gases is not included in these calculations. RFI was never intended to be used to calculate the total effect of current aviation, and is therefore not appropriate for our purpose.

To summarize, RFI is not the correct metric for determining total climate effects of aircraft emissions in order to calculate climate footprints of air travel passengers. Or, as the IPCC states:

[T]he RF index (RFI) introduced by IPCC (1999), should not be used as an emission metric since it does not account for the different residence times of different forcing agents. (IPCC, 2007, WG I, section 2.10.4, p 215)

4.3 Integrated Radiative Forcing

Researchers are aware of the limitations of RF and have been developing metrics that can express total climate response, including future impacts.

4.3.1 Understanding RF versus Integrated RF

To express the future effects of GHGs, RFs of current (or future) GHG emissions over a chosen time frame can be summed (in mathematical terms: integrating emissions over time). The results incorporate future effects of GHGs. This method places an equal weight on impacts occurring at each point of time within the chosen time frame. (See Figure 3 for a schematic illustration of integrated RF.) Integrated RF is expressed in Watts per square meter year (W/m^2y), i.e. it expresses the energy that is added to the system during a chosen time horizon due to the GHG emissions.

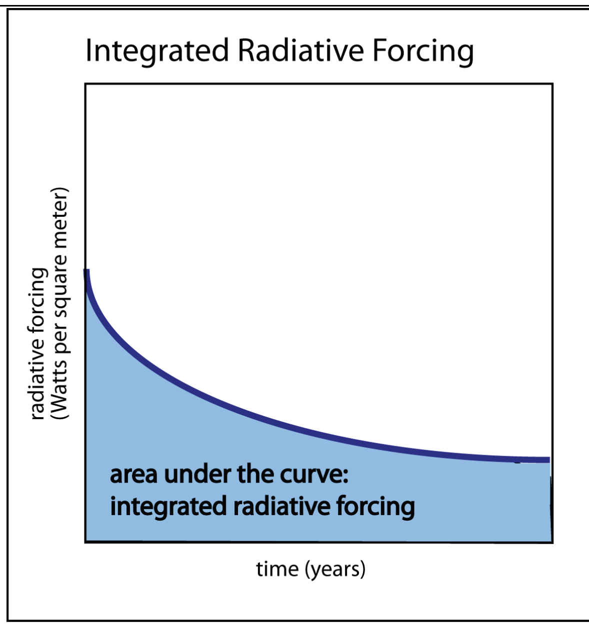

Figure 3: Integrated Radiative Forcing: the sum of RF over a chosen time period (area under the curve) measured in Watts per square meter year (W/m^2 $year^1$)

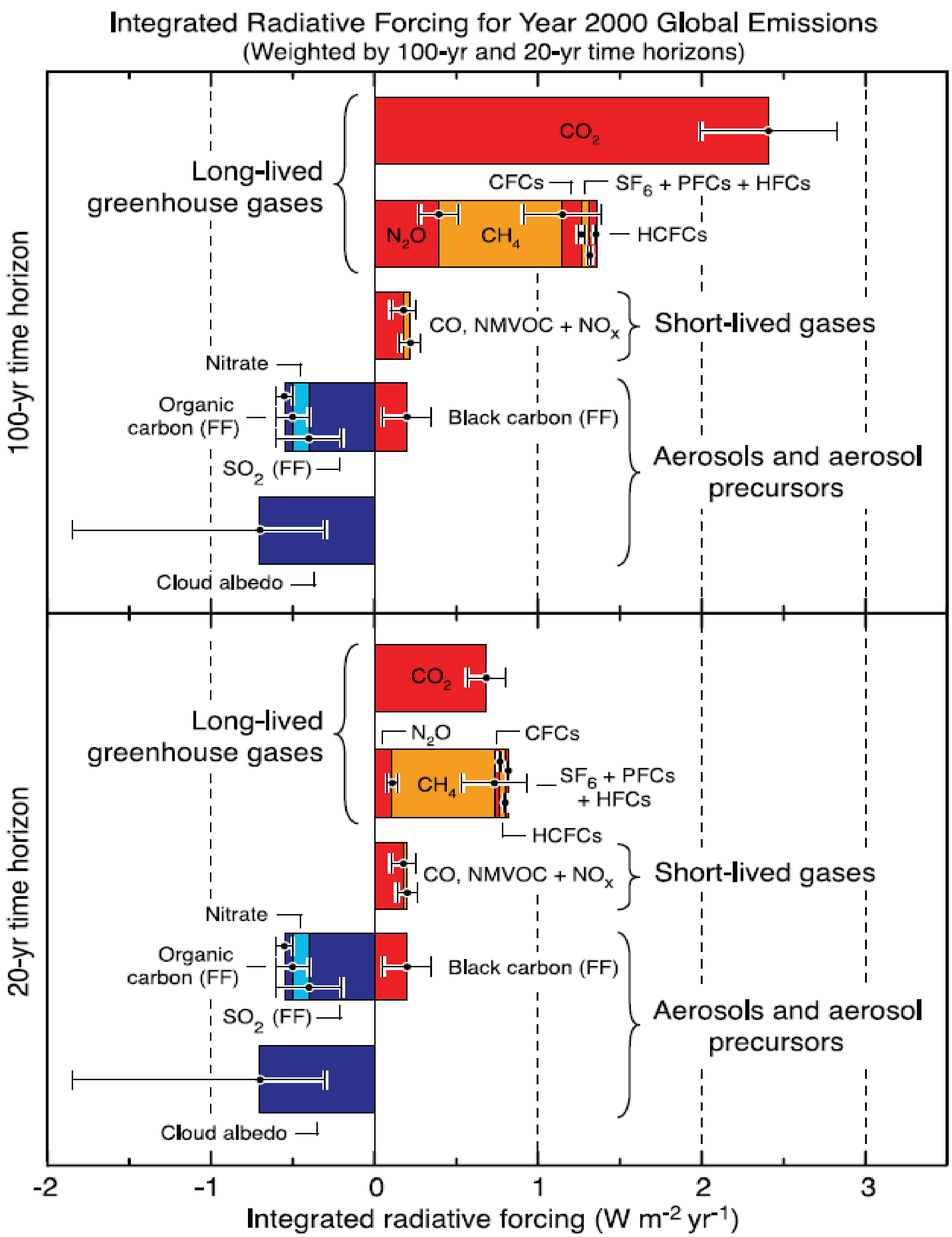

Figure 4: Integrated RF of All Anthropogenic GHGs Emitted in the Year 2000 over Two Different Time Horizons.

Top graph: integrated RF over a 100-year time horizon, i.e. the bars express the cumulative energy that will be added or subtracted from the global energy balance over the next 100 years due to the different GHGs emitted in 2000.

Bottom graph: integrated RF over a 20-year time horizon.

(Source: IPCC, 2007, WG I, p 206)

Choosing the time frame for integrated RF greatly influences results. For example, as Figure 4 shows, integrated RF of CO_2 is much larger over the 100-year time frame than over the 20-year time frame, whereas the contributions from short-lived gases stay the same over the two time horizons, because they decay much faster and do not cause additional forcing after the first 20 years.

Choosing the time horizon for integrated RF is not a scientific matter but a policy choice. If we are concerned about the long-term warming impacts of GHG emissions, we should choose a longer time horizon. If we are concerned about warming impacts in the short term that may lead to irreversible changes (‘tipping points’), we should choose a shorter time horizon (Berntsen and Fuglestvedt, 2008).

4.3.2 Understanding Pulse versus Sustained Emissions

Integrated RF can be calculated using different assumptions. Figure 4 uses a pulse emission (the emissions from the year 2000) and integrates RF as GHG emissions from that year decay over time. Short-lived GHGs will decay faster, long-lived gases more slowly.

Yet integrated RF could also be calculated assuming sustained emissions. For example, instead of using only the emissions from the year 2000, as in Figure 4, emissions over the chosen time frame (say 20 years) could be assumed to remain constant and cumulative integrated RF of these constant emissions could be calculated. The RF for short-lived emissions would then stay constant (not decay). The RF for long-lived gases would grow over time because these gases accumulate. Figure 5 is a simplified illustration of RF for a pulse emission and RF for constant emissions. If we expect that emissions will grow or decrease, we can also calculate integrated RF scenarios with growing or decreasing emissions.

The choice to calculate pulse or sustained emissions is a policy decision. As Figure 5 illustrates, the results can vary dramatically depending on which method is chosen. A pulse emission is suitable for air travel calculators, since the interest is in calculating the effects of a single flight. Sustained emissions would be appropriate for modeling, for example, the effects of future aviation: either constant emissions or the predicted emissions projections should be chosen in that case.

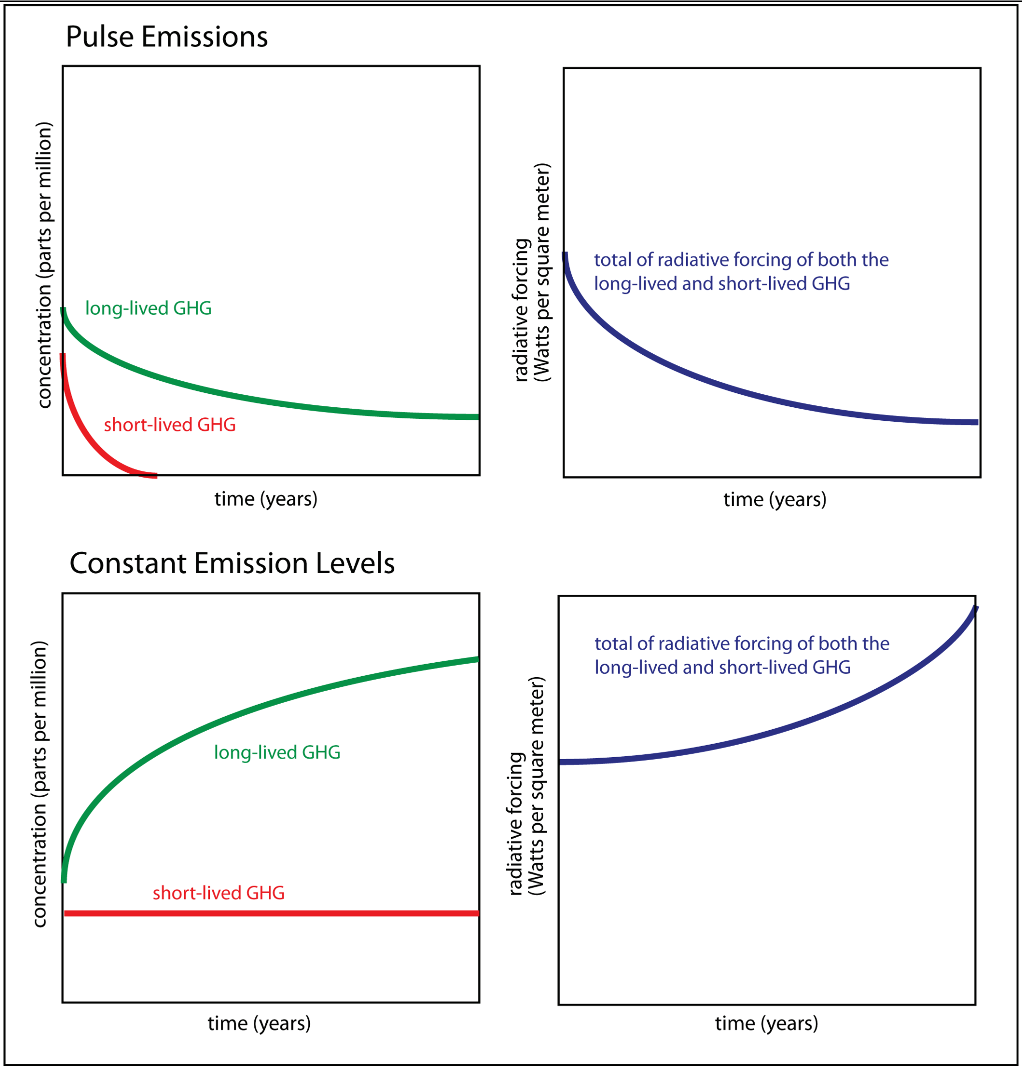

Figure 5: Atmospheric Concentration and Radiative Forcing Over Time for a Pulse Emission (top) and Constant Emission Levels (bottom).

Top left: A pulse emission of two hypothetical GHGs: a short-lived one (red) and a long-lived one (blue). The concentrations of both GHGs decrease over time: the short-lived GHGs decays much faster than long-lived GHG.

Top right: The total RF (blue line) of these two pulse emissions also decreases over time because both gases decay over time. Integrated RF is the area under the blue curve.

Bottom left: Constant emissions of two hypothetical GHGs: concentration of the short-lived GHG (red) stays constant; concentration of the long-lived GHG (green) accumulates over time.

Bottom right: The total RF of these two constant emissions (blue line) increases over time because the concentration of the short-lived GHG stays constant and the concentration of the long-lived GHG increases over time. Integrated RF for these two constant emissions is the area under the blue curve.

4.3.3 What Integrated Radiative Forcing Does Not Show

Temporal differences in warming

Integrated RF only sums the radiative forcings over a chose time horizon. It does not show at what point during that time horizon warming occurs. For example, short-lived GHGs with strong warming capacity, such as methane, will cause temperature changes early on, but will then decay and no longer cause warming. Long-lived gases with comparatively weaker warming capacities, such as CO_2, will warm the climate more gradually, but for a much longer time. Figure 6 shows the same total integrated RF value for two very differently-acting GHGs. Despite the fact that they share the same value for integrated RF, their effect on the climate will play out quite differently. Neither integrated radiative forcing nor Global Warming Potential (see next section) takes these differences into account.

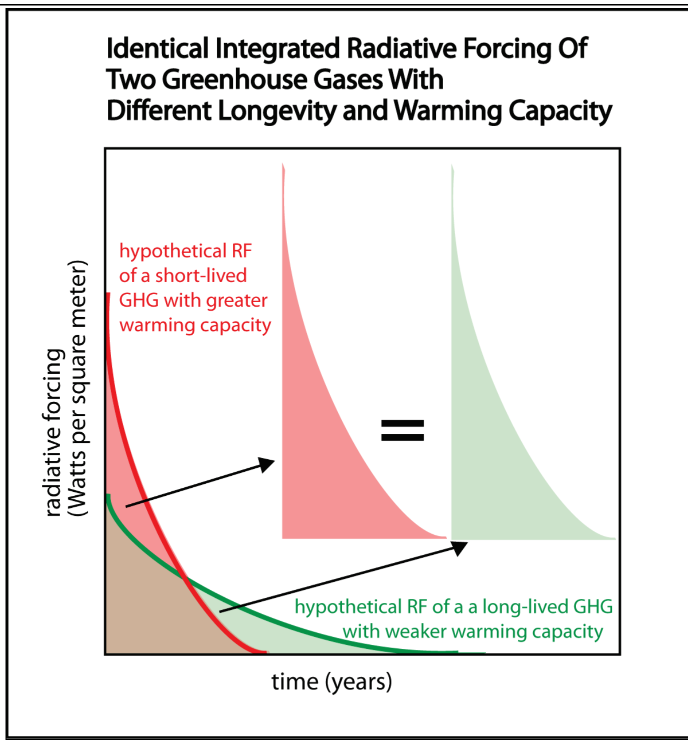

Figure 6: Identical Integrated Radiative Forcing of Two Hypothetical GHGs with Different Longevity and Warming Capacity.

The red line shows the RF of a short-lived GHG with a high warming capacity, such as methane. The green line shows the RF of a long-lived GHG with a weaker warming capacity, such as CO_2. Both GHGs have the same integrated RF value (area under the curve) yet because the warming they cause occurs at different points in time and with different strengths, their effect on the climate will not be the same. Integrated RF does not reflect this difference.

Thermal Inertia

Integrated RF does not account for the thermal inertia of the climate system (Fuglestvedt et al., 2008). Thermal inertia refers to the delay in the change of Earth's energy balance in response to climate forcing, or the imbalance caused by a lag between the effects of forcing and the return to energy equilibrium (Hansen et al., 2005).

To summarize, integrated RF can be used to expresses the future effects of current aviation. The chosen time horizon greatly influences the results: short time horizons emphasize the warming due to short-lived emissions, whereas longer time horizons emphasize the warming of long-lived gases. The choice of pulse versus sustained emissions also influences the results: sustained emissions give more weight to short-lived effects than pulse emissions do.

4.4 Global Warming Potential

Global Warming Potential (GWP) is based on the integrated RF of a pulse emission. It is used as a tool to compare the potency of different greenhouse gases with that of CO_2. GWP calculates the integrated RF and lifetime of each gas relative to that of carbon dioxide[34]. Carbon dioxide has an assigned GWP of 1 and is used as the baseline unit (i.e. reference gas) to which all other greenhouse gases are compared. Thus GWP is unit-less. GWP values can be used to convert various greenhouse gas emissions into comparable CO_2 equivalents when computing overall sources and sinks; greenhouse gases can thus be expressed in terms of Carbon Dioxide Equivalent (CO_2e) (IPCC, 2007, WG I, pp 210-213).

Because they are based on integrated RFs, GWP values depend on the time span over which the potential is calculated. Short-lived GHGs initially have large effects that become less significant over time relative to CO_2, since the integrated RF of CO_2 increases over time. Methane, for example, has a GWP of approximately 25 over 100 years but 62 over 20 years (IPCC, 2001). The Kyoto Protocol uses the GWP time frame of 100 years. If a climate policy is enacted to limit long-term temperature increase, effects of short-lived emissions may be overestimated if the time horizon chosen is too short (Berntsen and Fuglestvedt, 2008). On the other hand, a time horizon of 100 years versus one of 20 years might underestimate the importance of short-lived emissions (IPCC, 2007, WG I, p 206).

[34] The GWP index, based on the time-integrated global mean RF of a pulse emission of 1 kg of some compound (*i*) relative to that of 1 kg of the reference gas CO_2, was developed (IPCC, 1990) and adopted for use in the Kyoto Protocol. The GWP of a component is defined as (IPCC, 2007, WG I, p 210):

$$GWP_i = \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt}$$

i = the greenhouse gas for which a GWP should be calculated
r = reference gas, in this case CO_2
RF(*t*) = radiative forcing over time
TH = time horizon

4.4.1 What GWP Does Not Show

As discussed in section 4.3.3, integrated RF and GWP do not indicate when the temperature changes occur given the varying residence times and warming capacities of different GHGs. GWPs also fail to account for thermal inertia of the climate system. GWP furthermore assumes that the warming response due to the various GHGs' forcings are all the same. Yet, as explained earlier, climate efficacy of different GHGs can vary considerably.

To summarize, while GWP is widely accepted as a reliable proxy for the warming impacts of long-lived, well-dispersed gases such as CO_2, GWP with a 100-year time frame, as used in the Kyoto Protocol, is not suitable for measuring the kind of short-lived emissions associated with aviation. Or, as the IPCC states:

To assess the possible climate impacts of short-lived species and compare those with the impacts of the LLGHGs [long-lived greenhouse gases], a metric is needed. However, there are serious limitations to the use of global mean GWPs for this purpose. While the GWPs of the LLGHGs do not depend on location and time of emissions, the GWPs for short-lived species will be regionally and temporally dependent (IPCC, 2007, WG I, p 211)

4.5 Global Temperature Change Potential

Global Temperature Change Potential (GTP) goes further than GWP and integrated RF in describing the effects of emissions: it estimates the change in global mean temperature for a selected year in the future. In other words, this metric tries to answer the question: ***What will the temperature change be in year X in response to the radiative forcing of certain GHG emissions?*** This metric is more complex because it calculates ***climate response*** and not just ***radiative forcing*** (see Figure 1). GTP is based on RF. Yet in order to model and calculate GTP, we also need to know the time scale of the climate response: because of Earth's thermal inertia, there is a lag between when the emissions occur and when they cause warming. In other words, GTP accounts for Earth's thermal inertia. In addition, the models need to include the Earth's climate sensitivity (see Chapter 2). This means that GTP calculations are more complicated and are less certain than simple radiative forcing calculations.[35] As illustrated in Figure 1, although uncertainty is increased, relevance is also increased since it is more useful for policy makers to know what the actual temperature change will be than only the amount of energy that has been added to the system.

GTP can be calculated using a pulse emission or sustained emissions (see section 4.3 on Integrated Radiative Forcing for a detailed explanation). Furthermore, climate efficacy can be integrated into formulas that calculate GTP.

As with all other approaches discussed here, the chosen time frame greatly influences the results. For example, if we choose to evaluate temperature change after 100 years, the effects of short-lived GHGs are de-emphasized, and changes of temperature in between the time of emission and the evaluation year are not captured (Berntsen and Fuglestvedt, 2008).

[35] The absolute GTP (AGTP) is the temperature change associated with a pulse emission (usually one year) of a specific GHG at a chosen point in time. The ratio between the AGTP for this gas and the AGTP for CO_2 gives the GTP for the specific GHG (Berntsen and Fuglestvedt, 2008). As with Global Warming Potential, this allows for comparisons between the climate responses of other GHGs to that of CO_2.

Figure 7 shows the net future temperature change from a 1-year pulse of current emissions for different transport modes for four future time horizons (20, 40, 60, 100 years). The difference in results between time horizons is starkest for shipping. The emissions pulse led to cooling in year 20 because of the high sulfate emissions associated with shipping, but a warming effect begins to become apparent in the second graph (year 40) because shorter-lived sulfates (cooling) have disappeared while longer-lived CO_2 (warming) is still in the atmosphere. The error bars for aviation in the 20-year time frame are very large. This is because of uncertainties surrounding the effects of contrails and cirrus clouds.

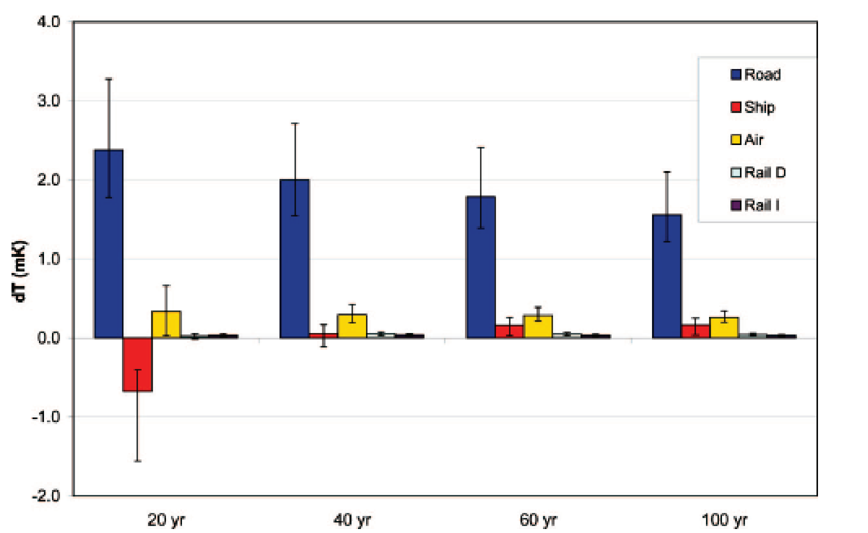

Figure 7: Contribution to Net Future Temperature Change (in milli-Kelvin) from a 1-year Pulse of Current Emissions for Different Transport Modes for Four Future Time Horizons (20, 40, 60, 100 years). The error bars express uncertainties primarily in the effect of contrails and cirrus clouds. Rail D refers to direct emissions (e.g. fossil fuel) and Rail I refers to indirect emissions (e.g. electricity) associated with rail travel. (Source: Berntsen and Fuglestvedt, 2008)

4.5.1 What GTP Does Not Show

Two different GHGs with equal GTPs describe the same temperature change at the end of a chosen time horizon, though not at specific points within this time horizon. In other words, two different emissions that give the same temperature effect at a chosen time can have different paths (Berntsen and Fuglestvedt, 2008). That means that total climate impact of these two gases might be very different, yet GTP does not reflect these differences.

To summarize, GTP can be used to express future climate responses to current aviation emissions. As with Global Warming Potential, the chosen time horizon greatly influences the results: short time horizons include the warming due to short-lived emissions, whereas longer time horizons exclude those effects.

4.6 Economic Cost Calculations of Aviation

Economic cost calculations go further than all the previously discussed metrics. This metric tries to answer the question: ***What will the economic costs in year X be due to the expected temperature change from anthropogenic GHG emissions?*** This metric is more complex because it calculates ***climate costs*** and not just ***radiative forcing or climate response*** (see Figure 1). Climate cost calculations can be based on GTP or on calculating the sum of temperature change over time (delta T over time: $\Delta T/t$); both metrics in turn are based on RF. In addition to all the assumptions made in order to calculate GTP, an additional range of parameters, such as discount rate, economic growth rates, and damage functions need to be determined.

This means that climate cost calculations are more complicated and their results are more value-based than radiative forcing and climate response calculations. Yet the results of climate cost calculations are often more relevant for policy makers (e.g. it is more useful for a policy maker to know the economic impacts than only the physical changes caused by GHG emissions.)

The U.S. Federal Aviation Administration/Aviation Environmental Portfolio Management Tool (FAA/APMT) model[36] calculates the economic costs of the climate impacts due to aviation and is based on delta T over time.

The FAA/APMT model looks at the future impacts of current (and future) CO_2 and non-CO_2 emissions (Marais et al., 2008). FAA/APMT looks at marginal air travel impacts by taking into account the background atmospheric GHG concentrations from all anthropogenic emission sources[37].

Figure 8 shows the FAA/APMT model's quantified impacts of one year of aviation. The FAA/APMT model is probabilistic in order to capture to the extent possible the impacts of many of the uncertainties. Because some of the behaviors are non-linear, this can be important. The figure shows the mean of the response for each GHG at each point in time.

Figure 8(a) shows the impact expressed in change in surface temperature (delta T) over time. The cooling effects of sulfate aerosols, methane decrease (in the figure legend labeled as: NO_x-CH_4), and long term ozone decrease (in the figure legend labeled as: NO_x-$O_{3\ long}$) can be observed. The total impact (x-line) is the sum of all warming effects minus the cooling effects.

Figure 8(b) illustrates the same effects expressed as impact on US Gross Domestic Product (GDP). In order to convert the warming impacts to an economic metric, Marais et al. (2008) assumed a discount rate, economic growth rates, and a damage function, among other parameters. These parameters explain the change in shape of the curves as compared to Figure 8(a).

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[36] The FAA/APMT model is part of a suite of software tools that are currently being developed by the U.S. Federal Aviation Administration Office of Environment and Energy (FAA/OEE) in collaboration with Transport Canada: "The main goal of the effort [FAA/OEE] is to develop the capability to assess the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operations, and market scenarios." (Sausen, Shine & Wuebbles, 2006)

[37] The model begins calculating current and future emissions with baseline emission concentrations from the year 1750, then adds the aviation emissions from 1940 onwards to calculate their contribution to climate change. For more on the mathematical details of this model, see Appendix 1.

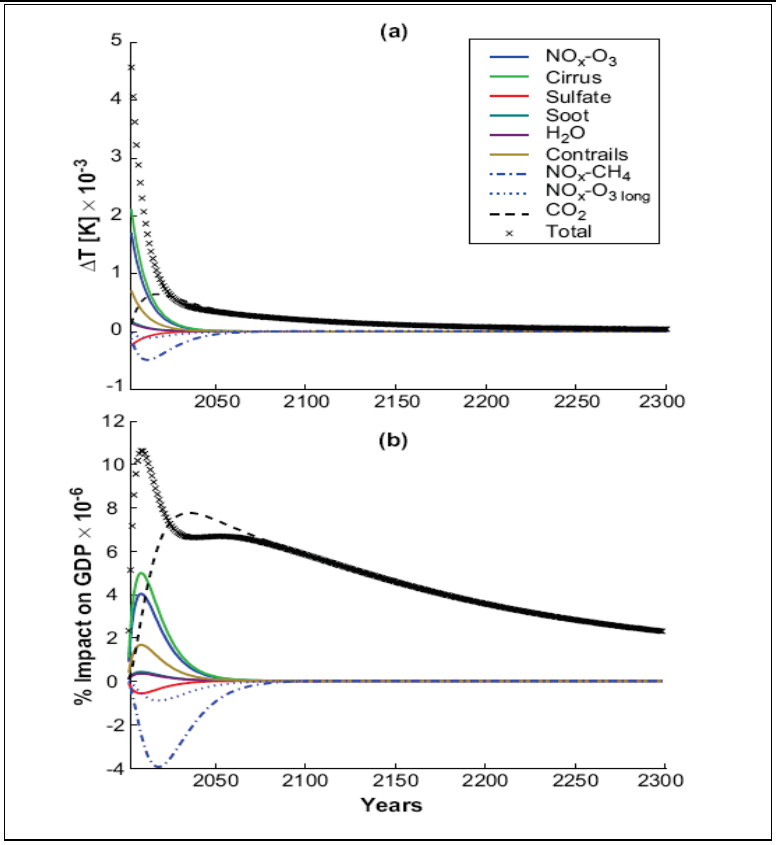

Figure 8: FAA/APMT Model's Quantified Climate Impacts of a One-Year Aviation Pulse with Fixed Inputs. (a) Baseline temperature change. (b) Baseline damage function, Nordhaus and Boyer (2000). The total impact (x line) merges with the CO_2 impact line after a few decades because the short-lived emissions no longer cause warming after a few decades. (Source: Marais et al., 2008)

The parameters in the FAA/APMT model (e.g. the time frame or the discount rate) can be adjusted depending on the policy option that is being researched. The parameters for this model do not have equally strong influences on the results. The relative importance of non-CO_2 effects changes depending on the time frame for which they are calculated. Furthermore, the modelers found:

[T]he climate sensitivity, the radiative forcing of different short-lived effects, the choice of emissions scenario and the discount rate have the most significant influence on the output metrics we considered. Other uncertainties were less important. (Marais et al. 2008)

Some of these factors will become more accurate as scientific knowledge improves. Yet others will not: discount rates, for example, cannot be established by scientific analysis because they are dependent on ethical choices and value judgments. They also depend on assumed economic performance in the future.

The FAA/APMT model can also be used to purely express the physical metric of climate impacts by using the integrated delta T-years (the area under the change in temperature graph for each greenhouse gas). In other words, it expresses the changes as a theoretical number that is the sum of all the temperature changes that occur over a given period of time. This result is then neither discounted nor used to make any economic estimates. This is what is shown in Figure 8a.

4.6.1 What Economic Cost Calculations Do Not Show

The FAA/APMT model does not take into account the spatial effects of aviation emissions. It uses a single variable – global-mean surface temperature – to express climate impacts. It therefore has the same shortcomings as Global Temperature Change Potential (see section 4.5.1).

In addition, the number and type of assumptions that have to be made in order to estimate climate costs mean that the results of such economic models are to a large extent value-based. For example, as mentioned in section 4.6, many important climate damages, such as loss of human life, cannot easily be expressed in monetary terms. Economic models frequently express all climate damages through a damage function, assuming a mathematically simple relationship between climate changes (measured by temperature increase) and the total value of associated damages. Yet such damage functions do not reflect the complexities and non-linear behavior of physical, biological and economic systems. The damage function in the FAA/APMT model is based on the climate economics model "DICE," developed by Nordhaus and Boyer (2000). For a critique of the DICE model and its assumptions, see Ackerman and Finlayson (2006).

Despite their shortcomings, economic models are important because they translate climate change into the currency that is most pertinent to policy makers and businesses: the monetary costs associated with the expected warming. It is therefore vital for evaluating and prioritizing climate mitigation strategies that more sophisticated models which explicitly discuss their underlying assumptions be developed. Any model that calculates climate costs should therefore explicitly state the assumptions that were made for the non-scientific parameters and their associated uncertainties.

To summarize, we are looking for a metric that is most suitable to calculate the effect on climate change from air travel so that an individual or a company can accurately calculate their climate footprint due to their current air travel. Economic cost calculations go beyond this task. A metric that compares the different forcings or climate responses seems more appropriate for this task and is more comparable with metrics that are used in other climate policy measures (such as the Global Warming Potential with a 100-year time frame used under the Kyoto Protocol).

5. Discussion

After explaining a number of different metrics that have been used to assess aviation's contribution to climate change, we now evaluate which one is most suitable for estimating the contribution to climate change of individual current air travel: in this final chapter, we summarize the most pertinent features of each metric, discuss the application of these metrics to current air travel impact calculations, and end with a set of recommendations on how to best account for non-CO2 effects in air travel calculators.

5.1 Summary of Metrics

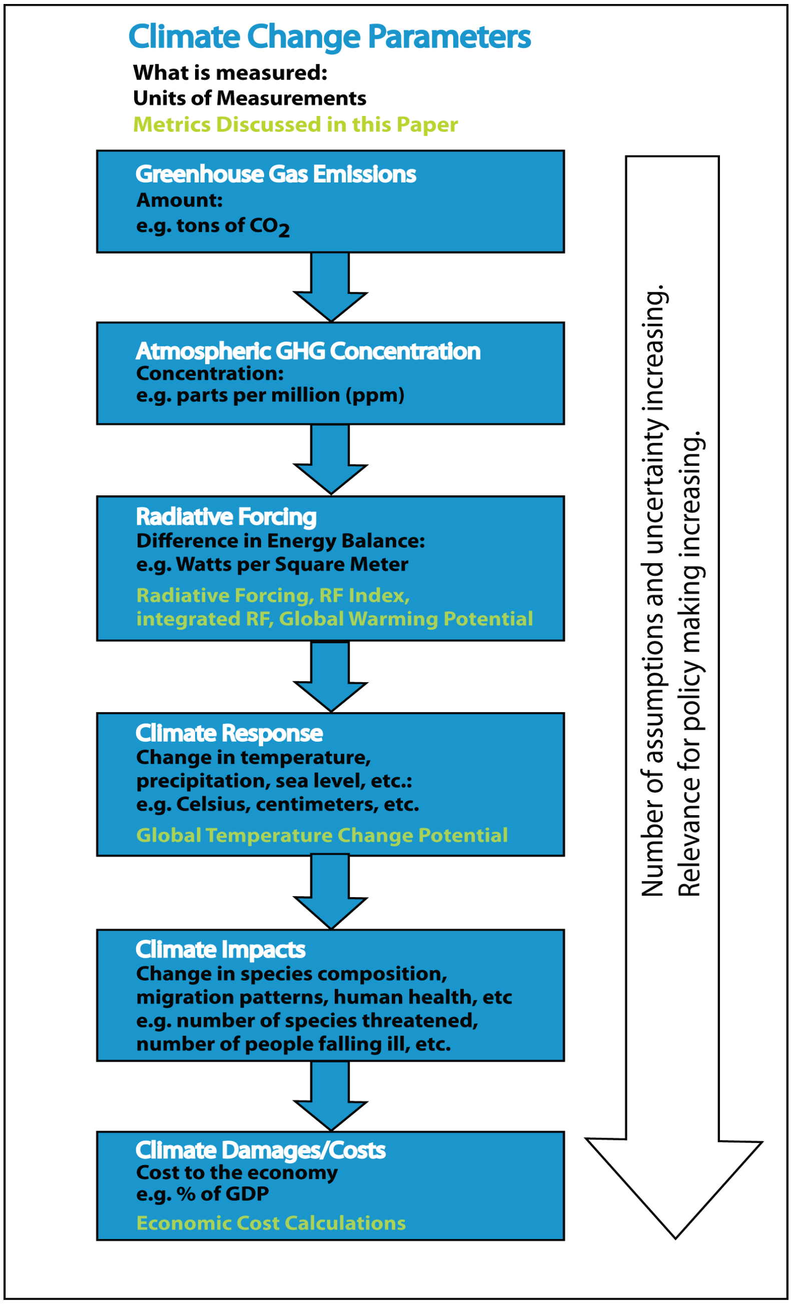

Figure 9: Climate Change Parameters and Their Associated Metrics.

Numerous modeling approaches have been used to estimate aviation's contribution to climate change. Figure 9 is modified from Figure 1 and shows the units of measurements for the climate change parameters and their associated metrics discussed in this paper. Radiative Forcing (RF), Radiative Forcing Index (RFI), Integrated Radiative Forcing, Global Warming Potential (GWP) and Integrated Change in Temperature over Time all express in some way the change in energy balance that GHG emissions are causing:

Radiative Forcing is an ***instantaneous measure***: it expresses the climate forcing of a greenhouse gas at a particular point in time. Yet it also has a temporal component: it is a ***backward-looking*** metric because it measures the RF of a GHG that has accumulated in the atmosphere over a certain period of time (see Figures 2 and 3). Long-lived GHGs will continue to warm the atmosphere for the duration of their residence. Consequently, RF values include effects of past air travel and exclude future effects of current air travel. RF values reported in the IPCC aviation report (1999) and by Sausen et al. (2005) are therefore not the correct metric for determining total climatic response of current air travel (and were never intended to be used that way).

Radiative Forcing Index (RFI), as used in IPCC 1999, compares the non-CO_2 warming effects of aviation to those of CO_2. RFI is the ratio of total radiative forcing (RF) of all GHGs to RF from CO_2 emissions alone. The RFI calculations in the IPCC aviation report from 1999 are based on RF values for aviation emissions from the last approximately 50 years. RFI has the same shortcomings as RF: RFI includes effects of past air travel and excludes future effects of current air travel. RFI is therefore not the correct metric for determining total climatic response of current air travel (and was never intended to be used that way).

Integrated Radiative Forcing enables us to calculate the future effects of GHGs. It sums the RFs of GHGs over a chosen time frame (in mathematical terms: integrating them; see Figure 3 for a schematic illustration of integrated RF). Integrated RF expresses the energy that is added to the system during a chosen time horizon due to GHG emissions. Integrated RF of current emissions excludes effects from past air travel and includes future effects of current air travel. Integrated RF of current emissions could therefore be an appropriate metric for our purposes. Yet results of integrated RF vary greatly depending on the chosen time frame and whether a pulse emission or sustained emissions are used (see further discussion below).

Global Warming Potential is used as a tool to compare the potency of different greenhouse gases with that of CO_2. In that way, GWP is similar to RFI. But whereas RFI is a backward-looking metric, GWP is a forward-looking metric that includes future effects of current emissions. GWP is based on integrated RF over a chosen time frame of each GHG relative to that of CO_2e. GWP values depend on the time span over which the forecast warming potential is calculated. GWP with a time horizon of 100 years is used in the Kyoto Protocol, yet such a long time horizon might underestimate the importance of short-lived emissions. While GWP is widely accepted as a reliable proxy for the warming impacts of long-lived, well-mixed gases such as CO_2, GWP with a 100-year time frame may not be suitable for measuring the kind of short-lived non- CO_2 emissions associated with aviation.

Global Temperature Change Potential (GTP) goes further than the metrics described above. It estimates the change in global mean temperature for a selected year in the future. This metric is more complex because it calculates ***climate response*** and not just ***radiative forcing*** (see Figure 9). Although uncertainty is increased, relevance is also increased since it is more useful to know what the actual temperature change will be than just to know the amount of energy that was added to the system. GTP excludes effects from past air travel and calculates future warming from current air travel.

GTP could therefore be an appropriate metric for our purposes. Yet, as with integrated RFI, the results of GTP vary greatly depending on the time frame and if a pulse emission or sustained emissions are used (see further discussion below).

Integrated Change in Temperature over Time expresses the climate impacts as a theoretical number that is the sum of all the temperature changes that occur over a given period of time. The FAA/APMT model (described in section 4.6) can also be used to calculate such a metric, expressed in integrated-delta T-years (shown in Figure 8a). Integrated Change in Temperature over Time could therefore be an appropriate metric for our purposes. Yet, as with integrated RF, the results if this metric will vary greatly depending on the time frame and if a pulse emission or sustained emissions are used (see further discussion below).

Economic Cost Calculations go further than all the metrics discussed above: they calculate ***climate costs*** and not just ***radiative forcing*** (see Figure 1). As mentioned above, assumptions that need to be determined by moral or political positions lie hidden in the economic assessment of the damages (e.g. the discount rate). This means that climate cost calculations are more complicated and their results more dependent on value-based decisions than simple radiative forcing calculations. Despite their shortcomings, economic models are important because they translate climate change into the currency that is most pertinent to policy makers and businesses: the monetary costs associated with expected climate effects. Yet economic cost calculations go beyond our purpose. A metric that compares the different forcings or climate responses is more appropriate for our task because it is more compatible with metrics that are used in other climate policy measures (such as the Global Warming Potential with a 100-year time frame used under the Kyoto Protocol).

5.2 Application of Metrics for Current Air Travel

We have established that, of the examined metrics, RF and RFI are not suitable for estimating the contribution to climate change of individual current air travel. We now discuss why value-based decisions impact the results even if more appropriate metrics such as integrated RF or Global Temperature Change Potential (GTP) are used. Aside from the scientific uncertainties related to certain warming effects from aviation (e.g. cirrus clouds, see error bars in Figure 10) there are two value-related choices that greatly influence the results: choice of time frame and choice of pulse versus sustained emissions.

Figure 10 shows three different metrics: Pulse Global Warming Potential (PGWP), Pulse Global Temperature Potential (PGTP) and Sustained Global Temperature Change Potential (SGTP). The impacts have been normalized to CO_2. In other words, the impacts of CO_2 have been assigned the value of 1 (similar to Global Warming Potential). The total aviation impacts are expressed as multiples of the impacts of CO_2 emissions alone. For example, the first red bar shows that over a 20-year time horizon, the total impact of aviation, using PGWP, is four times as much as that of CO_2 alone. In general, the graph shows that at the 20-year time horizon (red bars), the effects of short-lived emissions dominate in all three metrics. At longer time horizons (orange: 50 years; yellow: 100 years), CO_2 effects become increasingly dominant, especially using the PGTP. Depending on the metric and the time frame chosen, total climate response to aviation is shown to be anywhere from slightly more than that of CO_2 alone to up to 6 times that of CO_2 alone.

Figure 10 includes the effects from aviation-induced cirrus clouds. These have a particularly large impact at shorter time horizons (Grassl and Brockhagen, 2007). As mentioned earlier, there is still quite a bit of scientific uncertainty surrounding cirrus clouds and their warming effects, and more research is needed to assess impacts more accurately (Burkhardt et al., 2008). Because of these uncertainties, the error bars in the 20-year time horizon are very large. Error bars for the longer time horizons are much smaller because the effects of cirrus clouds are short-lived and no longer appear after 50 or 100 years.

The multipliers (normalized emission weighing factors) that Forster and Rogers (2008) calculate for non-CO_2 aviation emissions range between 1 and 6, depending on the time frame and metric used. Using a time frame of 20 years and including cirrus effects, multipliers range from 2 to 6. Appendix 2 shows the complete graph from their paper.

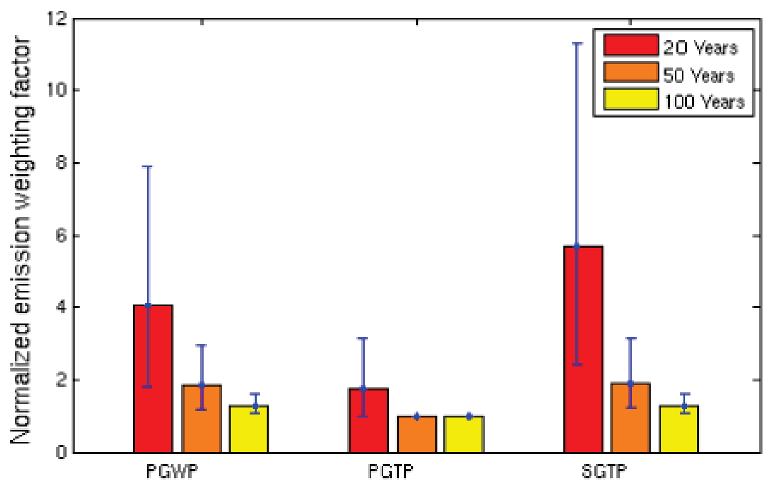

Figure 10: Normalized Impacts of Total Warming Effects From Aviation Compared to CO_2 Alone.

Total aviation impact has been normalized to CO_2 impact, creating an emission weighting factor appropriate to the current fleet. Error bars represent uncertainties arising from NOx and contrail forcings.
PGWP: Pulse Global Warming Potential
PGTP: Pulse Global Temperature Potential
SGTP: Sustained Global Temperature Change Potential
Red (Left Bar): 20-year time horizon
Orange (Middle Bar): 50-year time horizon
Yellow (Right Bar): 100-year time horizon
(Source: Forster and Rogers, 2008)

5.3 Recommendations

There is no single metric, no single multiplier and no single answer to the question of how the effect on climate change from air travel should be calculated so that an individual or a company can accurately calculate the climate footprint of their current air travel. Metrics and underlying assumptions have to be chosen according to the questions we are trying to answer and the goals we are trying to achieve (Fuglestvedt et al., 2009). For example, if the main concern is the near-term impacts of climate change, a shorter time horizon is more appropriate. Nevertheless, we would like to make the following final observations and recommendations:

The Science:

There is still uncertainty related to quantifications of the climate impacts of non-CO_2 air travel emissions. Clearly, more research and more sophisticated models[38] are needed[39]. Although there is no simple answer to what the overall impact of aviation is, it is clear that total contribution to climate change is greater than that of CO_2 alone.

It seems therefore less defensible to exclude non-CO_2 effects than to choose a multiplier that is greater than 1.

Time Frame:

As we have illustrated, the chosen time frame greatly influences the results. For example, if we choose temperature change after 100 years for the evaluation, the effects of short-lived GHGs are de-emphasized, and changes of temperature in between the time of emission and the evaluation year are not captured (Fuglestvedt et al., 2008). Yet including these short-lived regional impacts into a climate metric is important because they might trigger feedback mechanisms (Berntsen and Fuglestvedt, 2008). For example, researchers have recently found that short-lived emissions in the Arctic result in an equal or greater climatic response than long-lived emissions due to the positive feedback mechanisms associated with ice albedo.. Reducing these short-lived but high impact non-CO_2 emissions in the critical near-term may be more effective in slowing Arctic warming and preventing a "tipping point" for ice disintegration than emphasizing long-term efforts to reduce long-lived GHGs such as CO_2 (Quinn et al., 2008).

For these reasons, we advocate a short time horizon (e.g. 20 years) that includes short-lived effects be used. (This is a value-based choice and only applies to calculating effect on climate change from air travel in order to best estimate the footprint of an individual or a company due to their current air travel, see discussion at the end of this section.)

The Climate Challenge:

It is becoming increasingly clear that climate change is happening faster than was expected (e.g. loss of Arctic sea ice, see e.g. Shepherd and Wingham, 2007) and triggering positive feedbacks (e.g. methane emissions in Siberia, see e.g. UNEP, 2007) that may lead to unprecedented and possibly irreversible

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[38] E.g. Forster and Rogers (2008) state: *Impacts of short-lived species depends on location (altitude and geography), season, time of day, and background conditions such as temperature, chemistry and weather yet none of the metrics take into account regional forcings and their effects on the climate.*

[39] For more on this topic, see the ACCRI report, "A Report on the Way Forward Based on the Review of Research Gaps and Priorities," available at http://tinyurl.com/4zuwhg

changes. At the same time, anthropogenic emissions are growing faster than was predicted by even the highest IPCC emissions scenario (Raupach et al., 2007). It is therefore no exaggeration to say that we are facing a climate emergency. Addressing this emergency will require changes on a scale we have never undertaken as a human society.

Given the urgency of the climate change challenge, it is an ethical imperative to proceed following the precautionary principle and include all warming effects to the best of our knowledge.

Equity:

The wealthy are disproportionately responsible for air travel, yet the impacts of climate change will be felt disproportionally by the poor (Grassl and Brockhagen, 2007).

We believe that an ethical argument can be made that the effects of aviation should be accounted for to their fullest extent, so that mitigation policies and offset options are based on fully internalized climate costs of aviation.

Multipliers or any other type of metric that tries to express the full climate impacts of aviation have to be chosen carefully depending on their specific intended purpose. Our recommendation is specifically intended for calculating the non-CO_2 portion of the climate footprint resulting from an individual's or a company's air travel. It is NOT a general recommendation for calculating the impacts of all emissions from air travel. For example, certain aviation policy choices might lead to a decrease of short-lived GHGs but an increase in fuel consumption and therefore (long-lived) CO_2 emissions. In this case, a long time frame would need to be used to evaluate the most climate-friendly policy, because long-term climate effects would likely outweigh short-term benefits from reducing shorter-lived GHGs. In this example, one policy option is being weighed against another. But for our purposes of calculating total climate footprint, CO_2 effects are already accounted for and the question we are answering is: how much should we add (expressed as a multiplier) to account for non-CO_2 effects?

For all of the reasons elaborated above, we advocate that a multiplier of at least 2 be used for air travel emissions calculators[40] to account for non-CO_2 warming effects[41].

We emphasize that our recommendation is not solely based on scientific arguments, but on ethical ones as well. It is based on our best understanding of the current knowledge of aviation emissions in particular and climate science in general. As the science progresses, the models become more sophisticated, and the ethical and political debates on climate change develop in the coming years, our recommendation should be revisited and refined.

[40] Coincidentally, the RFI figure of 2.7 frequently used and cited in air emissions calculators fits with our own recommendation of a multiplier of at least two. Although the numeric figures happen to be very similar, they are based on different metrics. We can therefore say that the results of calculators that do use the RFI figure of 2.7 are not necessarily wrong, despite the fact that they are based on an inappropriate choice of metric.

[41] An exception to this might be short-haul flights. Many non-CO_2 climate change effects (such as NO_x catalysis and contrail/cirrus formation) tend to take effect when aircraft cruise in the upper troposphere/lower stratosphere. Short-haul flights either spend a small portion of their overall air time in the UT/LS, or none at all (in the case of turboprop short-haul aircraft). This could imply that it would be inappropriate to assign the full emissions multiplier to these flights. It would be interesting to elaborate on this topic, which goes beyond this paper. We welcome suggestions and comments: please contact us at anja@sei-us.org.

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Appendix 1

Simplified Mathematical Background for the FAA/APMT Model

The RFI attempts to answer the question, “Given the gases currently present in the atmosphere, what is the current impact on the Earth’s radiative energy balance?” It is an important question to answer in order to understand climate, but is not as useful for addressing economic concerns or for comparing the non-CO_2 effects of aviation to the CO_2 emissions caused by air travel. In contrast, the FAA/APMT asks, “If someone travels today, what is his or her total impact on the Earth’s climate, considering both short-term and long-term effects?” Thus FAA/APMT is forward-looking, while RFI is backward-looking. The question that the FAA/APMT seeks to answer is better suited for economic analysis.

Other than the question of whether future or past cumulative impacts are being assessed, the calculations underlying the FAA/APMT approach are very similar to those that lie behind the RFI. Yet they differ in that the FAA/APMT model allows us to calculate future damages:

To understand the FAA/APMT approach, suppose that during year zero ($t = 0$), 1 kg of CO_2 is emitted. Then over time the atmospheric concentration of CO_2 due to that 1 kg of emissions will change in a way that can be predicted. Call the time-dependence of the atmospheric concentration $G_C(t)$. Then the change in the concentration of CO_2 $\Delta C(t)$ from that 1 kg over time is:

$$\Delta C(t) = G_C(t) .$$

In reality there will not just be 1 kg emitted at one time. Instead, there will be a series of emissions, one in each year, and the effects will add up. That means the emissions have to be added up. If the emissions over time are denoted by $Q(t)$, then:

$$\Delta C(t) = \int_0^t Q(t')G_C(t-t')\, dt' .$$

If the emissions are known, and the link between emissions and atmospheric concentration over time is known, then the change in atmospheric concentration from those emissions can be calculated. This can then be used to calculate the radiative forcing $RF(t)$, since radiative forcing depends on the atmospheric concentration. This is a way to calculate a RF which is forward-looking. It differs from the RF which was used in the IPCC report to calculate the RFI, which takes into account cumulative emissions but does not take into account future effects. (Again, this is relevant only for long-lived gases because short-lived gases will not accumulate over time).

$$RF(t) = RF_0 + 5.35 \times \ln\left(\frac{C_0 + \Delta C(t)}{C_0}\right) .$$

The change in temperature from radiative forcing at a specific time can be delayed. For this reason, there is not a direct connection between $RF(t)$ and the change in temperature. Instead, it follows a relationship much like the relationship between emissions and concentration:

$$\Delta T(t) = \int_0^t RF(t')G_T(t-t')\, dt' .$$

These are the basic equations that lie behind the FAA/APMT approach. In order to calculate them, they require an understanding of how the carbon cycle responds to carbon emissions (captured by $G_C(t)$), and an understanding of how the climate system responds to a change in radiative forcing (captured by $G_T(t)$). A nice feature of this approach is that it can take into account the uncertainties in those connections by varying $G_C(t)$ and $G_T(t)$ over the range of possibilities, multiplied by the probability that they could have one value or another.

In order to draw economic conclusions from a change in climate, it is necessary to link the change in temperature to potential damages via a damage function. While acknowledging the difficulty of constructing such a function, the authors of the FAA/APMT model chose the damage function of Nordhaus and Boyer (2002), which has the form:

$$D_k(t) = a_{1,k}\Delta T_{1900}(t) + a_{2,k}\Delta T_{1900}(t)^2 .$$

In this equation, $D_k(t)$ is the percent change in GDP, k represents a region, and $\Delta T_{1900}(t)$ is the change in temperature since 1900 in Kelvin. To estimate the global average impact, use a_1 = -0.0045 and a_2 = 0.0035. In order to estimate the marginal damage from a particular effect, the damage from all anthropogenic effects except the effect of interest is subtracted from the total damage from all anthropogenic effects. (This roundabout approach is necessary because the damage function does not change linearly with changes in temperature. It is also required for background CO_2 emissions since the marginal RF of CO_2 depends on the background concentration of CO_2 as shown in the logarithmic relationship.) That is,

Damage[effect_i] = Damage[all anthropogenic effects] – Damage[all anthropogenic effects – effect_i].

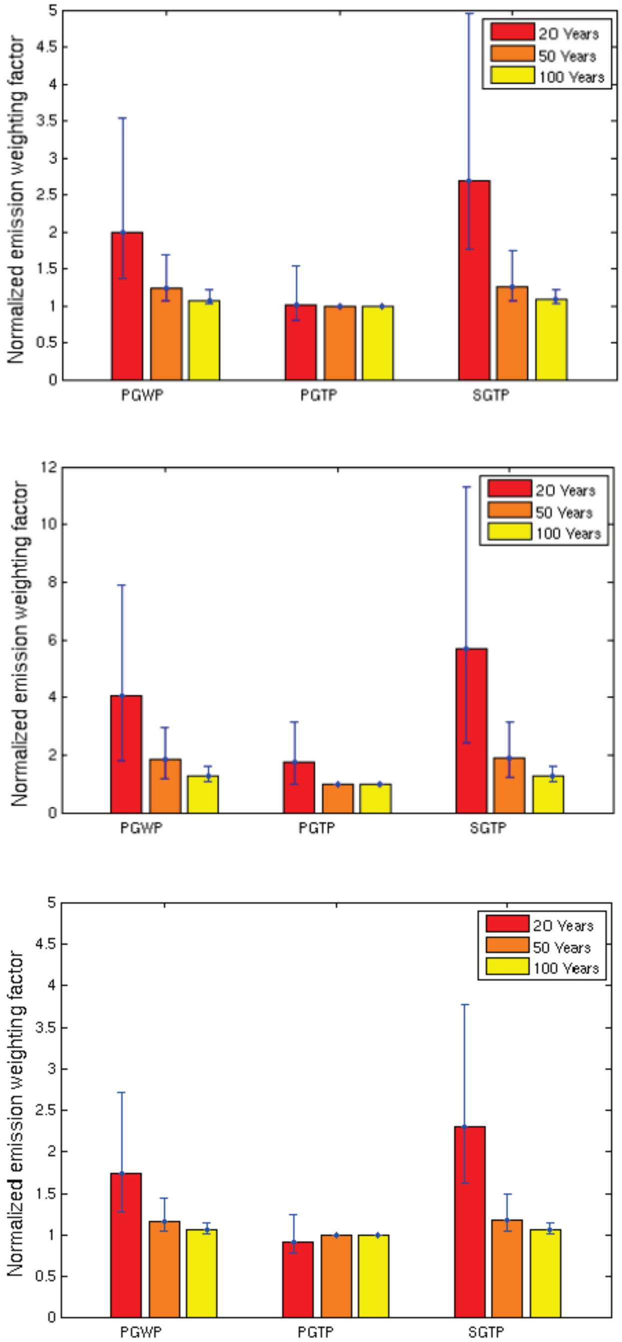
Finally, the costs from damages are discounted over time at a particular discount rate r to calculate the net present value (NPV) of the climate impact, using the standard financial formula

$$NPV(T) = \sum_{t=0}^{T} \frac{\Delta D(t)}{(1+r)^t} ,$$

where t runs over all of the years from the initial year zero to year T and $\Delta D(t)$ is the marginal damage from the effect of interest.

Appendix 2

Figure 9 from Forster and Rogers, 2008, p 35



Total aviation impact has been normalized to CO_2 impact, creating an emission weighting factor appropriate to the current fleet. Error bars present uncertainties arising from NOx and contrail forcings.
Top: Excluding the highly uncertain aviation-induced cirrus (AIC).
Middle: Including AIC.
Bottom: Excluding AIC, and assuming an efficacy of 0.6 for contrail forcing. Note that the scale on the y-axes varies between frames. (Source: Forster and Rogers, 2008)